PRINCIPLES AND PRACTICE OF WAR SURGERY

TRUETA

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With Reference to the Biological Method of the Treatment of War Wounds and Fractures

BY

J. TRUETA, M.D.

Formerly Director of Surgery, General Hospital of Catalonia,
University of Barcelona; Assistant Surgeon (E.M.S.)
Wingfield-Morris Orthopaedic Hospital, Oxford;
Acting Surgeon-in-Charge, Accident Service,
Radcliffe Infirmary, Oxford

With Introduction by

OWEN H. WANGENSTEEN, M.D.

Minneapolis, Minn.

WITH 144 TEXT ILLUSTRATIONS

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Nihil est hic opus disputationibus,
sed contemplatione natura tacita.

JUAN LUIS VIVES
in *De Tradendis Disciplinis*, 1531

One of the greatest figures of the Renaissance, Juan Luis Vives, a scholar of Catalan stock, lived in Oxford from 1523 to 1528, a voluntary exile from his native Valenica. He was in residence at Corpus Christi College where he was made Doctor of Laws and lectured on philosophy.

PREFACE

When the results obtained with the treatment that forms the subject of this book were first reported in Great Britain, the immediate reaction was one of skepticism. This did not surprise me, for I had seen the same reaction among my fellow countrymen, the Catalan surgeons, in 1934, and among the surgeons of the Spanish Republican Army in 1938, and among French surgeons in 1939.

Much has happened since then, however, and the spread of the war has offered many occasions for putting the treatment, and the claims made for it, to the test. Among others, Cohen and Schulenburg (1940) have published the results of 84 cases treated without a single death by a technique which, if not identical with mine, was at least based on the same principles. Shepherd (1941) gave an account of the 49 cases he had treated, following the technique more closely, with one death—probably from heart failure. Ball and Qvist (1941) declared that the cases they had treated on these lines "gave excellent results." In America Wilson (1941) published equally favorable impressions based on a series of 50 cases. Scott (1942) has given a detailed account of his good results in 32 cases with one death. Higgs (1941) published 44 cases treated at his hospital after the evacuation of Dunkirk. There were no deaths, although most of the men had already been operated on under difficult conditions. His impressions, too, were very favorable. To these citations more could be added, but I will mention only the 200-odd cases treated at the Wingfield-Morris Orthopaedic Hospital during the past two years, with only one death—from pulmonary collapse under anesthesia during the changing of a plaster. Adding together all these cases, over 450 have been reported with three deaths. This mortality is not far from the six deaths among my 1,073 cases in Barcelona: but as this was the period of trial, in Britain I feel sure that even lower death rates may be expected. Thus my first statement about the value of the method may, I think, be considered proved; and I can only urge those surgeons who are still averse to encasing wounded limbs in plaster, preferring methods which permit of daily examination of the wound, to try the treatment for themselves and accept the evidence of their own results. But the technical procedures must be adopted as a whole. Every item in the "five-point program" described in Part II is essential: to practice some and omit the rest is to invite failure, or at least only a qualified success.

The second fact which emerges from experience in Great Britain is that the quality of the results is to a large extent independent of the

surgeon's skill. Success depends mainly on a clear understanding and careful practice of the principles on which the method is based. At the Wingfield-Morris Orthopaedic Hospital results have been uniformly good, including those of several house surgeons with but a short experience in this branch of surgery. Still more conclusive proof comes from a provincial hospital connected with the Wingfield-Morris Orthopaedic Hospital where, during a short visit, I was invited to operate in a case of compound fracture of the tibia and fibula which had just been admitted. Some local surgeons were present at the operation. A month later I came back to the hospital to find my patient still in the first plaster and making an uneventful recovery. But I also found in bed five other patients, among them one with a serious gunshot fracture of the humerus, all free from complications. The operations on these patients had all been performed by the local surgeons. It was a striking corroboration of my view, expressed when I first arrived in this country, that the method is the only one that can be employed in all conditions by all sorts of surgeons. A system which needs either elaborate apparatus or a high degree of specialization in the surgeons is of little use in war conditions.

Nevertheless, it would be misleading merely to state that the method is simple and leave it at that. Nothing—to take a familiar example—could be simpler than the ritual of asepsis followed in every well-ordered operating room; yet, as every surgeon knows, few procedures are so fraught with possibilities of dangerous error, not indeed from willful negligence but from a failure to appreciate the reasons for, and the significance of, every step in the ritual. Similarly with this surgical technique. Every detail represents the fulfilment of the fundamental principles discussed in the first part of this book. The more thoroughly these are mastered, the more precisely will the technique described in the second part be carried out.

Within the narrow limits of my first volume on the subject—published in Catalonia during the Spanish War, and later, on the outbreak of the present wider conflict, in English*—it was impossible to give full weight to every factor involved in successful treatment. Writing under the stress of active warfare, I dwelt mainly on those factors which seemed in greatest danger of neglect. Thus I assumed that less need be said about the principles of wound excision than about the need for complete immobilization, the vital importance of which seemed less generally appreciated. While, then, I was content to draw repeated attention to the former, I devoted the greater part of the work to the latter, with the unfortunate consequence that the encasement of wounded limbs in

*Treatment of War Wounds and Fractures. Hamish Hamilton Medical Books, London; Paul B. Hoeber, Inc., New York.

plaster came to be regarded, by some surgeons, as the one essential of my technique. It is perhaps not surprising that from this error there arose yet another: namely, the view that the method is usually complicated by the development of infection beneath the plaster.

Obviously it would have been better to have taken nothing for granted; and one of the chief aims of the present work is to supply all the details of technique that the earlier one lacked. It is also concerned with the scientific basis of my methods, a subject on which, in view of the limited opportunities for research in wartime Catalonia, I could formerly have said very little. Since returning to hospital life, however, I have supplemented my clinical work with studies which have gone far to explain how the treatment produces its effects. To these observations, clinical and experimental, I have added those made previously in my own hospital in Barcelona, extracting from my memory all the matters which then constituted my special problems and endeavoring to supply an answer relevant to our time.

Inevitably it has had to be my own answer. In the conditions forced upon us by war it is often impossible to direct cases to the appropriate specialists, and the surgeon thus finds himself again and again under the necessity of solving his difficulties for himself. It is perhaps not altogether a disadvantage, then, to show how such difficulties presented themselves to one surgeon and how he learned to deal with them. No doubt some sections could have been written differently if their authors had been specialists concerned exclusively with their own subjects—e.g., bacteriology, anesthesia, or plastic surgery; but in the conviction that the surgeon can do his best work only when he feels competent to deal alone, if necessary, with all the problems that may come within his experience, I have preferred to discuss these problems in the forms in which he is most likely to meet them, bringing in the point of view of the specialist less in the hope that the general surgeon will make it his own than that it will give him insight into his own limitations, and thus encourage him to take full advantage of specialist help when it is available.

It is impossible to make fitting acknowledgment to all the friends and colleagues who, by their help and encouragement, have enabled me to carry out the work on which so much of this book is based. My thanks must be wide enough to embrace the whole of Britain, which has most generously given me a refuge, and more than that, a home in the warmest sense of the word. I arrived an exile and found myself among friends. First among those to whom I must express thanks individually is Mr. G. R. Girdlestone, consulting surgeon to the Wingfield-Morris Orthopaedic Hospital, through whose kind offices I have been able to

return to hospital life and to enjoy the opportunities for work and research so abundantly offered by the hospitals and University of Oxford. Much of the research was carried out at the Sir William Dunn School of Pathology, Oxford, in the laboratories of Professor H. W. Florey, from whom I received every facility and much stimulating criticism. The animal experiments were made with the collaboration of my friend Dr. J. Barnes, and it is to his care and severity of judgment that our results must be attributed. I also received great encouragement from Professor H. J. Seddon, to whom, as to the other friends and colleagues I have named, I am glad to express my deep gratitude. My most sincere thanks are also due to Dr. A. E. Barclay, honorary radiologist to the Nuffield Institute for Medical Research, Oxford, where, with invaluable advice and help from him and his staff, part of the investigation was carried out and a number of the radiographs were made. On the clinical side I am particularly indebted to Mr. J. A. Scott, assistant orthopaedic surgeon at the Wingfield-Morris Orthopaedic Hospital, with whom it has been my privilege to share most of the operations which illustrate this book; and to Mr. W. B. Foley and other members of the staff, through whose generous help I have been able to add so many cases to those reported from Barcelona. For their kindness in revising and criticising some of the special chapters I must express my gratitude to Professor R. R. Macintosh and Dr. P. Gabarro. To Dr. Durán Jordá, former director of the Spanish Republican Army Blood Transfusion Service and now clinical pathologist to Ancoats Hospital, Manchester, I owe warmest thanks for his help in the rearrangement and revision of the chapter on Blood Transfusion, and for placing at my disposal his vast experience in this field. I wish also to express my most sincere gratitude to Miss M. M. L. Prichard, through whose patient and untiring labor the chapters of this book gradually took form. Without her help the work could never have been produced. For further assistance in the presentation of the matter I acknowledge with gratitude the help of Mr. D. Harcourt Hitchin; and for his great kindness in helping me over the laborious task of proofreading I owe the warmest thanks to my colleague Mr. R. Bransby Zachary. Most of the drawings which illustrate the text are the work of Miss A. J. Arnott; and most of the photographs were taken by the photographic department of the Wingfield-Morris Orthopaedic Hospital, under the direction of Mrs. M. Crossley. I am deeply grateful for their help. To my friend Dr. M. Newfield, of Hamish Hamilton Medical Books, I wish to express appreciation and thanks for his help in giving the material final shape and in seeing the work through the press.

Finally, some acknowledgments which must be made separately. The reader who has the patience to persevere to the end of this book will realize that there is little new in the technique described; on the contrary, most of its components have been used and described in the past. My main contribution has been to combine several established principles, so that the benefits of each might be increased by their logical use in a single method of treatment. To all those who discovered and taught the value of these principles I owe a great debt. But it is to Friedrich and more particularly to Winnett Orr, who above all others lighted the path I have followed, that my gratitude is chiefly due. I have proclaimed this before, but there is no other or more fitting note on which I would wish to introduce this book.

J. T.

Oxford, England

INTRODUCTION

OWEN H. WANGENSTEEN, M.D., MINNEAPOLIS, MINN.

Dr. Trueta's account of his surgical experiences during the recent War in Spain has made him well known to American students of surgery. His advocacy of encasement of injured extremities in plaster-of-Paris casts struck a familiar note and a sympathetic interest among his American readers. This larger and more inclusive discussion of the problems of military surgery should find a warm reception in this country.

Two new therapeutic expedients which have come on the scene since World War I already have established themselves as agents of the greatest worth in military surgery, viz., the sulfonamides and transfusions of plasma. The Pearl Harbor experience with these agents, as recorded by Ravdin and Long* and the surgeons of our Military Forces† in attendance at the time of that disaster suggests definitely that these two therapeutic agencies, new to the surgery of warfare, will prove a great boon to the wounded and to military surgery.

With the advent of the triumphant exploits of the new science of bacteriology during the last decade of the past century came the hope of an immunologic specific for almost every bacterial disease. That hope, the fulfillment of which seemed almost assured, never materialized. Suddenly, bacteriology, which in a relatively short space of time revolutionized the practice of medicine, seemed to have become therapeutically sterile and promises of conquests almost within grasp in the immediate offing were no longer capable of realization.

Only as we scan the experiences of our predecessors can we appreciate fully how grateful we should be for the sulfonamides. Prior to the innovations of Lister, Nikolai Pirogoff, a Russian military surgeon of many campaigns wrote, in discussing "Fortune in Surgery": "The influence of the surgeon, the therapeutic resources and mechanical dexterity are of no importance; the results of an operation are dependent entirely upon chance." The sulfonamides also may prove not to be the long awaited chemical Messiah to lead us out of the bondage and fear of all suppuration; yet, the sulfonamides already have met fully, in many respects, the most sanguine expectations of a pharmacologic specific for pyogenic infections, entertained in the hopes of our medical antecedents of the first decade of this century.

*Army Medical Bulletin, No. 61, April, 1942.
†Hawaii Medical Journal, September-October, 1942.

The first care of the surgeon was the management of accidental wounds. With the advent of antisepsis and asepsis, the surgeon abandoned the epithet of "externist" and concerned himself as well with problems of the body interior, diseases which previously had been the sole domain of the internist. The surgeon devoted less thought and attention to the treatment of wounds. More and more, however, it became increasingly apparent that the surgeon who had schooled himself well in the fundamental tenets of wound healing could undertake successfully tasks which were impractical for the surgeon who failed to appreciate the great significance of careful hemostasis and accurate approximation of divided tissues for the success of any formal surgical undertaking. For the American surgeon, this doctrine of the management of the clean wound is represented best by the teachings of Halsted.

In the management of compound injuries and potentially infected wounds, World War I reawakened interest in the teachings of Desault and the practices of his pupil, Larrey, with reference to débridement and wound revision. The observations of Friedrich (1898) lent experimental support to the thesis of Desault that early excision of damaged tissue encouraged wound healing.

In the appearance of Dr. Trueta's book on The Principles and Practice of War Surgery in an American edition, it is perhaps not out of place to point out that Frederic S. Dennis, a New York surgeon, incorporated in his practice with considerable success, sixty years ago, the principles of wound revision and fixation very much as we know them today. Writing under the title of "The Treatment of Compound Fractures, Including a Report of One Hundred and Forty-Four Cases Without a Death From Septic Infection, and One Hundred Cases Without a Death From Any Cause," Dennis described in the June 21 issue of the *Journal of the American Medical Association* in 1884, his experiences with the management of compound fractures. The following paragraphs taken from the paper of Dennis appear to have a very modern touch. Only the local implantation of a sulfonamide and the use of plasma for grave injuries are wanting:

"It will be the aim of this paper to demonstrate by the results of a large number of cases that the treatment of compound fractures is best accomplished by adherence to three well-recognized and established principles.

1st. Absolute cleanliness.
2nd. Immediate fixation.
3rd. Provision for free drainage when necessary.

"The treatment which has been employed for the most part in the cases to be reported is in brief as follows:

"The patient having been taken to the operating theatre, is placed upon the table, and if the exigencies of the case demand, an anaesthetic

is at once administered. Anaesthesia relaxes the muscles, affords the surgeon an opportunity to explore thoroughly the extent of the injury without inflicting pain. The injured limb is washed with soap and warm water and scrubbed well with a brush. The dirt, debris, and blood are thus removed, and the hair on the extremity is cleanly shaved, and then the limb is irrigated for a few moments with a solution of carbolic acid (1:40) or with a solution of corrosive sublimate (1:2,000) or with any other well-known disinfectant. Gentle traction is made upon the extremity, while at the same time counter-extension is employed with a view to bringing the broken fragments into coaptation. If the bones protrude through the wound and cannot be reduced without the exercise of too much violence, the projecting end is removed by a chain-saw. It has been my custom when the protruding bones cannot be reduced without the exercise of undue violence, to divide subcutaneously all tendons and thus overcome all resisting forces. This operation secures physiological rest during the repair of the fracture.

"Attention now must be directed to the wound itself. Any loose fragments or spiculae of bone are removed, except where they are adherent to periosteum, in which case these detached pieces are preserved, and they seldom exfoliate owing to the blood-supply through the periosteum. The interior of the wound is thoroughly irrigated by a syringe, or by a tube from an Esmarch's wound-douche. Having cleansed the limb, including even the fingers and toes, and having adjusted the fragments and having washed out and disinfected the interior of the wound, the application of a splint is now made. The limb is elevated, and under it are placed towels saturated in some disinfectant solution, which keeps the limb from coming in contact with the covering upon the operating-table, or from the opposite limb, or from any part of the body. If the wound is small a piece of surgically clean adhesive plaster is placed over the seat of fracture, and then collodion is painted over the plaster. If the wound communicating with the seat of fracture is too large to hermetically seal in the manner already described, a part of the wound can be closed by catgut suture, and a drainage-tube is introduced into the bottom of the wound. Decalcified bone drainage-tubes are used, as they seem to answer the purpose in the most satisfactory manner. Into the wound, and over, and around the wound is sprinkled a layer of iodoform and then over this any of the many differently prepared dressings, such as corrosive sublimate gauze, or iodoform gauze, or absorbent cotton. The limb is now ready for the splint. A roller of Gamgee's absorbent cotton is heated which causes it to swell, and this is now made to envelope the entire limb. Heating the cotton seems to permit to it expand, and any dressing, such as a plaster-of-Paris bandage, can be snugly applied over it, and the cotton will not lose its wonderful elasticity. During the application of the bandage, extension and counter-extension should be employed,

the patient being at the same time well under the influence of ether. The bandage is now permitted to dry, and great care must be exercised while the bandage is drying, lest the patient while returning to consciousness, disturb the setting of the plaster and consequently the wound. The patient is placed in a suitable bed after the plaster-of-Paris bandage is firm. If there is no irritation or unpleasant sensation at the seat of fracture, if the toes or fingers are free from any numbness or cyanosis, if the respiration, pulse and temperature are normal, the first dressing is left undisturbed. In many cases the plaster-of-Paris bandage is worn until the fracture is repaired and primary intention has been obtained.''

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PART I

PATHOLOGY OF WAR WOUNDS AND GENERAL CARE OF THE WOUNDED

CHAPTER I

THE BIOLOGICAL PRINCIPLES OF TREATMENT

What are the defensive mechanisms which the body sets in motion to repair wound damage and to protect the whole system from the consequent dangers? This is a vital question to which we should know the answer before undertaking any kind of treatment. Although our knowledge of the defensive actions of the body in injury is still limited, we are now in a position to understand many of the processes which protect it against every form of attack.

Bleeding from a wound is arrested first by local reactions, such as contraction of arteries, occlusion of the ends of severed vessels by the apposition of the intima, and clotting of fibrinogen. When these fail to achieve their object, a general reaction produces a fall in blood pressure, which immediately limits the hemorrhage. Great disturbances are caused by the entry of pathogenic bacteria when the body has not been fortified against them by previous assaults. The resources of the body for repelling attack are enormous; nevertheless it stands to reason that the fewer the number of the invading organisms and the less their pathogenicity, the more successful are these resources likely to be. Bacteria require time for their development, and their opportunities for growth in tissues richly supplied with circulating blood are very poor. The dead tissues, as well as supplying an ideal medium for bacterial growth, lay on the body a heavy task of elimination and thus delay the reparative processes. The retention of organic fluid in a wound facilitates bacterial reproduction.

When an inflammatory process is developing, the body takes measures to limit the infection; e.g., automatic immobilization depending on periarticular muscular spasm (in arthritis), intestinal paralysis and rigidity of the abdominal muscles (in peritonitis), decrease in thoracic movements (in pleurisy). All these are familiar defensive reactions. The only way in which, as surgeons, we can reinforce them is by assisting Nature in the removal of obstacles to healing. In excising a wound we anticipate Nature in eliminating the dead tissues, a process which would otherwise be long and hazardous, and so ensure that the repara-

On the whole, the Arabs appear to have been influenced more by Galen than by Hippocrates, whom they followed only in the use of the cautery. This was largely due, no doubt, to the religious scruple of Mohammedans against drawing blood.

A further stimulus to the practice of cauterization (or to the use of its substitute, boiling oil) came with the discovery of gunpowder. This agent for the propulsion of missiles resulted in so great an increase in the complications of wounds that a widespread idea sprang up that the wounds produced by it were poisoned (di Vigo, 1514), and thence followed an even greater insistence on the need for cauterizing. It was not until the middle of the sixteenth century that the error was recognized, when Ambroise Paré by his insight made a contribution to surgery no less beneficial than that of Lister three centuries later.

Hippocrates, in all his other aphorisms concerning surgery, expressed views based on sound principles. To mention only one example, he stressed the therapeutic value of rest. But the most important feature of his work and teaching, one which alone would have made his name immortal, was his firm belief in the "healing power of Nature." This maxim incorporates the essential truth of the whole art of healing and is the fundamental basis on which the medical science of today has been built. Thanks to the advances made in recent years in other scientific fields, such as optics, chemistry and physics, we now have adequate means of investigating the various mechanisms by which Nature works, and much of our effort today is directed, first, to discovering the reactions of the body to external aggression, and then, when these are known, to cooperating in their fight against the invader. In reinforcing antibodies and leucocytes in their fight against bacteria, in limiting the absorption of toxic products and removing the "foreign bodies" present in all wounds, medical practice of today is following the precept of Hippocrates and "assisting Nature."

Galen.—Whereas the teaching of Hippocrates was largely sound, that of Galen (A.D. 131-201), the other outstanding figure in the ancient world of medicine, was fundamentally wrong. Galen was the founder of experimental physiology, and as such deserves much credit, but the fact that surgery made virtually no progress for the next fourteen centuries is largely due to the speculative theories and false conceptions which he introduced and which, by virtue of his great personality and wide reputation as the leading physician of his age, were accepted without question both by his contemporaries and by many succeeding generations. Among his many errors the two most important from the point of view of surgery were his view that suppuration or, as he termed it, "*coctio*"—a Latin version of the Greek *pepsis* or natural tendency to recover—was an essential part of the healing process, and his belief in the "miraculous" healing effects of certain substances.

After Hippocrates and Galen.—In the light of the teaching of Hippocrates and Galen the surgeons of the succeeding ages can be classified into two groups. Those of the one group, to which by far the greater number belonged, followed the Galenist school and labored to heal wounds by various methods of constant interference and by the application of certain "miraculous" substances. These men accepted suppuration as an inevitable feature of wounds, and, not understanding what Nature's action really was, confused the complications with the healing process. In the other group—a very small one—were those who, with Hippocrates, believed in the supreme power of the Creator to which all their actions must be attuned, and which in some instances must be redirected when deflected from its normal course by interfering agencies. To form a picture of the gradual emergence of modern conceptions from the fallacious beliefs of ancient times, it will be worth while to consider briefly the work of these comparatively few enlightened men, whose achievements shine out as beacons in the dark days of the past.

With the fall of the Roman Empire of the West under the onslaught of the invading barbarians of the North, the knowledge of Greek medicine was entirely obliterated throughout western Europe. Charles Singer (1923), in his study of biology in ancient Greece, says: "Had a translation of Aristotle's *Historia animalium* or *De generatione animalium* survived, had a Latin version of the Hippocratic work *On Generation* or the treatise of Theophrastus *On Plants* reached the earlier Middle Ages, the whole mental history of Europe might have been different and the rediscovery of nature might have been antedated by centuries." As an example of the fate of the Greek treatises Singer mentions the *On Plants* of Aristotle. The Greek original was lost, and (apart from a Latin version) only an Arabic version of a former Arabic translation of a Syrian rendering of a Greek commentary is known!

In the East, however, the Byzantine Empire, which was familiar with all aspects of Greek culture, preserved the teaching of Greek medicine for more than nine centuries. The Byzantines made no contribution to the progress of surgery in its wider sense as a science, and little from the point of view of technique, but we owe them a great debt for being the faithful custodians of all the great works of the Greek period; so that when the Byzantine Empire was destroyed by the Turks in 1453, and its servants were dispersed, Europe was given the opportunity of studying the culture and teaching of the Greeks, not from the garbled translations of the Arabs but from the original manuscripts brought away from Constantinople. This factor played no small part in the revival of all intellectual and artistic pursuits in the Renaissance period.

Salerno.—Meanwhile, however, two important schools of medical teaching had been established in the West, one at Salerno in South Italy (founded in the 10th century) and the other as Montpellier in the South of France (founded in the 8th century). Salerno was the first center of revival of the Hippocratic teaching. Here, in that part of Italy which formed part of Magna Graecia, this school inherited some of the traditions of Greek culture and was in contact with men from other cities where Greek teaching had been preserved, such as Byzantium in the East and Toledo (a great center of Arab and Jewish culture) in the West. These varied influences produced a school of thought which, by the great part it played in establishing the medical schools of Bologna, Pavia and Padua in North Italy, served to link Hippocrates to the men of the Renaissance period. Montpellier, by contrast, had no traditions of Greek culture, and being very largely under the influence of the flourishing centers of Arab culture in Spain, never clearly understood Greek ideas, which reached it only through Arab misinterpretations. The Catalans Arnold de Vilanova and Ramon Lull were the greatest figures of that Arab-Montpellier period (13th to 15th centuries).

The leading surgeon of the Salerno school was the Bishop of Cervia, Teodorico Borgognoni, or Theodoric (1205-1296), whose father Hugo de Lucca, also a surgeon, had gained much experience during the Crusades. As son and pupil of his eminent father, Theodoric used his authority to oppose the Galenist doctrine of "coction" and was the first to recommend the expectant treatment of wounds, known as dry treatment, saying, "It is not necessary that pus should be generated in wounds. No error can be greater than this. Such a practice is indeed to hinder Nature, to prolong the disease, and to prevent the conglutination and consolidation of the wound" (see Brown, 1931). Theodoric also introduced arterial ligatures. Another surgeon of the Salerno school, Bruno de Longoburg, held similar opinions, and in his *Chirurgia Magna* (1252) advocated the same principle of dry treatment. He, too, contributed to the technique of surgery by using sutures with separated stitches to allow drainage (see Giacosa, 1901). Henri de Mondeville, who was of Norman origin and a lecturer in Montpellier, appears to have become acquainted with Theodoric's work in Italy, and was another of those who believed that suppurating wounds should be washed clean and nothing whatever put in them. His manuscript, passed over at the time of the Renaissance because his pupil Guy de Chauliac had described it as being incomplete and of little value, was published for the first time only in 1892 (see Nicaise, 1893).

Montpellier.—Surgeons of the Montpellier school, led by Guy de Chauliac (1300-1368), a man of great talent and personality, followed

the Galenist doctrine that the surgeon must interfere in the healing of the wound. De Chauliac and many others of his school spent endless time and ingenuity in trying to find some "miraculous" substance which would help to produce suppuration and so, as they believed, promote healing. One of de Chauliac's pupils, Pietro d'Argelata, who after his training at Montpellier went as professor to Bologna, taught the dry treatment of wounds, but under the influence of his teacher also advocated various strange powders. D'Argelata also used sutures and was the first surgeon to put drainage tubes into wounds (1499). Owing to de Chauliac's great influence the Montpellier surgeons were all imbued with principles which were fundamentally wrong, and therefore this school, in other respects an important medical center, made no advance in surgical technique. Moreover, de Chauliac's authority and prestige were such that his methods were adopted throughout Europe as the orthodox treatment of wounds, with the result that surgical interference with the body's natural power of healing was the general and widespread practice until the Renaissance (see Malgaigne, 1840).

Paracelsus.—Perhaps the greatest medical man of this period, and one of the most interesting of all time, was Aureolus Theophrastus Bombastus von Hohenheim (1493-1541), better known to us as Paracelsus. This extraordinarily vigorous and versatile Swiss was a man of wide culture, with a keen faculty of observation. Among his many notable achievements was the re-introduction of the Hippocratic principle of assisting the healing power of Nature. In his book on the treatment of wounds published in 1528 he made the wise observation that it is Nature's balsam, not the surgeon's interference, that heals wounds.

Vesalius and Servetus.—Meanwhile great progress was being made in the field of anatomy and physiology. The teaching of Vesalius (1514-1564) in Padua and Paris and the publication of his book *De Fabrica Humani Corporis* (1543), in which he confuted the Galenist teaching of anatomy and thereby made enemies of a number of his contemporaries, furnished surgeons with better knowledge and a sounder basis for the logical treatment of wounds. Three years older than Vesalius, and a fellow-teacher of anatomy in Paris, was Miguel Servet (1511-1553), who may be considered the real founder of human physiology. He wrote the first description of the pulmonary circulation and oxygenation of venous blood in the lungs which was wholly contrary to the Galenist school of thought. The year in which Servetus made this discovery is not known, but a full description of the pulmonary circulation has been found in the manuscript of an unpublished work entitled *Renovatio Christianismi* (dated 1546). A similar account ap-

peared in his *Christianismi Restitutio,* the book for whch he was burnt at the stake as a heretic by Calvin in the year of its publication, 1553.

The discovery of the truth about the circulation of the blood had a profound influence on subsequent medicine, but tradition and prejudice yield very slowly to revolutionary innovations, and it was only after Harvey's time that the new conception was universally accepted. It is unlikely that Harvey knew Servetus' work at first hand, but his period of study in Padua undoubtedly provided him with the influence which determined the lines of his future investigations. The various references to the pulmonary circulation by Vesalius, Colombo and Cesalpino, and the discovery of the existence of venous valves by Harvey's own teacher, Fabricius ab Aquapendente, all indicate the interest in the circulatory system which Servetus had stimulated in the Paduan and other schools of North Italy, and the direct chain of thought linking Servetus with Harvey.

The work of these two great men of the 16th century, Vesalius and Servetus, combined to provide the fundamental basis on which the principles of modern surgery have been established. Every anatomist of today is a pupil of Vesalius, every physiologist a pupil of Servetus.

Paré and Botallo.—The steady increase in knowledge of human anatomy and physiology at this period had far-reaching results, for it stimulated physicians to disregard philosophical theories and to investigate the facts for themselves. Surgery followed the advancing trend of general medicine, although at a somewhat slower pace, and it is not a matter of chance that this era produced the two first great surgeons of modern times, Paré and Botallo. Ambroise Paré (1509-1590) was a man of real genius who, like all the best surgeons of bygone days, acquired his experience on military service. At the age of 19, convinced by a chance experience that a wound healed better when not cauterized with boiling oil, he introduced a simple paste made of turpentine, oil of roses, and yolk of egg. The surgery of subsequent years owed much to Paré, not only for many improvements in surgical technique but also for his supreme confidence in the healing power of Nature, which he epitomized in the well-known saying "Je le pansay, Dieu le guarit" (1586). His book on the treatment of war injuries, "*La méthode de traicter les playes faictes par harquebutes et aultres batons à feu,*" may still be read with pleasure and interest today.

Leonardo Botallo, an Italian born in 1530, served in the French Army and went to Paris in 1564, where he won favor with the Royal family and particularly with Catherine de Medici, the widow of Henry II. The prevailing belief that gunshot wounds were poisoned led him to investigate the various ingredients of gunpowder, and he showed that it contained nothing poisonous or caustic. He then concluded that the

poisoning of wounds was due to foreign bodies, under which term he included not only matter introduced from outside but also fragments of bone, contused and lacerated tissue, and clots of blood. These foreign bodies, he declared, must be removed and the affected area restored to conditions as approximately normal as possible. If only the surgeons of his day had been prepared to accept this discovery, the essential truth about the treatment of wounds, the surgery of the next two hundred years would have undergone an immeasurably healthier development. Botallo's book, *De Curandis Vulneribus Sclopetorum* (1560), like that of Paré, contains much of interest to the modern reader.

Magati.—Another army surgeon whose powers of accurate observation secured a further stage of advance was Cesare Magati (1579-1647). For the first time in the history of surgery, Magati pointed out as an indisputable fact the danger of surgical interference with the healing power of Nature. Born in Scandiano and a student of medicine in Bologna, he appears also to have spent some time in Rome, where he came to appreciate the advantages of the "rare cure." In his book, *De rara medicatione vulnerum* (1616), he makes some interesting comments on the practice of dressing a wound daily: "There are fourteen reasons why daily dressing of wounds is said to be necessary. One of these is that 'by uncovering the wound the putrefaction is exposed to view,' another that 'gangrene may supervene if wounds are not dressed frequently.' Thirdly, it is held to be necessary to renew the medicaments daily and observe their effects, to give a daily prognosis, to remove causes of irritation, and finally it has already been done, hence why change?" In opposing this method of treatment Magati says: "That method of cure by which wounds are treated most happily and quickly is the best and the most judicious. Experience has shown that with this new method (infrequent change of dressing) wounds are treated more happily and quickly than with any other, and therefore this new method is the best and most judicious."

After Magati, surgery made no real progress for a whole century. The intellectual ferment that characterized the Renaissance gradually died and was followed by an era of stagnation throughout Europe. In some countries the prestige of the surgeon fell so low that he was subjected to inconceivable indignities, a typical example being the flogging to which the Prussian surgeons of Frederick the Great were submitted when soldiers of his guard died of wounds: the higher the rank of the deceased, the greater the number of strokes the surgeons received.

Harvey, Hunter and Hewson.—England, however, did not experience the decline which followed the Renaissance. On the contrary, it was

in this period that William Harvey (1578-1657) made his invaluable contribution to the progress of medical science (1621). Harvey's detailed description of the circulation of the blood was based on direct observation and experiment, a revolutionary method of approach which also characterized the work of John Hunter (1728-1793) a century and a half later, and to which we owe the great progress of the last century. Hunter's experience as an army surgeon was limited, but his service with the expedition to Belle Île in 1761 and in Portugal a year later provided him with material for a book on the treatment of war injuries (1794). In this he described shock and inflammation and gave an excellent account of the part played by the lymphatic system in the absorption of foreign matter from the tissues, a conception which was given additional support by the discovery by Hunter's pupil, William Hewson (1739-1774), that the lymphatic system existed also in birds, reptiles and fishes (see Gulliver, 1846). Hunter's view that absorption is the function of the lymphatic system was generally accepted until a rival theory was put forward by Magendie (see p. 74).

The Pioneers of Conservation.—Johan Ulrich Bilguer (1720-1796) was the first person to advocate conservative treatment. According to Larrey, however, Bilguer's recommendations, published in his book *De amputatione membrorum rarissime administranda aut quasi abroganda* (1761), did a good deal of harm and led to many a life being lost in the attempt to save a limb. Other early exponents of conservative surgery were James Syme (1799-1870), whose book *The Excision of Diseased Joints* was published in 1831; and William Fergusson (1808-1877), who held that "It is a grand thing when by prescience even the tip of a finger can be saved" (1842).

THE BEGINNINGS OF MODERN TREATMENT

Desault.—Pierre Joseph Desault (1744-1795) was the real founder of the modern treatment of war wounds. He was the first surgeon to adopt the technique of *débridement,* which he taught to his pupils Larrey, Bichat, and Cassious. The exact meaning of the term *débridement* has been much discussed in recent years, but the sense in which Desault used it is clearly shown in the account given by him and Larrey, in which they described *débridement* as being a deep incision made for the purpose of exposing the anatomical structures and for exploring and draining the wound (Larrey, 1812). Desault also advocated conservative treatment, but he recognized that it must be based on certain definite principles, explaining, as Bichat (1813) quotes, "Sacrifier une partie à la conservation du tout, est la dernière ressource de l'art; il faut, avant de s'y resoudre, épuiser celles qui peuvent

rendre à la vie et à leurs fonctions l'ensemble de nos organes."* Desault was in charge of the surgical work at the Hotel-Dieu in Paris in 1785, and during the French Revolution gained much experience in the treatment of war wounds. His technique of initial *débridement* was quickly and widely adopted and led to an immediate improvement in results. But modern surgery is indebted to Desault for an even greater contribution, in that he established as a fundamental principle of treatment the precept, first introduced by Botallo in the 16th century, that dead tissues must be excised. His teaching on this subject is described by Larrey in the following words: "On prétendait que les incisions changeaient la nature des plaies d'armes de feu. Desault nous apprît qu'il ne suffit pas de rendre une plaie saignante pour la faire passer de l'état compliquée à l'état simple; que le seul moyen d'y parvenir est de réfraîchir avec instrument tranchant les bords contus."†

From this quotation it is clear that Desault himself attached far greater importance to the excision of dead tissues than to the simple incision, or *débridement,* of the wound. Larrey (1812) gives us an idea of the extent to which he himself carried the excision technique in a criticism of an operation performed by an army surgeon in Egypt: "L'officier de santé avait cru sufficient d'exciser avec cissaux quelques lambeaux desorganisés qui pendait au moignon . . . dans une désorganisation telle, de moins jusqu'à une certaine étendue, que sans la resection totale de l'os au-dessus de ses fracas et celle des parties molles dans le lieu où la circulation des fluides n'etait pas entièrement anéantie, le blessé devait périr, après avoir parcouru un cercle de deuleurs atroces."‡ Since the time of Desault and Larrey the two procedures, *débridement* on the one hand and excision or resection (the latter term is commonly used for bones) on the other, have formed the general basis of surgical technique, although the exact interpretation of each has varied from time to time (see p. 214).

Larrey.—To mention Larrey only as a disciple and follower of Desault, however, would be to do him an injustice, for he was undoubtedly one of the greatest military surgeons of all time. Dominique Jean Larrey (1766-1842) had the gift of being able to solve any problem to which he set his hand. A good organizer, a skilled technician and a hard worker, he was a man of complete sincerity and simple modesty. While

*"The sacrifice of a part for the preservation of the whole is the last recourse of the (surgeon's) art; before deciding on it the possibilities of restoring life and function to the sum total of organs should be exhausted."

†"It was claimed that incisions changed the character of wounds produced by firearms. Desault showed us that merely to make a wound bleed does not suffice to change it from the complicated to the simple state—that the only means to this end is to trim the bruised edges with a cutting instrument."

‡"The medical officer had thought it sufficient to remove with scissors some shreds of disorganized tissue hanging from the site of amputation . . . so disorganized, at least to a certain extent, that without the total resection of the bone beyond the injured area, and of the soft tissues in the region where the circulation had not been entirely destroyed, the wounded man would inevitably die, after a period of dreadful suffering."

still a student in Paris he took part in the storming of the Bastille, and at the age of 26 he was appointed chief of the medical services of the French army in the South. In 1797, after a short period as professor of surgery and anatomy at the military school of Val de Grâce, he accompanied General Bonaparte to the campaign in Italy, and thereafter was one of Napoleon's most loyal supporters, serving in his campaigns in Egypt, Spain, Germany, Poland and Russia.

The four volumes of his *Mémoires de chirurgie militaire* still make interesting and profitable reading. Many of his observations in this work are so accurate and show such great insight that it is hard to believe that they were written over a hundred years ago. His account of the techniques of *débridement* and excision has already been mentioned. He described the beneficial effect of maggots on wounds, an observation which more than a century later was made and put into practice by the American surgeon Baer. Larrey also declared that "traumatic gangrene" (gas gangrene) was a mortification of the tissues due to changes in the sympathetic nervous system which impair the nutrition and affect the secretions. He said: "Les principaux vaisseaux du membre affecté participent promptement de la maladie et cessent leurs mouvements; le sang s'y arête, surtout dans le système capillaire, se carbonise et le calorique s'en dégage."* In such cases he recommended immediate amputation. After the "bacterial theory" had been accepted, the idea that the sympathetic nervous system, by its influence on the blood vessels, played a part in the production of gas gangrene was entirely discredited, but recent evidence has shown how true this conception was. Clinical and experimental results have convinced me that vascular spasm is a factor of no less significance in the production of ischemia than the actual anatomical lesion of the blood vessel. So once again Larrey was right.

But the feature of Larrey's work to which modern surgery probably owes most of the improvement in its results was his insistence on the importance of early treatment. He was convinced that prognosis depended largely on the interval that elapsed between the injury and surgical assistance; and in order to reduce this interval and to bring hospital facilities within closer reach of the wounded, he developed an ambulance service. Ambulances were not an innovation; they had been used (for the first time, as far as I know) during the siege of Malaga in 1487 by the army of Ferdinand, King of Aragon, and again by Ferdinand's grandson, Charles V, during the siege of Metz in 1552. But before Larrey's time their use had been only occasional and it was he who created, as an inherent part of the army organization, that

*"The chief vessels of the affected limb are immediately involved in the malady and their movements come to a stop; the blood is arrested, above all in the capillaries, and becomes carbonized with the liberation of heat."

regular ambulance service which has ever since been indispensable in all mobile warfare. Larrey's own words, written after the campaign in Egypt, testify to the efficiency of the ambulance service under his command: ". . . Les blessés reçurent dans cette affaire de la part de tous les chirurgiens de l'ambulance les sécours les plus prompts et les plus efficaces; pas un ne resta plus d'un quart d'heure sans être pansé."*

Percy.—Another great army surgeon of Larrey's time, Pierre Percy (1754-1825), contributed much to the development of the ambulance system and to many other aspects of surgery in Napoleon's army. He worked on lines similar to those of Larrey and published the first account of the difference between wounds of entry and of exit, describing also the features of the wound track (Longing, 1904).

Pirogoff.—After the Napoleonic wars military surgery made no further progress until the campaign of the Caucasus in 1847 and, more particularly, the Crimean War in 1854 provided further opportunities for trying new surgical methods. The Crimean War produced another of the really great army surgeons of history, Nicolai Ivanovitch Pirogoff (1810-1881), who was in charge of the treatment of Russian troops in the siege of Sebastopol, which lasted for fourteen months. The conditions under which he had to work were appalling, and the number of men who died as a result of erysipelas, pyemia, hospital gangrene and purulent edema was so high that Pirogoff defined war as "a traumatic epidemic." Almost unaided, he toiled at his great task, striving to improve conditions and making many sound recommendations to combat the prevailing sepsis. Through the influence of the Grand Duchess Helena Pavlovna he was able to introduce female nursing for the Russian soldiers at the time when Florence Nightingale was providing a similar organization for the British army. Pirogoff was a firm believer in the importance of early surgical treatment and was one of the first to adopt all the more recent advances of surgery, as is shown by his use of ether anesthesia in 1847 only a few months after this was first advocated by Bigelow, and of plaster-of-Paris bandages in 1854, two years after Mathijsen's first description of this technique.

Ollier.—The next step forward was made in 1870, during the Franco-Prussian War, by the French orthopedic surgeon Louis Ollier (1825-1900). Ollier believed that absolute rest helped greatly in the healing of wounds, and introduced a technique of completely immobilizing the limb in a plaster-of-Paris cast, which he called the "occlusive technique." This was the first application of the principle of rest, in its best form, and it is interesting to recall the words Ollier used in 1872,

*". . . Through this activity on the part of all the surgeons of the ambulance, the wounded obtained the promptest and most effective help; not one remained more than a quarter of an hour without attention."

at a meeting of the Congrès Médicale de France held in Lyons, to describe the purpose of his treatment. "L'occlusion inamovible," he said, "repose sur deux principles essentiels et d'égale importance: (1) la protection de la plaie par un corps isolant que la mette à l'abri des germes infectieux; (2) l'immobilité complete, absolue, permanente de la région blessée dans un appareil fixe, enfermant toutes les parties dont les mouvements peuvent influer d'une manière quelconque sur les tissus devisés."* Ollier clearly appreciated the important part played in healing by protection of the wound and complete rest. He also pointed out the beneficial effect of the cotton-wool that he applied over the wound in absorbing the discharge and thus providing drainage; he did not, however, lay any great stress on this part of the treatment. It was left for Winnett Orr, more than fifty years later, to emphasize the importance of providing good drainage in the plaster-cast treatment of infected wounds. Ollier was aware of the dangers of applying his technique to recent wounds with serious bruising of the soft tissues. To quote him again: "Une complication que l'occlusion inamovible ne prévient pas plus que la septicémie aiguë, c'est la gangrène humide, ou gangrène septicémique, qui accompagne les grands traumatismes. J'en ai eu un certain nombre de cas l'année dernière, et je me suis demandé si la méthode que j'employais ne favorisait pas cette complication."† As a result of this doubt he advocated continuous irrigation instead of the plaster cast for cases of serious trauma. We now know that Ollier's hesitation in applying a plaster to these cases was fully justified, in view of the incomplete surgical technique which he used. In his day the importance of wound excision, stressed by Larrey, had been forgotten, and surgeons paid little attention to the dead tissues.

The importance of Ollier's work was not realized by the surgeons of his generation, but today, in the light of Winnett Orr's work, it can be fully appreciated. Ollier based his treatment on the protection of the wound and the complete rest of the affected region, while at the same time he provided some measure of drainage. Winnett Orr, in his technique, attached as much importance to the protection of the wound and the principle of rest as Ollier, but assigned an equal value to drainage. This marked a great advance, which made it possible to extend to a wider range of patients the principles of rest and wound protection by the use of a closed plaster cast.

*"Persistent occlusion is based on two essential and equally important principles: (1) the protection of the wound by an isolating substance which excludes infective germs, and (2) the absolute and persistent immobilization of the wounded region in a rigid structure which encloses all those parts of which the movements could in any way affect the divided tissues."

†"One complication which persistent occlusion does not prevent, any more than it prevents acute septicemia, is the wet or septicemic gangrene which accompanies severe trauma. I had a certain number of these cases last year, and I wondered whether this method which I was using did not encourage this complication."

Lister.—Meanwhile the introduction of antiseptic technique by Lister in 1867 altered the whole aspect of surgical problems and quickly enlarged the field of operative treatment. Though not discovered in the course of war, this technique had a great influence on surgical treatment in subsequent campaigns. It proved by no means an unmixed blessing. The ease with which good results could be obtained by antiseptic methods hindered the development of surgical technique, for many surgeons came to think that the actual operative procedure was a matter of minor significance, and that success depended entirely on the use of carbolic acid or some other antiseptic—a conception which was far from what Lister himself had in mind (see p. 184). In this connection it is of interest that Lister was one of the first surgeons of the modern period to advocate the use of drainage tubes. These had been employed in the Middle Ages by d'Argelata; and the practice was re-introduced almost simultaneously by Lister, and the French surgeon Chaissaignac (see Billroth, 1871).

With the general adoption of antisepsis there came a revival of the former Galenist attitude to the problems of surgery. The use of the new "miraculous" factor seemed to make unnecessary the more laborious task of learning intricate surgical procedures. The view spread that the surgeon's main task was to kill the germs in the wound, and that *débridement,* excision, drainage and all other purely surgical measures were of secondary importance. Thus, although the use of antisepsis, and of asepsis by steam sterilization which gradually replaced it (von Bergmann, 1888), led to a striking improvement in the results of treatment in surgical diseases, the outlook for compound fractures and wounds remained highly unsatisfactory. The reason for this difference lies in the fact that wounds inevitably produce areas in which the tissues are destroyed and the natural defense mechanisms are impaired; whereas in disease the tissues of the affected region lose little of their defensive powers and only in exceptional cases become necrosed. In these rare cases, however, as in gangrenous appendicitis, the results of antiseptic treatment were disastrous, for this, even when combined with drainage, was powerless to prevent an extension of the infective process. Only when surgeons began to excise the devitalized tissue (as in appendectomy) before they applied drainage did their results show improvement.

THE TWENTIETH CENTURY

In 1898 P. L. Friedrich, a German surgeon, published some experimental findings which showed conclusively that the excision of dead tissue was vitally important. The great value of Friedrich's work was that it furnished a scientific basis for the technique which Botallo had

recommended and Desault and Larrey had introduced as a clinical measure. Yet his findings, because they were derived from experimental work, made little impression on the surgeons of the day; and even though later they were accepted by a number of German surgeons they appear to have been unknown to the rest of the world. Thus in 1914 the practice of excision as an essential part of surgical treatment was limited to a few German surgeons, a fact which accounts for the surgical disasters of the first six months of the War of 1914 to 1918, and particularly for the high incidence of gas gangrene, which was specially marked in the Allied armies.

By the early part of 1915 it was generally recognized that a revision of surgical technique was imperative. Milligan (1915), Ranzi (1915), and Lemaitre (1916), published the first cases in the British, German, and French armies, respectively, in which excision had been used, and stressed its fundamental importance. This led to an immediate improvement in results. The success of the technique, however, encouraged surgeons to resort to primary suture after the excision in all cases treated within 8 hours (Gray, 1915; Gaudier and Hamant, 1916), a practice which led to another increase in the incidence of gas gangrene, closure by primary suture being permissible only where the surgeon can be sure that a sufficient local blood supply remains, a condition which, in war wounds, is often difficult to establish with certainty. The area over which the circulation may be impaired as a result of vascular spasm is considerable, and the tissues which are thus deprived of their proper nutrition may extend well beyond the reach of the surgeon's knife (see p. 46).

In injuries of civilian life gangrene occurs less commonly, owing to the smaller degree of shock, both local and general. Primary suture is successful in the treatment of many such injuries for two main reasons. First, in most cases there is little deep bruising, the damage being markedly less in the deeper tissues than in the superficial layers, and the wound is comparatively clean. Secondly, in peacetime patients can usually be brought quickly and carefully to hospital for skilled treatment by specialist surgeons. In wartime, however, both the nature of the injury and the facilities for treatment are entirely different. During the War of 1914 to 1918 when primary suture was used as a standard practice, the results varied in direct relation to such factors as the amount of dead tissue in the wound, the degree of general and local shock, the time of admission to hospital, the number of patients requiring treatment at the same time, and, perhaps above all, the individual skill of the surgeon.

In the present war, bad results following primary suture have also been numerous, owing to the peculiar nature of the most frequent

wound of today: that caused by the aerial bomb. This destructive weapon produces far greater damage in the deeper than in the superficial tissues; the patient suffers immediate and severe shock, both general and local, and the blood supply to the affected region is diminished by arterial spasm. Moreover, large numbers of persons suffering from wounds of this kind may be admitted to hospital at the same time, and the surgeon often has to work under continuous bombardment from the air. All these factors tend to give rise to complications when primary suture is used as a regular practice and not as an exceptional measure.

In an attempt to reduce the number of infective complications that followed either incomplete or incorrectly applied surgical treatment, Alexis Carrel (1915) introduced the use of sodium hypochlorite, a solution prepared by Dakin. Working in a field ambulance at Compiègne, he laid the foundations of a technique of irrigation which did much to improve results. He believed that the efficiency of the hypochlorite was due to its bactericidal capacity, but today we realize that it is actually due to the proteolytic capacity of hypochlorite, its lack of toxicity to the tissues and, more especially, to the fact that the continuous irrigation involves little interference with the natural healing process.

While Carrel was fighting infection with hypochlorite, Robert Jones was emphasizing the importance of rest in the treatment of wounds, and reintroducing the Thomas splint, which had been forgotten. Toward the end of the war Winnett Orr caught a glimpse of the possibilities of the plaster-of-Paris cast, which led him later to develop his technique for treating osteomyelitis and infected wounds.

THE PERIOD SINCE 1918

Winnett Orr's Plaster Technique

Toward the end of the War of 1914 to 1918 the American surgeon Winnett Orr made an observation which was destined to have far-reaching results. Among the soldiers who were admitted to his hospital he noticed that those whose wounds had been enclosed in a plaster cast to facilitate transport to America were generally in a better condition than others who had been treated by the orthodox methods of the time. In spite of the bacterial infection present in all these cases, the granulation process was proceeding undisturbed, the patients showed no clinical sign of sepsis, and the majority were doing well. This observation led him, after the war, to develop a technique of treating infections of the extremities, and in particular osteomyelitis (see Orr's papers), by the provision of drainage and complete immobilization of the limb in plaster. He also advocated this technique

for infected compound fractures, and later suggested that it could be applied to fractures at an early stage. His readiness to appreciate the importance of immobilization by plaster was due to his experience as a pupil of John Ridlon, who—as he himself writes in his preface to Orr's book *Osteomyelitis and Compound Fractures* (1929)—for forty years had immobilized all his operative wounds of the soft tissues, as well as of bones, with plaster-of-Paris casts and then watched the patients, not the wound.

After many years of persistent teaching, Orr's technique was accepted for the treatment of osteomyelitis, and many surgeons published successful results. But its value in the treatment of old infected compound fractures (that is to say, postfracture osteomyelitis)—on which, it is true, Orr laid less emphasis—was appreciated all too little. Even his demonstration, during a visit to England in 1930, of a highly satisfactory result in such a case (Hey Groves, 1930), failed to impress British surgical opinion. There were no similar cases published in the English medical journals; nor apparently did his suggestion that the technique should be applied to fractures before the development of infection meet with any response. I am unable to find in the medical literature up to 1934 any record of cases of this type having been treated in this way. The reason for the hesitation to use the technique is obvious: everybody was afraid of treating serious cases by what appeared to be so simple a procedure as mere drainage incision and enclosure of the limb in plaster. But the idea that the method was simple was not only fallacious but actually a potential danger, as I saw for myself in the gangrenous infections that supervened when young surgeons in my own country, unfamiliar with the special character of war wounds, applied the technique as though for osteomyelitis. The tendency to complications in cases treated by inexperienced surgeons has always been the principal cause of the scepticism I have encountered when advocating the enclosure of wounds in plaster casts, both in my own country and in France and England.

Undoubtedly Winnett Orr made an exceedingly important contribution to surgery in re-establishing, among the surgeons of a generation which had forgotten Ollier's work (see p. 33), the Hippocratic belief in Nature's power of healing. Moreover, he introduced the most effective technique yet known for the treatment of osteomyelitis and infected wounds. It would, however, be a great mistake to think that the Orr technique, without modification, can be applied with equal success to serious wounds and fractures within the first few hours of the injury, for in such cases, and particularly in wartime, drainage and immobilization are not enough. Botallo, Desault, Larrey, Friedrich and Milligan, each in his turn, taught that the essential factor in the

treatment of wounds was the excision of dead and dying tissues; and only when this technique of excision has been fully learned, with the teachings of Lister constantly in mind, can the surgeon safely begin to treat early wounds and fractures by immobilization in a closed plaster.

In a book recently published by Winnett Orr (1941) the following paragraph is printed on the cover: "The Orr method is not simply a matter of infrequent dressings with a vaseline pack. It calls for all the other essentials of surgical care—namely, adequate primary drainage; protection of the patient's wound against secondary infection; immobilization in correct position; and good general care."

The idea that Winnett Orr's fundamental principles might be of value, not indeed alone but as a complement to the surgical technique I was then using, came to me in 1929, when I was in charge of the surgical service of the *Caja de Prevision y Soccorro,* an organization which dealt with the majority of industrial and road accidents in Spain.* I had been thoroughly trained by my old teacher, Professor M. Corachán of the University of Barcelona, in the art of incision and proper excision, and had had much experience in these procedures. By 1929 I had treated over 40 cases of osteomyelitis with the Winnett Orr technique and had been much impressed by its success, particularly in two respects: first, the rarity of secondary infections, and secondly, the extraordinary ease and comfort experienced by the patient. If, therefore, I argued to myself, the protection of the wound by a plaster cast can arrest an infection already in progress, surely it must have an even better chance of success if applied before the infective process has begun. Accordingly I began to treat some minor cases by a method which combined the Larrey-Friedrich technique with the drainage and plaster technique which I had been using in osteomyelitis.

Modifications of the Orr Technique

My first results encouraged me to apply the technique to more serious cases, and in these I gradually introduced various modifications. First, I decided to omit the application of iodine recommended by Orr. Then, finding that in some cases the very long incision, made to facilitate a thorough excision of devitalized tissues tended, if left open along its full length, to make the wound gape, with consequent prolapse of the muscles and slow healing, I took to suturing each end of the initial incision after I had completed the excision, leaving open only a length approximating that of the excised area. Later, I reduced the amount of gauze used for drainage, inserting only a few layers between the exposed muscles with a single layer over the wound. I also dis-

*In 1932 over 42,000 cases, representing every type of accident, were treated by this organization.

carded Orr's use of vaseline on the gauze, since I had noticed that in some cases when I removed the gauze a mass of discharge had accumulated under the vaseline. I first replaced the vaseline with liquid paraffin, which, although better in some respects, did not entirely serve my purpose, for I was trying to avoid any possible retention of the tissue fluid which exudes from every clean wound during the first few hours, providing, if not drained away, a suitable culture medium for bacteria. So I finally decided to substitute drainage by suction for Orr's vaseline drainage, and, abandoning every kind of fatty substance, applied dry gauze to the wound in all cases treated before the onset of infection. Even the dry gauze, however, had certain disadvantages, the chief being that granulations grow into and through the relatively coarse mesh of ordinary standard gauze, so that when in due course the gauze was removed, the granulations were damaged. This was a great drawback, particularly since it was obvious that the cases that did best—that is to say, those in which there was never a trace of sepsis—were those in which the gauze had been placed in closest contact with the wound and had thus immediately absorbed any discharge. I eventually got over the difficulty by using very fine-mesh gauze, similar to that used for the best bandages. This readily absorbs any slight discharge, leaving the wound dry, and in most cases is easily removed when the plaster is changed. If the gauze is more firmly adherent, saturation for a few minutes with peroxide will enable the surgeon to withdraw it without damaging the granulations.

Meanwhile, in addition to these details, I had been gradually devising a series of individual plasters for immobilizing different parts of the body, developing in particular the thoracobrachial plaster, the value of which has been emphasized by the Spanish orthopedic surgeon M. Bastos (1935).

Spread of the New Technique

My first lecture on this technique, delivered in 1934 to the Catalan Society of Surgery, was received with considerable scepticism. Only a few surgeons were convinced, among them Gubern, who quickly applied it in a number of road-accident cases, with very good results. At the time of the outbreak of the war in Spain on July 19, 1936, I was chief surgeon at the General Hospital of Catalonia. From the very first day my assistants, who were all personally experienced in the technique, and I applied it to the casualties brought in from the street fighting. In September, I gave another lecture to the Catalan Society of Surgery (1936), and on this occasion, when Gubern also reported his successful results, the surgeons of Catalonia showed a greater inclination to give the method a trial. From that time the technique was

gradually adopted. In 1937 the Spanish Government, having been obliged to leave first Madrid and then Valencia, established itself in Barcelona; and the general staff of the Army, with Col. J. d'Harcourt, an experienced Madrid surgeon, in charge of the army surgical service, also set up its headuqarters there. Hitherto I had encountered considerable opposition from the medical authorities of the army (although one of my strongest antagonists in those early days, Lieut.-Col. Linares, subsequently published in collaboration with Soulie (1940) an article emphasizing the merits of the technique and giving an account of more than 300 cases treated by it in France). On Col. d'Harcourt's arrival in Barcelona my difficulties with the army were soon overcome. After some initial hesitation he decided to try the method in the army, and during the Republican offensive at Teruel in December, 1937, and January, 1938, he himself applied it in more than 100 cases. Thereafter he was one of its most enthusiastic exponents. His position as Chief Surgical Consultant to the Spanish Republican Army enabled him to build up an extensive organization, providing training in the technique for every army surgeon in Catalonia and establishing a scheme for the coordinated treatment of all casualties throughout the various stages from the frontline casualty station to the convalescent home. The first article on my technique published by Col. d'Harcourt (1940) gives a vivid picture of its value in warfare.

Early in 1938 I wrote up my own experiences of the technique in a small book published in Catalan; this was the only publication on my technique that appeared during the Spanish War. It was later translated into Spanish and provided the basis of the small book which was published in England in September, 1939. By now the number of cases treated by the method therein recommended should have furnished enough material to ensure a proper understanding of the technique, at least by those who have used it, and to secure a substantial improvement in results over those obtained in the early days when surgeons were adopting it without previous experience.

On the whole, the attitude of the British medical press to the method has been favorable, though surgeons have been inclined to regard suppuration as one of its inevitable accompaniments. This pessimistic view is not entirely unjustified, certainly not in connection with wounds sustained on the battlefield, where surgical treatment must often be delayed on account of military operations. In bombed cities, however, every possible step should be taken to facilitate operation before infection develops. The results depend largely on two factors: the skill of the surgeon and the effectiveness of the arrangements for dealing with casualties. When surgeons have a good knowledge of

all the details of the technique, and when the organization is such that they can deal with a steady stream of cases instead of sudden overwhelming numbers, the results should be as consistently good as is possible within the limitations of human endeavor.

The most recent prewar development is antipyogenic chemotherapy. In 1935, Gerard Domagk in Germany and M. and Mme. Tréfouël and others in France published papers on the effects of sulfonamide compounds in the treatment of streptococcal infections. Since that time a steady flow of publications has appeared, and this new chemotherapy has proved by far the best auxiliary of war surgery. Nevertheless we should beware of repeating the error that followed the discovery of the antiseptic technique by Lord Lister. The chemical product is often a good adjunct to surgical technique but should never be used as a substitute for it.

Late Cases

What I have said refers to the treatment of early cases, for it was as a method of dealing with wounds in the early stages that this technique was developed and that the army used it in Catalonia during the Spanish War. When infection has already begun, and particularly when osteomyelitis has developed, Winnett Orr's method of treatment as described by himself is the most effective. The Germans Billroth (1871), Schede (1915), and Braun (1915) also treated such cases by drainage and immobilization in plaster, but they cut a window in the plaster to expose the wound and its secretions to the drying effect of the air. My own opinion of the window is that it should be used only in those rare cases in which there is an exceptional amount of initial discharge which would soak through the plaster in a single day; that even then it should be used for only a very short period; and that as soon as the discharge has diminished a completely closed plaster should be applied to give the fullest possible scope to the natural healing powers of the body and to prevent the development of secondary infections.

The Winnett Orr technique, besides being simple and effective, has also the great advantage of being a standard method consisting of a number of routine procedures to be applied in every case. On the other hand, the technique I recommend for the treatment of wounds and fractures at an early stage requires the most painstaking care and skill, owing to the risks which accompany all war injuries during the first few hours, particularly the effects of shock and anaerobic infections of the soft tissues. To avoid complications every stage in the procedure must be carried out accurately. The difficulties must not be underrated: if it is assumed that the only requirements are to make a quick incision, apply sulfanilamide to the wound, provide some form of drainage and put the limb in plaster, the result can

only be disaster. It cannot be too strongly emphasized that the method demands the most detailed knowledge in the surgeon, who must be well versed in the art of excision, able accurately to distinguish dead from living tissues, and know the right method of approach for each region of the body.

Moreover, from first to last he must be constantly making immediate and important decisions, such as only wide knowledge and experience will enable him to reach correctly. From the moment he sees the patient he is faced with several vital questions: Is the patient fit for immediate operation, or does he need resuscitation first? If resuscitation is needed before operation, how long is it permissible to wait without endangering the future of the limb? Can the limb be saved, or must it be amputated? If the limb can be saved, how much of the wound, if any of it at all, may be closed by primary suture? Can a closed plaster be applied as soon as the operation is finished, or must it be deferred till later? Can the patient be evacuated, or must he be detained in hospital? To each of these questions, and to many others, the surgeon must give an immediate answer when examining every patient; moreover, he often has to examine a large number of patients at the same time and estimate the relative urgency of each case. Both the immediate and the ultimate future of each case will largely depend on the decisions made at the outset and in every successive stage.

The modifications necessarily required in the adaptation of a peacetime technique to the treatment of war injuries, and the large numbers of surgeons employed in modern armies, make special training urgently necessary for those who come new to the problem of dealing with war wounds. In my country the success of the technique, when it was adopted as the standard method of treatment, must in large measure be attributed to the provision of such instruction for all our young medical officers and thus to the attainment of virtually the same technique throughout the services.

In this brief sketch of the history of war surgery I have tried to pay tribute to some of the great surgeons of the past and at the same time

TABLE I

PRINCIPLES OF TREATMENT AND THEIR EXPONENTS

CLEANSING THE WOUND	REST	DRAINAGE	EXCISION OF DEAD TISSUES	PROMPT TREATMENT
Theodoric de Longoburg de Mondeville Paré Lister von Bergmann Carrel Domagk Tréfouël	Magati Ollier Billroth Thomas Jones Orr	d'Argelata Chaissaignac Lister Orr	Botallo Desault Larrey Friedrich Milligan Gray Ranzi Lemaitre	Larrey Pirogoff Nightingale

to show how certain main principles, which are the basis of surgery today, have been emphasized by surgeons throughout the ages. The pioneers can be grouped as in Table I, in relation to the principles of treatment to which they have attached chief importance. The cardinal teachings of these great personalities may be pictured as the main pillars supporting the war surgery of today. The underlying base of the whole structure is formed by the Hippocratic doctrine of the healing power of Nature, and the pillars which spring from this base represent the various means by which these surgeons have sought to assist Nature in her task.

I realize that this list does not include all those who have contributed to progress in the treatment of wounds, but they are outstanding figures in the gradual advance toward the position we now hold.

CHAPTER III

THE HEALING OF WOUNDS

The process of wound healing has been the subject of continuous experimental study since the end of the 19th century, but from the time of Billroth (1865), Klebs (1875) and Loeb (1898), the first workers to make accurate observations, little progress was made until 1910, when Alexis Carrel laid the foundations of a systematic and detailed investigation of the problem. Since his day our knowledge has steadily increased.

Most of the tissues of the human body have highly recuperative power, although this varies with the type of tissue. The skin ranks first and the muscles and central nervous system last.

Both from the clinical and experimental points of view, wound healing must be studied in two different processes, those of primary and those of secondary healing; though only in the latter can every stage of the process be followed. The differences in the two types of healing are very important clinically but have little histological significance.

In all traumatic wounds, particularly in war wounds, the interruption in continuity of the tissues is of secondary importance in the reparative action. The normal process of repair—the formation of new tissues—begins as soon as the elimination of the dead tissues or cells is complete, and so depends largely on the extent and degree of tissue disintegration. For this reason in war wounds, where the quantity of damaged tissues is frequently very great and the local circulation and nutrition are seriously impaired, the reparative process seldom follows normal lines. In treating these wounds the surgeon's main object must be to create a condition in which the healing process may begin within a short time after the injury, i.e., three to five days.

Whatever the type of healing process, the formation of new tissues depends on the capacity of the cells to increase their normal rate of metabolism; and for the cells to acquire the necessary reserve of energy an increase in the blood supply to the damaged area is essential. The rate of healing bears a direct relation to the amounts of nutrient elements, particularly oxygen, carried to the tissues by the blood. Obviously, different conditions in the wound will produce marked variations in the healing process. The most important of these conditions may be classified in two groups:

1. The extent of trauma and necrosis, the degree of infection, the shape, size, and locality of the wound, and the nature of the tissues

involved. These features depend largely on the nature of the traumatic agent, but various external stimuli, such as foreign bodies, temperature, humidity and mechanical and chemical influences, also play a large part in determining the course of healing.

2. Various factors depending on the general condition of the patient, of which the most important are hormone and trephone action, trophic nervous activity, vitamin concentration and cytotrophism, the influence of which on the nutrition of cells in wounds has been definitely proved.

THE PROCESS OF WOUND HEALING

In all wounds there are two main zones of damage. In the first a great many cells are immediately destroyed by the traumatic agent, while others die subsequently through being cut off from the capillaries and arterioles which normally supply them. All cells which depend for their blood supply on vessels that have been damaged suffer necrosis owing to their lack of nutrition. It is not surprising, therefore, that the efficacy of the reparative process is governed by the extent of the devitalized area. Beyond this first zone there is a wider area of damage, in which, although the anatomical integrity of the vascular system is preserved, the blood supply is initially impaired by the vascular spasm induced by sympathetic stimulation. The cells in this area may die by secondary necrosis; or if their nutrition is only temporarily affected, they may regenerate. This area of vascular spasm, with its diminished power of resistance to infection, constitutes one of the main sources of danger in war wounds, and will be discussed in detail in a later chapter (see p. 141).

Borst (1920) described all contused wounds as composed of three areas; including in the first all tissues destroyed by the direct action of the trauma, in the second those deprived of their nutrition as a result of the traumatic section of the blood vessels, and in the third those affected by contusion alone. As, however, the damage in the first two areas is due to one and the same cause—the direct action of the traumatic agent—it appears simpler and anatomically more correct to consider them as one: in short, as constituting the first zone of my classification above. From the surgical point of view, the component traumatic areas are almost equally important. The first area is contaminated from the onset and, the surrounding tissues being also devitalized, the risk of spread is very great, for this always bears a direct relation to the extent and severity of the damage in the second zone—the "area of vascular spasm" of the classification I prefer.

EFFECT OF PROJECTILES ON THE TISSUES

The Skin

The skin is highly resistant to external damage. This is due largely to its elasticity and the ease with which it is displaced over the underlying tissues. Moreover, it is endowed with a very rich blood supply and so has great vitality. The only type of injury which really destroys it is the lacerating wound, for this is very apt to interfere with its blood supply. Concussion wounds, which cause extensive destruction of the muscles and bones, produce relatively little damage in the skin; the only part of the skin which dies as a result of this type of injury is a narrow strip surrounding the wound, and the necrosis is due to the direct action of the traumatic agent.

Subcutaneous Tissues

The damage which a projectile causes in these tissues is often confined to the area immediately surrounding its track. The capillaries preserve their function and react with early inflammatory changes, supplying the necessary leucocytes and plasma proteins to the injured regions.

Muscular Tissue

The effect of modern explosives on the muscular tissue depends largely on the anatomical characteristics of the muscle affected. The short and segmented muscles, e.g., those of the shoulder, lumbar region, foot and skull, and the rectus abdominalis, must be considered separately from the long muscles, particularly those of the limbs. In the short muscles the nutrient arteries are short too, and the area they supply is limited. For this reason the damage in a short muscle is determined by the type and features of the projectile, particularly its size, shape and velocity. On the whole, this type of muscle reacts favorably to injury. A layer of dead and disintegrated muscular fibers will be found surrounding the track of the projectile. The dead fibers are easily distinguished from the living on microscopic examination, but with the naked eye distinction is difficult because the color and bleeding capacity of the devitalized muscle is often not very different from the normal. In the long muscles, on the other hand, each of the nutrient arteries has a much larger portion of muscles to supply, and consequently if one of these vessels is damaged by a projectile a considerable area is deprived of its nutrition.

Bone

Of all the tissues of the body, bone is the most susceptible to injury. This is due to its rigid structure, as is clearly seen in the greater degree of damage which bone suffers in injuries of adult life, when it is

highly calcified, and more especially in old people in whom rarefaction has begun, compared with the damage suffered by children, in whom the bone has some degree of elasticity owing to its cartilaginous structure. Highly calcified bony tissue, like the shafts of the femur and humerus, is more vulnerable than the spongy tissue of the expanded ends and short bones.

THE REGENERATIVE PROCESS IN WOUNDS

As Carrel (1910) pointed out, there are four distinct periods in the healing of a wound: preparation, granular retraction, epithelization, and cicatrization.

First Period: Preparation

The first stage extends from the time of the injury to the beginning of the period of granular retraction and consists of preparation of the wound for the reparative process. It is initiated by the trauma itself and consists of traumatic inflammation, which is very similar to infective inflammation and is characterized by the usual inflammatory features; namely, mild fever, pain, discharge, edema and leucocytic migration. This combination of reactive phenomena leads to the reabsorption of blood on the surface of the wound and to the removal of necrotic tissues by phagocytes and enzymic digestion. In the wound which has been properly treated from the onset, the reparative phenomena proceed in an orderly sequence.

Hemostasis.—The first reparative or, more properly, defensive phenomenon is the spontaneous cessation of hemorrhage. Bier (1897) was one of the first to describe this, and Magnus (1924) and Stich (1930) made observations which enable us to picture the mechanism. The elastic retraction of the damaged vessels and the coagulation of the blood fibrinogen stop bleeding from the vast majority of the blood vessels; but in the larger arteries the comparatively high blood pressure prevents the initial formation of clot. A fall in blood pressure, produced either by acute anemia or, more frequently, by shock, also plays a considerable part in ending hemorrhage when the bleeding is not checked by surgical intervention.

Once the vessels have ceased to bleed, the coagulated fibrinogen both of the blood and of the lymph, soon covers the wound with a thin layer which prevents further contamination from outside. This layer is so thin that it is easily destroyed, even by a mere change of dressing.

Elimination of Dead Tissues.—The next reparative phenomenon is the elimination of dead tissues. This is generally accomplished by a process of liquefaction, and dead cells form the chief constituent of the discharge that comes from an untreated wound in the early stages.

The increased exudation during the first few days after an injury is designed to assist this process; the amount of discharge is directly related to the extent of the tissue damage, the greater the concussion and irregularity of the wound the greater being the flow. The elimination of disintegrated tissues—in itself a defensive action, constituting in fact the first step in the regeneration of the tissue—is effected by the cooperative action of several enzymes, derived from various sources. One comes from the leucocytes, which are very rich in trypsin and are reinforced by living cells surrounding the wound. The action of this enzyme is limited to dead cells, by whose disintegration it prepares the ground for the regenerative process. On the other hand it also carries an element of danger, the disintegrated tissues forming an excellent culture medium and the surrounding tissues sometimes becoming infected from the initial colonization in the devitalized cells. Among the other heterogeneous enzymes which appear in any serious traumatic wound are those produced by the bacterial toxins which attack living cells. The chief role of bacterial toxins, however, is the disintegration of the dead tissues.

The products of disintegration either are eliminated with the discharge or else are absorbed into the lymphatic system and passed on into the blood stream *via* the thoracic duct. The work of many investigators (see p. 60) has shown conclusively that foreign bodies, ranging from proteins of small molecular size to some of the largest organisms, can be eliminated from the tissues by the lymphatic system; but most of the products of tissue disintegration make their way directly to the exterior.

The amount of dead tissues present in a wound being important in determining its evolution, the main object of surgical treatment must be to convert a contused wound into an incised one. When the dead tissues have been eliminated, the wound is ready for the active process of repair. Where they consist of large portions, the process of liquefaction is incomplete and elimination takes the form of sloughing.

Bacteria

Even the cleanest traumatic wounds, and particularly war wounds, are contaminated by bacteria from the outset. This initial contamination varies in degree according to the number and toxic capacity of the organisms introduced into the wound, but the changes in the bacterial flora that follow depend for the most part on the special characteristics of the wound and on the time that has elapsed without surgical assistance.

Experimental work, especially that of Carrel, has shown that in secondary repair germs are required to stimulate healing activity. The

toxic capacity of these germs, however, must be limited, and they must cause no more than an irritation on the wound surface. When, as a result of the large number of bacteria or their toxicity, inflammatory changes take place within the tissues, the normal process of healing is checked and the biological power of the cells is applied to counteracting infection instead of to reparative action. Fortunately, even the most active pathogenic bacteria require several hours to multiply sufficiently to invade the wound tissues, and the future of the patient thus largely depends on whether or not surgical treatment is given before this period is over. If proper surgical measures are applied before inflammatory changes begin, infection will be prevented. The bacteria on the surface of the wound will be removed in the operative procedures, and if a few remain they will quickly be isolated from the tissues by the coagulated fibrin, so that clinically the wound may be considered sterile. The coagulation of fibrinogen is a typical example of syneresis, similar to the drying of collodion, whereby the fibrin loses its capacity to filter colloidal substances.

Duration.—The duration of the preparatory period varies considerably. If the wound is covered with dead tissues, the actual process of repair is delayed and the period is prolonged. Carrel's experimental wounds showed no reduction in size for the first few days, but then the active period of healing, as indicated by the granular retraction, began. Many surgical wounds give a similar history. The preparatory period is shortened by the presence of certain mild irritants which have a stimulating effect on the wound. Carrel and du Noüy (1921) showed that if turpentine or staphylococci are applied to a sterile experimental wound, the period can be reduced from 20 to 4 days. Other factors affecting its duration are the size and location of the wound, the tissues involved and the age and general health of the patient.

Second Period: Granular Retraction

After the preparatory period, the active healing process begins, with the formation of granulations and a reduction in the size of the wound. Thus the wound is provided with a second and stronger covering which, when healthy and undisturbed, has the effect of a new skin. As early as 1879 Devaine and Nissen had shown the effectiveness of the barrier to absorption furnished by healthy granulations; and this observation was confirmed in 1893 by Afanassieff working with toxins of virulent bacteria. Noetzel (1897) showed that none of the bacteria, toxins, or products of disintegrated tissues with which he worked, penetrated a layer of granulation tissue; his results with tetanus toxin, recently confirmed by H. E. Hutchison (private communication), were particularly striking. Melchior and Rosenthal (1920) made similar

observations working with methylene blue, and more recently d'Harcourt, Folch and Oriol (1940) obtained similar results with sulfophenolphthalein.

Afanassieff was the first to point out that this resistance of the granulation tissue to absorption is easily broken down. He found that a granulating wound contaminated by anthrax will show no sign of absorption if left undisturbed for five or six days but that a mere change of dressing is immediately followed by toxic effects. This is due to the fact that removal of a dressing causes multiple tiny abrasions in the layer of fine connective tissue covering the granulations. Thus, to preserve its full protective value the granulation tissue must be left completely undisturbed. *Only healthy granulations, however, have this quality of resistance.* They are firm, uniform in size and bright red, and produce little exudate. In a properly treated wound they become so confluent that to the naked eye they appear as one continuous layer of tissue. If for some reason—for instance infection, poor nutrition, repeated mild trauma (i.e., incomplete immobilization), or a lack of uniform and persistent pressure—the granulations are neither healthy nor undamaged, if, that is to say, they are pale or cyanotic, spongy, fluffy or hypertrophic and bleed very readily, they afford far less protection to the underlying tissues. Fortunately, however, the formation of healthy granulations can be largely ensured by proper surgical treatment: the prevention of infection, the retention of only those tissues which have a good blood supply, the maintenance of gentle pressure on the wound, and the most complete immobilization of the injured region.

Besides having great protective value, healthy granulations play an important defensive part in fixing and eliminating bacteria and toxins —a function similar to the filtration of bacteria and viruses by the lungs and spleen. Halley, Chesney and Dressel (1927) excised a piece of skin from the back of a rabbit and left the wound to granulate. They then injected 0.1 c.c. of a testicular emulsion containing *Treponema pallidum* into the testes and found that syphilitic lesions appeared on the surface of the wound. Viruses are also eliminated through the capillaries of granulation tissue, and Fujinami and Hatano (1929) showed elimination of the cells of the Rous sarcoma of hens. The surgeon will see, therefore, how important it is to have a layer of healthy granulations covering the wound and not to disturb it in any way.

The contraction of the wound during the period of granular formation not only approximates the edges of the epithelium but also fills the gap and draws the divided tissues closer together. During the first few days such contraction is very rapid, but it gradually becomes

slower until finally, with the beginning of the next period, it ceases almost entirely. The rate of contraction is directly proportional to the size of the wound. In a wound with a diameter of 60 to 70 mm. the normal reduction in size is about 9 or 10 mm. in 24 hours; in the same period in a wound of 40 mm. diameter it is about 3 mm.; in a wound of only 20 mm. diameter it is very slow. Reduction ceases entirely in all wounds when the margins have approached to within 10 to 15 mm. of each other.

Third Period: Epithelization

Before this point, epithelization makes little progress. Its rate does not depend on the age of the wound but is inversely proportional to its size. If the wound is large, epithelization is tardy. The growth of the epithelium is very slow if the distance between the edges is more than 15 mm., but is quicker if the distance is less than 10 mm. *If the granular contraction ends before the edges of the old epidermis have closed to within 25 mm. of each other, the new epithelium cannot spread any farther over the granulations and so the healing process comes to a standstill.* In wounds of irregular shape epithelization always begins at those points where the edges of old epithelium are nearest to each other.

Once the regeneration of epithelium begins, the contraction of the wound slows down; if the epithelization is accomplished quickly, contraction will come almost to a complete standstill, and the final scar will consequently be less fibrotic than when the process takes a long time. Some contraction is necessary to reduce the space between the divided tissues, but from the point of view of the final scar it is important that it should not be excessive. When a large area of skin has been lost, the production of a good scar is favored by postponing a skin graft until epithelization is ready to begin—that is to say, until the beneficial effects of contraction have been secured, but before fibrosis is established. The advance of epithelial cells from all sides of the wound over the surface of the granulations is achieved, in the view of most workers, rather by an amoeboid movement than by the mitotic division of the cells, which indeed plays but a small part in the process.

In traumatic wounds the progress of epithelial cells over the granulations is partly governed by the number and toxic capacity of the organisms present, but depends more on certain purely mechanical factors. The fragile and delicate nature both of the detached epithelial cells and of the fine layer of connective tissue over the granulations which forms their bed renders these cells very liable to destruction by the slightest mechanical interference, e.g., the movement of a

dressing. Another important mechanical factor, to which too little attention has hitherto been given, is the obstacle sometimes imposed by the type of the granulations. Epithelial cells find it extremely difficult or even impossible to advance when the peripheral granulations rise above the level of the epidermis, for, although they can travel across a flat surface or a slight depression, they cannot move upwards. Amoeboid progress of epithelial cells is also impossible where the base of the granulations is narrower than the body (see p. 290).

The general condition has a great influence on healing. Chronic infections, such as tuberculosis and syphilis, definitely hinder healing, and more recent work has shown that a deficiency of vitamins (particularly of A, C, and D), diseases of the circulation (particularly cardiac and renal disease), diabetes, and acute infections originating from the wound, all retard the repair process. Nevertheless, the main obstacles to healing are local, and are all directly connected with the supply of blood.

Fourth Period: Cicatrization

The evolution of a scar is very slow and the cicatricial stage is of long duration. As soon as epithelization is complete the distance between the edges of the old epidermis begins to increase, leading to a progressive enlargement of the scar which continues over a long period.

EFFECT OF PRESSURE ON WOUNDS

The beneficial effect of external pressure on healing was not recognized until the surgeon and obstetrician Charles White (1762) published his results of treating chronic ulcers of the leg with sea sponges applied with gentle pressure. In 1797 another English surgeon, Thomas Baynton, published a full description of the pressure treatment of chronic ulcers. The first to use adhesive plaster for this purpose, applying it across the ulcer, he found that the discharge was noticeably diminished and granulation and epithelization were complete in a relatively short time. Baynton also noted that the treatment had a good effect on the circulation of the leg. In 1853 J. S. Gamgee published his results of treating wounds and fractures by bandages; these he applied with a certain amount of pressure, the degree of which he compared to "that with which one holds the hand of a lady when one greets her," and he emphasized the beneficial effect of this treatment on wound healing. In 1881 James Hardie took up the use of the sponge for treating wounds, pointing out that by the pressure the divided tissues were apposed and thus the wound was provided with conditions similar to those produced by suture; he also emphasized that the pres-

sure of the sponge prevented accumulation of discharge. In recent years Douglas (1935) re-introduced the pressure technique for the treatment of chronic ulcers.

One result of all wounds is to deprive the underlying tissues of the elastic pressure of the skin and often of the aponeuroses also. The lack of balance thus produced damages the cells in the superficial layers of all the tissues in the wound, and the swelling of the injured region adds a further factor which adversely affects the nutrition. Evidence of these disturbances is seen in the granulation tissue. Wounds treated without pressure often show hypertrophic granulations which reach well above the level of the surrounding skin and newly formed epithelium; a copious discharge which saturates the wound and in many cases macerates the tissues; and edema, not only in the wound itself but in the surrounding area also. For all these reasons the healing of the wound is slow. Wounds to which, on the other hand, some gentle and persistent pressure has been applied show firm, even and healthy granulations, only a small amount of discharge (for this depends on the degree of bacterial colonization and disappears quickly after a few days of pressure), and no edema.

Pressure by Plaster-of-Paris Cast

One of the many advantages of the plaster-of-Paris cast is that it can exert and maintain a gentle, uniform and persistent pressure. To do so, however, it must be properly applied. The only soft tissues which should be padded beneath the plaster are those of the actual wound. Here some layers of gauze should be applied over the gauze placed in the wound for drainage, but elsewhere, apart from the protection of bony prominences, the plaster should be applied directly to the skin. In moulding the plaster care must be taken to establish good contact with the limb, particularly in the region of the wound, where slightly greater pressure is needed. As soon as the danger of primary infection is past, a plastered leg should be lowered from its elevated position for an increasing period each day, and as soon as the condition of the wound permits, the patient should be made to walk about so as to avoid muscular atrophy. With these precautions good contact between the plaster and the wound is more easily maintained, and the beneficial effect of the pressure is exercised over a long period. In a few cases it is helpful to put a layer of sponge rubber between the wound and the plaster.

Experiments on Wound Healing in Plaster

Recently at the Strangeways Laboratory, Cambridge, Dann, Glücksmann and Tansley (1941) carried out a series of experiments on wound

healing. Finding Carrel's method of plotting the wound area at different stages unsatisfactory, as it provides no information about the quality of the scar tissue, they took a series of histological measurements in each group of wounds and plotted them against time after the operation. The measurements they took were as follows:

1. The distance between the cut edges of the old epithelium, giving the decrease in the size of the scar.
2. The distance between the margins of the regenerated epithelium, giving the rate of epithelial regeneration.
3. The distance between the cut edges of the old collagen fibers, indicating the tensile strength of the scar (Howes, Sooy and Harvey, 1929).
4. The distance between the margins of the regenerated collagen, giving the rate of collagen regeneration.
5. The thickness of the regenerated collagen fiber bundles at different levels in the scar.

THE EFFECT OF DIFFERENT TREATMENTS ON STANDARD WOUNDS

The effects of several forms of treatment in current use for the acceleration of wound healing were compared with the following results (see Table II):

TABLE II

EFFECTS OF TREATMENT ON WOUND HEALING

PHENOMENON STUDIED	METHOD OF TREATMENT				
	APPLICATION OF COD LIVER OIL	APPLICATION OF OTHER OILS AND VITAMIN A PRODUCTS	APPLICATION OF EPICUTAN TREATMENT	APPLICATION OF UREA	APPLICATION OF PLASTER OF PARIS
Decrease in size of scar	Accelerated	Retarded or no effect	Slightly accelerated	No effect	Accelerated
Epithelial regeneration	Slightly delayed	Markedly delayed	Slightly retarded	Markedly retarded	More rapid
Collagen regeneration	Improved	Improved	Improved	Improved	Retarded
Latent period of collagen regeneration	Shortened	No effect	Shortened	Shortened	Prolonged
Tensile strength of scar	Improved	Harmful or no effect	Improved	No effect	Much the best treatment
Muscular regeneration	No effect	No effect	Marked improvement	Not tested	Not tested
Thickness of regenerated fiber bundles	Increased	Increased	Increased	Increased	Increased

Cod Liver Oil Treatment.—Several types of cod liver oil were used and a number of control animals were treated with other oils and fatty acids, either with or without vitamins A and D.

Epicutan Treatment.—Epicutan was dusted on the surface of standard wounds under different experimental conditions.

Urea Treatment.—Solid crystals of urea were applied to standard wounds.

Plaster-of-Paris Treatment.—Superficial standard wounds and burns were covered by a broad plaster belt round the animal's thorax.

These research workers say: "Of the above four treatments (five including the controls) the plaster method gave far the best results. Next in order of merit came cod liver oil, then epicutan, and finally urea."

The results of these investigations confirm my twelve years' clinical observations, that no method of treatment fulfills all the optimal conditions for wound healing as effectively as the enclosure of the affected limb in a plaster cast. When infection is prevented—as by the correct use of the whole technique it easily can be—epithelization is produced more rapidly than by any other treatment, and the scar is more resistant and elastic. The protection of the wound against secondary infections, the pressure on the surface of the wound, the prevention of damage to the granulation tissue, the absorption by the plaster of excessive discharge which might damage the newly formed epithelial cells, the avoidance of edema, the maintenance of a good circulation, and above all the absolute and continuous rest of the affected limb—all these factors combined form the fundamental basis for the success of closed plaster casts in the promotion of wound healing.

CHAPTER IV

INFECTION

Infection is the chief problem in the treatment of war wounds, the final condition much depending on whether or not they run an aseptic course. Largely as a result of the study of thousands of casualties during the last twenty years, especially those of the Spanish War, and the observations of a few research workers, the outlook of surgeons and pathologists on the problem of infection is fundamentally different today from that which prevailed during the War of 1914 to 1918. The modern idea of infection was formed by such men as Pasteur, Lister and Koch; but it may be recalled that these were preceded by men who had prepared the ground not only for their actual discoveries but also for a better understanding of the principles behind them.

Before Pasteur discovered the process of fermentation, the great French physiologist Claude Bernard (1866) said: "On aurait tort . . . de renoncer à l'espoir de rattacher un jour ces manifestations morbides (maladies septiques) aux lois de la physiologie. S'il nous est pour le moment impossible de le faire, nous y parviendrons sans doute dans un avenir plus ou moins éloigné."* Bernard's theory, constantly found in his writings, that the development of infection is due to improper functioning, was forgotten after his death and only quite recently resuscitated. That this concept of infection should have been discarded was due not to Pasteur and Lister themselves, but to the effects of the widespread diffusion of the revolutionary "germ theory" which followed Pasteur's great discovery. Lister, in particular, laid great stress on the importance of the natural defense mechanism of the body and claimed that one of the advantages of antiseptics was that they helped this mechanism. But for most surgeons bacteria were now the "cause" of the infective complications of wounds, and as a result of this conception and of the patent success of Lister's antiseptic technique, the attention of the medical profession was largely confined to the destruction of bacteria. Consequently, in a comparatively short time Bernard's suggestion that the natural function of the body provided the controlling influence in the development of infection came to be almost completely ignored. It seems curious that no one in those days should have wondered how, in view of the innumerable millions of

*"It would be wrong to give up hope of one day bringing these morbid manifestations (septic disorders) under the laws of physiology. Though we cannot do so yet, we shall no doubt succeed in the more or less distant future."

these pernicious bacteria that had surrounded mankind since the beginning of time, the human race should have survived thus far!

Bernard's theory has been re-introduced several times and has been given some support, particularly by Pavlov, whose theory of conditioned reflexes made the concept of immunity comprehensible (Podkopaeff and Saotchian, 1928), and by Métalnikov (1929), who showed that by the destruction of their third dorsal gland immunized worms could be rendered susceptible to cholera (see also Ermolaeff and Métalnikov, 1932).

It has been stated by some writers that Bernard discussed with Pasteur the relative parts played in an infection by bacteria on the one hand and by the living tissues on the other. No trace remains, however, of such a discussion. In Bernard's last work (1879), which was not published in full until after his death, he took up the subject of alcoholic fermentation, carrying his theory on the properties of the living tissues so far as to maintain that the fermentation of alcohol was effected, not by a fermenting substance introduced from without, but by a soluble ferment in the juice of the rotten fruit. Pasteur, greatly disturbed by this idea, published a small book (1879) attacking it, emphasizing, however, in the preface his cordial relationship with the great physiologist and pointing out that this was the first occasion on which they had disagreed.

Today we can state with confidence that the primary factor in the development of infection lies in the immediate environment of the invading organism. A pathogenic germ which thrives in one animal is powerless in another, and even in the same animal an organism which will successfully attack certain tissues will have no effect on others. More correctly, perhaps, we should say that a given animal or tissue may be susceptible to a certain germ or toxin which will give rise to no symptoms in other animals or in other tissues of the same animal. The germ in each case is the same; the variable factor lies in the receptor medium.

INFLAMMATION

In the higher animals the normal mechanism of defense against an invading organism is initiated by an inflammatory process. This process, the clinical signs of which were first described by Celsus ("rubor, tumor, calor, dolor"), constitutes the basis of the body's defense mechanism. Inflammation may be stimulated by various external causes, such as trauma, a burn, or frostbite, or by the sudden entry of a large variety of foreign substances into the "milieu intérieure" of the body. Achard and Loeper (1923), discussing the changes brought about in the tissues and fluids of the living body by the entry of any foreign

substance, gave what seems to be a true explanation to these changes, namely, that they are the result of a natural function of the body designed to regulate the conditions prevailing within it and to keep them constant. It is now fairly generally accepted that the extent to which the defense mechanism of the body is brought into play and the scale of the inflammatory process depend upon the aggressive character of the invader, or according to Achard and Loeper's theory, upon the extent of the disturbance caused in the "milieu intérieure."

The different forms which inflammation may take are well known. In every case the process is directed to the same end, namely, the elimination or neutralization of the disturbing factors. When inflammation is caused by an organism which secretes toxic substances, the body, in order to limit the disturbance, attempts by a process known as "fixation" to check the invader at the site of entry and to prevent its diffusion through the fluids and tissues of the system. Further, the local permeability of the capillary walls permits leucocytes and plasma proteins to pass from the blood stream into the tissues surrounding the invader and to discharge in them their respective phagocytic and antitoxic functions. This transudation probably takes place in the arterial rather than in the venous capillaries (Landis, 1934), but there is not yet agreement on this point; and a large proportion of the substances transuded and dispersed through the interstitial fluids immediately make their way into the lymphatic system. It is now becoming more and more generally believed that lymph and the tissue fluids are one and the same substance; although probably a more correct description of lymph is that it consists of interstitial fluid which, by entering the lymphatic vessel, has passed beyond the sphere of the various controlling influences of the circulatory system. Starling's theory that there is a definite balance between the fluids of the blood and those of the tissues is fundamentally sound. Hydrostatic pressure on the one hand, and the osmotic pressure effected by the proteins and salts in both kinds of fluid on the other, are the chief factors in maintaining the balance between the two fluids, which bathe the entire body. Recently, however, additional controlling factors have been recognized in the pressure of the tissues (Drury and Jones, 1927), the temperature (Landis, 1937), and the electrical potential of both fluids (Donnan, 1911; F. McLean, 1925).

Inflammation is caused by a stimulus which is probably nervous (Bernard, 1872; Bruce, 1910; and others). This stimulus incites a reflex which effects a brief initial local vasoconstriction, followed by a vasodilation and a rise of capillary pressure. The increased capillary pressure, combined with various other factors (e.g., Menkin's leukotaxine), initiates a filtration of plasma through the vessel walls and thus augments the protein content of the interstitial fluid; this, in turn,

by the laws of osmosis, absorbs more fluid from the circulation. This is the cause of local edema, one of the signs of inflammation, which stretches the interstitial spaces and so increases the pressure inside the tissues, thus contributing a secondary factor to counterbalance the increased capillary pressure.

Once edema is established, the lymphatic flow, that is to say, the drainage and removal of the interstitial fluids in a changed form, is greatly increased. The view that the lymphatics are thrombosed or compressed in edematous tissues has been shown to be incorrect. On the contrary, by the attachment of their walls to the adjacent tissues they are held widely open as these tissues become stretched, and the flow of lymph along them is greatly augmented (Pullinger and Florey, 1935; McMaster and Hudack, 1934; Barnes and Trueta, 1941). This, which may be looked on as a washing of the inflammatory focus, is another of the body's defense mechanisms.

The "purpose" of inflammation, from the defensive point of view, is to bring the leucocytes and antibodies into action against bacteria and toxins so that the latter may be destroyed or neutralized. Once this destruction is accomplished, the foreign elements must be absorbed from their place of entry and carried into the blood stream for elimination from the body. But just as overaction of every mechanism of the body may be injurious, so the absorption process, which is designed for defense, may come to have an opposite effect. If the aggressive elements are so numerous or so powerful that they are absorbed without having first been rendered harmless, their distribution through the body brings them into contact with cells specifically sensitive to them; and if these cells happen to be vital to the existence of the body, this contact affects not only the life of the individual cells but that of the body as a whole. Clearly, then, absorption is a process of great importance from the point of view of infection.

ABSORPTION

The route by which germs and toxins are carried from the site of entry into the system generally has only recently been established. When Magendie and, later, Bernard took up the study of the action of certain poisons and drugs, using strychnine, curare and other substances, they stated that all poisons pass into the blood stream by way of the capillaries. This is not strictly true. While crystalloid substances of small molecular size, such as strychnine, do in fact pass directly into the blood stream through the capillary walls, proteins, many enzymes (such as some snake venoms and bacterial toxins) and most dyes are absorbed from the tissues into the lymphatic vessels and thence make their way *via* the lymphatic system and thoracic duct into

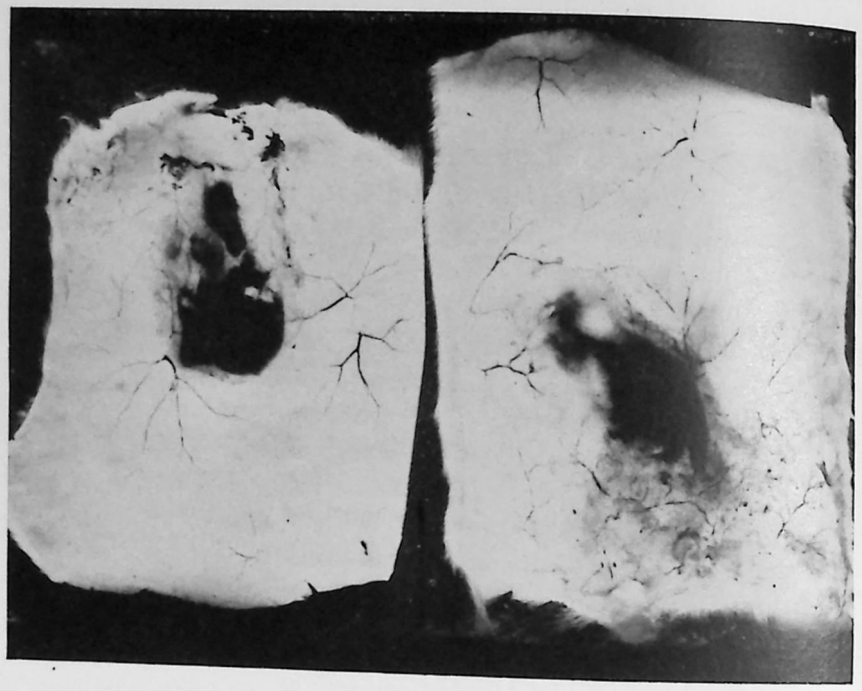
the blood stream (Barnes and Trueta, 1941). Bacteria also follow the lymphatic route of absorption, a fact which is not surprising in view of their relatively large size.

Clearly, therefore, the process of lymphatic absorption is designed not only to fulfill its function in normal metabolism, but also to carry away noxious substances from the tissues, to be neutralized or eliminated by way of the blood stream. Bernard (1872) emphasized the importance of elimination in preventing the toxic manifestations of poisons introduced into the body. Thus, hydrogen sulfide injected intravenously passed through the lungs and was eliminated before doing any harm. If the same substance was inhaled, however, it passed straight from the lungs into the arterial blood, and so to the tissues where its poisonous effects were exerted. Bernard also pointed out the importance of the *rate* of absorption in modifying the effects of certain poisons. Thus, he showed that many times the normal lethal dose of a poison may be safely administered if it is given very slowly, so that the body is given the opportunity of destroying it before it has time to accumulate.

Clearly, therefore, the process of lymphatic absorption, while vital as the first stage in the elimination of foreign substances, is also a possible source of danger to the system in facilitating too rapid a diffusion of the disturbing agent. That the body tries to check this diffusion, however, is indicated by local reactions to the entry of foreign substances such as proteins, i.e., hypersensitivity and anaphylaxis, and even local immunity in varying degree. The aspect of the defensive mechanism which consists in localizing the infection is known today as "fixation." Pawlowski (1909) found that, whereas staphylococci injected into the knee of a guinea pig normally pass into the blood stream in 24 to 48 hours, they fail to do so at all if an irritant substance such as turpentine is injected beforehand. Besredka's "local immunity" can be attributed to a decrease of permeability in the affected area (Amoss and Bliss, 1927).

The earliest account of the localizing or isolating process of the body's defense mechanism was given by Corvisart (cited by Bernard, 1872), a heart specialist of the early years of last century. A girl poisoned herself by swallowing a large quantity of arsenic. To Corvisart's great surprise she did not die immediately but lived on for some considerable time, suffering from acute gastric disturbances. When finally she died, autopsy revealed a series of ulcers in the mucous membrane of the stomach and a large tumor in which the bulk of the arsenic was found completely enveloped in fibrin. In 1925 Krause described the fixation mechanism. He showed that, if bacteria are introduced into an animal after the injection of some irritant substance, the local production of fibrin stimulated by this substance

makes a barrier which isolates the bacteria from the interstitial fluids and the lymph and so prevents their diffusion; that is to say, diffusion will not take place when bacteria find a protective barrier. Now to prevent diffusion the body needs time to build up this protective barrier, and the significance of Krause's experiment lies not in the nature of the first injection but in the fact that this injection gives the animal the necessary time to construct the barrier before the second and active injection is made. Fig. 1, *A*, shows the limiting barrier made by the injection of *Staphylococcus aureus;* and Fig. 1, *B*, the failure of an imperfect barrier to prevent diffusion.



A. *B.*

Fig. 1.—Diffusion of "Pontamine blue" injected into abscesses in the skin of rats.
A. Limitation of spread of the dye by the granulating barrier of a well-constituted abscess produced by the injection of *Staphylococcus aureus* culture.
B. Diffusion of the dye through an incomplete layer of reactive granulations. The dye was injected together with "spreading factor."

In immunized animals, that is to say, those which have a previous "experience" of the aggressive agent, the defensive mechanism operates rather differently, for diffusion is prevented by bacterial agglutination which is affected by the antibodies (Shibley, 1926; Rich, 1933, and others). Once the bacteria are agglutinated their destruction by polymorphonuclear leucocytes is greatly facilitated.

It seems clear, then, that the natural defense mechanism is largely concerned with the regulation of the absorption process, accelerating or retarding it in relation to the body's capacity to destroy and eliminate the aggressive element.

In the light of these considerations we should be able to appreciate, in relation to the war-wounded patient's future, the importance of the absorption, not only of bacteria and their toxins, but also (for these ultimately become "foreign" elements and produce toxins of varying capacity) of the products of cellular disintegration caused by the trauma. Fortunately the human body has previous "experience" of nearly all the bacteria commonly found in traumatic wounds, and to a greater or lesser degree has antibodies ready to meet and deal with them. Fiessinger's aphorism (1934), for which he borrowed an idea from Bergson, is very apt: "Partout où quelque chose vit, il y a ouvert quelque part un registre où le temps s'inscrit."*

Provided that the defensive mechanism of the body can operate under good conditions and no excessive number of bacteria are suddenly introduced into the interstitial spaces, bacterial invasion will be prevented, and in consequence the wound will follow a normal and aseptic course of healing.

VIRULENCE AND DIFFUSION

A clear distinction must be made between the diffusive capacity of an organism and its virulence. Goodpasture (1933, 1937), in studies of bacterial diffusion in the chorio-allantoic membrane of the chick embryo, showed that whereas hemolytic streptococci, the staphylococcus, and the diphtheria bacillus can diffuse through this medium, the typhoid and tubercle bacilli have no such power but are taken up and scattered by embryonic cellules and leucocytes.

Each bacterium has a virulence, or power of aggression, peculiar to itself, and this is probably related to the diffusive capacity either of itself or of its toxin. For example, the staphylococcus, having a toxin which coagulates fibrin, is easily confined to its place of entry, whereas the body requires more than 48 hours to build up the necessary protective barrier against the hemolytic streptococcus (Menkin, 1940).

Exactly what constitutes bacterial virulence has not been definitely established. Some believe that it depends almost entirely on the power of the organism to spread through the tissues, and certainly it is true that the most virulent organisms are among the most vigorous tissue invaders. Others believe that virulence is related to the power of producing toxins, and I myself incline to this view.

The virulence of bacteria and their diffusive capacity are both very important to the development of the infective process. A nonvirulent germ which makes its way to the blood stream with great ease and in large numbers may produce fatal results, as, for example, in vegetative

*"Wherever something lives, a register is opened in which Time writes its signature."

endocarditis. Nonpathogenic bacteria commonly found in the mouth and alimentary canal of normal persons may prove disastrous, not by reason of any virulence but because of the vital importance of the tissue in which they colonize. This is a striking example of the harmful action which may be produced by diffusion. A toxin-producing germ, on the other hand, even when it has little diffusive capacity and takes a long time to enter the blood, produces what may be fatal consequences by its virulence alone.

LYMPH AND THE LYMPH NODES

The antiseptic properties of lymph have been studied very carefully. In 1888 Nuttall pointed out that blood has bactericidal properties and suggested that the same might well be true of other body fluids. Meltzer and Norris (1897) found that lymph has an antibacterial capacity inferior only to that of serum, an observation which was later confirmed by Hughes and Carlson (1908). It is now known that blood and lymph are the two most powerful germicidal fluids of the body; and it has also been shown that, after isolation from the tissues, lymph preserves its antibacterial capacity for a noticeably longer period than blood (Meltzer and Norris, 1897). Freund and Whitney (1929) found that the lymph of the liver of immunized rabbits gave a higher titer of antibodies than the serum.

One of the functions of the lymph nodes is to filter and destroy bacteria that pass through them, and they are also believed to play some part in the regulation of the lymph flow. In pyogenic infections of wounds the nodes draining the region frequently show all the signs of acute inflammation, and the fact that very often the infection stops here indicates that these small organs are probably able to destroy large numbers of bacteria. They are loaded with reticulocytes and endothelial phagocytes, and possess relatively high concentrations of antibodies.

Movement of any kind, however slight and whether active or passive, has a marked effect on the whole process of diffusion. It stimulates the initial absorption of foreign substances from the tissues, accelerates their liberation from the glands, and increases the lymph flow throughout the area. Drinker (1938) showed how the movements of deglutition play a large part in the diffusion of septic material from the tissues of the neck to the cervical stems of the lymphatics.

Bacteria of great diffusive capacity pass almost unimpeded through the lymph node barrier, and so generally cause little inflammation in the glands. In such cases there are few local signs and symptoms and there is no pain or local congestion and little swelling; on the other

hand, the general condition of the patient is rapidly affected and he will show a high temperature and other signs of toxemia.

Three main points emerge from these considerations:

1. The future of the wound, and in many cases of the patient himself, depends on the quantity and toxicity of the foreign substances which remain in the tissues of the wound.
2. The mechanism of the body primarily responsible for the development of an infection is absorption, which leads to the diffusion of germs and toxins. To affect the patient's general condition the bacteria or their toxins must reach the blood stream, preferably the arterial, for this is the means by which they are spread through the body and carried to those tissues which have a specific affinity for them.
3. The route by which bacteria and their toxins make their way to the blood stream is the lymphatic system.

Clearly, therefore, to prevent infection developing in a war wound, the surgeon must do all that he can, first, to prevent the colonization of bacteria and the formation of toxic products in the wound, and secondly, to impede the lymph flow so as to prevent the absorption and diffusion of the foreign elements that are always present.

CHAPTER V

THE PASSAGE OF BACTERIA AND THEIR TOXINS THROUGH THE BODY

COLONIZATION

The first factor in the development of infection in the body is the colonization of bacteria in the wound itself. No traumatic wound is free from saprophytic and few are free from pathogenic organisms, but they do not multiply in every wound, their growth depending largely on local conditions. The actual virulence of the bacteria plays an important part, but it is not the only and possibly not the most important factor.

The local conditions significant in this connection are the site of the wound and the nature of the injured tissues.

Site of the Wound

The development of a septic process as a result of a wound bears a direct relation to the vascularity of the affected part. For instance, superficial wounds of the face, which bleed profusely, normally have an aseptic evolution. On the other hand, wounds on the anterior aspect of the knee and in the leg on the tibial side, where the blood supply is relatively poor, run a greater risk of sepsis. The infection of deep wounds is also related to certain anatomical facts, which, however, concern chiefly the nature of the injured tissues rather than their arrangement. The regions in which deep wounds tend to run a septic course are the buttock, the anterior aspect of the thigh, the upper part of the calf, and the tendinous regions of the hand and foot.

Nature and Susceptibility of the Injured Tissues

The various tissues of the human body differ widely in their natural resistance to infection.

The Skin.—The surface of the skin is capable of destroying large numbers of bacteria. Colebrook (1930) showed that hemolytic streptococci are rapidly and spontaneously eliminated from the skin of the hand. He contaminated a finger by rubbing it gently with a culture and, three minutes later, when the finger was apparently dry, made a further culture and obtained a count of 30,000,000 streptococci. An hour later the figure had fallen to 1,722,000, and after a further hour to 7,000. Similar results have been obtained with other organisms;

thus it has been shown that *Proteus vulgaris, Bacterium coli, Pseudomonas pyocyanea* and Friedländer's pneumobacillus will disappear very rapidly when placed on normal skin (Arnold, 1934). This antiseptic action of the skin may be due to the sebaceous secretion (Colebrook, 1930), or possibly to the persistently acid reaction of uninjured skin (Arnold and others, 1930).

Clinically, the skin's resistance to anaerobic or ordinary pyogenic bacteria is well known. Postoperative spreading gangrene is very rare, the total number of cases recorded up to 1937 being 37 (Stewart-Wallace, 1937). This infection is caused by a combination of the staphylococcus with a streptococcus which though naturally anaerobic can grow aerobically in a culture medium. In some cases an element of hypersensitivity seems to play a part in the development of this infection; in others the tension of the sutures, by diminishing the blood supply, is a contributory cause. Erysipelas too is very rare considering how often the epidermis is damaged. Hemolytic streptococci seldom give rise to infection, in spite of frequent contamination of the skin. Even in extensive laceration in which the blood supply is seriously reduced, a dry necrosis of the damaged skin, with little or no sepsis, is commoner than a moist gangrene, particularly when the cellular tissue has not been materially damaged by the trauma. In view of its great natural resistance to septic infection, the surgeon should be very conservative with the skin.

In certain cases of lowered resistance, general or local, the defensive action of the skin may be overcome, and in these circumstances the pyogenic streptococcus may cause erysipelas. Staphylococci seldom give rise to serious septic infections except where the general metabolism is upset, as in diabetes.

The Connective Tissue.—

Subcutaneous and Interstitial.—The resistance of the connective tissue is very feeble. Its histological constitution and poor vascularity make it vulnerable to pathogenic bacteria, and its elasticity and mobility undoubtedly contribute largely to the diffusion of infections. Its laminated arrangement subjects it to every kind of pressure whenever the muscles contract or go into spasm; this further facilitates the spread of infection. When one of the cellular spaces is attacked, the infection often spreads rapidly to all the cellular tissues of a whole "compartment," thus suggesting an anatomical unit, while the close contact and intercommunication between the different cellular spaces may lead to spread of the infective process from one space to the next.

Infections of the connective tissue by hemolytic streptococci—the commonest infective agents—are difficult to localize. If the viability

of the tissue is impaired by trauma, i.e., if the blood supply is diminished, sepsis is usual. The elasticity of the tissue and its intimate contact with the muscles favor the lodgement of small clots of blood caused by interstitial hemorrhage, and the combination of devitalized cellular tissue and coagulated blood forms what is perhaps the best culture medium to be found *in vivo* for the growth of pyogenic and of some anaerobic organisms.

Tendon Sheaths.—The tissues of the tendon sheaths, owing to their more fibrous structure, offer a somewhat greater resistance to invasion than the lax cellular tissue; nevertheless they have little capacity for defense and protection. Their external surfaces are far more resistant than the internal, a fact proved clinically by, on the one hand, rarity of the septic necrosis when the injury has not penetrated within the sheath, and, on the other, the frequency with which the whole structure is destroyed when pyogenic organisms have been introduced right through the sheath, either by a septic puncture or other trauma. The movement of the tendon facilitates diffusion of sepsis in the surrounding sheath, just as movement of the muscles facilitates it in the interstitial tissues.

The hemolytic streptococci are the organisms that develop most readily in these tissues. Some infections caused by them spread so rapidly that the bacteria arrive in the blood stream almost immediately, even though they have first to pass through the whole lymphatic system. In such cases there is practically no local reaction and little or no glandular reaction. The exudate, which is serous or slightly purulent, contains very few leucocytes. Extensive edema increases the flow of lymph and so facilitates bacterial absorption and toxemia. Some cases show a serous-hemorrhagic exudate, due to a marked increase in the vascular permeability. Infections due to the staphylococcus alone are easily localized, but when this organism is accompanied by the streptococcus it has a marked tendency to disseminate. In cellulitis of slow development and long duration *P. pyocyanea* is often associated with the streptococcus and staphylococcus. In diabetic patients a form of staphylococcal cellulitis is apt to occur as a result of the subcutaneous penetration of *Staph. aureus.*

Tendons.—These tissues have little resistance to pyogenic infections, mainly because of their poor vascularity but also because of their constant movement and the consequent friction against the sheath. When pyogenic organisms, particularly hemolytic streptococci, attack them, the infection is rarely checked before the whole tendon is involved. The same pyogenic organisms colonize in the tissues of the tendons as in the other cellular tissues. Infection by anaerobic organisms is much rarer.

Muscular Tissue.—Of all tissue, muscle has undoubtedly the greatest power of resistance to pyogenic infection. It is well known that many infections involving the tendon and other cellular tissues surrounding the muscle stop at the surface. Similarly, an infection of the tendon is often seen to halt where the muscle fiber begins. From the biological point of view the muscles can be considered as an extension of the vascular system, and it is probably this very rich blood supply which inhibits bacterial growth. Their mobility, greater than that of any other tissue, does not nevertheless affect their own defensive power, though it does play a great part in the spread of infection in the neighboring tissues.

In a study of the distribution of dyes among the various tissues, Cappell (1929) showed that the muscle fibers did not readily take up the pigment, which colored only the cells of the sarcolemma and cellular interfascicular tissues. The facts that the muscle fibers are nonabsorbent, and that they contain a plentiful supply of antibodies (a feature recognized by Turró and Pi-Sunyer as early as 1905), are clearly important in their defense. In my opinion, however, the primary factor lies in their rich blood supply, for their power of resistance approximates closely that of blood.

Muscular tissue is less resistant to anaerobic infections. A decrease in the quantity of blood supplied to the muscle will produce highly favorable conditions for anaerobic infections; whereas pyogenic organisms would not in the same circumstances succeed in effecting necrosis. When a muscle has been severely bruised, small hematomas are commonly found in the fascicular interstices, and a combination of this clotted blood and a reduced blood supply provides an extremely favorable soil for the reproduction of anaerobic organisms. This fact has an obvious bearing on the surgery of war wounds.

It is sometimes stated that the spread of infection along muscle is hampered by the absence of lymphatics. The demonstration of lymphatics in muscle (Aagaard, 1913) makes this view untenable.

Bony Tissue.—Two features distinguish bone from the other tissues of the body: (1) its peculiar constitution, with its wealth of mineral components and the rigid framework within which the living elements are enclosed, and (2) the profusion of terminal blood vessels in the metaphyseal portions during the period of growth, and the relatively meager supply of blood that passes through the periosteal and capsular tissues.

The periosteum is highly resistant and, if undamaged, will effectively isolate the bone from an adjacent septic process. Consequently infection will very rarely penetrate bony tissue from without so long as the periosteum remains intact. Once this protective covering has been

damaged, however, the exposed cortex, even though it is extremely rich in inorganic substances, is wide open to infection. As in all other tissues, vulnerability turns on the blood supply; and it is for this reason that the frequency and severity of an infective process bear such a direct relation to the site, for the nutrition of bony tissue varies greatly from one bone to another, and even in different portions of the same bone. The patient's age, too, has a close bearing on the blood supply of the metaphysis and epiphysis. Up to the end of puberty many of the metaphyseal blood vessels are terminal, serving as blind alleys in which organisms circulating in the blood stream may be detained and, owing to the poverty of the blood supply, readily colonize. The exact age at which vascular anastomoses are formed varies according to the bone or epiphysis, but generally the process takes place during the later period of infancy and puberty. Consequently, infections due to the formation of septic emboli are less common after puberty, although the intercommunication between the vessels of the epiphysis and diaphysis, respectively, remains very tenuous for several years longer.

The organic elements of bone (nerves, blood vessels, lymphatics and bone cells) are enclosed in a rigid framework. Any inflammatory process inside this framework compresses the blood vessels and so gives rise to thrombosis, and thus endangers the vitality of cells situated far from the inflamed area. Where an artery is occluded in this way, the whole area of bone which it supplies is suddenly deprived of blood, and necrosis sets in. This necrotic process is sometimes confined to small areas of bone which break away immersed in pus, and are then either extruded with the discharge, or else disintegrate and are partially or wholly reabsorbed. When, however, a larger area of bone is affected, the necrosed fragment constitutes an irritating foreign body within a closed cavity and must be surgically removed. Sequestra behave like all other necrosed tissues and generally show a clear line of demarcation where the healthy bone ends and the affected portion begins. In the spongy bones, however, and at the metaphysis of a long bone, sequestra are slow to form and do not become sharply defined for a long period.

It follows from this that radical surgical treatment of infections in such spongy bones as the astragalus or calcaneus may do more injury than the infection itself; indeed, unless the dead tissue is clearly differentiated from the living, operations on these bones call for excessive care. In the compact tissue such as the diaphyseal cortex, on the other hand, sequestra form more rapidly, owing to the poor vascularity of this portion, which is in part supplied with blood through the periosteum. Thus in a severe fracture, when the periosteum is torn away from the cortical tissue, this is immediately deprived of the greater

part of its blood supply and is therefore very susceptible to bacterial infection. Moreover, its compactness makes it very difficult for newly formed blood vessels to penetrate, and for this reason it is seldom possible to revascularize such an area. In dealing with such severe injuries the surgeons should therefore remove at once those portions of bone which have been stripped of their periosteum, a procedure which incidentally will also facilitate drainage from the medullary cavity. Only in those cases, rare in war, in which a suture of the soft tissues is permissible, is it possible to conserve large fragments of periosteum-free cortex, and even then it is safer if they are perforated with a Kirschner wire to facilitate the redevelopment of the blood vessels.

In view, then, of this susceptibility of bone to infection once its periosteum has been torn away, any extension of the traumatic avulsion must be avoided. In many cases postfracture osteomyelitis is the direct result of mistaken surgical avulsion.

The organism which most rapidly initiates an infective process in the bone when introduced *via* the blood stream, as in juvenile osteomyelitis, is the staphylococcus, especially *Staph. aureus*, although suppurating periostitis is in many cases caused by a streptococcus. Perhaps the power of the staphylococcus to coagulate fibrinogen is responsible for its fixation at the narrow vascular necks. When, however, the infection is introduced directly into the bone as a result of a compound fracture, the streptococcus, staphylococcus, and in some cases *P. pyocyanea* may be found. Most cases of postfracture osteomyelitis are caused by *Strep. pyogenes;* in some cases anaerobic organisms contribute.

The Clinical Importance of Osteomyelitis.—Of all tissues, bone, when disrupted by a missile, is the one which may most easily be invaded by bacteria in a manner that leads to chronic infection. It is so easily colonized, in fact, that *all chronic suppurations of war wounds which are properly drained and free from foreign bodies must be attributed to bone infection.*

At the time of operation such infection must be prevented by the excision of sufficient devitalized bone. Most cases of osteomyelitis developing after war injury are due either to delay in operation or to defects in technique. This is abundantly evident from the large number of persistent bone infections which occur in wounds operated on by the "well" technique—that is to say, through the original wound without any previous opening of its two main angles. The difficulty of excising deep-lying damaged structures through this insufficient field is obvious.

In dealing with an already established osteomyelitis, the surgeon has two alternatives. He may either excise most of the devitalized bone at once, a course that is particularly desirable when the cortex of the

shaft of a long bone is involved; or he may wait for the sequestration of the necrotic bone and remove the fragments. His decision will depend mainly on the nature and character of the osteomyelitis. In the early stage of an infected wound, when the bone is suppurating profusely, the best measure is to excise a large portion of cortex, open up the bone marrow cavity, and establish free drainage. The part of the bone which ordinarily suppurates is the one which has no muscular attachments; e.g., the anteroexternal aspect of the middle third of the femur, and the anterointernal aspect of the middle third of the tibia. On the other hand, when osteomyelitis has been long established and the fracture is consolidated but with the persistence of chronic suppuration, surgical intervention should be confined to the removal of the sequestrum and resection of the sclerotic bone surrounding it, to facilitate healing of the bone. Fortunately the area of sclerotic bone in postfracture osteomyelitis is usually smaller than in the hematogenous condition.

The foregoing views may be summarized as follows: Chronic suppuration from a wound which does not contain a foreign body comes in all probability from devitalized bone, and should be treated by the removal of sequestra, if they exist, or by resection of the devitalized cortex.

Nerve Tissue.—A distinction must be made between the tissues of the peripheral nerves and those of the central nervous system. The peripheral nerves offer considerable resistance to infection, particularly if they have not been separated by trauma from their connection with the neighboring tissues. The fact that war wounds, though generally septic, seldom give rise to a true acute neuritis indicates that the nerve tissue is not a good culture medium for bacteria and not without resistance to toxins. In most cases of open trauma in which the nerves are affected, the tissue is subjected to an infiltration of blood at many points. The nerve tissue is seldom involved in an inflammatory reaction, but when it is, new connective tissue is formed which makes its way into the damaged nerve with disastrous consequences. For this reason it is very important to avoid sepsis in the injured nerve such as may result, with consequent ascending neuritis, from attempts at suture in a field which is not absolutely sterile.

The tissues of the central nervous system are less resistant, and acute septic encephalitis occurs more often than ascending neuritis. Though able to withstand the long exposures of modern cerebral surgery, as is shown by the rarity of septic complications following major operations on the brain, they are highly vulnerable to injuries, in response to which they disintegrate and become fluid; and in this disintegrated tissue, with its impaired nutrition, infections develop freely. While

then the importance of the central nervous system demands the greatest possible conservation of its tissues, the risk of losing the patient altogether from meningo-encephalitis necessitates radical excision of all contused nervous tissues.

Most of the pyogenic organisms can settle in central nervous tissues disintegrated by trauma, particularly the streptococcus.

Vascular Tissue.—The defense of the vascular tissues is provided by the blood. It is very effective, for the inner surface of the vessels is permanently in contact with the plasma, and the exterior with the fluids of the adjacent tissues.

Local Immunity

Apart from a general immunity to bacterial invasion, the body may acquire also an antibacterial resistance limited either to a particular kind of tissue or to a specific region. This phenomenon was studied by Cobbett and Melsome (1894), who, experimenting with erysipelas in rabbits, showed that an attack effected an immunity of the skin against subsequent inoculation. The mechanism by which this local defense is achieved is not yet fully understood, but Amoss and Bliss (1927) showed that when an injection of *Strep. pyogenes* was made into the flank of a rabbit an erysipelatous rash appeared over the ventral surface, following the line of the lymphatic flow; but later, when a second injection was made at the same site, the area formerly affected offered a definite resistance, which however was strictly confined to the limits of the previous rash. This process of local immunization, which has been shown by many workers, appears to be wholly unrelated to the general production of antibodies in the blood. It is true that after several localized injections of *Strep. pyogenes* into a rabbit an increased production of antibodies can be found in the general system, but this process is entirely independent of the local immunity. This feature of local immunity is not confined to the skin; thus Cooper (1926) showed that an injection of pneumococcal vaccine into the buccal mucosa of a rabbit will immunize this tissue and protect it from the effects of a subsequent injection of virulent pneumococci. Favilli and McClean (1937) believe that this local immunity is due to a decrease in tissue permeability.

The importance of local immunity was stressed by Besredka (1919, 1924), who based a theory on the marked tendency of certain bacteria to attack specific tissues—e.g., anthrax bacilli the skin; typhoid, paratyphoid and dysentery bacilli the intestinal mucous membranes; pneumococci the respiratory system. According to Besredka the seat of bacterial attack is not determined by the route of invasion, and the effects of virulence are manifest only in those tissues that are specifi-

cally susceptible to the invading organism. Consequently, if these tissues are locally immunized against a specific organism, then the whole animal is immune. Tested by actual experience, Besredka's theory appears to go too far.

These two phenomena, the tendency of certain bacteria to attack specific tissues (the old theory of Rosenow), and the local immunity which the body may acquire, have an important bearing on the treatment of wound infections. The mechanism of the body's local defenses against bacterial invasion must also be understood, in order that measures to prevent the development of infection may be based on logical principles.

Finally, the active part played by the tissue cells in the mechanism of immunization must not be overlooked. Turró and Pi-Sunyer (1905) demonstrated the bacteriolytic capacity of all the tissues, particularly of epithelium, and stressed the point that the factor of immunity is closely connected with the nutrition of the cells.

During the past few years several authors have put forward a theory that local immunity is a nonspecific reaction probably connected with an increase in the local permeability of the capillaries in the previously inflamed area (e.g., Burrows, 1932; Menkin, 1940; etc.). Other workers (e.g., Rich, 1933), however, have emphasized the importance of a combination of factors which contribute to the resistance of the tissues against invasion.

To sum up: the natural defense mechanism of the tissues consists of three processes: in the first the bacteria are localized, in the second the organisms are destroyed by lytic or leucocytic action, and in the third they are eliminated from the body. Interference with any one of these processes may seriously hinder recovery.

ABSORPTION

The next stage in the passage of bacteria through the body is their absorption from the tissues of the wound. In 1794 John Hunter pointed out the fundamental part played by the lymphatic system in the absorption of foreign substances from the tissues and showed that the vascular system played only a secondary part in this process. The lymphatics had been first observed and described by Gaspar Aselli (1627), but it was left for Hunter to establish the value of this discovery to surgery. François Magendie (1785-1855), the great French physiologist, disputed Hunter's ideas, and his view that foreign substances passed directly into the blood stream was generally accepted until the end of the 19th century. Having observed that strychnine was absorbed through the capillary walls, Magendie (1837) reached the extreme view that all substances were thus absorbed, entirely excluding the possibility that the lymphatic vessels might play a part in the process. Halban (1897), Manfredi (1899), Noetzel (1906), and Pawlowski (1900, 1909) each in turn showed that bacteria pass out of the tissues by way of the lymphatics and never by the blood vessels.

Since then there has been much experimental work to prove that inert particles travel solely by the lymphatic system. Batchelder, Field and Drinker (1931) found that only a very few particles of an inert colloidal nickel preparation were absorbed by the blood vessels of the omentum—an organ which is said to contain no lymphatics. On the other hand, it might be imagined that bacteria in freshly made wounds could enter the blood stream directly through the open ends of the divided blood vessels, although theoretically this is unlikely because either the blood is flowing from them or else they are occluded by clot. McMaster and Hudack (1934), examining freshly made wounds in the ear of the mouse, saw the blood vessels shut down within a few minutes of the injury, while the lymph vessels remained patent for over 48 hours and readily took up a large-molecule dye such as pontamine blue. These observations have recently been confirmed by Barnes and Trueta (1941) who showed that bacteria in freshly made wounds in the legs of rabbits reached the blood stream only when the lymphatic drainage from the limb was intact.

Absorption of Toxic Substances

According to Drinker and Field (1933), the path of absorption of chemical substances seems to depend on the size of their molecules: the smaller molecules are absorbed by the blood stream, the larger by the lymphatics. Unfortunately we do not yet know where the dividing line is to be drawn; in other words, what is the size of the molecule that is just able to enter a blood capillary while one slightly larger must perforce travel by the lymphatics. It is not simply a matter of the molecular weight, but rather of the state of the molecules in solution. Thus, strychnine travels by the blood stream (Magendie, 1823), whereas a dye such as trypan blue, with a molecular weight only a little greater, travels by the lymphatics. Starling (1895) showed that serum proteins were not removed from the limbs by the blood stream, and the work of Lewis (1921) and Field and Drinker (1931) provides evidence that these proteins are absorbed from the tissues and carried to the blood by the lymphatics.

I believe that when once we know exactly what factors regulate the absorption of substances from the tissues, we shall be able to make a great advance in the treatment of disease. Unfortunately we have as yet no knowledge of the degree to which inflammation affects absorption by the blood vessels. Recently it has been possible to show that

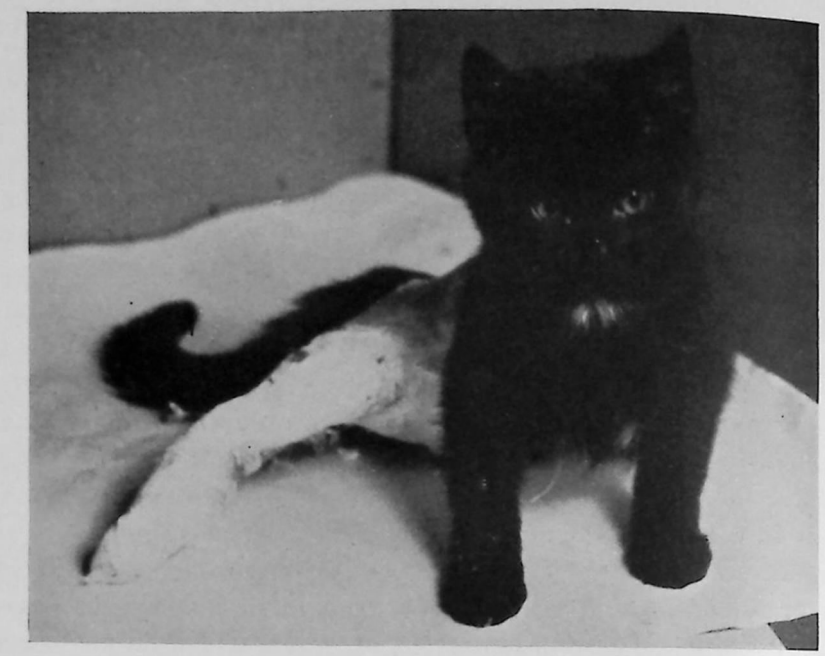


Fig. 2.—Cat three days after the injection of 20 mg. of viper venom. A control cat, not immobilized, had died twenty-four hours before.

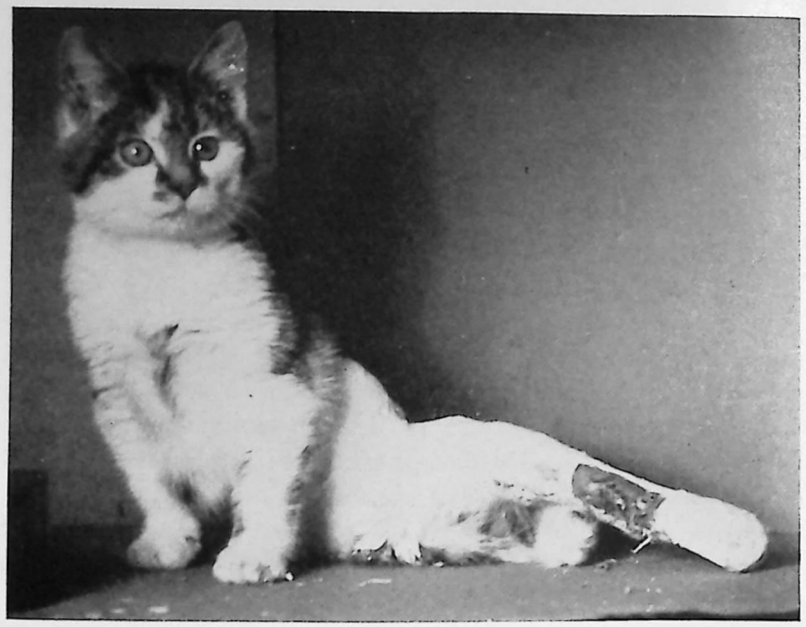


Fig. 3.—Cat three days after injection of 50 mg. of viper venom. The control cat had died forty-eight hours before.

certain snake venoms are absorbed from the tissues by the lymphatics; moreover, that this absorption can be very sensibly delayed by the complete immobilization of the limb into which the toxin has been injected. This was true when venoms with large molecular weights (over 20,000) were employed, whereas one whose molecular weight was probably below 5,000 was absorbed by the blood (see Figs. 2 and 3). In the same way it could be shown that the absorption of two bacterial toxins, diphtheria and tetanus, took place by the lymphatics (Barnes and Trueta, 1941).

From these experiments it seems clear that the absorption of the types of toxic substances normally present in infected wounds is *via* the lymphatic system.

Once foreign substances such as bacteria and their toxins are absorbed into the lymphatics, they are passed on through the nodes and, if not stopped by them, eventually find their way into the blood stream through the thoracic or right lymphatic ducts. One of three things then happens:

1. They may be retained in one of the organs whose function it is to destroy or eliminate foreign substances, e.g., the spleen, liver or lungs, and thus rendered harmless.

2. They may reach an organ susceptible to their action, and damage or destroy it. In such an organ bacteria may settle and multiply, and thence be poured into the blood stream to give rise to pyemia and possibly metastatic infections.

3. Bacteria may multiply in the blood stream and give rise to true septicemia.

BACTERIEMIA

Bacteriemia does not necessarily indicate septicemia. Bacteria are often present in the blood for short periods in the course of their journey toward the centers of elimination. If the natural defensive capacity of the blood is greater than the invasion force of the bacteria, they are destroyed without giving rise to significant signs or symptoms.

Barrington and Wright (1930) showed that ureteric catheterization was in many cases followed by a rise in temperature and the entry of bacteria into the blood, the likelihood of these results varying directly with the bacterial content of the urine and the amount of trauma produced by the technique. Okell and Elliott (1935) published a study of the bacteriemia that follows dental extraction. In a series of 138 cases they found that positive blood cultures were obtained most often when the amount of sepsis in the teeth or gums was greatest; and that such

bacteriemia, noted shortly after extraction, persisted for some hours. A positive result was obtained in 75 per cent of the patients operated on for severe oral sepsis, whether in the teeth or in the gums, the temperature in most cases reaching 99° to 102° F. within four to nine hours of the operation, and after a further two to four hours returning to normal.

In the course of my experience of treating wounds by the closed plaster method I have been interested to note how often a change of plaster is followed after a few hours by a rise in temperature. In a number of these cases blood cultures were made and more than half gave a positive result. All the patients who showed this feverish reaction, and the great majority of those in whom the blood culture was positive, had experienced some degree of local reaction, pain and fever immediately after the injury and for a few days afterwards. On the other hand, in three cases out of seventeen, organisms were found in the blood in patients who had had no fever or local reaction during the first few days. The manipulation involved in changing a plaster inevitably produces some trauma in and around the wound. In certain instances this may break down defensive barriers, stimulate lymph flow, and so lead to the entry of bacteria into the blood stream. While the majority of such cases of bacteriemia settle down within a few hours, there is always the danger of infection in some deep-seated organ or the formation of a venous thrombosis. From here a stream of infected emboli may be discharged, giving rise to a true pyemia with the danger of multiple abscesses in the kidneys, liver or brain.

The exact relation of bacteriemia to the fever which accompanies it has not yet been fully determined. It is an established fact that foreign proteins in the blood cause a rise of temperature. When heterogenous proteins are injected for therapeutic purposes, there is generally an interval of four to six hours between the injection and the temperature rise. A similar interval was noted by Barrington and Wright (1930) and by Okell and Elliott (1935) in their observations on the effects of ureteric catheterization and dental extraction, respectively, and I have observed the same time sequence in the bacteriemia that follows a change of plaster casts in the treatment of war wounds. In a few cases, however, the temperature does not rise until after 24 hours (Trueta, 1939). We have not yet been able to determine the exact correlation between the time when the fever begins and the intensity of the bacterial absorption, nor have we proved the relation between the degree of the fever and the time of its onset, although in most cases the patients who have the higher temperatures are those in whom the fever appears at an early stage.

TOXEMIA

Some specific organisms, including the most highly pathogenic such as *Clostridium tetani* and *Corynebacterium diphtheriae,* have the property of implanting themselves in the tissues either at their site of entry or in another region, whence they liberate soluble toxins which make their way into the blood stream *via* the lymphatic system and are then distributed over the whole body. Although these specific toxins thus produce harmful results remote from the site of implantation, tetanus and diphtheria are not generally considered as examples of toxemia. The term "toxemia" is applied to a clinical picture which may be produced by other less specific but highly pathogenic bacteria, the toxins of which attack the cells of important organs which are sensitive to them, e.g., the liver, kidneys, and nerve centers.

SEPTICEMIA

The concept of septicemia has noticeably changed during the past few years. Investigations on the colonization of bacteria and the diffusion of their toxins in the blood have shown ever more clearly how seldom germs live or multiply in the circulation. Joberheim and Murata (1924) showed that the amount of *Bacillus anthracis* required to kill a guinea pig is ten times greater when the organism is introduced intravenously than when it is given by either subcutaneous or intramuscular injection.

Yet the term "septicemia" is used for a clinical picture of general intoxication due to local colonization of highly pathogenic bacteria travelling rapidly through the blood stream. The clinical picture created by the entry of bacteria into the blood stream depends on the same two factors as determine the effect of an invasion into the tissues, namely, the number of germs entering in a given period, and their virulence. The term "septicemia," however, should be used to define the clinical picture produced by the multiplication of bacteria in the blood. The following two examples show how septicemia can be caused either by large numbers of bacteria or by their virulence.

A small, nonpathogenic, nonhemolytic streptococcus, which normally resides in the mouth and alimentary canal, is frequently found in the blood of patients suffering from what is known as bacterial endocarditis (Osler, 1880). According to Lewis and Grant (1923), 23 per cent of all subjects possessing bicuspid instead of the normal tricuspid aortic valves acquire, on reaching adult life, an infective endocarditis of the type of Osler's disease. The primary factor in the disease is a congenital defect in the valve structure which allows a nonpathogenic organism to settle and colonize in the cardiac tissues. It is interesting,

however, that although the congenital abnormality occurs in the base, at the point of attachment, the organism attacks the cusps, first along the lines of apposition and later over the whole surface—that is to say, it affects the most active parts of the valve. Some degree of fever, though generally slight, accompanies this disease, but the almost invariably fatal result is due not to the general infection but to the resulting cardiac changes. These clinical observations have been proved in experiments on dogs by Kinsella and Sherburne (1923), who showed that if the aortic valve is injured by passing an instrument through the left carotid artery and an intravenous injection of a culture of *Streptococcus viridans* is then given, the bacteria become implanted on the injured valve.

A severe septicemia caused by the moniliform streptobacillus of Levaditi is introduced by a rat bite; this infection may be confused with sodoku, but is distinguished from it by having a shorter period of incubation and producing comparatively slight local reactions. Other characteristics of the disease are a high temperature, dark maculae, polyarthritis, affections of the pharynx, and the absence of any response to arsenobenzene. Although the tissues are invaded, the insignificance of the local reaction indicates that the infection meets with no effective barrier but passes immediately into the blood stream, thus causing a serious form of septicemia (Morin, 1938).

Thus, in vegetative endocarditis the organism responsible for the bacteriemia, though not pathogenic to man, achieves its ill effects by attacking a vital organ in great numbers. On the other hand, the septicemia caused by the moniliform streptobacillus is serious because a highly virulent organism passes directly into the blood stream without encountering any barrier which would effectively localize its attack.

There is yet another method by which bacteria are disseminated and admitted into the blood stream. In many forms of septicemia the process of phagocytosis, contrary to the doctrine of Metchnikoff, actually protects the individual bacteria. In such cases a plasma culture gives a negative result and a seroleucocyte culture a positive one, the explanation being that the leucocytes, having ingested the organisms, effectively isolate them from the antibodies in the plasma.

ELIMINATION

The importance of bacterial elimination was fully appreciated by Claude Bernard (1872), who showed that large amounts of poisons could pass through the body without producing harmful effects when the rate of elimination and that of absorption were properly balanced.

Present knowledge of the process is due largely to the work of Aschoff, although before him Wyssokowitsch (1888), Pfeiffer and Marx

(1898), and Bull (1914, 1915) had shown that the spleen, bone marrow, liver and lungs contain a higher concentration of antibodies than the blood, and play an important part in the destruction of bacteria. Aschoff (1924) described the phagocytic power of the cells of the reticulo-endothelial system, and drew particular attention to the sessile histiocytes of the lymphatic glands. By the process of bacterial agglutination effected by the antibodies, clumps are formed which are detained in the capillaries of the lungs (Wright, 1927) and in other organs rich in polymorphonuclear cells. The germs are ingested by macrophages and then destroyed by intracellular digestion.

Cappell (1929), in a comparative study of the diffusion of dyes in various organs, remarked on the great part played by the lungs in the elimination of foreign substances. The lungs are very abundantly supplied with macrophagic endothelial cells, and are therefore the site of the final destructive process. Wright's experiments show how the passage of germs and their toxins through the blood stream contributes to their elimination. Injecting pneumococci intravenously into rabbits, he obtained the results shown in Table III.

TABLE III

FATE OF ORGANISMS IN THE BLOOD STREAM

VIRULENCE OF BACILLUS	COUNT PER C.C.				
	IMMEDIATELY AFTER INJECTION	AFTER 5 HOURS	AFTER 24 HOURS	AFTER 48 HOURS	AFTER 96 HOURS
Nonvirulent	9,000,000	2	0	–	–
Moderately virulent	1,030,000	340	1,300	–	0
Highly virulent	1,070,000	25,000	1,510,000	Animal dead	–

The minus sign signifies "not investigated."

The decrease in the counts taken five hours after injection is a result of the normal process of bacterial destruction. After this period the blood is sterilized with more or less difficulty according to the virulence of the germ: when the germ is highly virulent the bacterial reproductive process, which begins after five hours, causes a progressive increase in the number of germs until finally the animal dies; the reproduction of the bacteria has outstripped the eliminative process.

A combination of three factors—large numbers, great power of reproduction, and high virulence of bacteria—produces the most serious cases of infection. Such cases are, however, rare, for bacteria enter the blood stream only after passing through the whole course of the lymphatic system. When batches of pathogenic organisms finally reach the blood, the protective mechanism is immediately engaged, and if it is normal and no more bacteria arrive, the blood soon becomes sterile. When reproduction overwhelms the protective mechanism, the reason is probably the arrival in the blood of further batches of germs which

progressively neutralize the antibodies. The spleen plays a particularly important part in the destruction of bacteria, and in so doing is a complement to the lungs. Moreover, live bacteria can be found in the spleen some time after they have disappeared from the blood.

Because, therefore, the entry of bacteria into the blood stream constitutes such a serious stage in an infective process, and because this stage is not reached until they have passed through the whole lymphatic system, it is of the utmost importance to prevent their progress through the lymphatic channels. This need should be constantly in the surgeon's mind: for, although the task of supplementing the body's natural and acquired defensive measures belongs to the bacteriologist and the chemist, the responsibility for preventing, or at any rate reducing to a minimum, the admission of germs into the general system rests with the surgeon. The body has its natural mechanisms for eliminating bacteria, even when they are highly virulent and attack it in great numbers, but the surgeon must allow time for these mechanisms to operate and must facilitate the process of elimination by reducing the inflow of bacteria.

CHAPTER VI

PYOGENIC INFECTIONS OF WAR WOUNDS

PRIMARY INFECTION

Most war wounds are infected by a diversity of bacteria, and it is only very rarely that a single type is found. In their studies of the bacterial flora of wounds which follow a clinically aseptic course, Levaditi, Trueta, d'Harcourt, Folch and Oriol, Spooner, Orr-Ewing, Scott and Gardner, and others workers have, in most such wounds, found streptococci, staphylococci, diphtheroids, *Pseudomonas pyocyanea (B. pyocyaneus)* and the common saprophytes; in many wounds *Clostridium welchii* is found among other anaerobic flora. Of this miscellaneous collection two species cause the most serious complications: the hemolytic streptococci and *Cl. welchii.* The former are responsible for all the serious pyogenic infections, including spreading cellulitis and septicemia; the latter for many of the gas infections discussed in the next chapter.

In the following pages matters of classification will be considered in no more detail than is strictly necessary for a correct interpretation by the surgeon of the bacteriologist's reports, and in particular for an assessment of the bearing of such reports on the pathogenicity and immunological reactions of the organisms concerned. Purely bacteriological matters, e.g., the morphology of the organisms, will not be dealt with.

Aerobic Streptococci

Many aerobic streptococci are normal parasites of man, and some produce soluble toxins. The early classification was based on the changes produced by them when grown on blood-agar plates; the nomenclature in common use today is that suggested by Smith and Brown in 1919. The changes are of three main types:

(a) Alpha Type. The colony is surrounded by a green zone of altered blood pigment. *(Streptococcus viridans.)*
(b) Beta Type. The colony is surrounded by a clear zone with complete hemolysis of blood pigment. *(Streptococcus hemolyticus.)*
(c) No change is produced in the blood in the culture medium. *(Streptococcus faecalis* or *Enterococcus.)*

The beta hemolytic streptococci appear chiefly in wound infections.

More recently, hemolytic streptococci have been further subdivided according to their serological reactions. Griffith (1926, 1927, 1935)

has isolated at least 27 different types by the agglutination reaction. Lancefield (1928), using precipitin tests with the various antigenic fractions of the streptococci, has described several groups, some of which have characteristic habitats and pathogenic powers.

Streptococcus hemolyticus.—

Group A.—All the streptococci of this group produce hemolysis when grown on blood-agar plates and in all cases form a soluble hemolysin. Strains have been derived from human infections such as puerperal fever, otitis media, and scarlet fever and have been isolated from the throat, nasopharynx and nose of normal persons. This group corresponds more closely to the *Strep. pyogenes* of the earlier classifications than to the *Strep. hemolyticus;* for, according to Topley and Wilson (1936), some other strains which produce hemolysis when cultivated on blood-agar plates do not belong to this group. Of Griffith's 27 groups, 23 fall into this group A of Lancefield's classification.

Group B.—Most, but not all, of these strains form a soluble hemolysin. They have been isolated from cases of mastitis in cattle and, to a lesser extent, from the human throat and vagina. They are rarely pathogenic to man.

Group C.—The strains of this group produce β-hemolysis when grown on blood-agar plates and form a filtrable hemolysin. Three of Griffith's 27 groups of pathogenic hemolytic streptococci belong to this group. Some strains of Group C are pathogenic to man, though not markedly so, and owing to their aggressive power might be classified with *Strep. pyogenes.*

Group D.—These streptococci are present in human feces, but most of the strains have been obtained from cheese. They have been described as hemolytic enterococci.

Group E.—The organisms of this group, which are found in cow's milk, are not pathogenic to man.

Group F.—The strains of this group live in the human throat and are responsible for tonsillitis and possibly for other infections of the respiratory tract.

Group G.—The strains of this group are very closely related to those of Group C. They are slightly pathogenic, but have been isolated from normal persons. One of Griffith's 27 groups belongs to this group.

Streptococcus viridans.—This organism, of which many types have been isolated, lives in the human throat and also in the feces of cattle.

Pathogenicity and Toxicity.—

Streptococcus pyogenes (hemolyticus-β).—This organism is responsible for most of the serious infections which occur in man, through its great capacity for invading the tissues and its production of filtrable exotoxins. Five such toxins have so far been isolated:

1. A hemolytic toxin, hemolysin or streptolysin. This toxin, studied in detail by Todd (1934), is in some cases produced only when the organism is grown on solid media, being too unstable to survive growth in a liquid. What part such an unstable toxin may play when the organism grows in the body is not clear, and the uncertainty indicates the shortcomings of studies *in vitro* unsupplemented by studies *in vivo.* Fry (1933) has described certain strains which show hemolysis of the type of hemolyticus-d when grown on blood-agar plates in aerobic conditions and of hemolyticus-β when cultivated in the same medium anaerobically.

2. A leucocidin which destroys the polymorphonuclear leucocytes.

3. An erythrogenic toxin which in sensitive persons produces a local erythema when injected in small quantities or a general rash and fever in larger quantities.

4. A fibrinolysin isolated by Tillet and Garner in 1933, which both dissolves human fibrin and inhibits its formation from fibrinogen.

5. A "spreading factor" isolated by Duran-Reynals (1933) from the lysates and filtrates of *Strep. pyogenes;* injected into the skin of a rabbit this increases permeability to suspensions of India ink and to bacteria.

Streptococcus viridans.—The organisms of this group are of low virulence, both in man and in animals; nevertheless, they constitute the commonest infective agent in bacterial endocarditis (see p. 80). In man they may be isolated from local infections, particularly those of the teeth and gums.

Mutation of the Streptococcus.—It is well known that streptococci of various strains may undergo mutation from one type into another. For example, *Strep. pyogenes* when transferred from one medium to another with a different oxygen content may lose its hemolytic character and turn into a streptococcus of the viridans type.

Anaerobic Streptococci

All naturally aerobic streptococci are facultative anaerobes. Certain types of streptococci, however, are strictly anaerobic. These are present in most suppurating and gangrenous infections and in many cases of puerperal fever and septicemia (Colebrook, 1930). There are many different groups, several of which are similar to some of the aerobic strains, but the only one pathogenic to man is the anaerobic *Strep. pyogenes.* This produces the same toxins as the aerobic *Strep. pyogenes* and has most of its other characteristics. In association with other

anaerobic bacteria, such as *Cl. welchii, Cl. oedematiens* and *Cl. septique*, it is a formidable aggressive agent and contributes to the gravity of the most serious cases of gas gangrene.

Immunity to Streptococcal Infections

All types of streptococci are normal residents either in the human body itself or in many objects with which the body comes into frequent contact. Consequently the body builds up an antibacterial resistance which suffices to protect it from invasion so long as one or other of two conditions does not arise—namely, (1) the introduction of a large number of organisms as a result of an injury which damages the protective surfaces (i.e., the skin or mucous membranes), or (2) an attack by an organism of great virulence with which the body is unfamiliar. The second factor is less important than the first, as is shown, for example, in scarlet fever. It is now generally accepted that any of the strains of the organism responsible for this infection, i.e., *Strep. pyogenes*, can form a soluble toxin which in man produces a skin reaction of the scarlet fever type. Schultz and Charlton (1918) showed that when 1 c.c. of normal human serum was injected into the skin of a patient with a scarlet fever rash, the red area was blanched around the site of the injection; and Mair (1923) attributed this effect to the presence of a specific antitoxin in the normal serum which neutralized the toxin in the skin. Young children who have not had scarlet fever possess this antitoxin in a much slighter degree: in similar tests their sera give a far higher proportion of negative results than do the sera of adults, although most of these have not had the disease. It seems clear, therefore, that the human body, without contracting the acute specific fever, can nevertheless build up a plentiful supply of antibodies specific to the causal organism.

This acquired immunity may be local only. For instance, although the hemolytic streptococcus may live in the throat without causing ill effects, either local or general, it becomes pathogenic immediately it is inoculated into a newly inflicted wound or into the endometrium after labor. Once it has been introduced into the tissue spaces, it has a remarkable power of diffusion, and this faculty accounts for the gravity of the infections it produces.

The surgical advance during the Spanish War revealed, however, the value of a "fixative treatment" in localizing septic processes and preventing the development of serious general infections. No such technique has yet been devised for localizing the organisms in puerperal fever, in which the decline in mortality is due mainly to chemotherapy by the sulfonamide group.

The following points should be remembered:

1. *Strep. pyogenes* is a normal resident in certain regions of the human body.
2. With increase of age, antibodies are formed which produce specific antitoxic substances that neutralize the action of some toxins. The best known of these antitoxins is the antierythematous.
3. The virulence of *Strep. pyogenes* is due chiefly to its great diffusive capacity, and perhaps partly to its production of a fibrinolytic toxin.
4. Localization of this organism at its site of inoculation noticeably decreases its virulence.

SECONDARY INFECTION

Secondary contamination of wounds is one of the surgeon's most serious problems, but only recently has its importance been sufficiently emphasized. Such contamination should ideally have no place in the modern operating room, and indeed is extremely rare when the principles of aseptic surgery are correctly applied. There is, however, a great difference between the clean operating room supervised by specialist nurses and the general ward where dressings are changed. In the ward there may be patients with wounds colonized by pathogenic bacteria; the nurses may have to handle several different dressings and wounds, and protection from contamination is accordingly much less effective despite the greatest care. In wounds closed by primary suture the fine clot of blood and lymph forms a protective barrier against contamination, but the changing of dressings exposes open wounds to serious risk of contamination, as well as facilitating entry of bacteria by the trauma inevitably produced.

Surgeons do not fully agree on the sources of contamination. Most bacteriologists believe, and in support of their view many papers have appeared in the last five years, that hospital infection is due to air-borne contamination, with the result that during the change of dressings masks are now worn to protect wounds from nasopharyngeal carriers of hemolytic streptococci. The work of Okell and Elliott (1936), Keevil and Camps (1937), R. Hare (1940), R. Cruickshank and Godber (1939) and many others has shown that air-borne infection is a factor to be reckoned with, but I do not think it is the main source of secondary infection.

Lorenz Böhler and other Central European surgeons who have treated many thousands of wounds by the so-called "open method," or "the air cure," have found secondary infections rare despite the fact that the wound remains uncovered and masks are not used—or at any rate were not when I visited the *Unfallkrankenhaus* in 1933. It may be

that the absence of bandage and gauze, by obviating manipulation of the wound, prevents damage to the granulations and so serves indirectly to protect the tissues from infection.

In my view the principal cause of secondary infection is manipulation, and the best way of preventing hospital infection is to isolate the wound from any contact with the exterior, including the hands, linen, instruments and air. The best way to avoid both manipulation and air contamination is to enclose the wound in a plaster-of-Paris cast at the end of a clean operation in the operating room. When the plaster is changed from three to six weeks later, the strictest aseptic precautions must again be observed—a point worth emphasizing, for the need of sterilizing plaster-removing instruments is not always realized. It is true that despite the greatest care new bacterial flora are often found in a wound after a change of plaster—for when a skin-tight plaster is removed, the shears touch the skin and may touch and contaminate the wound—but their number and pathogenicity are least when the precautions are greatest.

Bacterial Flora of Wounds Treated Under Plaster

In my hospital in Barcelona the bacteriologist investigated the changes of bacterial flora under plaster; but owing in part to the rush and urgency of hospital work in air raids and in part to the lack of materials due to the blockade, the work was too limited in scope to yield definite or far-reaching conclusions. Similar investigations by d'Harcourt and others (1940) in the base military hospital at Barcelona suffered from the same difficulties. It was, however, shown that a great diversity of organisms may be present under the plaster. In wounds which had been carefully operated on at the right time the first change of plaster revealed only a few saprophytes, which persisted until the end of treatment, a few similar organisms being added in some cases at each change of plaster. In other wounds which had been operated on late, or incompletely, large numbers of bacteria were found, including streptococci, staphylococci, *Ps. pyocyanea, Pr. vulgaris* and *Cl. welchii.*

Investigations in Great Britain on soldiers evacuated from Dunkirk and on the victims of air attacks and road accidents have generally confirmed the Barcelona findings, and have also revealed the importance of secondary infection. Miles, Paterson Ross, Pilcher and others (1940) found bacteria colonizing on the outer surface of most of the plasters; and it seemed that in the cases concerned the discharge was profuse and the bacteria in the wound had percolated through the soaked plaster. They made the wise suggestions that the escape of pus from the ends of plasters and from cracks should be minimized and that plasters should be disinfected on the outside. Undoubtedly the

best way to avoid undue passage of germs through the plaster from the wound is to prevent the formation of pus. According to these authors 82.5 per cent of the clinically ill patients and 50 per cent of the healthy patients had streptococci in their wounds; facts which emphasize the importance of keeping the wound free from hemolytic streptococci after the operation and of avoiding secondary infection.

Spooner (1941) described small changes of flora at successive removals of the plaster and occasionally the appearance of a new species: three of his cases acquired *Pr. vulgaris,* two acquired diphtheroid bacilli, one acquired *Ps. pyocyanea* and it was probable that one acquired *Strep. hemolyticus.* The most conclusive work so far published on the bacteriological flora of wounds treated in plaster casts is that of Orr-Ewing, Scott and Gardner (1941). These workers, by an ingenious device which gave access to the wound with a minimum of disturbance, found that some species, namely, *Pr. vulgaris, Staph. albus* and other micrococci, diphtheroids and *Ps. fluorescens,* seemed to be completely and permanently removed by thorough excision and cleansing within a few hours of the accident.

Time of Introduction of Organisms

"Hospital Infections."—In normal circumstances infection of the wound does not occur through the plaster cast; but it has been shown to do so fairly often during plaster applications. Thus, in the above investigation, a total of 11 species new to the wound were detected in 7 out of 12 samples examined immediately before the first change of plaster. On the other hand, 21 samples taken at subsequent plaster changes showed no new species. Of the 10 patients submitted to these tests, 4 were found to have become secondarily infected; a fifth also acquired new species during a period when the plaster had no window

TABLE IV

NEW SPECIES APPEARING IN WOUNDS AFTER FIRST 15 DAYS OF TREATMENT IN PLASTER

ORGANISM	CASE NO.	PLASTER NO.	FATE OF ORGANISM	
A. IN PATIENTS FITTED WITH "WINDOW" IN PLASTER				
Strep. pyogenes (Group A)	I	2	Persisted	> 7 months
Cl. welchii	III	2	Disappeared	< 63 days
Strep. viridans	VI	2	Disappeared	< 19 days
Staph. albus	VI	2	Disappeared	< 21 days
Micrococci (1)	VI	2	Disappeared	< 21 days
Micrococci (2)	VI	2	Persisted	> 40 days
Bacterium	I	2	Disappeared	< 50 days
Ps. pyocyanea	I	3	Persisted	>135 days
Plectridium	II	2	Persisted	> 63 days
B. IN PATIENTS WITHOUT "WINDOW" IN PLASTER				
Diphtheroids	V	3(?)	Disappeared	< 39 days
Strep. pyogenes	V	Uncertain	Persisted	
Strep. viridans	V	Uncertain	Disappeared	< 48 days

TABLE V

NEW SPECIES ISOLATED AT VARIOUS TIMES DURING FIRST 15 DAYS

CASE	DAY 1	DAY 3	DAY 7	DAY 12
I				
Wound excised 2 hours after accident	*Staph. albus*	0	0	0
	Diphtheroid (1)	0	0	0
		Staph. aureus	+	
		Diphtheroid (2)	+	
		Micrococcus (1)	+	
		Micrococcus (2)	0	0
			Micrococcus (3)	
			Diphtheroid (3)	
			Plectridium	
			Bacillus	
II				DAY 15
Wound excised 3 hours after accident	Bacillus	+	+	+
	Cl. bifermentans	+	+	+
	Cl. sporogenes	+	+	+
	Ps. fluorescens	+	0	0
	Bacterium sp.	+		0
		Chromobacterium	Proteus	+
				Diphtheroid
				Ps. Pyocyanea
				Plectridium
III				
Wound excised 3 hours after accident	Diphtheroid (1)			
	Diphtheroid (2)		0	0
	Micrococcus (1)		0	0
	Micrococcus (2)		0	0
	Staph. albus		0	0
			0	0
			Strep. pyogenes (Group A)	++
			Enterococcus	0
			Proteus	+
			Ps. pyocyanea	+
			Diphtheroid (3)	+
IX				
Wound excised 2 hours after accident	Sterile			*Staph. aureus*
				Diphtheroid Type 1
				Bacillus
X		DAY 4		DAY 16
Wound excised 2 hours after accident	Hemolytic streptococcus (Group B)			
	Staph. aureus	+	+	0
	Diphtheroid (3 types other than 1)	+	+	+
		0	0	0
		Diphtheroid Type 1		
		Bacillus		
		Hemolytic streptococcus (Group A)	Enterococcus	
			+	+

Persistence or disappearance shown by + or by 0.
The numbers in parentheses refer to the different types of the organism.

and the source of infection could not be traced. The bacteria so acquired during the first fifteen days in cases treated within eight hours of the accident are listed in Table IV.

It should be noted that new species, often in considerable numbers, appeared earlier than the fifteenth day. These, the authors suggest were introduced before or during the first plaster application.

Prehospital Infection.—There appears to be a considerable lag in the development of many species in wounds which have been thoroughly cleansed within a few hours of the accident; and as stated above some seem to be permanently removed by this procedure.

The progressive development of those that do appear during the first fifteen days (in cases treated within eight hours of the accident) is shown in Table V.

Table VI shows new species isolated in the first fortnight in cases operated upon sixteen to forty-eight hours after the accident.

TABLE VI

NEW SPECIES ISOLATED AT VARIOUS TIMES DURING FIRST FORTNIGHT IN CASES OPERATED UPON LATE

CASE	DAY 1	DAY 4	DAY 10	DAY 14
V (48 hours)	*Staph. aureus*	+	+	
	Micrococcus	0	0	0
	Pr. vulgaris	0	0	0
	Diphtheroid Type 1	+	+	+
	Bacillus	+	+	+
			Bacterium	+
				DAY 23
VII (16 hours)	*Strep. pyogenes*		++	++
	Staph. aureus		++	++
	Bacillus		+	+
			Micrococcus	0
			Diphtheroid Type 1	+
VIII (16 hours)	*Strep. pyogenes*		+	+
	Staph. aureus		+	+
	Micrococcus		+	+
	Bacterium		+	+
	Bacillus		+	+
			Ps. pyocyanea	+

Delayed development occurs more commonly in the group of cases treated early. A time lag of three or four days is here to be expected, for many species of organisms introduced at the time of injury are likely to be present in numbers too small to be detected at the first examination, carried out only two or three hours later. Thus, in the above investigation six new species appeared between the third and eighth days, one between the fourth and tenth, and four between the seventh and fifteenth days—making a total of eleven species in all. Although these may conceivably have been introduced during the opening of the window, the authors believe it more probable that they were

in fact present but undetected at previous examinations. This view seems well founded, for if the first assumption were correct eleven new species would have been introduced in the course of eleven examinations between the third and tenth days, whereas none were detected in twenty-one similar examinations at later periods. The delay in bacterial development at this time, when the barrier of granulation tissue is being built up, may be of great benefit to the patient. The authors suggest that most (though doubtless not all) of the organisms were introduced before and not during wound excision (1) because the number of new species was far greater in the early than in the comparatively late cases, and (2) because such infection was comparatively rare at subsequent changes of plaster.

To sum up: cases operated on during the first three hours showed delayed growth of new species—the great majority being saprophytes. During the first few days bacteria contaminating the wound were much less numerous in such cases than in those operated on after sixteen hours; moreover, in the latter group either *Strep. pyogenes* or *Staph. aureus,* or both, were present. The investigation also showed that plaster protects the wound against secondary infections provided that all the necessary precautions are taken in applying it.

CHAPTER VII

GAS GANGRENE

Although recognized since ancient times, gas gangrene was never systematically studied until the War of 1914 to 1918. In every war it has been one of the chief causes of death, and even today it accounts for a fair proportion of fatal war wounds. The earliest reference to the infection was by Fabricius of Hilden in 1607 (Kellett, 1939), who appears to have published the first clinical description. Since his time accounts have appeared in the writings of a number of army surgeons. Larrey (1812), who wisely attached great importance to arterial spasm in the production of gas gangrene, called it "traumatic gangrene." Velpeau (1849) referred to it as "bronze erysipelas," because of the color of some of the patients in the advanced stages. During the Crimean War Salleron made a study of 65 cases which he had himself treated; and in the Franco-Prussian War of 1870 Fréry, surgeon to the French troops in the siege of Belfort, collected many cases, of which he published an account in a short monograph.

During 1914 and 1915, particularly in the first six months of the war, many descriptions of gas gangrene appeared in Great Britain, France and Germany. According to the published statistics the incidence at the beginning of the war was appreciably higher in the Allied armies than among the Germans and Austrians, although they fought over the same battlefields. This suggests that the development of gas gangrene turns on more than one factor—not only the specific bacterial agents but also the conditions in which their pathogenic effect can be exercised. In March, 1915, Weinberg and Séguin described the whole range of bacterial flora that produce gas gangrene, and prepared the first antigangrene serum. Vincent, Levaditi, Sacquepée, D'Este Emery, Bullock, Fleming, McIntosh, and others gave accounts of the infection from the bacteriological point of view, and Lardennois and Baumel, Duval, Cuthbert Wallace and others described its characteristic clinical features. In recent years little further progress has been made in the general study of gas gangrene, but some advance has been achieved in its treatment. Thus, the statistics of today, thanks in part to the use of sulfonamide compounds but above all to the methods of treatment developed in Catalonia during the Spanish War, show a very marked improvement on those of only a few years ago.

BACTERIOLOGY OF GAS GANGRENE

Many patients with gas gangrene harbor a diversity of bacteria, both aerobic and anaerobic; and in fatal cases it is rare for only a single species to be present.

Clostridium welchii (French: "perfringens"). This organism, first isolated in 1892 from a cadaver by Welch and Nuttall, lives in soil, milk, water, dust, sewage and the intestinal canal of man and animals. It produces four types of exotoxin, and varies in pathogenicity from one strain to another. It is a great producer of gas. Weinberg and Combiesco (1930) described the effects caused by the welchii toxins, which include lysis of the red corpuscles (producing hemoglobinuria), local areas of necrosis in the kidney and liver, and a rise in blood pressure which may lead to hemorrhage. The minimum lethal dose for a mouse is about 0.25 c.c. *Cl. welchii* produces the spreading factor described by Duran-Reynals (McClean, 1936). It invades the tissues in the advanced stages of the infection, and in fatal cases will generally be found well beyond the limits of the initial focus. Its action is predominantly saccharolytic, but it is also proteolytic, and the extent of its production of gas depends on the degree of fermentation in the surrounding medium.

Like other spore-bearing anaerobes, *Cl. welchii* requires an increase of carbon dioxide and cannot flourish in a medium supplied with oxygen, though the spores may live for a long time in oxygenated culture media.

Cl. oedematiens.—First isolated by Sacquepée and by Weinberg and Séguin (simultaneously) in 1915, this organism lives in the soil and produces a highly aggressive exotoxin. The average minimum lethal dose for a mouse is 0.002 c.c. The organism does not invade the tissues, and hence, like *Cl. tetani* and *C. diphtheriae,* its poisonous effects are due entirely to its toxins. Duran-Reynals (1936) noted the presence of "spreading factor" in the medium surrounding it—a surprising observation considering that it cannot invade the tissues, and one which McClean (1936) could not confirm. The toxin, on the other hand, is highly invasive. *Cl. oedematiens* produces extensive gelatinous edema, which is nonhemorrhagic and can thus be readily distinguished from the markedly hemorrhagic edema produced by *Cl. septique.* It produces little or no gas.

Cl. septique.—Originally described by Pasteur and Joubert in 1877, this organism lives in the soil and produces exotoxins. The average minimum lethal dose for a mouse is 0.005 c.c. It produces less gas than *Cl. welchii* and an edema which, though highly hemorrhagic, is less extensive and gelatinous than that produced by *Cl. oedematiens.*

Muscles infected by this organism are rendered soft, and during the first few hours are intensely red.

Cl. fallax, Cl. sporogenes and *Cl. histolyticus.*—These three spore-bearing anaerobes are related to *Cl. welchii, Cl. oedematiens* and *Cl. septique,* respectively, but none by itself seems sufficiently aggressive to produce gas gangrene. Weinberg and Séguin (1918) cited a series of 91 cases of which 67 had both anaerobic and aerobic bacteria, and 24 anaerobic alone. In the latter group there were only 10 cases in which the wound was infected by a single bacterial species. In the whole series the types of organisms and the relative numbers in which they were present varied greatly, some 38 different combinations of anaerobic flora being observed. The proportion of the various types in cases of gas gangrene are set out in Table VII (Weinberg and Séguin, 1919).

TABLE VII

RELATIVE NUMBERS OF ANAEROBIC ORGANISMS IN CASES OF GAS GANGRENE

	WEINBERG & SÉGUIN (91 CASES) %	MC INTOSH (41 CASES) %	MC INTOSH (52 CASES) %	HENRY (50 CASES) %
Cl. welchii	77	43.9	67.3	80
oedematiens	34	–	4.0	10
sporogenes	27	36.5	38.7	–
fallax	16.5	–	–	6
septique	13	19.5	16.3	16

Weinberg and Séguin also found *Cl. histolyticum* fairly frequently, both this organism and *Cl. sporogenes* seeming to contribute in some measure to the aggressive capacity of *Cl. welchii.*

DEVELOPMENT OF GAS GANGRENE

Apart from the presence of the responsible organism, the essential condition for the development of gas gangrene is lack of oxygen in the wounded tissues; in other words, an inadequate blood supply. *In vivo* the only oxygen capable of impeding the growth of anaerobes is that in the blood. Local anoxia may be induced by various factors, as the following four examples show.

1. The intramuscular injection of *Cl. welchii* into guinea pigs may cause some degree of gas gangrene, but does not do so invariably. Vincent and Stodel (1917, 1918) found that genuine gas gangrene followed such an injection in only 25 per cent of cases; but that when after the injection the muscles were bruised and their circulation was consequently impaired, a typical gas gangrene always developed. This contribution of trauma to the production of gas gangrene can be demonstrated even when there is a considerable delay after the injec-

tion. Vincent and Stodel showed that gas gangrene will develop when the muscles have been bruised as long as ten days after the introduction of *Cl. welchii*.

2. Infection does not follow the injection of organisms, even in large numbers, that have been thoroughly washed and freed from their toxins. If, however, a sublethal dose of toxin is injected together with the toxin-free bacilli, an intensely virulent reaction will result (de Kruif and Bollman, 1917), for the toxin produces a lesion which interrupts the local blood supply and so provides the conditions required for the multiplication of anaerobic organisms.

3. Calcium has a similar effect. Bullock and Cramer (1919) injected mice with calcium salts of various kinds (soluble calcium, sodium calcium chloride, calcium nitrate and calcium citrate), and then, elsewhere in the body, introduced a washed suspension of *Cl. welchii* or *Cl. septique*. These toxin-free bacilli produced serious lesions, not locally in the area in which they had been introduced but at the site of injection of the calcium to which the bacteria had migrated through the tissue spaces. Russell (1927) and Fildes (1927) found that calcium salts produce extensive necrosis of tissue.

4. Wamoscher and Vásárhelyi (1933) found that a small amount of sterile agar would also activate previously injected anaerobic organisms. In this case, however, the effect was achieved, not by any interference with the blood supply of the tissues, but by the agar forming a protective covering which isolated the organism from the oxygen in the blood.

From these experimental findings we may conclude that in normal tissues the oxygen content is sufficiently high to prevent the spores from germinating, but that in damaged or necrosed areas the concentration falls to a point low enough to allow them to reproduce. It must be stressed that the amount of tissue damage needed to enable the spores to germinate is very slight. Moreover, as the agar experiment shows, a mere enclosure of the spores, separating them from the oxygen in the blood, is sufficient without any tissue damage to permit anaerobic bacteria to multiply. Such enclosure may be provided by any kind of foreign body, especially soil.

Working on the fundamental fact that anaerobic organisms do not thrive in an oxygenated medium, surgeons have for many years regarded atmospheric oxygen as the chief preventive of anaerobic infection, favoring the injection of oxygen into the infected area as a therapeutic measure. I believe that this view is mistaken and that techniques based on it have resulted in more harm than good. Atmospheric oxygen plays indeed a very small part in the prevention of gas gangrene, for anaerobic bacteria multiply freely and produce their characteristic lesions in wide-open, well-oxygenated wounds from which the bruised tissues have not been properly excised; whereas they do not develop or produce lesions in wounds which, after appropriate and detailed surgical treatment, have been enclosed in plaster casts and have thus been isolated from the oxygen of the air.

It is, of course, true that gas gangrene cannot develop unless the wound is contaminated by one of the specific organisms, but equally true that such contamination does not necessarily by itself result in gas gangrene. On this point surgeons and bacteriologists are agreed.

Since the introduction of the closed method, many cases have been reported in which *Cl. welchii* has been recovered from wounds at the change of plaster. I have observed such cases myself (Trueta, 1939), and Spooner (1941), Gardner (1941) and others have published similar findings. In none of these cases has the organism proved harmful, a fact which emphasizes the error of the old view that atmospheric oxygen is essential for the prevention of gas infection.

Levaditi and others (1940) have cited a case of perfect recovery following suture of a wound known to harbor *Cl. welchii*. This example is cited to indicate not that anaerobic organisms are harmless, but that an essential factor in the development of the infection is the condition of the tissues. The following passage from a paper by Sir Anthony Bowlby (1915) is representative of views that developed during and after the War of 1914 to 1918:

> "In the vast majority of wounds, although the same anaerobes are present they are comparatively powerless to do much harm . . . but I have seen a whole limb gangrenous, and the patient dead from hemic infection, sixteen hours from the time he was injured. It is evident, therefore, that in such cases the organisms meet with no resistance from the tissues; and the question to decide is why the tissues do not resist in some cases, when in very many other wounds the anaerobes have evidently but little power of harm."

Later in the same paper he pointed out that gas gangrene developed more often in limbs which had suffered arterial injury. Thus as early as 1915 the part played by the blood supply in the pathology of gas gangrene was given the place it deserves.

PATHOLOGY OF THE MUSCLES IN GAS GANGRENE

Most war wounds produce an area of disintegrated muscle. Immediately round this area is a zone of healthy, living fibers, the interspaces between which have, however, suffered concussion and become exposed to bacterial penetration. These interspaces form an ideal soil for the growth of organisms. The work of Aagaard (1913) has established the existence of lymphatics in muscle, though the anatomical

details are not yet well understood. It is through the intertissue spaces and lymphatics that infection spreads from the initial area of contamination.

The susceptibility to infection of any individual muscle bears a direct relation to its anatomical structure, and the two main types of muscles, namely, the segmented or short muscles of the trunk and the long muscles of the limbs, must therefore be considered separately. In injury to a long muscle the area subjected to the secondary effects of interference with blood supply is very much greater than when the segmented or short muscles of the trunk are damaged.

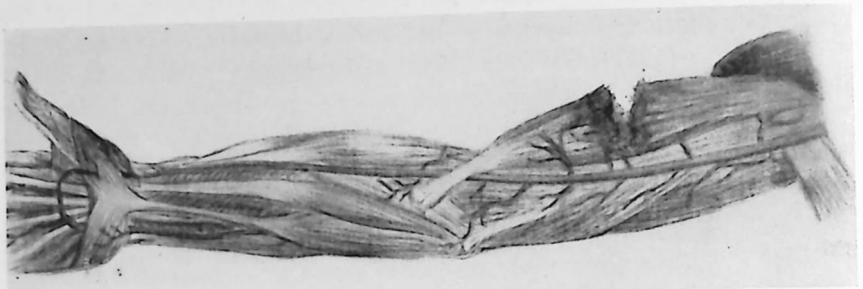


Fig. 4.—Blood supply of the muscles of the arm. The great majority of the vessels run transversely. The area of muscle supplied by each artery is small.

There are accordingly marked differences between the clinical pictures of gas gangrene in long and in segmented muscles. The spread of infection, the rapidity of evolution and the gravity of gas gangrene are all greater in the former than in the latter. In segmental and short muscles the area supplied by a single artery is small, and the vessels run parallel; they approach the muscles from the side and expand into them transversely. In long muscles the arteries enter at the proximal end and run along the tissue for a variable distance. A good example is found in the thigh, particularly in its anterior and superior part, the sartorius being one of the most typical of the long muscles. Wounds in the upper part of the thigh may damage the blood supply so that the muscles distal to the injury become ischemic from the first (see Figs. 4 and 5).

Effect of Gas-Forming Infection in Muscles

At a very early stage of the infection three zones can be defined: (1) The first zone corresponds to the area where the fibers, both in their anatomical structure and arrangement, have been immediately destroyed by the trauma. Disintegrated muscle and organized clot are commonly seen and a vast number of organisms are found. (2) In the second zone the structure of the fibers has been destroyed but their

anatomical arrangement has remained undisturbed. These fibers may also have been killed immediately; but as they are always covered by a mass of bacteria and products of bacterial infection, their destruction is more probably due to bacterial action. The muscle fibers are sepa-

Fig. 5.—Blood supply of the anterior muscles of the thigh. The most important muscular arteries run downward. Any severance of the arteries leaves an extensive area of the distal portion of the muscle without blood supply.

rated from each other by an exudate which may or may not be packed with leucocytes, according to the type of infection. When the infection is mixed, i.e., anaerobic bacteria together with pus-forming cocci, there is local leucocytosis; but not when the infection is exclusively anaerobic. In mixed infections the number of leucocytes is so great

that in some places they even obliterate the capillaries between the fibers. (3) In the third zone the muscle is normal, except for some cellular infiltration.

Briefly, the tissues of these three zones may be described, respectively, as dead, dying, and normal. Organisms are more often found in the lymph surrounding the muscle fibers than in the fibers themselves, and in mixed infections large numbers may be seen inside the leucocytes in the second zone. The bacterial invasion extends rapidly through the damaged muscle up to the point where the circulation is still intact and normal fibers begin. Here it is temporarily checked. Thus, although the tissues of the first and second zones are quickly destroyed by the combined effect of the trauma and infection, the vitality of the third zone may prevent a further spread of infection for long enough to allow successful treatment.

The damage is many times greater in the distal than in the proximal part of the wound. Gas infection has at first a tendency to be limited to the latter, but unfortunately progressive and rapid invasion soon follows. The intensity of the resulting process may often be traced from the central fibers toward the sheath, which frequently remains uninfected, but may be the chief source of spread of the bacilli. The septa between muscles, the connective tissue surrounding veins, or anatomical structures such as Hunter's canal may provide paths of extension. In long muscles the successive stages of tissue disintegration and bacterial invasion follow one another with great rapidity and involve not only a single muscle but a whole group and sometimes even the entire limb. Near the wound many large bubbles can be seen with the naked eye, both outside the muscle sheath and inside the sheath itself, but never in the muscle fibers themselves. The diffusion takes place through the fluids that surround the fibers, and once the bacteria reach the neighborhood of the muscle insertion they proceed along the walls of the capillaries without, however, passing through them. Only after the sarcolemma has been destroyed do bacteria make their way inside the actual fibers; at a late stage they even invade the vessels, thus rupturing capillaries and causing multiple small hemorrhages.

Thrombosis

Thrombosis, a well-known accompaniment of wound infection and one of the causes of secondary hemorrhage, occurs at many points and, as a result of the interference with the circulation and of the intramuscular hemorrhage due to rupture of capillaries, new areas of tissue are converted into a medium ideally suited for bacterial growth. The thrombi may form at a distance from the site of the original inflammatory lesion and together are the main cause of extensive gangrene of the limb. Occasionally secondary gas gangrene will appear

in a different limb (the most common extension is from the thigh to the arm), the cause here lying in an embolic metastasis. Just as an anaerobic invasion of the muscles in the region distal to the wound is largely due to traumatic interruption of the blood supply, so a spread of the infection to the muscles on the proximal side is produced by thrombosis—which, it must be remembered, occurs the more readily when the circulation has been impaired by vasomotor disturbance, shock and diminished nutrition of the vascular endothelium.

The constant appearance of these anatomical changes in gas gangrene makes it clear that the infection is inseparably connected with impaired blood supply, and that this must be regarded as a factor essential for the multiplication of anaerobic organisms and the production of their toxins.

LOCATION OF THE INFECTION

The regional distribution of gas gangrene bears, as has been shown, a definite relation to the anatomical arrangement of the muscles. It occurs most commonly in areas in which the muscles are long and narrow, whence the high proportion of gangrenous infection in the thigh, amounting to nearly one-half of all cases, and in the leg, amounting to nearly one-third of all cases. In the remaining sixth the infection occurs most commonly in the arm, and less often in the forearm and in other parts of the body such as the buttock, shoulder and retroperitoneal region. In the rarer cases of gas gangrene in and about short and broad or segmented muscles, as in the retroperitoneal spaces of the abdomen, the decisive factor is not only the necrosed muscular tissue but also the large hematomas produced by the injury.

All parts of a given region are not equally susceptible. For instance, in the thigh gas gangrene develops most commonly from wounds in the upper third, less often from wounds in the middle third, and still less so from wounds in the lower third. Furthermore, it develops more commonly from wounds of the front than from those of the back of the thigh, the proportion being approximately the same as that of infections in the arm to those in the forearm. In the arm there appears to be less distinction between one part and another. Both in leg and arm a lesion of the main arteries is an almost invariable predisposing factor.

RELATION TO THE TYPE OF PROJECTILE

The nature and form of the projectile inflicting the wound play an important part in determining the development of gas gangrene.

Rifle Bullets.—Rifle bullets fired at long range, and those that retain their proper shape, seldom produce a gas infection. When, however, bullets are misshapen, either deliberately or by ricochet, or when they

have been fired at short range (thus often producing an explosive effect, particularly noticeable at the exit wound), the chances of gas gangrene are far greater.

Trench-Mortar Grenades.—The trench-mortar grenade is always liable to produce gas gangrene, perhaps because it causes extensive vascular damage and severe shock.

Shell Fire.—During the War of 1914 to 1918 the wounds in which gas gangrene appeared most commonly were those made by high-explosive shells. The irregular shape of the wounds, the extensive damage to the soft tissues, and the impairment of both local and general circulation all facilitated infection. In such wounds, moreover, there was extensive bruising of the muscles, owing to the considerable size and irregular shape of the pieces of shell-case.

Aerial Bombs.—The aerial bomb used in the War of 1914 to 1918 caused wounds very similar to those made by shells. Many of the bombs employed today, however, are quite different, and inflict wounds of a special type. The majority of modern aerial bombs, especially those of medium and small size intended to injure personnel, throw off vast numbers of small splinters, many no larger than a fingernail; and these, by reason of their high velocity and rotary movement, damage the tissues in the depth of the wound out of all proportion to the minor injury in the skin. Being very light, they therefore seldom traverse the limb but come to rest in the tissues at the bottom of the wound. In such cases gas gangrene will sometimes appear if early and proper surgical treatment is not instituted. Heavy high-explosive bombs produce wounds similar to those caused by shells, but more serious owing to the ischemic effect of the blast.

The projectiles of modern warfare may be listed, according to the frequency with which they produce gangrenous wounds, in the following descending order:

1. Heavy aerial bombs
2. Shells
3. Medium and small aerial bombs
4. Trench-mortar grenades
5. Rifle bullets fired at short range
6. Rifle bullets fired at long range

CLINICAL PICTURE OF GAS GANGRENE

Gas gangrene is not a specific disease, for it may be produced by anaerobic organisms of various groups. Moreover, its severity varies remarkably, ranging from a slight inflammatory reaction with some

local edema, gas formation and an offensive smell, to an extensive generalized toxemia which may prove fatal in less than twenty-four hours. There are four distinct types of anaerobic infection:

1. Gangrene with gas (regional gangrene)
2. Anaerobic toxemia
3. Toxic edema
4. Gaseous phlegmon (local gangrene)

Gangrene With Gas (Regional Gangrene)

Gangrene with gas is the form most common in patients who have not received proper treatment within the first six hours. Its most frequent site is the thigh, particularly the upper anterior aspect. It is an emphysematous gangrene that spreads, in some cases very extensively, from the initial local focus. The wound is very dirty and exudes a thin, dark, evil-smelling discharge; escaping bubbles of gas may also be observed. The edges of the wound are dark, often coal black. During the first few hours the surrounding skin is pallid, but after a short while this tinge may change to yellowish blue, and, if the patient survives for more than twenty-four hours, areas of necrosis may become visible in the skin. At first the patient is excitable and has a highly flushed face, a dry tongue, and a rapid pulse associated with what may be only a slight rise of temperature. After a few hours emphysema appears, the skin turns blue, crepitus is observed, and a marked tympanic note is obtained on percussion. These features increase in proportion to the invasive character of the infecting organism. The patient has a strained appearance, profuse sweating, dilated pupils, distressing air hunger, and a still more rapid and running pulse. The temperature at this stage is variable, being sometimes very high in patients who offer a good resistance but usually subnormal in those with serious toxemia.

While this clinical picture is generally typical of this type of gas gangrene, variations in detail are found in individual patients. These, however, do not consist of differences in the actual symptoms, but of variations in their time relations. For example, in one case the infective process may take three days before the patient's condition is serious, whereas in another the same stage is reached in less than twenty-four hours.

The organism responsible is *Cl. welchii,* either alone or in association with another anaerobe (normally either *Cl. oedematiens* or *Cl. septique*) or with *Strep. hemolyticus.* The most invasive and grave of these gas infections are largely due to this combination, and particularly to the association of *Cl. welchii* and *Cl. oedematiens.*

Anaerobic Toxemia

In this form of gas gangrene, the most rapid of all, gas is not produced locally and there is practically no swelling or smell. The muscles are dry, friable and markedly pale. They are soft and free from pain and contain no gas. Within twenty-four hours the skin is cold and dry and has a deathly pallor; the patient's temperature is very low and the pulse too rapid to be counted. A striking calmness of mind and of facial expression characterizes these cases. In some patients suffering from this hypertoxic anaerobic infection, signs of hemorrhage or shock appear within the first few hours; in others who survive longer, edema is seen; but in both groups there is the same complete absence of pain in the wounded limb. Autopsy reveals gas in the brain, liver, kidney, and spinal cord.

Cl. welchii, the organism which produces this toxemia, may be found in the blood from the initial stage onwards; and the serious and widespread general effects of this bacteriemia are out of all proportion to the amount of local damage. Fortunately the condition is rare, for *Cl. welchii* survives with difficulty in human blood. (See also Emery, 1916.)

Toxic Edema

This anaerobic infection is due to local colonization of *Cl. oedematiens,* sometimes alone but more often in predominant association with *Cl. welchii, Cl. septique,* or *Strep. hemolyticus.* A highly invasive infection, its most characteristic features are the absence of gas (in cases in which *Cl. oedematiens* alone is the responsible agent), widespread and rapidly progressive gelatinous edema, immediate and severe general intoxication, and a time-lag of 48 hours—in many cases as long as the patient survives—before the appearance of gangrene.

In operations performed soon after the onset of the infection, the cellular spaces and subcutaneous tissues are found invaded by a clear gelatinous edema, and the muscles are dark red. When the infection is in an extremely advanced stage, gangrene spreads rapidly from the most distal part of the limb and invades the whole member. In cases in which *Cl. oedematiens* is associated with *Cl. septique* the edema is hemorrhagic and a small amount of gas may be found. Examination of the blood rarely reveals *Cl. oedematiens.* This type of infection is nearly always fatal.

Gaseous Phlegmon

Gaseous phlegmon, the mildest form of anaerobic infection, is localized especially in the cellular connective tissue. It commonly appears in wounds of the leg and arm and in the more superficial wounds of the thigh; it may also sometimes appear in deeper and severely bruised wounds of the latter region. In many cases the only symptoms are gas

bubbles, some crepitus in the inflamed area, local pain and a slight general reaction; in some the only indication is the offensive smell of the wound. This mild type of gas-forming infection spreads slowly if at all. It is most important to distinguish it clearly from the more serious forms.

DIFFERENTIAL DIAGNOSIS

The following points should be considered in the differential diagnosis.

1. **Lapse of Time Since the Injury.**—The more serious types of infection generally develop earlier after the wound than the milder type.

2. **Type and Site of Wound, Presence or Absence of Fracture.**—An infection from a wound which is not greatly destructive, in a region such as the anterior aspect of the leg or the posterior part of the arm, and in some cases an infection from a wound on the back of the thigh without an accompanying fracture may well be a simple gaseous phlegmon.

3. **Treatment Applied.**—If the wound has not received proper treatment for many hours after it was produced, and particularly if the tissues have not been excised and are not deeply bruised, the infection may be of this mild localized type.

Further signs are a dirty, evil-smelling discharge; some inflammatory reaction in the surrounding skin, which is sometimes very warm and dry and a peculiar dirty yellow; and inflammation of the regional glands. The wound gives rise to pain both spontaneously and on pressure over the inflamed area.

The general condition of the patient is not seriously affected, but there may be a rise of temperature, in some cases to 103° F., with a corresponding increase in the pulse rate. Apart from gas in the area surrounding the wound and an offensive smell (which is not that of putrefaction), the clinical picture of gaseous phlegmon is not very different from that of early pyogenic infections, before the pus has formed. *Cl. welchii* may be found in the blood. The patient is torpid and somnolent until the blood is sterile (Anderson and Richardson, 1917). Qvist (1941) has recently given a clear description of this infection.

If an operation is performed on a patient in whom the infection is already established, the wound is found dirty and may show a certain amount of tissue damage; necrosed portions of fat and connective tissue are distributed throughout. This necrosis is not extensive, but appears to be confined to a limited and comparatively superficial layer of the tissues which have been directly damaged. When the wound is opened some gas escapes. In a number of cases the gas extends some distance from the wound (sometimes far beyond the actually infected areas): it is important to remember that the limits of the gas are not necessarily those of the infection. A spreading cellular gangrene may be seen in the subcutaneous tissues.

Patients suffering from this form of gas infection, when correctly treated, generally recover rapidly. Fatal results are exceptional, and mostly occur in cases complicated by some other type of infection or by poor general condition due to some other cause. Without proper treatment, however, the condition may become serious.

The treatment, which must be carried out without delay, consists of a radical opening-up of the cellular spaces and excision of all damaged tissues. The technique differs from that used for invasive gas gangrene in that the principal part is here played by drainage instead of excision.

SIGNS AND SYMPTOMS OF ANAEROBIC INFECTIONS

Pulse Rate.—A rapid pulse is normally the first sign of onset. While the patient is still suffering from the initial shock and hemorrhage, its significance is difficult to assess, but once he has recovered, a rising pulse rate, particularly when accompanied by a rise of blood pressure, may be taken to indicate that an anaerobic infection is probably developing.

Temperature.—Owing to the wide variation in the degree of fever that occurs in gas gangrene, the temperature alone is not a reliable diagnostic sign. It does, however, serve for prognosis, a low temperature accompanying a rapid pulse suggesting that the outlook is grave. In the mildest type of gas infection, gaseous phlegmon, there is sometimes a considerable rise in the temperature, but the pulse rate shows a corresponding increase.

Pain.—The amount of pain is directly related to and varies inversely with the extent of the bacterial invasion. In the early stages, particularly when the deeper structures are subjected to great pressure by gas or edema, pain may be one of the most striking symptoms, but in the advanced stages it disappears. Complete absence of pain is one of the most marked characteristics of the toxemic forms.

General Appearance.—In the initial stages of gangrenous infection the patient has a flushed face and shows considerable mental activity. Any patient who, within 24 hours of being wounded, passes from the normal drowsy condition to one of mental excitement must be watched with special care.

The Tongue.—The tongue very quickly becomes dry and coated.

Vomiting.—The occurrence of vomiting, a not uncommon symptom, is suggestive of gas gangrene.

Signs and Symptoms Specific to Closed Plaster Cases.—The immediate diagnosis of gas infection in tissues enclosed in plaster, a matter

obviously of the utmost importance, is facilitated by the following further symptoms which do not generally occur with other forms of treatment.

A Sensation of Heat at the Site of the Wound.—In some cases this sensation, perhaps best described as a burning pain, may cause much acute discomfort. It is probably due to the greatly increased pressure on the affected region, due to the formation of gas under the plaster.

Edema in the Toes or Fingers.—Edema in the toes or fingers is always present when gas gangrene develops under plaster; although it also appears in other infections (e.g., streptococci), its occurrence within the first three days after the wound, accompanied by a local sensation of heat, is always highly suggestive.

Cold Toes and Fingers.—From a very early stage in the development of gas gangrene the toes and fingers of the affected limb are colder than those of the sound side. The symptom is due to pressure of the plaster on the emphysematous tissues.

These signs, combined with a rising pulse, a rise of temperature, and occasionally with vomiting, necessitate immediate removal of the plaster cast.

Signs in the Gangrenous Area

The Wound.—Gas and edema may or may not be present; the color of the muscles may be necrotic or dark red; there is often an evil-smelling discharge. The surrounding skin is usually dry at first, but after a while it may turn a yellowish blue and show areas of necrosis. The area of gangrenous skin is always much less than that of the underlying damaged muscles.

Crepitus.—Crepitus is produced by the escape of gas from the muscles into the cellular connective tissues and subcutaneous area. It is common in many forms of gas gangrene, but the diagnosis should not be deferred until it is observed. In some of the most serious cases, i.e., those in which the infection is due to *Cl. oedematiens*, and to a lesser extent those in which it is due to *Cl. septique*—there may be no crepitus because no gas is formed. On the other hand, in the relatively mild gaseous phlegmon, there is a great deal of gas and consequently much crepitus.

Tympanism of the Skin.—Also connected with the presence of gas, tympanism of the skin accompanies crepitus and is most noticeable in cases of massive gangrene with marked distention of the subcutaneous spaces.

Changes in the Appearance of the Skin.—In the earliest stages there is no appreciable change in the color, but after some hours the skin often becomes pallid. Later, it commonly becomes a dirty cream color with

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areas of purple staining which enlarge and coalesce. Finally, in the most advanced stages a dark, yellowish tint may be seen.

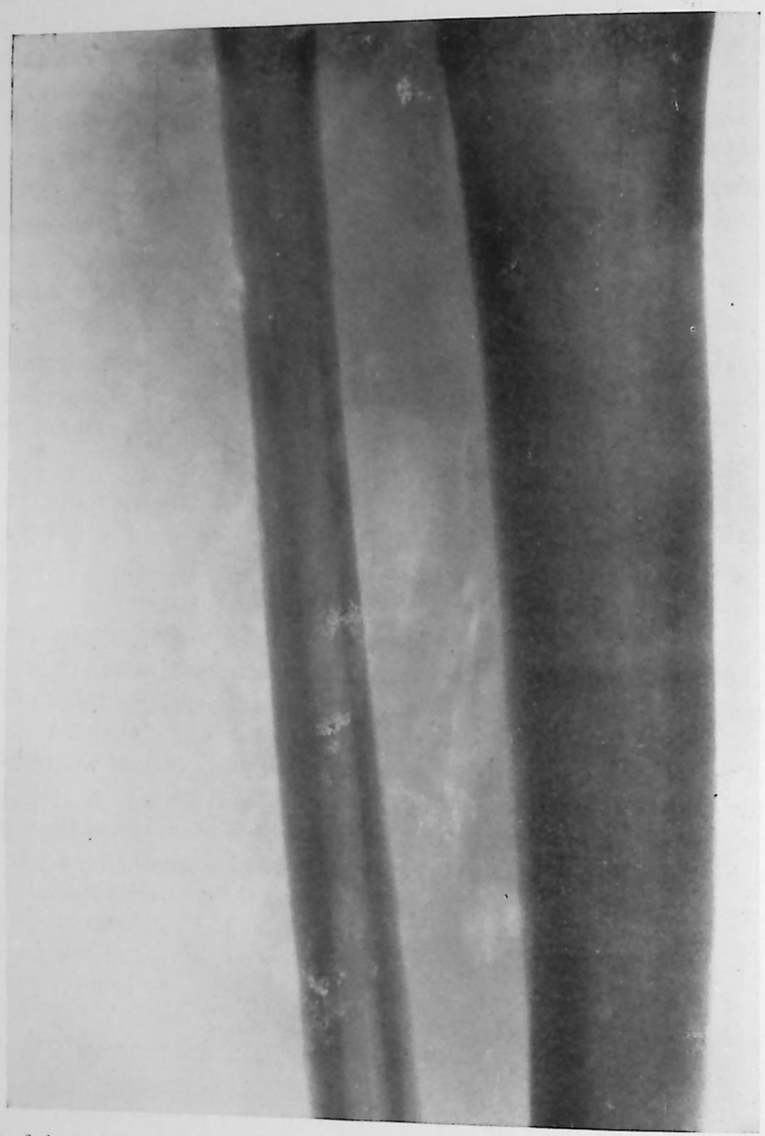


Fig. 6-*A*.—Radiograph showing gas in the tissue spaces. The appearance was produced by the application of sodium hypochlorite to a small wound in the leg.

The changes in color depend largely on the site of the gas gangrene. In cases in which the infection is superficial and confined to a small area, the purple may appear very quickly; in those in which the gangrene is highly invasive, the staining may be very slight and delayed.

In many cases a fairly widespread gangrene in the muscle occurs beneath what appears to be an entirely normal skin. In retroperitoneal gangrene the skin becomes bronze colored.

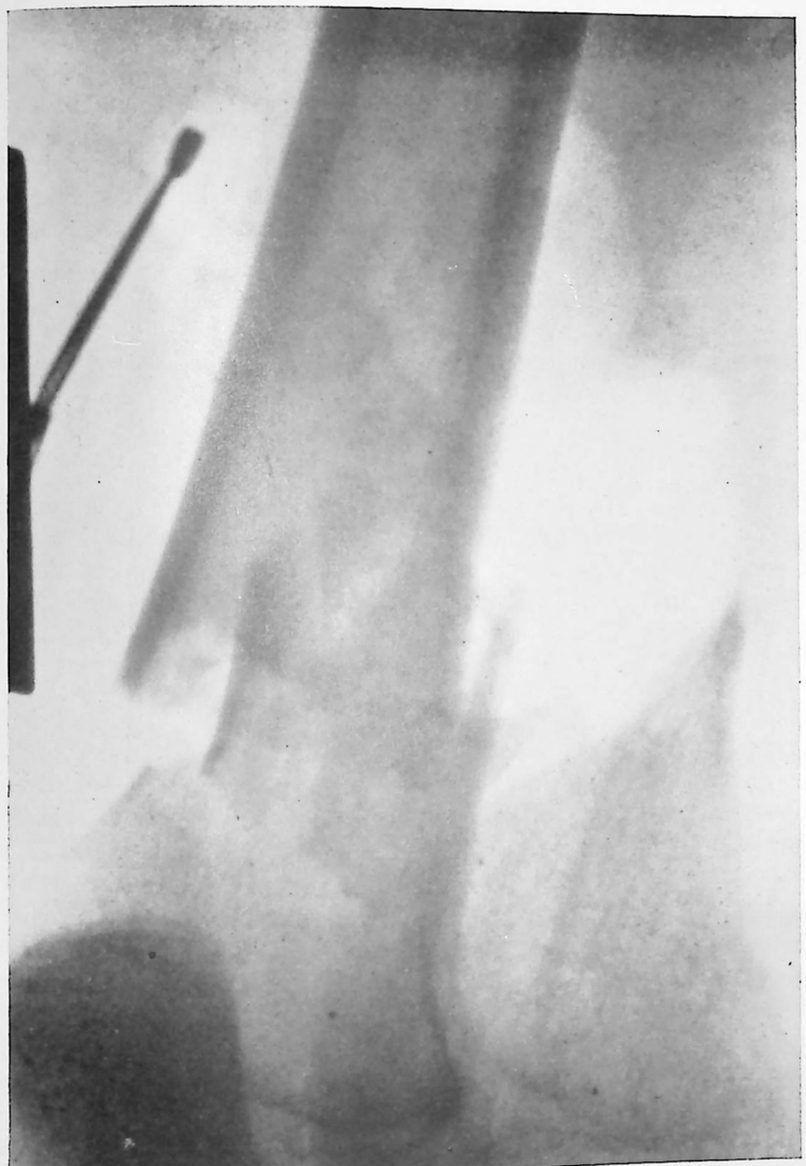


Fig. 6-*B*.—Radiograph showing gas in a wound, in a patient who was not suffering from any anaerobic infection. Note the limited space occupied by the gas.

Changes in the Appearance of the Muscles.—In the early stages the muscles lose their contractile power, and become hemorrhagic and the

color of red brick; when gangrene is complete the color is greenish black. When the responsible organism is *Cl. oedematiens,* the muscle remains dark red for a long period.

X-rays in the Diagnosis of Gas Gangrene

The presence of gas in a wound is not proof of gas gangrene. Gas gangrene is a clinical entity and its diagnosis is based on clinical signs only. Recently, however, attempts have been made to diagnose anaerobic infections by radiography. This seems to me a completely wrong approach. In the first place it is sometimes difficult during the first few hours to secure a convincing radiograph of gas spreading through the tissue spaces; in the second place other causes than gas gangrene may produce gas in the tissues surrounding a wound (see Figs. 6-*A* and 6-*B*). The radiographic discovery of gas in a wound may lead to amputation, indeed has sometimes done so, in cases free from anaerobic infection.

PROGNOSIS

The prognosis depends on several factors, by far the most important of which is early diagnosis. In gaseous phlegmon the outlook is usually good. The regional type of gangrene causes a high proportion of deaths, and toxic edema is nearly always fatal. In serious cases a more favorable prognosis can be secured only by rapid diagnosis followed by immediate and drastic operation.

PROPHYLAXIS OF GAS GANGRENE

All measures, however careful and thorough, against an established gangrenous infection have only a limited usefulness. Even when the most scrupulous technique is used, many of the patients die. It cannot, therefore, be too strongly emphasized that the real essence of successful treatment lies in the adoption of every possible preventive measure. Above all, operative treatment must be conducted on the most rigorous lines, particular attention being paid to the following points:

1. The operation should be performed within six hours of the injury. In some cases gas gangrene develops within four hours, but in the great majority six hours or more are needed.
2. The wound must be thoroughly cleaned with soap and water and a nail brush.
3. All dead or dying muscles and other tissues must be radically excised, special attention being paid to those distal to the wound. Success mainly depends on the thoroughness with which the excision of the distal part of the damaged muscle is carried out.

4. All organic foreign bodies (pieces of clothing, earth, wood, etc.) must be removed.
5. All hematomas must be removed.
6. The cellular connective spaces must be left free from tension. No war wound in which muscle has had to be excised should be closed with a primary suture.
7. Good drainage must be established.
8. Efficient immobilization must be provided.
9. Sulfonamide compounds injected or applied locally from the earliest possible moment may help to prevent gas gangrene.
10. In severe concussion or shock, antitoxins may be given by intramuscular or intravenous injection: gas-gangrene antitoxin (perfringens) B.P., 4,000 international units; gas-gangrene antitoxin (vibrion septique) B.P., 5,000 international units; gas-gangrene antitoxin (oedematiens) B.P., 20,000 international units.

TREATMENT OF GAS GANGRENE

Once gas gangrene is established, the most drastic treatment must be employed. The general principles are the same as those on which prophylaxis is based: radical excision of all damaged muscular, cellular, integumentary and other tissues. Owing to the spread of the infection in a longitudinal and upward direction, and its rapid passage from the initial focus through the whole muscle and then to the adjoining muscles, gangrene sometimes spreads from the thigh to the trunk in less than twenty-four hours. It is therefore vital that treatment should be carried out before the infection has passed beyond its localized stage.

Four weapons are available against an established infection: surgical operation, antisera, chemotherapy, and deep x-ray therapy.

Surgical Operation

Conservative Treatment: Radical Excision of All Infected Tissues.—This operation is termed "conservative" because, despite the radical excision, the limb is not amputated. It is the best method available in cases of "regional" gas gangrene. A long and deep incision is made through the center of the wound in the long axis of the limb, extending far beyond the limits of the muscles involved. The skin, cellular tissues, and fascia are thoroughly opened and the muscles exposed and carefully examined.

The second stage consists of the excision of dead and dying tissues. If the operation is performed in the early stages, or if the infection is localized, the area of skin to be excised may not be very extensive; all blue areas must be removed (Fig. 7). The necrotic cellular tissue

and muscular tissue must also be unhesitatingly excised. Just as damaged muscle lying distal to the wound must be completely removed for the prevention of gas gangrene, so is its excision proximal to the wound essential for the cure of an established infection. A muscle damaged by the infection must therefore be excised from end to end. The muscles adjacent to the gangrenous area must be carefully examined, and if there is the slightest sign of abnormality in the rate of bleeding, or in the color or contractile capacity, they must be excised immediately. The importance of studying the rate of bleeding must be stressed, for this is the most reliable of all indications. If there is any decrease in the extent of bleeding, even though the color remains normal and stimulation with a forceps still produces some contraction, the muscle must be excised until a point is reached where the fibers bleed normally.

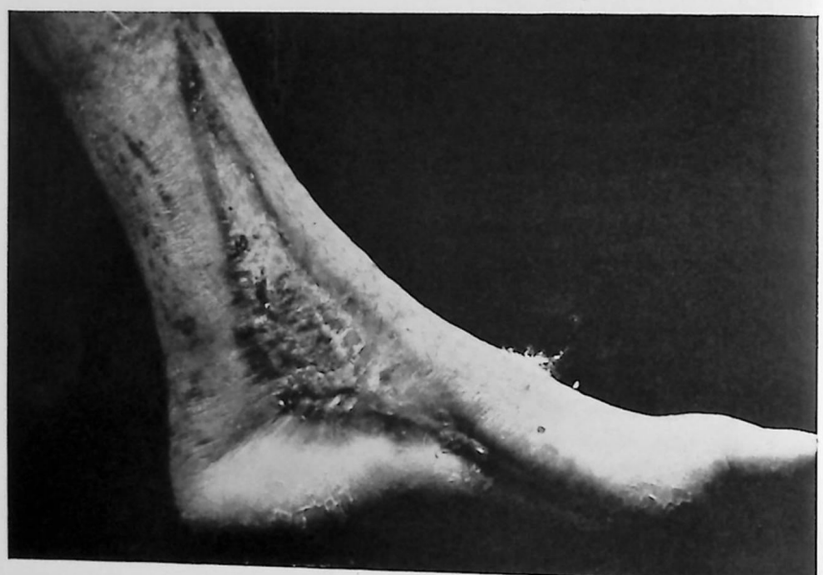


Fig. 7.—Case of gas gangrene of the foot and lower half of the leg treated by excision, plaster, and ultimately skin graft. Movements of the ankle joint are almost normal.

To obviate any constriction in the limb, further incisions will be necessary. These should be parallel with the original incision, but far enough away from the wound to avoid interference with the blood supply of the skin immediately surrounding it.

It should be remembered that gas beneath the skin a long way from the wound does not in itself indicate that the infection has extended to that area, for gas spreads through the tissue spaces in regions which are still perfectly healthy. Similarly, the presence of *Cl. welchii* in

healthy muscle, as for instance in many amputation stumps, does not indicate an extension of the danger area. The only criterion for distinguishing healthy tissues from those affected by gas gangrene is their vitality.

Amputation.—Since gas gangrene spreads through the tissues and along the various groups of muscles in a longitudinal and upward direction, amputation seems illogical except for gangrene due to arterial lesions. In many cases, however, it is the one and only means of saving life; indeed the few patients who have survived a massive infection due either to an arterial lesion or to an anaerobic organism such as *Cl. oedematiens* or *Cl. septique,* undoubtedly owe their lives to amputation of the affected limb. Amputation must also be performed in cases in which gangrene immediately attacks large areas of muscle in the leg, the site of amputation in these cases being the middle of the thigh. Where the thigh is involved in the infection amputation is not satisfactory, for, even if the transverse section of the muscle is made at a very high level, it may nevertheless not be high enough to include all the infected muscle, and the process of elimination will thus be incomplete. Moreover, high amputation of the thigh is a very severe operation, and patients who are already gravely ill from a highly invasive gas gangrene seldom tolerate the additional exhaustion. Unfortunately, it is the only available method of saving life in otherwise hopeless cases.

Before deciding on amputation, the surgeon should in most cases thoroughly explore the wound and do all he can to save the limb by excising the damaged tissues. Only in massive gangrene of a whole limb is amputation justifiable without previous exploration. When amputation is the only possible method, the choice of the right level is made on the principles outlined in Chapter XXIV.

An amputation in the thigh must usually be made as high as possible. The flap type, besides being elaborate, is risky, since the superficial tissues retained to form the flaps often include contaminated areas which should be removed. Moreover, the infection may well extend into the muscles of the stump, which must therefore be opened up to allow excision of necrosed muscles right to the upper limit of the infection. Guillotine amputation should be employed for this type of case.

A thigh-level amputation for gas gangrene in the lower third of the leg may be of the flap type, but there must be no primary suture; if no sign of gas gangrene has appeared in the stump after four or five days, a secondary suture may be made without risk (see also Chapter XXIV).

Anti-Gas-Gangrene Sera.—In 1917 Weinberg, working at the Pasteur Institute, prepared a mixture of anti-gas-gangrene sera obtained from horses in which immunity had gradually been built up against *Cl.*

welchii, Cl. septique and *Cl. oedematiens.* The animals were immunized separately against each of these anaerobes, and the three different types of sera thus obtained were mixed together to form the original (trivalent) Pasteur anti-gas-gangrene serum. Pierre Duval (1918) showed that this serum, given prophylactically to 381 wounded soldiers, reduced the incidence of gas gangrene to 4.7 per cent, against 16 per cent in a control group. The serum is only antitoxic and has no antibacterial properties.

Weinberg found that in many cases the pathogenic anaerobic organisms were associated with other anaerobes which, although incapable of producing gas gangrene themselves, tended to increase the severity of the gas infection. The most important of these were *Cl. sporogenes,* which is highly proteolytic, *Cl. fallax,* an organism of relatively low toxicity, and *Cl. histolyticum,* the most frequent companion of the pathogenic anaerobes. As a result, he prepared a new serum design to combat the effects of five anaerobic organisms, including *Cl. sporogenes* and *Cl. histolyticum* with the three pathogenic types. This quinquevalent serum is made up by mixing monovalent sera as follows:

Anti-welchii serum	3 parts
Anti-oedematiens serum	3 parts
Anti-septique serum	3 parts
Anti-histolyticum serum	1.5 parts
Anti-sporogenes serum	0.5 part

The individual sera should have potencies equal to 100 international units of antitoxin per cubic centimeter for the anti-welchii, anti-septique and anti-histolyticum sera, and to 1,000 units for the anti-oedematiens serum.

Weinberg (1939) quotes some results obtained with these two types of sera in 1919. Of 60 patients suffering from gas gangrene, 43 were given trivalent serum, and of these 33 recovered and 10 died; the remaining 17 patients were given the quinquevalent serum and all recovered. He advocates the following dosages and methods of administration: (1) for the treatment of serious cases, 200 c.c. of serum in 800 c.c. saline, given intravenously by continuous drip injection; this avoids anaphylactic reactions; (2) as a prophylactic, 20 c.c. of serum injected subcutaneously.

Another anti-gas-gangrene serum said to be both antitoxic and antibacterial was prepared by the French pathologist Vincent. This serum, obtained from horses progressively immunized against all the 17 bacterial species, aerobic and anaerobic, which have been found in cases of gas gangrene, is believed to be equally effective against all types. Vincent (1939) claims striking results which he attributes to the antibacterial properties of the serum and to its varied antibody content. For prophylactic purposes the prescribed dose is 20 c.c., and for treatment from 80 to 150 c.c.

In Great Britain a preparation similar to Weinberg's original trivalent serum (see p. 114) is put up in rubber-capped bottles, each containing an amount equivalent to one therapeutic dose (20 c.c.) or three prophylactic doses; it can be used for either purpose. The dosage is as follows:

Prophylactic:	Cl. welchii antitoxin	3,000 I.U.	Given by intravenous or intramuscular injection.
	Cl. septique antitoxin	1,500 I.U.	
	Cl. oedematiens antitoxin	1,000 I.U.	
Therapeutic:	Cl. welchii antitoxin	7,500 I.U.	Given by intravenous injection and repeated as necessary while symptoms of toxemia persist.
	Cl. septique antitoxin	3,750 I.U.	
	Cl. oedematiens antitoxin	2,500 I.U.	

These three antitoxins are also issued separately for more intensive therapeutic use in cases in which the specific organism has been identified. They are put up in ampules each containing one therapeutic dose.

[Some American preparations are available and a tetanus gas gangrene antitoxin is available for prophylactic use; the constituents are as follows:

1,500 units, Tetanus antitoxin (Cl. tetani)
2,000 units, B. perfringens antitoxin (Cl. welchii)
2,000 units, Vibrion septique antitoxin (Cl. oedematis-maligni)

For therapeutic purposes in treating gas bacillus infection, there is available a polyvalent gas gangrene antitoxin without tetanus antitoxin, each vial containing the following:

10,000 units, B. perfringens antitoxin (Cl. welchii)
10,000 units, Vibrion septique antitoxin (Cl. oedematis-maligni)
3,000 units, B. histolyticus antitoxin (Cl. histolyticum)
1,500 units, B. oedematiens (Novyi) antitoxin (Cl. oedematiens)
1,500 units, B. sordelli antitoxin (Cl. oedematoides)]

Chemotherapy.—Since the Spanish War sulfonamide compounds have been used as a matter of course. The first results, published by d'Harcourt and his colleagues in 1939, were most encouraging. One patient in whom the infection was too far advanced for a radical surgical operation made a spectacular recovery after treatment with sulfanilamide. In Barcelona the drug was given by mouth and the treatment was supplemented by several bleedings and blood transfusions.

At the Pasteur Institute Legroux (1940) investigated the therapeutic action of sulfanilamide in infected guinea pigs. The infection was produced by inserting in the wound a piece of cloth soaked in a culture of *Cl. welchii*. Legroux found that local application of sulfanilamide enabled the animal to survive as long as the treatment was continued, but that when it ceased the animal died. If, however, the wound was reopened, the piece of infected cloth removed, and a fresh application of sulfanilamide made, the animal survived and recovered. The action of sulfanilamide seems to be bacteriostatic, its local application probably playing an effective part in bacterial "fixation" and possibly limiting the production of toxins, which when not excessive can be neutralized by antitoxic sera (see p. 114). The only point that should be stressed here is that, the infection being so serious, the systemic administration of the drug should always be supplemented, after the radical excision or amputation, by a local application to the wound, so that the organism may be prevented from spreading by a direct attack on the focus of infection. Sulfathiazole seems to be much the most active drug. Needless to say, all drug and serum treatment must be accessory to surgery, not a substitute for it.

X-ray Therapy.—X-rays were first used for the treatment of gas gangrene in 1928 by J. F. Kelly (1932), who in the course of the next nine years, made a study of 143 cases treated by himself and other workers in the United States and Canada. Kelly and his colleagues claim that x-rays were highly successful, particularly when applied in the early stages, and that they also lowered the mortality rate in cases in which no amputation was performed and no serum given. Kelly states that of 17 patients with well-established gas gangrene, only 2 died. He stresses the importance of early treatment, maintaining that if treatment is started while a case is still under suspicion and before a definite diagnosis is made, gas gangrene should not develop; that in cases treated within 24 hours of the infection there should be a very high percentage of recoveries; and that if treatment is not started until after the first 24 hours recovery will be less likely and 10 to 15 per cent of patients will probably die.

The x-ray technique advocated (Kelly and others, 1938) is as follow:

Kilovoltage: Sufficient thoroughly to penetrate the infected area: varies from 90 to 135 KV.

Dosage: From 60 to 100 R units per treatment through each port: the dosage should vary with the size of the port. A smaller dose may be used on the third and fourth days of the disease; 50 R units is probably sufficient for late treatments.

Ports: Large enough to cover all infected tissues and adjacent suspected area.

According to these workers there are no contraindications to this treatment, provided that it is given under the direction of a qualified radiologist. In fact, they regard it as so effective as to render all radical operative techniques unjustifiable. If further experience justifies this view, the use of x-rays will be the best treatment for gas gangrene. Unfortunately the results of other workers are not so encouraging, and the method is still under trial. As far as I know, it was never used during the Spanish War and has not yet been adequately tried in this one.

Treatment of the Acidosis.—In patients suffering from gas gangrene there is an immediate deterioration of the liver function with consequent acidosis. This was first noticed by Sir Almroth Wright during the last war and confirmed by Marquis, Clogne and Didier in France (1918). How far the acidosis contributes to a fatal issue is not yet known, but the prognosis is related to its intensity. Treatment must therefore be established at once and should persist until the danger is over. Intravenous injections of sodium bicarbonate should be given, 10 c.c. of a 20 per cent solution twice a day. Urine and blood must be investigated and the treatment adapted to the condition of the patient.

SUMMARY

1. Prophylaxis of Gas Gangrene.—

(a) Essential Factors

1. Early operation, if possible within 4 hours of the wound.

2. Thorough cleansing of the wound and the surrounding skin with soap and water and a nail brush.

3. Opening up of the cellular spaces in the injured region, and careful removal of all hematomas.

4. Radical excision of all damaged muscle, particularly any damaged portions of the long muscles of the limbs lying *distal* to the wound.

5. Provision of good drainage both for the wound itself and for the neighboring cellular spaces.

6. Effective immobilization of the limb, the maintenance of a good circulation, and protection of the wound from the entry of germs after operation. These conditions are best provided by a plaster cast applied directly to the skin, which gives complete rest and immobility without impeding the normal circulation of the limb or the local circulation of the injured part. If the circulation, general or local, is in doubt, particularly in wounds of the thigh, the application of the plaster should be deferred for two or three days. In such cases relative immobilization of the limb in a Thomas or Braun splint (with continuous traction by a Kirschner wire in cases of fracture) makes it possible to keep the wound under constant observation, so that, if necessary, more drastic

measures may be taken without delay. The Billroth-Schede technique of leaving the wound open to view also enables the surgeon to watch its nutrition.

(b) Subsidiary Factors

1. Application of a sulfanilamide pack.
2. Administration of anti-gas-gangrene sera, preferably of the quinquevalent type, 20 c.c. by subcutaneous injection.
3. X-ray treatment.

Treatment of Gas Gangrene.—

Important Factors

1. Early diagnosis.
2. Immediate surgical treatment.
   (a) *Local and regional types:* long incisions to expose the affected area, and radical excision of gangrenous tissues and of any adjacent tissues suspected of contamination—particularly the muscles.
   (b) *Massive type:* amputation of guillotine or flap type, according to the site of the gangrene. No primary suture.
3. Application of a sulfanilamide pack.
4. Initial rest and relative immobilization of the affected limb with (for the lower extremity) a Thomas or Braun splint, with or without traction according to whether or not a fracture is present, or (for the upper extremity) abduction apparatus, such as an aeroplane splint.
5. Administration of anti-gas-gangrene sera, 200 c.c. in 800 c.c. saline, intravenously by continuous drip injection.
6. X-ray treatment.
7. Anti-acidosis treatment: 10 c.c. sodium bicarbonate solution (20 per cent) intravenously twice daily.

CHAPTER VIII

TETANUS

Of all fatal infections of any war, tetanus has probably been responsible for the highest mortality, the only other infection at all comparable being gas gangrene. Fortunately, the steady improvement in surgical technique and the discovery first of the tetanus antitoxin, and more recently of the tetanus vaccine, have led to a noticeable decrease in the incidence of this deadly infection.

ETIOLOGY

Tetanus is caused by a feebly motile and flagellated organism, first discovered in garden soil by Nicolaiev in 1885. Later Kitasato was able to isolate it in pure culture. *Clostridium tetani* characteristically appears as a rod with a little knot at one end, the spore. It is a strict anaerobe and can grow only in the absence of oxygen. Association with other types of bacteria which consume oxygen facilitates its growth, a fact which increases the menace of mixed infections.

Cl. tetani commonly lives in humid, warm soil, particularly in cultivated ground, and according to Loewe (1937) its development is considerably influenced by the composition of the soil. It is a normal inhabitant of the intestinal tract of the horse and is present in large quantities in stable manure. The spores may survive for many years, and may remain actually inside the tissues. This fact carries with it the unexpected (and often forgotten) risk of exciting tetanus by disturbing an old wound many years after the initial injury. In a case reported by Bonney and others (1938) this happened after ten years. Some human races are relatively immune: for instance, tetanus is very rare among the people of Pekin, one-third of whom carry the organism (Dejou, 1938).

Tulloch (1919) has divided *Cl. tetani* into four groups according to the characteristics of its growth and the agglutinating power of the antitoxin. The first group is less pathogenic than the others and is used in the United States for the preparation of antitoxin. The existence of four different types may possibly explain the varying therapeutic results obtained with antitoxin and the special gravity of the infection in certain countries.

PATHOLOGY

Until recently the tetanus toxin was supposed to be absorbed and diffused by a route different from that of other bacterial toxins. It

was commonly believed to reach the nerve cells by way of the peripheral nerves or by the perineural lymphatics. Abel and his co-workers (1938) and Harvey (1939), however, affirmed that it follows the same route as all other bacterial toxins. They repeated and confirmed experiments by Leo Zupnik (1905) on the production of local tetanus, showing that the toxin did not travel by the nerves, and assuming that it must follow the lymphatic and venous routes. More recently, Barnes and Trueta (1941) demonstrated that the toxin travels only by the lymphatic system (see p. 77). Abel, Hampil and Jonas (1935) have shown that if tetanus toxin is injected in the sciatic or crural nerves of dogs, with due precautions against contamination of the surrounding tissues and particularly of the muscles, the characteristic intoxication of the central nervous system does not appear. If numerous small injections of the toxin are made into the muscles, a local rigidity is caused by the toxic impregnation of the muscle nerve endings, but this rigidity is entirely different from the spasms and contractions that follow the toxic impregnation of the motor cells of the spinal cord.

Where a wound involves muscular tissues there is always a greatly increased risk of tetanus, as of gas gangrene. Zupnik (1905) was unable to produce local tetanus by injecting the toxin into the cellular tissues between the tibia and the tendo achillis, a region where there is no muscle; similarly, the absence of muscular involvement probably accounts for the mild form of tetanus which occurs among natives of the French colonies after perforation of the ear.

Abel and his co-workers (1935) have shown that if a small dose of toxin is given intravenously it does not reach the nerve cells but is apparently removed from the circulation by the lungs.

The incubation period varies from five days to several weeks, and with the first appearance of symptoms the disease is already established.

The various clinical forms are determined by a number of factors, of which the most important are (1) the portal of entry, (2) the anatomy and pathology of the lesion, (3) the presence of other infections, and (4) certain factors probably connected with the group to which the organism belongs.

A very mild form follows perforation of the ear. A more serious form is the "medical" or "splanchnic" tetanus, so called because the portal of entry is not external. The tetanus which follows a prick on the sole of the foot (the commonest form in peacetime) is still graver, while the most serious form of all is postoperative tetanus. Of seven cases of postoperative tetanus which I have seen, where the infection was due to imperfectly sterilized catgut, the most drastic treatment saved only one patient. Tetanus is more serious in the upper than in the lower extremity.

The symptoms vary according to the factors mentioned above, but the following stages are often identifiable when the disease runs its full course:

1. Headache and shivering, followed by stiffness in the muscles of the face, lower jaw and neck, trismus being the most obvious and sometimes the only sign. In some cases the rigidity begins in the limb infected by the organism.

2. When the picture is fully developed the spine becomes arched, backwards (opisthotonos), forwards (emprosthotonos), or to one side (pleurothotonos). Sometimes the intercostal muscles are involved and respiration becomes very difficult, being carried out solely by the diaphragm. In the lower limb the most usual signs are spasm of the extensors of the leg and of the abductors of the thigh. In many cases the arms are comparatively little affected, although the shoulder is generally fixed by a spasm of the pectoral muscles. Painful convulsions accompany this widespread rigidity, and increase the spasm. Reflexes are exaggerated and there is a sharp rise in temperature, which may in some cases reach 107° F. before death. Death is due to cardiac or respiratory failure.

SPECIAL TYPES OF TETANUS

Local Tetanus

The early signs are similar to those in other forms, but muscular rigidity is more conspicuous and is sometimes the only apparent sign. Rigidity plays a greater part than contractions, which in turn are more frequent than spasms, although in some instances a slight spasm does accompany the local rigidity. Harvey (1939) believes that the rigidity of the masseter muscles is due to impregnation of the nerve endings by the tetanus toxin. When the disease is localized in an extremity there is sometimes neither rigidity of the neck nor trismus. Such cases suggest that the advance of the disease is halted at a stage which normally represents its initial phase. Probably the amount of toxin absorbed is not very great and its action is largely confined to the nerve endings in the muscles. The fixation of the toxins in the peripheral nerve endings is responsible for the long time the disease often takes to develop. Occasionally, the patient is not himself aware of the stiffness, and the surgeon is the first to notice it. The stiffness of local tetanus is wholly different from the first effects of involvement of the central nervous system, which consist of slight spasms and tremors in the injured limb; if these are the first indications of tetanus the prognosis is very unfavorable. I have seen three patients in whom the first sign was local tremor and all three died in a very short time.

A guide to the prognosis is thus the length of time between local stiffness and the first spasm. When this is less than 48 hours the prognosis is very grave. In many cases local rigidity is the only sign of tetanus in the early stages, and this makes accurate diagnosis difficult at a time when active therapeutic measures are urgently required. Hence if when a wound is being treated the affected limb shows any slight rigidity, the proper course is to give antitoxin.

The term "local tetanus" is thus used for those cases in which rigidity is the principal, if not the only, feature of the disease.

Facial Tetanus

Facial tetanus, first described by Rose under the name of "tetanus hydrophobicus," follows an injury of the head or face and affects the whole area supplied by the cranial nerves. In many cases the muscles of the throat also show violent spasm. Facial paralysis often occurs on the side of the injury and sometimes on both sides. One of the first signs is a stiffness of the masseter muscles, and this is followed by contraction of all the facial muscles, which produces the "risus sardonicus." This is not one of the more serious forms of tetanus, but treatment is often long and difficult.

Delayed Tetanus

In its first stage delayed tetanus is like local tetanus and develops slowly. The absence of striking symptoms may lead to insufficient administration of antitoxin—an error which may prove fatal. The incubation period may be very long, and in some cases the first signs do not appear until several weeks after the injury. In the interval complete healing may have occurred, an event which makes early diagnosis more difficult, particularly when the injury was trivial.

Chronic Tetanus

Chronic tetanus has no special characteristics and may develop from any of the other forms. The only significant feature is that for some reason (e.g., the patient's resistance, the portal of entry, and perhaps the type of organism) the disease lasts for several weeks; generally, however, it is not one of the most serious forms.

DIFFERENTIAL DIAGNOSIS

Tetanus is not often confused with other diseases. Strychnine poisoning, encephalitis and meningitis present a similar clinical picture, and hydrophobia resembles facial tetanus with throat spasms; but mistakes are not often made, because strychnine poisoning and hydrophobia are rare, and encephalitis and meningitis can be diagnosed by examination of the spinal fluid.

It is, however, important to distinguish the effects of tetanus itself from the anaphylactic reaction which may be produced by serum therapy. The commonest initial sign of tetanus is trismus; a similar difficulty in opening the mouth may occur in wounded patients who have been given a prophylactic injection of tetanus antitoxin, for an articular anaphylactic reaction may appear in the temporomaxillary joints. If such a picture is attributed to tetanus and a further large injection of antitoxin is given, it may even lead to a fatal result. I have seen two such cases of grave anaphylactic shock. The first patient died, but the second, although desperately ill, survived. Both patients had had a prophylactic injection of antitoxin, but neither joint pains nor anaphylactic rashes had appeared until after the second injection, which consisted of 50,000 I.U. of tetanus antitoxin.

In such cases a differential diagnosis must be made after careful examination of the rigidity. In tetanus the limitation in opening the mouth is due to hypertonic rigidity of the masseter muscles, and the patient can voluntarily lower the mandible more easily than it can be moved by hand—that is to say, active movement is more effective than passive movement; moreover, the trismus is not painful. A patient suffering from anaphylactic arthralgia, on the other hand, cannot himself move the mandible at all, although it can, with some pain, be moved passively. Any attempt to produce lateral movements causes acute pain, which is strictly localized to a small area in the region of the joint. A careful examination of the other joints may, after a short while, reveal arthralgia elsewhere, and a rash in the neighborhood of the injection may help the diagnosis.

THERAPEUTIC MEASURES

Before the discovery of antitoxin, the treatment of tetanus had been largely confined to local applications of antiseptics such as Baccelli's phenol acid and Lumière's 5 per cent permanganate of potash. In 1890 von Behring prepared tetanus antitoxin, which has ever since formed the basis of all treatment, and for a long period was also the only prophylactic known.

Prophylaxis

Until recently preventive treatment was confined to injections of tetanus antitoxin; i.e., the serum of horses immunized by the administration of tetanus toxin in progressively increasing doses. The incubation period of tetanus is sufficiently long for the first injection to

be given before the onset of infection; but, to be effective, prophylactic injection should always be given within 24 hours of injury. If the patient requires surgical treatment it is best to give the injection during the operation, for anaphylactic shock is very rare under general anesthesia, and particularly under ether (Koontz and Shackelford, 1939). The immunity afforded by the antitoxin is of limited duration however—not more than 20 days; another injection of antitoxin is therefore essential if the wound requires further surgical intervention after this period.

It would be a great help to know which types of wound need prophylactic treatment and which do not. Unfortunately, it is impossible to classify wounds into those in which the risk of tetanus is great and those in which there is none, since *Cl. tetani* can be active in almost all types. Wounds involving muscle, however, are definitely the most liable to tetanus infection. The old idea that this anaerobic organism cannot survive in a superficial wound, owing to its inevitable contact with the oxygen of the air, is entirely fallacious, as shown by the following example:

A carter received a small superficial scratch about one-fourth inch long on his thumb, from the tooth of a horse. Owing to the triviality of the injury, the doctor was inclined to forego the administration of tetanus antitoxin, but at the patient's own request gave 1,500 international units, an insufficient dose. Seven days later tetanus developed, but thanks to the injection—inadequate though it was—the attack was not very serious.

Like all anaerobic infections, tetanus develops more often in wounds in which the circulation has been impaired, as, for example, those caused by high explosives. Vaillard and Vincent (1891) showed that the presence of dead tissue also favors its development. Since it is impossible to know which type of wound requires preventive treatment, a prophylactic injection must in wartime be given to all wounded patients, avoiding anaphylactic shock either by the Besredka technique (an intradermal injection of 0.5 c.c., followed four hours later by the prophylactic dose injected subcutaneously), or by injection under ether anesthesia.

The number of units considered necessary to prevent the development of tetanus has been increased in recent years, and today the dose generally given is 3,000 international units (one I.U. being the amount of serum which protects a mouse weighing 10 grams against 4,000,000 times the minimum lethal dose of tetanus toxin). Several cases have been published in which, despite this high dose, tetanus has developed and even proved fatal. Most of these patients, however, were already very ill before the antitoxin was introduced.

Active Immunization

In 1931 Ramon, at the Pasteur Institute, prepared a vaccine, called "anatoxine" in France and "toxoid" in Britain, which he afterwards declared would provide active immunity from tetanus for five years. This claim is today regarded as excessive. The immunization consists of three intramuscular injections of the vaccine, 1 c.c. being given in the first injection; 2 c.c. in the second, made three weeks after; and a further 2 c.c. in the third, now given after an interval of six months. The British technique differs from the French in omitting the third injection. Marvell and Parish (1940) showed that when only two injections are given the antitoxin titer in the circulating blood is often inadequate and that the period of immunity is less than one year.

For wounded patients who have not been previously immunized with toxoid, a combination of active and passive immunization may be used. For this purpose 3,000 I.U. of tetanus antitoxin and 1 c.c. of toxoid are injected together on the day of the injury; ten days later a further 3,000 I.U. of antitoxin are given, followed ten days later by 2 c.c. of toxoid. By this means the patient is protected against tetanus infection throughout the period of treatment even when this is lengthy.

Treatment

The administration of antitoxin forms the basis of all treatment. The motor cells of the central nervous system have a great affinity for the tetanus toxin which, once implanted in these cells, can be displaced only with difficulty. The fact that patients who recover from an attack of tetanus show no evidence of permanent damage to the central nervous system suggests that the toxin irritates but does not damage it. This is in contrast to the permanent damage often left by poliomyelitis. It was probably with this consideration in mind that Dufour (1929) devised a method of treatment which aims at the displacement of the toxin from the nerve cells and its neutralization when it is again circulating in the blood. General anesthesia is induced with ether or chloroform, with the object of displacing the toxin from the cells, which have an even greater affinity for these anesthetics than for the toxin. During the anesthesia, the toxin is neutralized by the antitoxin. The patient is given 20 c.c. of chloroform, drop by drop, which induces a light anesthesia for 30 minutes. Half an hour before the anesthetic, and again half an hour after it, 20,000 I.U. of tetanus antitoxin are administered either intramuscularly or, preferably, intravenously. A maximum of two periods of anesthesia may be given each day. In very severe cases Dufour gives an intraspinal injection of 20,000 to 50,000 I.U. of warmed antitoxin, after withdrawal of the equivalent volume of spinal fluid, but this practice is not recommended.

Dufour's technique has led to some improvement in results, and I have seen two seriously ill patients recover. General anesthesia, moreover, does a great deal to relieve severe muscular contractions, and to a large extent prevents anaphylactic reactions.

Couvy uses hexamine (urotropine) instead of ether or chloroform. He gives 0.5 to 1 gram of a 25 per cent solution, after an intraspinal injection of 6,000 I.U. of antitoxin; and half an hour later injects 30,000 I.U. intramuscularly. The results are not as good as those of the Dufour technique.

The amount of antitoxin required to treat a case of tetanus varies considerably, but the average may be taken as 300,000 I.U. The customary routes of injection are subcutaneous, intramuscular, intravenous and intraspinal. Any of the first three may be used, but intraspinal injection is not only ineffective, since there is no contact between the spinal fluid and the majority of nerve cells, but apt to be dangerous. I saw a patient die as a result of an injection of 30 c.c. of Pasteur Institute antitoxin by this route. Local injection of antitoxin into the tissues surrounding the wound has been advocated, but is not satisfactory, for it appears that neutralization in the tissues is difficult and, to be effective, must be carried out in the blood.

A large dose of antitoxin, that is to say, at least 100,000 I.U., should be given at an early stage of the infection. Cole and Spooner (1935) advocate the intravenous injection of as many as 200,000 I.U. They found that, seven days after such an injection, 50,000 units still remained in the blood, while 15,000 units were left after a further period of seven days. If this is true in all cases, a further injection of antitoxin appears unnecessary, but I personally think it wiser to do as Cole (1936) suggests and, in all serious cases, give a second injection of 50,000 I.U. seven days after the first.

If, when all the signs of general intoxication have disappeared, the patient still has some contractions or paralysis, the infection may be assumed still to be present, and a further injection should be given. If more than ten days have elapsed since the patient received the last injection, antianaphylactic measures must again be taken.

General Treatment.—The patient should be kept warm and very quiet in a darkened room. An injection of isotonic glucose solution, if the spasms will permit, will compensate to a large extent for the loss of glucose that results from the great muscular activity: 200 c.c. a day is sufficient to maintain muscular nutrition. The diet should be confined to milk, and the patient may have to be fed through a stomach tube.

Treatment of the Wound.—Many workers have recommended excision of the wound, particularly of its deeper parts, to remove the

tissues infected by *Cl. tetani*. Others, on the other hand, rely on complete noninterference, and I believe this is the right policy. The excision of infected tissues leads to a great increase in the absorption of toxins and so intensifies the effects of the disease.

Treatment of Spasms and Contractions.—Patients suffering from tetanus infection commonly die of cardiac or respiratory failure as the result of general exhaustion. The collapse is chiefly due to the continuous muscular spasms, and it is therefore essential to treat these throughout, so as to allow time for the antitoxin to achieve its tasks. A number of drugs have been used, of which the following are either the most efficient or those most commonly employed.

Magnesium Sulfate.—In 1906 Blake adopted the then new technique of intraspinal therapy for the treatment of tetanus. He injected 1 gram of 25 per cent magnesium sulfate solution daily for four days. This method was, however, soon abandoned for, although magnesium sulfate often inhibits the contractions—and in fact satisfactory results have been published quite recently—its action on the nerve centers is so powerful, as Meltzer and Auer have shown, that in some cases it produces complete paralysis. Meltzer (1916) used magnesium sulfate subcutaneously, injecting 2 to 6 c.c. of 25 per cent solution daily. A certain number of cases have been published, however, in which necrosis of the skin followed a subcutaneous injection.

Chloral Hydrate.—Chloral hydrate inhibits contractions, but must be given in high dosage. A suitable average dose is 30 grams in 50 c.c. each of water and milk, given rectally.

Barbiturates.—Large doses of phenobarbitone (luminal, gardenal), phenobarbitone sodium (luminal-sodium, gardenal-sodium), or amytal, e.g., 4 to 8 grams daily, are effective in reducing the spasms.

Atropine.—One and five-tenths milligrams of atropine (1/40 grain) injected subcutaneously each day may have a sedative effect.

Avertin.—General anesthesia under avertin two or three times a day is of considerable value in serious cases. From 0.07 to 0.12 gram per kilogram of body weight controls the spasms.

Immobilization.—Before the discovery of antitoxin many empirical methods were used, some of which were followed by complete recovery. Three are worth mentioning, because, although entirely unrelated to each other, their success, such as it was, resulted apparently from their capacity to bring about absolute cessation of muscular activity.

Claude Bernard tried curare (1866), and recorded four cases so treated: two developed paralysis and recovered, the other two did not and died. That is to say, the beneficial effect of curare was produced by the same means as that of the intraspinal injection of magnesium sulfate, i.e., by persistent muscular paralysis. Florey and others

(1934) have suggested that treatment by curare should be supplemented by the use of a mechanical respirator.

More than sixty years ago papers were published advocating the stretching of the main motor peripheral nerve of the affected limb, generally the sciatic nerve. Some cases treated in this way recovered after paralysis of the affected limb (Thomas, 1879; Callender, 1878; Clark, 1879).

Several Italian surgeons of the last century published successful results after absolute rest of all the senses, particularly of sight and hearing; no other treatment was given (De Renzi, 1892; Nigris, 1882).

The results of experimental work (see p. 75) seem to prove beyond doubt that the real cause of success in each of these three different forms of treatment lay in the complete absence of muscular activity. Muscular activity is the supreme, if not the only, factor responsible for the absorption of toxins from the tissues by the lymphatic system and their conveyance to the blood. Our experiments showed, first, that the route by which tetanus toxin is absorbed and carried to the blood is the lymphatic system, and secondly that immobilization of the affected limb in plaster of Paris either completely prevents absorption or else very markedly diminishes it. Rabbits immobilized with a plaster spica and injected with a highly lethal dose of tetanus toxin survived for an average period of 11 days, death occurring in most cases without any sign of tetanus, while control rabbits similarly injected, but not immobilized, died of tetanus in an average of less than four days.

It seems abundantly clear, therefore, that in all cases in which tetanus develops as the result of a wound, the affected limb should be immediately immobilized in a plaster cast in order to diminish absorption of the toxin and give the antitoxin time to operate.

Treatment of Anaphylactic Shock.—If, in spite of due precautions (see p. 124), the patient develops anaphylactic shock, one of the following drugs should be used; none of them are, however, very effective.

Adrenaline.—Two subcutaneous injections of 1 c.c. of a 1 in 1,000 solution daily.

Calcium Chloride.—Two intravenous injections of 5 to 10 c.c. of a 10 per cent solution daily.

With the combined use of these methods and drugs the mortality rate of tetanus has fallen from 75 to 25 per cent, but the factor on which successful treatment depends above all others is immediate diagnosis. It would perhaps be better to say that in tetanus the only really efficient treatment is prophylaxis.

CHAPTER IX

SHOCK

The term "shock" is used to denote the acute state of depression of all vital activities, and in particular of the circulatory and nervous mechanisms, that follows the abrupt action of agents alien to the body.

From the first description of this syndrome by James Latta in 1785 until the present time, there have been many varying conceptions of shock and many different theories of its cause. Claude Bernard's work was continued by Mitchell, Morehouse and Keen (1864), who were the first to put forward the theory of the nervous origin of shock by describing it as a consequence of reflex inhibition of the vasomotor nerves. In 1891 Heidenhain produced the theory, based on laboratory research, that shock is due to the absorption of toxins; he had found that animals injected with peptone collapsed in shock. This theory was reintroduced many years later by Dale and Laidlaw (1919), who produced the characteristic effects of shock by intravenous injections of histamine.

The emphasis laid in recent years on animal experiments has tended to distract attention from the importance and value of the study of human subjects. Much of the experimental research, however, is very useful, particularly when it can be correlated with clinical work, and in the following account of the clinical aspects of shock I shall take into consideration the results of the most important animal experiments, especially those of Freedlander and Lenhart (1932), Slome and O'Shaughnessy (1937), Parsons and Phemister (1930), Blalock (1931), Harkins and Harmon (1937), Bross and Lueken (1938), the clinical observations of Szántó (1937) and Atkins (1937), and the study of burns by Lambret, Driessens and Cornillot (1938). To the various theories thence derived I shall add the results of my own experience in the study of war casualties, and that of Kekwick and his co-workers (1941) and of Grant and Reeve (1941), whose observations in many points confirm my clinical findings in Barcelona.

THE PATHOLOGY OF SHOCK

I propose here to deal only with shock caused by trauma, omitting many very similar types such as those caused by frost, burns or infections. The essential basis of shock is that it may be produced by any condition which causes a marked and acute disturbance of the nerve centers. Human shock must be studied in human beings; most of the

enormous amount of experimental work performed on animals during the last twenty years only complicates the picture. The higher centers in man play such a preponderant part that the pathogenic conditions of human shock cannot be exactly reproduced in laboratory animals. To attempt to explain traumatic shock as a consequence of loss of blood, loss of fluid by transudation, intoxication, anoxemia and so forth is, in most cases, like starting a book at the second chapter. My object is to follow the clinical picture of shock as closely as possible.

My own observations and those of others have now evoked sufficient support for the view that the fall of blood pressure is in many cases preceded by a sudden and brief increase in arterial tension. The rise in blood pressure comes on so soon after the trauma and lasts so short a time that it is difficult to investigate. Surgeons who have practiced arterial sympathectomy are familiar with the phenomenon described by Leriche: the immediate contraction of the artery after denudation of the adventitia, followed after a few hours by persistent dilation. This secondary dilation results from paralysis due in its turn to lack of sympathetic control, but it does not appear until some time after the excision of the plexus; the first reaction is an immediate energetic contraction. This contraction is seen in Raynaud's disease, Volkmann's syndrome and other local or general disorders arising from sympathetic stimulation of the vascular plexus. For instance, in some cases of post-traumatic decalcification of the foot the clinical picture is that of local secondary capillary sympathetic paralysis indicated by edema, cyanosis, pain, paresis and marked decalcification of all the bones of the foot. The sympathetic is under the control of the vasomotor centers, but these in their turn are apt to be disturbed by the peripheral sympathetic.

The disturbance of the nervous centers which starts off the state of shock produces a general vascular spasm and a sharp, short rise of blood pressure, and these in turn disturb the blood and oxygen supply to the organs and tissues, particularly those of the central nervous system. This train of related events is commonly called "primary shock." If it persists, it produces serious damage through anoxemia of the centers and of the injured area; increase of capillary permeability to the injured region, resulting in local edema; and decrease of blood volume and increase of blood concentration, impeding the capillary circulation by the agglomeration of red corpuscles, thus bringing about still more anoxemia and initiating a vicious circle. Lennox and others (1935) show that unconsciousness supervenes when the oxygen content in the jugular vein falls below 24 per cent. Quastel (1939) showed that interruption of the cerebral circulation for only a few minutes caused irreparable lesions in the nerve cells of cats.

When this vicious circle has become established, the condition is termed "secondary shock." The change from primary to secondary shock depends on many varying factors, among the most important of which is whether or not the proper treatment is applied at the proper time. A patient with fully developed secondary shock shows a lowered temperature and metabolism, very low blood pressure and blood volume, decrease in blood chloride, and increase in sugar and nonprotein nitrogen. If a badly bruised wound is not treated by early excision of dead tissues, the damage to the highly sensitive central nerve cells is enhanced by the absorption of the toxic products of tissue disintegration, often coupled with those of bacterial invasion. The transition from primary to secondary shock is progressive, the rate varying from several minutes to many hours.

The importance of local edema in the development of shock is now fully appreciated. If 3 per cent of the body weight (representing nearly 50 per cent of the total blood volume) is lost as fluid, the patient will soon die; this means a loss of more than two quarts from a man of 150 pounds. In most cases the local edema does not cause a decrease in blood volume until more than an hour after the injury.

Clinically, the type and intensity of the shock depend on the injury. I shall therefore describe the types of shock in relation to various injuries, with particular reference to the average time of onset of secondary shock. This latter information has a close bearing on treatment, for in general this is successful only if carried out in the stage of primary shock, or in the transition period between primary and secondary shock.

SHOCK CAUSED BY INJURIES TO LIMBS

Shock in limb injuries may be of three types:

a. Produced by bruised wounds and fractures.
b. Produced by multiple splinter wounds (peppered wounds).
c. Produced by crush injuries.

Shock Produced by Bruised Wounds and Fractures

In these injuries as in all other types, primary shock is due to nervous stimulation. If this stimulation is not stopped, secondary shock follows, resulting from the stimulation itself, or from hemorrhage or from both. But it is the absorption of toxic products from the wound which makes secondary shock practically irreversible. Once such absorption is established, the patient gets steadily worse and no treatment is of any avail. For this reason early removal of dead and dying tissues is essential in the prevention of secondary shock. This does not mean that patients with bruised wounds in the limbs must be

rushed into the operating room without consideration for their general condition. If they have reached the hospital within an hour of being injured and if immediate treatment can be established, the surgeon must determine the best time for operating, remembering that the sooner the better. He must take into consideration the patient's condition, the anesthesia required, and the duration and gravity of the operation.

The first measure, and that which lays the foundation for all subsequent treatment, is to get seriously wounded patients to the hospital quickly. After that, the surgeon must make the best combination he can of the three other measures: rapid and efficient resuscitation, nontoxic anesthesia, and a rapid and smooth operation involving the minimum loss of blood and followed by complete immobilization and elevation of the injured limb. If all this can be effected within three hours of the injury, infection and toxic complications can easily be avoided.

Shock Produced by Multiple Splinter Wounds (Peppered Wounds)

Such wounds are generally due to aerial bombs or trench mortar grenades, and manifest a slightly different kind of shock. The primary shock is generally more intense, and from the first there is greater nervous exhaustion, especially if there is a fracture. The shock is increased by movement—indicating the part played in its production by stimulation of nerves in the wound. Hemorrhage may also be a contributory cause, but in many cases it is interstitial rather than external. The patient must be immediately immobilized, because if he is not, secondary shock supervenes without any interval. The nervous exhaustion brought on by movement is quite unrelated to pain; it is very striking to see how casualties of this type may show exaggerated displacement of the injured limb without suffering any pain, and yet fall into the most intense depression when the limb is moved.

Shock Produced by Crush Injuries

If no essential organ is damaged primary shock may persist for several hours and secondary shock be considerably delayed. People crushed and imprisoned by falling masonry may lie for several hours under the pressure of the débris, which produces local ischemia, and not arrive at the hospital until secondary shock is well developed. Rest, postural treatment, plasma transfusion and slight but persistent compression of the limb form the basis of successful treatment.

SYMPTOMS OF SHOCK

Shock is a clinical entity and its diagnosis rests solely on clinical signs and symptoms. Laboratory findings may help in the estimate of its degree but are at the very best only complementary to the clinical picture. Blood pressure is the essential factor in the intensity of shock, and everything else must be related to it.

Mental Condition

Except for cases of head injury, most patients suffering from shock are mentally clear, with a tendency either to drowsiness or to depressed indifference and distraction. Occasionally there is excitement, but this is usually in less serious cases. Many patients remain conscious and clear in mind until a few minutes before death.

Pain

Pain has no precise relation to shock but depends on the type and site of the injury. Most patients have some pain which can usually be controlled by morphine. Its persistence after the subcutaneous administration of morphine means that the capillary circulation is so paralyzed that the drug is not absorbed, in which event it should be given intravenously.

Color of Skin, Nails, and Mucous Membranes

In the preliminary stages of shock, especially in young people, a relatively high blood pressure is often associated with pallor of the skin due to peripheral vasoconstriction. If during resuscitation the skin becomes pink, this indicates a good reaction. Cyanosis of the limbs and especially of the fingernails suggests serious interference with the peripheral circulation and a variable degree of anoxemia; its disappearance is a good sign in prognosis.

Sweating

Sweating is variable and may be absent in severe shock. It probably depends more on idiosyncrasy than on shock itself. In some patients sweating during resuscitation is a sign of good reaction.

Temperature

One of the most constant phenomena of shock is low temperature and the facility with which heat is lost from the periphery. The lack of control of body heat produces extreme sensitiveness to external cold.

Pulse Rate

Pulse rate varies remarkably and does not invariably follow the blood pressure. During the early stages it depends on many factors, including constitution, age, and previous pulse rate. In some cases a

very slow pulse is associated with low blood pressure. The effect of blood transfusion on the pulse rate is very variable, but an outstanding feature of recovery is the slowing of a rapid pulse while a low blood pressure rises.

Pulse Volume

The pulse volume is more important than the pulse rate, and any variations during resuscitation must be noted. Special apparatus is necessary, and I have obtained valuable information from the Pachon-Boulitte oscillometer.

Blood Pressure

On blood pressure the diagnosis of shock and the measurement of its intensity chiefly rest. Nevertheless, during the air raids over Barcelona our view of the significance of blood pressure underwent a change. Perhaps for the first time in history a large number of casualties were examined in the hospital within half an hour of being wounded, and the surgeons observed with surprise that many of the seriously injured had a slightly lowered, a normal, or even a high blood pressure for a variable period, in most cases up to one hour after the injury. This initial high pressure was most striking in young people or in the old who had previously had high pressure. Many of such patients showed a gradual reduction of blood pressure and sank in a remarkably short time into a condition bordering on collapse.

A blood pressure reading above 100 mm. Hg before resuscitation in a recent casualty may usually be regarded as a sign of good prognosis provided that proper treatment can be instituted almost immediately. Any patient with a blood pressure lower than 80 mm. Hg is in grave danger and urgently needs resuscitation before irreversible lesions occur in the nerve centers. It would, however, be a serious error to assume that a recently wounded patient with a blood pressure of 120 mm. Hg twenty-five minutes after injury does not need resuscitation, for less than an hour later such a patient may have a lower blood pressure than one whose first reading was only 80.

To determine the severity of shock in any patient, all these factors must be considered together with the actual injury and the time that has elapsed since it was sustained. The last factor to be considered is the need for operation. Because they always need operation patients with limb wounds are often in more serious danger than those with equally serious wounds in the chest. It is also important to ascertain whether there is any external or interstitial bleeding. Every symptom must be evaluated rather in terms of its evolution during treatment than of its original intensity.

SHOCK CAUSED BY ABDOMINAL WOUNDS

In patients with abdominal wounds secondary shock follows primary shock without any interval, but many abdominal wounds do not produce primary shock at once. The patients with a low blood pressure and rapid pulse who show a period of recovery between the injury and the secondary shock are those suffering from hemorrhage; they may recover from the primary depression after a blood transfusion and then a little later sink into progressive exhaustion due to the fall in blood volume when hemorrhage recurs.

Abdominal shock is most commonly produced by lesions of the solar plexus and splanchnic ganglia. The gravity of wounds entering through the umbilical region is well recognized, as also is the fact that little or no primary shock may occur after perforating intestinal wounds with a different site of entry. I have seen people with several perforations of the intestine walk into the hospital soon after being wounded; they did not suffer from shock because the retroperitoneal region had not been damaged by the injury; but when a few hours later this area became infiltrated with blood, a fall in blood pressure and other signs of shock appeared.

The treatment of abdominal shock depends on precise diagnosis. The symptoms generally indicate the difference between depression from internal hemorrhage and shock caused by stimulation of the sympathetic centers; sometimes both factors are present. A familiar instance of the second factor is the fall in blood pressure produced when, during abdominal operations, the sympathetic nervous system is stimulated by manipulation of the mesentery and traction on the intestine.

SHOCK CAUSED BY THORACIC WOUNDS

Splinter or bullet wounds in the chest, even small ones, commonly cause shock, a fall of blood pressure resulting from stimulation of the inhibitory reflex from the pleural or pulmonary centers. Primary shock is increased by the inadequate respiration, the pain and the emotional reaction to a chest wound. Patients who survive the initial inhibition usually recover easily from the shock but are in some danger from such complications as lung damage or infection of the pleura, or from the serious operations they may have to undergo. The pneumothorax and mediastinal displacement increase the gravity of open chest wounds, and secondary shock appears early and without any recovery from primary shock. If blood leaks into the pleural cavity the resulting respiratory inefficiency increases the shock. The first precaution is immediately to compress the chest by tightly encircling it with adhesive plaster and to give morphine. Local and ganglionic infiltration with procaine (novocain, planocaine, sevicaine) assists recovery from shock and so enables the surgeon to operate in time.

SHOCK CAUSED BY HEAD WOUNDS

Most head wounds do not cause shock but rather a high blood pressure with good peripheral capillary circulation, flushed skin and mucous membranes, and often excitement. The phenomena vary with the site of the wound and the particular nerve centers affected, but if the patient arrives at the hospital in a state of shock the prognosis is very grave: I have seen few cases of recovery from head wounds with shock. Bastos (1937) says that he failed to save any patients with marked low pressure after head injury. Even when the wound produces hemorrhage a high blood pressure is often present, the pulse falling only when there has been much loss of blood.

DIAGNOSIS OF SHOCK

Trauma has two main results: shock and hemorrhage. These may have similar symptoms: fall of blood pressure, decrease of blood volume, increase of pulse rate and respiration rate, depression and severe general prostration; but the two causes of this reduction of all vital activity respond very differently to treatment. Acute anemia should not be included, as is sometimes done, under the heading of shock, although the initial symptoms are similar. It is true that hemorrhage when not immediately treated produces shock, but simple acute anemia responds immediately to blood transfusion, whereas true shock responds much less.

Hemorrhage must be treated first. The signs are primarily produced by reduction in the total blood volume and not by transudation of plasma through the capillary wall. Shock in cases of hemorrhage is produced by the rapid exhaustion of the anemic and anoxemic nervous and cardiac centers. Blood transfusion at this stage has the same limited effect as in other types of secondary shock.

If the hemorrhage is external, and indicated by the nature and site of the wound, or by a bandage or tourniquet, the cause of the low blood pressure is usually clear; but the diagnosis is more difficult and sometimes almost impossible if the hemorrhage is internal or interstitial—especially in crushed limbs. Very early thirst is a sign of hemorrhage. In abdominal hemorrhage the diagnostic signs include fluctuation, fluid thrill, and dullness on percussion of the lower quadrants. The diagnosis of hemorrhage must always be based on clinical signs alone; the blood characteristics are indefinite in the early stage, the only time when they could be of value. Significant changes occur at a later stage, however; thus secondary shock without hemorrhage is accompanied by a high red blood count and color index. Serious hemorrhage should be suspected where a low hemoglobin content accompanies low blood pressure. Unfortunately, the simplest hemoglobin determination needs laboratory workers and equipment which are seldom available under disorganized conditions. If the surgeon is in doubt whether or not to give blood, plasma or both, a simple colorimetric test like that of Sahli is useful, but must be regarded as only accessory to the clinical diagnosis. In patients who arrive at the hospital with serious depression and bruised wounds, hemorrhage is indicated by a very clear fluid venous blood collected from a vein in the forearm.

Secondary shock may, of course, be due to causes other than hemorrhage if the primary shock is not properly treated: such factors as pain, fear, cold and exhaustion of the cortex must be considered together, but in relation to the main factor producing primary shocks; namely, the central and peripheral sympathetic stimulation.

Briefly, therefore, the surgeon must investigate the cause of every case of shock, decide whether or not there is hemorrhage, determine the exact interval that has elapsed between injury and the reduction of vital activity, and ascertain the nature of the projectile, the time of injury, the conditions of evacuation, and the characteristics of the pulse, temperature, respiration and blood. He must then carefully examine the injured region. An experienced surgeon can do all this in five or ten minutes, but some loss of time is less important than a mistake in treatment.

TREATMENT OF SHOCK

Preventive Measures

Bleeding must be stopped at once; this can usually be done by direct pressure on the wound, especially in the arm. The tourniquet should be applied only when direct pressure fails. All stretcher cases must be immediately sent to the hospital, but with the utmost precautions against movement of the injured region.

Treatment of Primary Shock

The patient is put to bed, examined, and provided with warmth, preferably by means of an electric cradle, but if radiant-heat apparatus is not available, by means of hot-water bottles. The lower end of the bed is raised on blocks; a mask for administering oxygen is fitted up, the best apparatus being the B.L.B. (Boothby and others, 1938; Marriott, 1940), and 7 to 8 liters of oxygen are given every minute. Morphine (grain ¼ to ⅓) or lobeline (grain ⅙ to ⅓) or both are administered according to the condition of the patient; pain and dyspnea are the chief indications. If there is excessive sweating, atropine should be injected. The blood pressure should be measured, if pos-

sible with an oscillometer. The red cell concentration or hemoglobin content should be determined, if this is feasible, but only more than three hours after the injury.

Transfusion.—The surgeon must then decide whether to give blood or plasma or both.

Wounded patients with serious hemorrhage should have blood only, in an amount related to the anemia. One patient of Durán Jordá was saved by a massive transfusion of 3½ liters of whole blood. The injection must be made rapidly, for a previously normal heart very soon deteriorates when the systole contracts "on a vacuum."

Wounded patients with primary shock and hemorrhage need blood and plasma in amounts related (as shown below) to their clinical condition and, when these are known, to the red cell or hemoglobin concentration. Primary shock with hemorrhage is most often seen in wounds of the limbs. The red cell concentration varies extraordinarily and seems to depend on the relative degrees of nervous shock and hemorrhage, and also on the interval since the injury. The first transfusion should be of two pints of blood; if there is then a tendency to recovery, a pint of plasma helps to stabilize the improvement, and thereafter plasma only should be given. When depression persists after the first two pints of blood, a third pint of blood should be given before the plasma transfusion is started.

Wounded patients with shock only should be given two pints of plasma by a quick method of administration. If this is not enough, a pint of blood should be given by the same technique. If there is still no improvement, a further pint of blood and a pint of plasma should be given, not necessarily by the quick method, in the course of an hour.

Operation.—A fifteen-minute record of blood pressure, pulse volume, and pulse rate should be charted to enable the surgeon to determine the moment for operation. When the successive readings show a constant tendency to rise, he should wait until the patient is as nearly normal as possible. If, after initial improvement, the line remains stationary or shows a tendency to fall, he must decide at once whether or not the patient is fit for operation, for this is probably his peak of recovery from which he will go downhill.

Consider, for example, a patient who arrives in the hospital twenty minutes after being wounded, with severe primary shock and a systolic blood pressure of 95 mm.; after resuscitation the blood pressure reaches 105 mm. at the first reading and 115 mm. at the second reading, but only 112 mm. after a further fifteen minutes' resuscitation. This patient has reached his peak and very great efforts by his attendants will probably be required if this level is to be maintained. It is in this "plateau period" that operation should be performed, and the surgeon must decide whether the patient can stand it and what anesthetic would be best. In my experience the sooner resuscitation can be instituted, the more easily is the plateau reached and the higher becomes its level.

Local anesthesia with 0.25 to 0.5 per cent procaine (novocain, planocaine, sevicaine) solution is a valuable factor in combating shock. Excision of dead tissues and the establishment of good drainage prevent shock due to toxemia. Immobilization in a plaster-of-Paris cast and elevation of the limb help to prevent secondary shock by averting pain, edema and sympathetic stimulation from the wound. Points to bear in mind during the operation are that a shocked patient is very sensitive to further loss of fluid (and accordingly that hemostasis must be thorough) and that the sooner the operation is completed the better.

Multiple Perforating Wounds.—Severe primary shock is more frequent with such wounds than with the bruised wounds (p. 131). Many patients lose consciousness immediately or very soon after being hit, and can often be seen moving the wounded limb without any appearance of pain. For many of them, since the sensory nervous system is already out of action, morphine is dangerously depressive and I do not recommend it. Lobeline (grain 1/6 to 1/3) and coramine (5 c.c.) are, however, valuable at the time of transfusion because of their stimulant action on respiration. These patients suffer more from nervous shock than from hemorrhage, and often secondary shock follows primary shock without delay and there may be plasma extravasation in the injured region from the very first.

The urgent need is for immediate immobilization, elevation of the injured limb, and radiant heat. Copious plasma transfusions are necessary in some cases: as much as four pints of plasma followed by two pints of blood can be given in the first two hours. Operation is often very dangerous because multiple small perforations in the extremities make the procedure prolonged and laborious. Resuscitation measures must continue throughout the operation and for several hours afterwards, for there may be delayed collapse. More blood than plasma must be given when an amputation is performed. Heart stimulants, with the exception of coramine, should never be given before transfusion, because they may cause a temporary improvement in the vital processes followed by worse shock than before; they may be given, however, when the wound is being treated. Coramine is an exception because of its stimulant action on respiration.

Abdominal Shock.—Unlike the primary depression due to internal abdominal hemorrhage (see p. 135), which usually responds well to treatment, true abdominal shock is extremely difficult to combat. Operation does not affect it nearly so favorably as it does shock due to injuries of the limbs; resection or suture of the intestines may fail to influence it at all.

The movements of the mesentery and the evaporation of fluid which inevitably accompany laparotomy increase the depression and the fall in blood pressure. Nevertheless the great risk of peritonitis forces the surgeon to operate at the earliest possible moment. Anesthesia still further increases the danger, and the choice of anesthetic is very important. I have tried all types, but only one in my experience, namely, splanchnic anesthesia by the posterior approach (Kappis' technique), allows immediate operation in shocked patients (Trueta, 1935). This technique interrupts sympathetic communications through the celiac and splanchnic ganglia and raises the blood pressure. The anterior approach (Braun's method) is unsuitable because the splanchnic injection is made after the incision of the peritoneum, when the fall in the blood pressure is greatest.

The technique of the posterior approach is as follows:

> The patient lies on his side and a needle five inches long is introduced just under the last rib 2½ inches from the spinal process. It is directed towards the body of the first lumbar vertebra, which it skims, entering a further half inch. An injection of 30 c.c. of one per cent procaine is given, and the same technique is then employed on the other side. Finally, the anterior abdominal wall is made insensitive by local anesthesia.

Spinal anesthesia is very dangerous for these patients, because it lowers the blood pressure despite all prophylactic measures.

Thoracic Wounds.—Morphine acts well on patients with thoracic wounds; and if breathing is shallow lobeline should also be given, subcutaneously or intravenously. The chest should be immobilized by an adhesive bandage. A small plasma transfusion is useful when there is no severe hemorrhage, and complete rest is very beneficial. If general anesthesia is used for surgical treatment, it must be supplemented by local and paravertebral anesthesia, which make it possible to operate without increased danger. If the operation involves the lungs, and especially in pneumonectomy, the hilus must be injected to destroy sympathetic conduction.

Head Wounds.—There is no adequate treatment for shock in these cases. Very low blood pressure with pallor and hypothermia usually betokens a fatal outcome. Radiant heat, morphine and plasma transfusion have very little effect, and operation seriously aggravates the condition. Fortunately shock in head wounds is very rare; although many of the patients are unconscious, few of them have any serious fall in blood pressure.

CHAPTER X

TRAUMATIC VASCULAR SPASM

Severe trauma of the extremities is always likely to stimulate the sympathetic nervous system and so give rise to persistent vascular spasm.

The influence of the sympathetic nerves on the vascular system has been recognized since the time of Bichat and Larrey, and the researches of Claude Bernard, and later of Brown-Séquard, showed something of how this influence is exerted. Jaboulay (1896) and Jonnesco (1903) were the first workers to treat affections of the sympathetic system by surgical measures, and René Leriche (1917), once an assistant of Jaboulay and the most famous student of this system in our time, introduced arterial sympathectomy.

During and immediately after the War of 1914 to 1918 a number of cases were published in which a decrease in the blood supply to a wounded limb was found to be due solely to sympathetic disturbances. (Kroh, 1915; Leriche, 1917; Jeanneney and Guyot, 1918; Küttner and Baruch, 1920.) The clinical descriptions were all very similar. In most cases an operation was performed for a suspected arterial lesion, but the surgeons found that the ischemia of the limb below the wound was due, not to a damaged or thrombosed artery, but to constriction of the vessel which lasted for several hours and often for more than a day.

A temporary local ischemia due to vascular spasm in the vitally important initial period aggravates the always serious prognosis of war wounds. When a main artery also is affected by spasm, the wound is more than ever at the mercy of bacteria. Capillary spasm is not necessarily accompanied by arterial spasm, and in contused wounds often occurs alone; but with spasm of the small arteries there always goes an increase of capillary permeability causing local edema, which further impedes the circulation in the damaged area. Moreover, when edema appears, the lack of elasticity in the aponeuroses increases the risk of complete occlusion of the circulation.

Most workers agree that a small amount of blood still passes through an artery constricted by spasm, and consequently that the effect of such spasm is a decrease of the circulation in the region of the wound rather than an ischemic gangrene of the whole extremity.

The most common cause of arterial spasm is severe concussion, whether this involves the artery directly or only the soft tissues sur-

rounding it. Spasm may occur without an actual wound, as in people who have been crushed under masonry in air raids.

SPASM CAUSED BY CRUSH INJURIES

In an attempt to determine the effect on the vascular system of prolonged constriction of a limb, Dr. J. M. Barnes and I carried out a series of experiments on rabbits.* To simulate the crushing produced

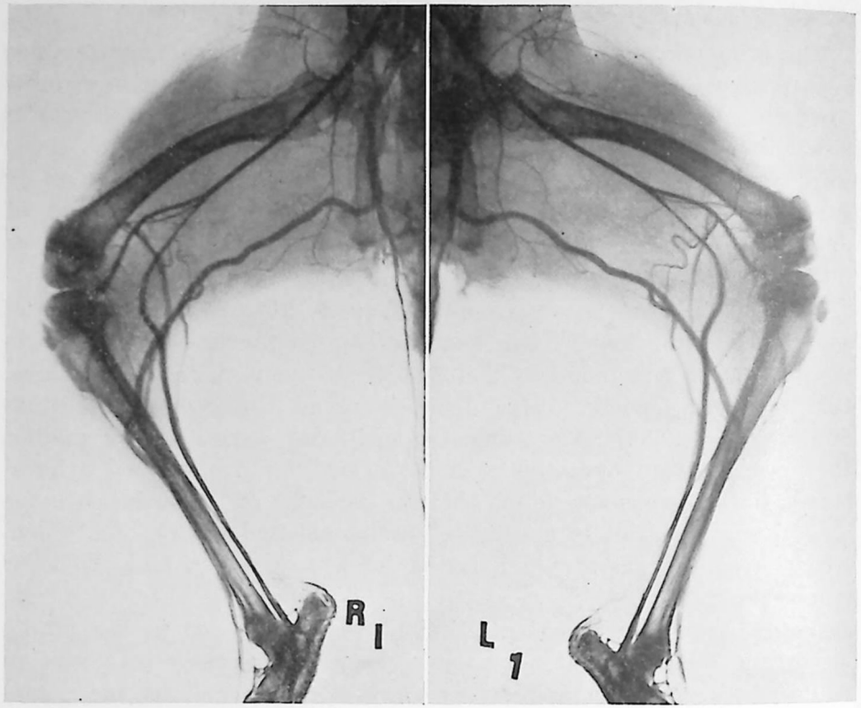


Fig. 8.—Vascular system of the legs of a normal rabbit during an intra-arterial injection of 5 c.c. of a 50 per cent sodium iodide solution.

by fallen masonry and to obtain a uniform standard of constriction, we used a rubber tourniquet; and we studied the circulation by injecting a contrast medium into arteries and radiographing the limbs. The tourniquet was applied to the upper part of one thigh and left for 4½ hours. It was then released and, after periods varying from a few minutes to three days, the animal was anesthetized, the abdomen was opened and an injection of 3½ to 5 c.c. of sodium iodide was made into the abdominal aorta, radiographs being taken of both hind legs towards

*This work was carried out, by the kind permission of the Trustees, at the Nuffield Institute for Medical Research, Oxford, and with the constant help of Dr. A. E. Barclay, Mr. M. S. Tuckey, and Miss M. Prichard, to whom we owe our deepest thanks.

the end of and a few seconds after the injection. A series of animals to which the tourniquet had not been applied were similarly injected and radiographed as controls.

The results gave a clear idea of the effect of prolonged compression on the arteries. In the controls the vascular picture was exactly similar in both legs (see Fig. 8). The arteries were clearly visible throughout the limb and showed no abnormality in size. The main veins were

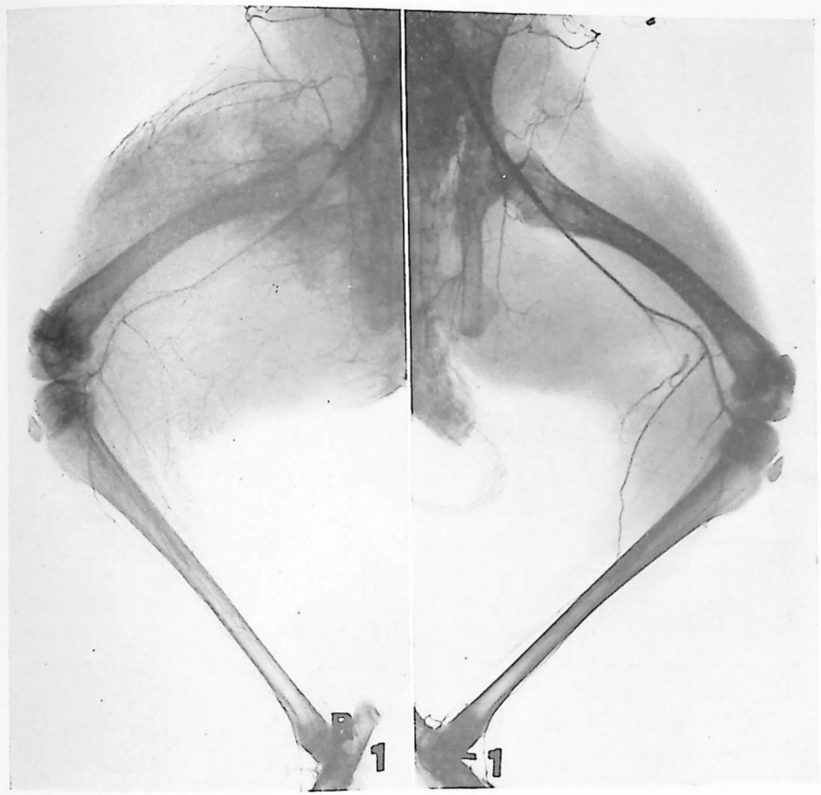


Fig. 9.—Vascular spasm caused by the application of a tourniquet at the top of the right thigh. There is frequently spasm of the left femoral artery although no tourniquet is applied on that side.

also clearly visible, the saphenous being particularly well filled, and there was no transudation of the contrast medium into the tissues. The animals to which we had applied a tourniquet, on the other hand, all showed persistent contraction of the arteries of the affected limb, starting immediately below the level of the tourniquet; the main arteries, particularly the femoral, were either very thin or else could not be seen at all, while the veins were completely invisible (see Fig. 9). In addition the radiographs showed a wide diffusion of the contrast me-

dium through the tissues immediately below the zone of constriction, thereby confirming the view that arterial spasm is accompanied by an increased permeability of the capillaries in the injured region. That the arterial spasm was due to sympathetic stimulation was suggested by the almost invariable appearance of similar spasm in the corresponding segment of the other leg. This spasm was not as pronounced as that in the compressed leg, but was always at the same level, suggesting reciprocal innervation. On dissection, the femoral vessels of the affected leg were noticeably smaller than normal, sometimes even far above the level of the tourniquet. The femoral artery and vein were free from clot and both would bleed when cut, but the artery did not spurt.

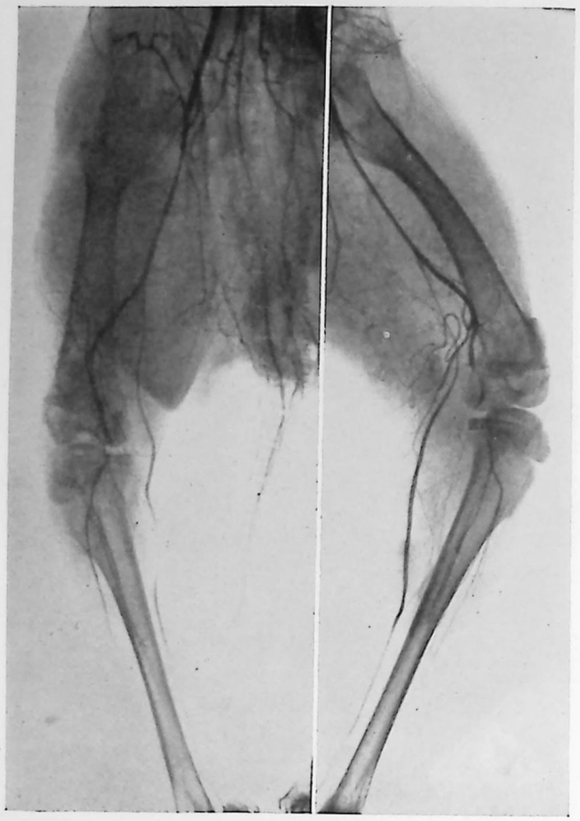


Fig. 10.—Appreciable decrease, after lumbar ganglionectomy, of vascular spasm produced in a rabbit by the application of a tourniquet as in Fig. 8.

In an attempt to prove that the spasm produced by the tourniquet was in fact due to sympathetic action, we carried out a further series of experiments, removing the lumbar sympathetic ganglia on the ligated side before, immediately after, or some hours after the application of the tourniquet. The radiographs of these animals (see Fig. 10) showed markedly less arterial spasm than those of the untreated animals, while on dissection the femoral vessels were apparently normal in size and the artery spurted with great, and even abnormal, vigor.

Vascular Spasm and Shock

Many animals to which a tourniquet has been applied die of a syndrome very similar to that of shock (extensive edema in the affected limb, hemoconcentration, progressive weakness, etc.). This fact has led many workers to the conclusion that the immediate cause of traumatic shock is the loss of blood volume due to increased permeability of the capillaries in the injured region (Andrews and others, 1937; Harkins and Harmon, 1937; and others). There seem good grounds for believing that the changes in the local circulation brought about by the sympathetic nervous system—changes which accompany all injuries caused by violent impact or persistent crushing, whether there is an actual wound or not—are identical with those which occur in shock and may indeed be considered as a local form of this condition. Thus the region which we call the "area of spasm" may also be termed the "area of local shock."

DIAGNOSIS

In crush injuries with no wound it is difficult to determine the degree of sympathetic disturbance. Our only guides at present are the readings on an oscillometer applied to each limb and the local temperature. Tests have shown that the injured limb (generally the leg) gives a somewhat lower oscillometer reading than the uninjured limb and a markedly lower reading than the other extremities. This result accords with our final experimental findings that a spasm, less pronounced but nevertheless substantial, also occurs in the leg to which the tourniquet has not been applied. This feature is most common where the blood supply is carried by a single main artery, as in the thigh and arm.

Arterial spasm resulting from a wound which causes direct irritation of the artery is shown by very similar oscillometer readings to those on a crushed limb with no wound. Surgical exploration, however, gives a more accurate diagnosis, for arterial spasm, unlike thrombosis, does not completely obstruct the flow of blood; in many cases pulsation persists in the distal arteries. The surgeon may be able to see the contracted vessel even if, as often happens, the contracted portion is only a few centimeters long.

Capillary spasm is less easy to diagnose, and can only be inferred from a decrease in the normal bleeding capacity of the tissues, a somewhat pale color of the muscles, and edematous infiltration, which appears a short time after an injury.

COURSE

In most cases the arterial spasm persists for several hours, and it may last for more than a day. It then relaxes and the full circulation is re-established. In some instances, however, and particularly in injuries caused by prolonged crushing, the initial symptoms disappear after a few hours but an increased edema and a progressive anuria produce a kind of delayed shock which may cause death after a week or more. The renal failure is probably due to spasm of the renal arteries (of which we found suggestive evidence in our experimental work) rather than to a loss of blood volume resulting from local edema. In some cases the edema has been wholly insufficient to explain such a serious condition, and the clinical picture of the patients who have died of renal failure has been very similar to that of ischemia of the kidneys.

In capillary spasm, if infection does not develop, the circulatory conditions will return to normal after a few hours.

TREATMENT

Since vascular spasm substantially decreases the blood supply and commonly leads to edema, treatment must be directed first to relaxing the spasm and secondly to preventing edema. In wounded patients these objects are best achieved by enclosing the affected limb in a plaster cast, for by the successive procedures of incision, excision, immobilization in plaster, and elevation of the extremity, tension is reduced, pain and other local stimuli are prevented, and the development of edema is impeded. When a main artery has been exposed, arterial sympathectomy at the level of or, better still, proximal to the injury may be performed with advantage.

In crush injuries, which do not provide the same opportunity for surgical measures, the treatment of primary shock, the complete immobilization of the limb under slight pressure, and its elevation to a high angle are still more important. With this treatment pain will quickly disappear, the limb will be maintained at a constant temperature inside the plaster, and the gentle compression and raised position will do much to prevent edema and so allow re-establishment of the circulation.

Catalan surgeons had to treat several thousands of people crushed by falling masonry in aerial bombardments, and this technique was very successful as a standard treatment. I have no personal experience of operation on the sympathetic nerves as a method of dealing with this type of injury, but the evidence in its favor seems sufficient to warrant its trial—at least as an alternative to the amputations which, according to some surgeons, afford the only chance of saving patients from death later.

CHAPTER XI

BLOOD TRANSFUSION

Out of the Spanish War came one development which is now universally accepted as part of the surgical treatment of war casualties: the dispatch to the front of stored blood from the civilian population.

Despite the collapse of the Republic at the most critical period in the trial of this method, the service steadily improved and it became evident that it had a place beside anesthesia, excision, immobilization and chemotherapy in the treatment of war injuries. Nevertheless, some of the most successful technical advances made in my country have not yet been adequately considered; and it is in the hope that under the stresses of the present greater war this deficiency will be remedied that together with more recent developments, I shall also outline the Catalonian experience, stressing what seemed then the most important factors in a service for the transfusion of stored blood.*

Blood transfusion for large numbers of casualties, either in an army or among the civilian population after air raids, presents completely different problems from those of blood transfusion in ordinary clinical practice. A large organization has to be built up for the enrollment and bleeding of donors and for the care of their health. It must also collect blood, arrange for its storage, prepare supplies of plasma and serum, and dispatch the blood or its derivatives to the bombarded or battle areas where they are needed. These problems, technical and administrative, are manifestly beyond the scope of this work. They hardly concern the surgeon, except in so far as their successful solution enables him to employ the transfusion services to the best advantage. But although most of the technical details, e.g., of grouping and collecting blood, are primarily the concern of hematologists, the surgeon must understand them well enough to carry on efficiently and avoid the risks of producing severe reactions when, as must sometimes happen in war, he is under the necessity of working without specialist help. The following pages deal with these fundamentals. The methods described are such as can be adopted by the individual surgeon; they are not in all cases quite as effective, nor are they as elaborate, as those now generally used in properly organized transfusion services.

*The Barcelona Blood Transfusion Service, under the leadership of Dr. F. Durán Jordá, built up in two years a body of 27,000 donors and gave more than 10,000 transfusions. In the final stages of the war, the organization of blood transfusion for all the Republican Armies was put under Dr. Durán Jordá's direction. It is with his help that I am able to review the results of this experience, and my thanks are due to him for his kindness in criticizing and modifying my original description. For valuable suggestions I am also indebted to my friend, Dr. J. M. Barnes.

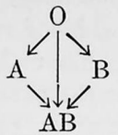
STUDY OF BLOOD GROUPS

There are four different blood groups which are determined by the agglutinogens A and B in the red blood corpuscles and by the agglutinins α and β in the serum. Using the International Nomenclature, based on the presence or absence of A and B agglutinogens, the groups may be classified as follows. The figures in parentheses refer to the corresponding Moss classification, still used occasionally in Europe and America.

GROUP	AGGLUTINOGENS	AGGLUTININS
O (IV)	O	α and β
A (II)	A	β
B (III)	B	α
AB (I)	AB	O

The phenomenon of agglutination depends on a mixture of an agglutinogen A or B with the corresponding agglutinin α or β.

From this description and the diagram below, it will be seen that any group can give blood to its own members and to group AB. Group O, because its red corpuscles do not contain any agglutinogen, can be transfused to any other group, its members being universal donors.



Certain other agglutinogens in red blood corpuscles (i.e., M, N, and P) do not appear to have any clinical significance; but a new agglutinogen, Rh, has been responsible for post-transfusional accidents.

The Rh agglutinogen is present in some 85 per cent of persons, the remainder being –Rh. If –Rh persons receive blood from + Rh donors they may develop the corresponding agglutinins, and if several transfusions of + Rh blood are given, the –Rh recipient may develop a very serious reaction. In the treatment of recent casualties, however, this Rh factor can be overlooked, for there is no risk from the first transfusion, no matter how much blood is given.

Technique of Grouping

Grouping can be most easily performed on a glass slide. The method is quick and, if the following precautions are observed, reliable.

1. There must be an excess of serum as compared with corpuscles.

2. The mixture of cells and serum must be allowed to stand for at least ten minutes, and if possible examined under a microscope.

3. The blood must be fresh and the slide warmed. (In cold weather or if the sample to be tested is old and infected false agglutination may be seen.)

Drops of sera of groups A and B are placed on the slide, continental workers usually add a drop of group O serum as well, and one drop of the blood to be tested is mixed with each serum, taking care not to mix the samples. The slide is gently rocked, left for 10 minutes, and then examined in a good light.

If there is:

agglutination in A the subject belongs to group B
agglutination in B the subject belongs to group A
agglutination in A and B the subject belongs to group AB
no agglutination in either the subject belongs to group O

Cross-Matching Test

A simple cross-matching test should always be carried out, except in the gravest emergency. A drop of serum from the recipient may be obtained by filling a capillary tube with his blood, sealing one end, and centrifuging for a few minutes. The serum is then mixed with red corpuscles from the blood it is proposed to give and the reaction watched as in the grouping test.

COLLECTION OF BLOOD

Blood for storage and transport is collected by the transfusion service and reaches the surgeon ready for use after the appropriate grouping and cross-matching tests have been carried out. When the surgeon has to collect the blood himself, he should use a wide-bore needle attached to the receptacle by means of a short tube so as to reduce the risk of clotting while the blood is being withdrawn. The admixture of 50 c.c. of a 4 per cent solution of sodium citrate with each pint of blood serves to prevent coagulation and the blood may be used immediately on collection.

To avoid skin and air-borne infections the donor's skin must be carefully prepared with a suitable antiseptic and the local venous region protected by sterile towels. A tourniquet should be applied and tightened at the minimal arterial pressure and left for about five minutes, by which time there is marked venous dilatation and the donor is ready for bleeding (see Fig. 11).

Whenever possible the blood should be collected fasting, or six hours after the last meal. In the fasting blood the plasma is clear, for it contains no products of digestion. It is also free from proteins insufficiently broken down by the liver (such as may be present in hepatic insufficiency or after large meals), allergens, and post-prandial bac-

teriemia, and is thus less liable to cause accidents than blood obtained after a meal. Following its collection the donor should be given a meal or a substantial drink.

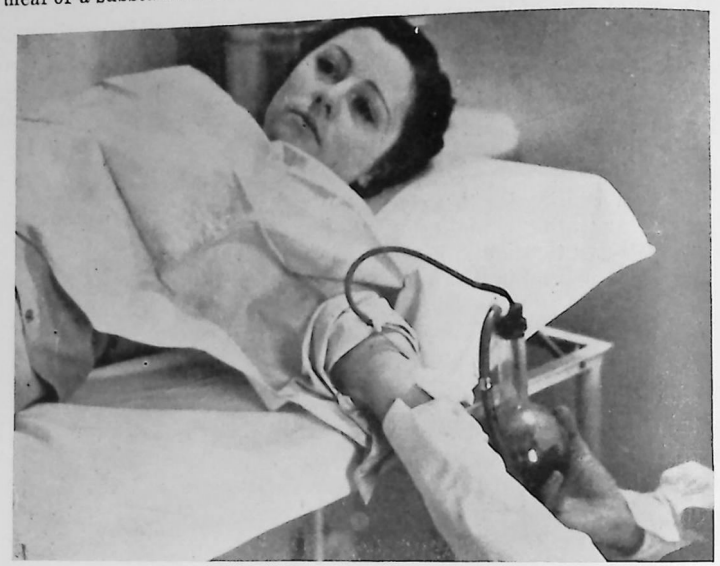


Fig. 11.—Collection of blood. The needle is directed against the venous current.

METHODS OF TRANSFUSION

The only methods to be described in this section are those that involve the use of stored or stabilized blood. Direct donor-recipient transfusing is practiced but seldom and, in any case, should be adopted only by those familiar with its special difficulties.

Preparation of Stored Blood for Transfusion

It may be recalled that during storage the blood cells sediment, forming three layers: red corpuscles, white cells and plasma. The white cell layer (by some authors called the "blanket") behaves like a gel, and the red cells form small clumps. Owing to reduction of oxyhemoglobin the hemoglobin becomes very dark, and diffuses out of the cells into the plasma, which becomes pigmented both by it and by hemoglobin liberated from dead red cells. Between the plasma and the cells there should be a very sharp layer free of clots or precipitates; if these are present, the blood must be rejected. Equally unsuitable is blood with a marked orange tint more than halfway up the plasma layer or (as occurs in contaminated blood) with purple-red pigment completely diffused through the plasma.

Immediately before use the plasma and the cells must be mixed, but very gently so as to avoid excessive hemolysis of the fragile cells. Serious accidents may result from transfusion of old blood which has been mixed too energetically, with consequent destruction of many red cells and the discharge of much hemoglobin into the plasma.

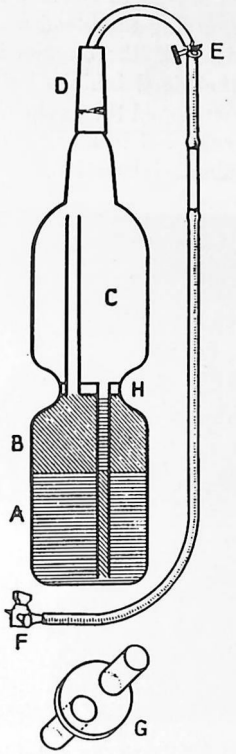


Fig. 12.—Tube for storage and administration of blood. *A*, Sediment of red cells; *B*, plasma; *C*, compressed air; *D*, sealed end of tube in rubber tubing; *E*, screw clip to control flow of blood; *F*, two-way cock; *G*, arrangement of small tubes in glass partition *H*, dividing the tube into two chambers.

Finally, when possible the blood to be administered should be warmed in a water bath at a controlled temperature of 40° C. It should not be left in the bath longer than strictly necessary, for this would favor the multiplication of any bacteria that might be present and so add to the risk of transfusion accidents. Heating to 45° C. is dangerous. It results in the destruction of red blood corpuscles and the modification of blood proteins, and is thus yet another cause of serious reactions. Blood which has been warmed but not transfused should be discarded; it should not be put back into the refrigerator.

Use of the Barcelona Container.—Infection can be most easily detected when the blood is stored in the type of container devised by the Barcelona Service (see Fig. 12). This was made entirely of glass and ended in a capillary tube which was sealed by an electric arc in a steel chamber. It was charged with filtered atmospheric air at 25 pounds to the square inch, which served to convert 99 per cent of the hemoglobin to oxyhemoglobin, giving the blood a ruby red color (Fig. 13). Two advantages resulted: first, the oxygen in the container and the intense oxygenation of the blood inhibited the growth of anaerobes; and secondly, if aerobes developed the oxyhemoglobin was reduced and the color changed from ruby red to black. The sterility of the blood could thus be verified by simple inspection.

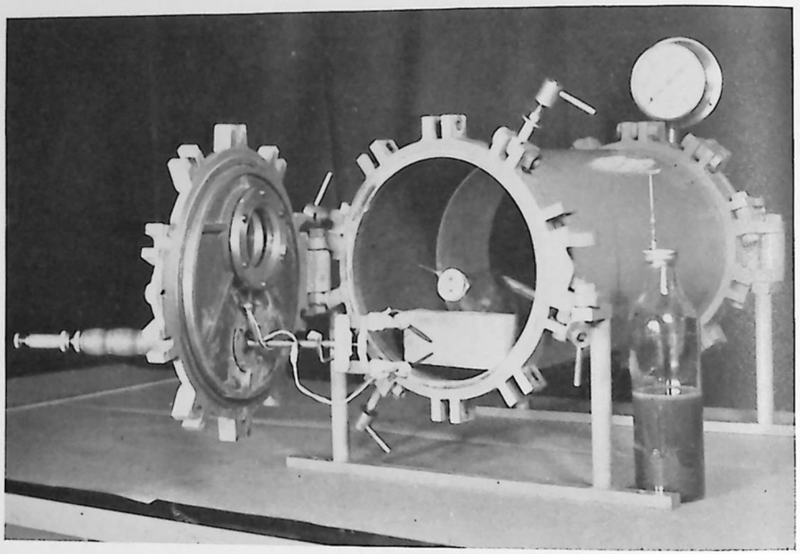


Fig. 13.—Durán Jordá chamber for the closing of bottles under 25 pounds of atmospheric pressure.

Apparatus Used for Transfusion

The types of apparatus used in the Emergency Medical Service and in the Army Medical Service resemble each other closely. The army Overseas Pattern (Fig. 14, *upper*), designed to enable transfusion to be given under active-service conditions, is available in a tin container, sterilized and ready for use. The Home Pattern (Fig. 14, *lower*), for use in hospitals and by organized transfusion services, is similar to the Overseas Pattern in principle but often has a filter of the glass bead instead of the mantle type. In both patterns the blood is transfused by gravity, the speed varying according to the height of the container and the width of the needle.

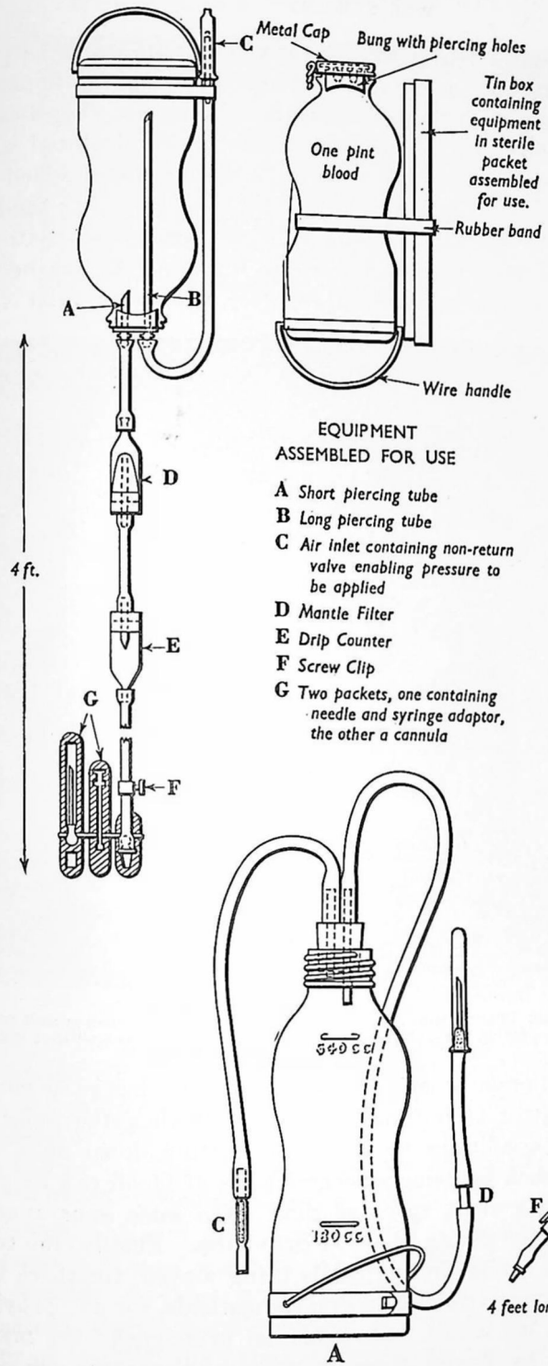


Fig. 14.—*Upper.* Overseas pattern equipment for giving stored blood or derivatives. *Lower:* Home pattern equipment for *A*, taking, and *B*, giving blood. *C*, Air filter; *D*, glass window; *E*, drip counter; *F*, speed-regulating clamp. (From the War Office Manual on Resuscitation, reproduced by permission of H. M. Stationery Office.)

For the treatment of battle casualties, when blood must be given under most difficult and primitive conditions, I prefer the apparatus designed for the Barcelona Service by Durán Jordá and his colleagues (Durán Jordá, 1939). In essence it consists of blood stored under pressure in a sealed bottle with a tube filter and needle attached (see Fig. 15). The seal is broken, the flow controlled by a clip, and the bottle pinned to the lapel of the surgeon's or technician's coat. Because of the high pressure inside the bottle, a fine needle can be used and the transfusion thus carried out by way of the smallest veins.

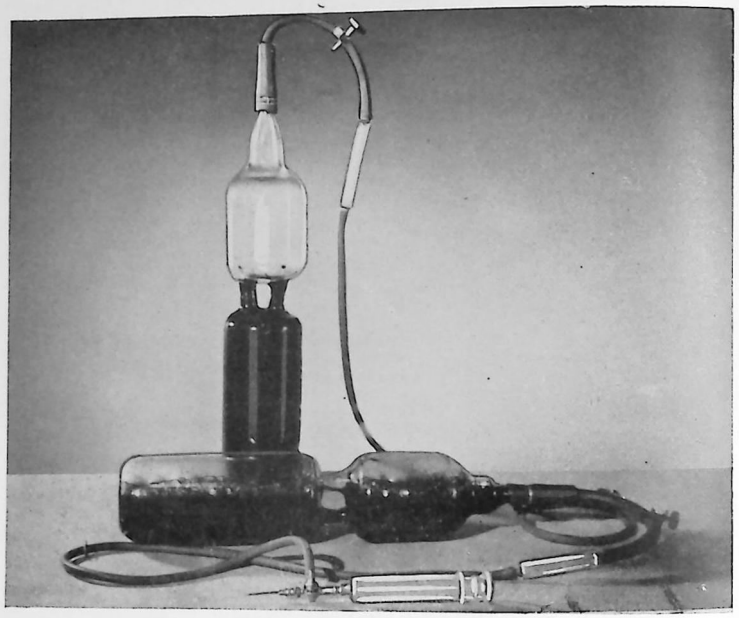


Fig. 15.—Barcelona Blood Transfusion Service bottle for mixing corpuscles and plasma before transfusion. Notice the thin needle used in the "air pressure" method.

This is a great advantage when the whole procedure has to be carried out by a nonspecialist technician; as it is too when the veins are collapsed or when conditions do not favor cutting down on a vein. With a supply of such containers several pints of blood can be given singlehanded within a short space of time. The same apparatus can be used, if desired, for giving blood at drip rates. Finally, the transfusion can continue while the patient is being moved, for there is no need, as with the apparatus used in gravity methods, for any provision for suspending the container. The essential principle of the method has been embodied by Durán Jordá in types of apparatus commonly used in Great Britain (see Figs. 16 and 17).

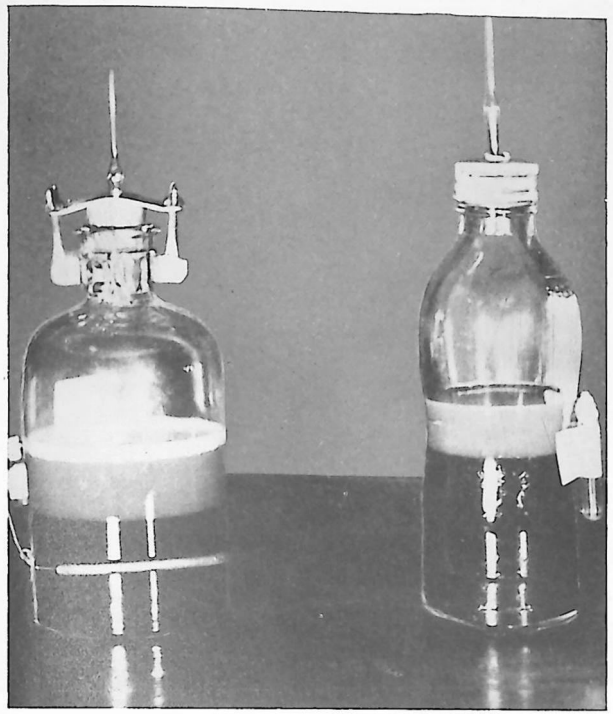


Fig. 16.—Adaptation to the "air pressure" method of bottles commonly used in Great Britain.

Left-hand bottle—800 c.c. capacity, containing 400 c.c. of blood under pressure. This type of bottle is in regular use at Ancoats Hospital, Manchester.

Right-hand bottle—approximately 600 c.c. capacity, containing 300 c.c. of blood under pressure. This is Durán Jordá's adaptation of the Emergency Medical Service model used for blood transfusion.

THE VENOUS PUNCTURE

One of the problems of blood transfusion is the venous puncture of a recipient suffering from severe anemia or shock. If the method is slow and much blood has to be injected, the proportion of cases which will need venous dissection is great; but if the method will permit the blood to be injected through a narrow needle, the transfusion can be made without cutting down on the veins.

Dissection should always be avoided if possible, for many patients need several transfusions during their treatment, and repeated dissection is obviously impracticable. If the blood can be injected through a small needle there are plenty of superficial veins which can be used. In small children the external jugular vein may be used without dissection.

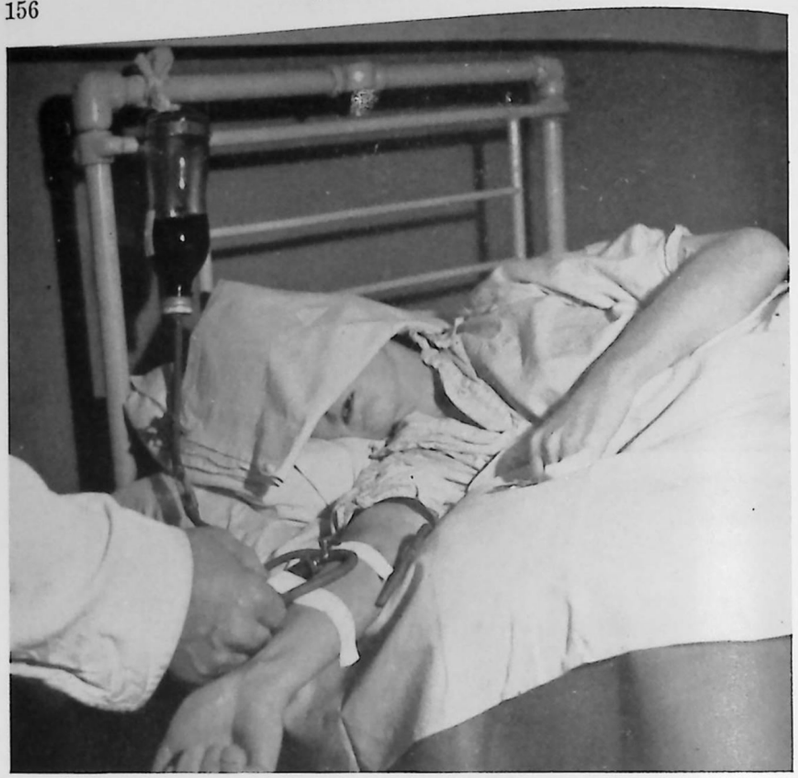


Fig. 17.—Patient receiving a blood transfusion by Durán Jordá's pressure method. The bottle is an adaptation of the Emergency Medical Service bottle. The photograph shows the suspended bottle, the screw on the rubber tubing, the drip apparatus, two-way tap and syringe. The syringe, needle, and tap are held in place by a strip of adhesive plaster.

Penile Transfusion

In exceptionally grave cases the transfusion of wounded males may be made into the corpus cavernosum penis. The method is very simple and resembles venous puncture. A long needle of medium size is introduced, pointing distally, half an inch from the base of the penis in its lateral aspect. The skin should be drawn very tight and punctured before the corpus is entered, and the injection should be made slowly.

Aortic Transfusion

Another route of transfusion, also for use in exceptional cases, is by the abdominal aorta (Tuohy, 1938). The puncture is made with an ordinary 15 cm. lumbar puncture needle at the left side of the first lumbar vertebra, in three stages:

1. The needle is introduced obliquely until the vertebral body is found.

2. It is then pressed along the lateral part of the vertebral body up to the anterior part.
3. Finally it is turned in an anteroposterior direction and pressed onwards until the aorta is punctured.

In an adult the skin must be punctured 8 cm. and in a child 5 cm. from the spinal process.

Sternal-Marrow Transfusion

Sternal-marrow puncture may also be used in emergencies, when the peripheral veins are inaccessible. A sternal-puncture needle is inserted through the cortex of the bone and a small amount of marrow fluid is aspirated. The blood or blood derivative flows in under gravity, so far as the resistance offered to it will allow. In conscious patients a rate above 10 c.c. a minute sometimes produces a feeling of fullness in the sternum, but this usually passes off when the transfusion is completed. If a more speedy transfusion is needed, the fluid may be introduced through two needles, one in each end of the sternum. Tocantins used the sternal-marrow route in 72 cases without untoward reactions of any kind (Lee, 1942).

INDICATIONS FOR BLOOD TRANSFUSION

Transfusion finds its most urgent application in the resuscitation of the wounded suffering from severe hemorrhage and of the wounded suffering mainly from shock. The latter group includes those with shock due to burns. These acute cases have been further subdivided to include a group with multiple injuries and considerable hemorrhage but without obvious shock (Grant and Reeve, 1941; Vaughan, 1942). In practice, however, the broader classification works well enough, patients with hemorrhage from multiple or from single wounds needing transfusion alike with the appropriate amounts of fluid and at the earliest possible moment. The employment of transfusion in resuscitation is discussed in Chapter IX.

Transfusion may also be required in the later stages of treatment of wounds and burns. Severe and persistent infection and toxic reactions from drugs of the sulfonamide group all result in secondary anemia, and the transfusion of whole blood raises both the hemoglobin concentration and the blood content of complement and antibodies. It is also valuable before and after severe operations, when it serves for the prophylaxis of shock, and as a pre- and postoperative measure in patients receiving definitive treatment in the hospital after having received only emergency treatment in the field.

TIME, AMOUNT AND RATE OF TRANSFUSION

In the acute cases mentioned above speed is manifestly the first consideration. Most urgent of all is the need for transfusion to meet the sudden decompensation produced by hemorrhage, when the patient is putting up the maximum resistance and the defense mechanisms are working to make up for the loss of oxygen-carrying cells, proteins and water. To overcome posthemorrhagic shock in such cases at least 40 per cent of the lost fluid must be restored at once, preferably by one of the quick methods. The blood pressure usually remains high if the amount of blood which passes through the heart per minute is above 60 per cent of the normal, but at this critical level it may fall as the result of the loss of only a few extra cubic centimeters of blood. For some time the pressure is sustained by the vasoconstrictor mechanism; but if, through the hemorrhage, the blood supply to the vasoconstrictor centers becomes deficient, the mechanism is put out of action and intense vasodilatation sets in. It is for these reasons that patients who receive a small or late transfusion often collapse, even though they may seem to recover for a time.

Unfortunately there are no quick and reliable methods for estimating the amount of blood lost after injury. Hemoglobin estimations are of little value, except, as is shown later, in cases of burns (see p. 412). A far more valuable guide is the systolic blood pressure, a fall of which to 50 mm. Hg or less indicates the need for a fairly large amount of blood, with a second transfusion should the level fall again after the first. Generally speaking, 500 c.c. of blood or blood derivatives is required for every 10 to 20 mm. fall of blood pressure below normal. Failure of such a transfusion to raise the pressure by the expected increment suggests continued bleeding, and accordingly the need for checking the hemorrhage and giving more blood. A transfusion of 500 to 1,000 c.c. should be given as a routine to patients whose systolic blood pressure remains below 100 mm. Hg.

Methods which restore the fluids very quickly are best, for the danger of cardiac failure is far smaller in war casualties, many of whom are young and healthy, than it is in patients suffering from chronic anemia or other debilitating conditions.

In 2,000 transfusions for hemorrhage the Barcelona Service gave an average of more than two pints per patient in an average period of 10 minutes. Many patients received three or four pints. The speed could be regulated from 100 c.c. per minute to a drip. Most of the patients received the first pint at a quicker rate than the rest, but no case of cardiac failure was reported from dilatation of the right heart. According to Whitby (1942) "subjects with a normal blood volume . . . have received from 700 to 2,100 c.c. of serum intravenously in 7 to 20 minutes, one as much as 2 liters in 16 minutes, with no more than a trifling embarrassment and certainly no pulmonary edema"; and he draws the sound conclusion that "in casualty work failure to restore blood volume is a danger greater than overloading of the circulation."

For the less urgent cases referred to above (see p. 158) speed of transfusion is usually not so important but considerable amounts of blood are sometimes needed. Thus, for the treatment of patients with infected wounds enough must be given to restore the hemoglobin to the normal level. Several transfusions of 500 c.c. or more may be needed for this purpose, and to maintain a normal hemoglobin level once this has been reached. The amounts given before and after operation naturally vary with the severity of the operation and the condition of the patient. I usually give amounts in the order of 1,000 to 1,500 c.c. Transfusion for the detoxication of patients who have received excessive amounts of the sulfonamide compounds has not, in my experience, given very encouraging results. The procedure of the Barcelona Service was to withdraw 400 to 500 c.c. of blood and immediately transfuse a like quantity. The amount of fluid that should be transfused in the later stages of the treatment of burns is discussed on p. 413.

POST-TRANSFUSIONAL ACCIDENTS

Hemolytic Shock

Hemolytic shock, a severe but fortunately rare accident, results from the transfusion of incompatible blood or of blood in which the cells have undergone gross hemolysis. It may also occur, as explained on p. 148, after the repeated transfusion of +Rh blood into –Rh recipients.

The symptoms, which include nausea, vomiting, headache, rigor and pain in the abdomen and back, usually develop rapidly, and in conscious patients may be noted after the transfusion of 50 c.c. or even less. The pain in the back is very severe and persistent. A high proportion of patients with true hemolytic shock die in the early stages with all the signs of acute heart failure—according to some authors as many as 50 per cent. In the survivors the most important and prominent symptoms are renal, i.e., uremia and anuria, but intestinal disturbances, including severe diarrhea, are also common.

The immediate treatment is to stop the transfusion and to give a quick transfusion of compatible blood (Hesse, 1936). The renal symptoms should be treated by measures designed to render the blood alkaline and to ensure a good urinary output. Large amounts of alkalies (e.g., sodium citrate) and fluid should be given to this end, both orally and intravenously. For parenteral administration the *War Office Manual on Resuscitation* (1941) recommends "150 c.c. of 3 per

cent sodium citrate given intravenously by syringe, followed by 450 c.c. of 3 per cent citrate mixed with 2,400 c.c. 5 per cent glucose by intravenous drip during the following 24 hours. Subsequently the patient should receive, by intravenous drip, 660 c.c. 3 per cent sodium citrate mixed with 2,400 c.c. 5 per cent glucose every 24 hours until the urine is free of pigment." If necessary, large amounts of glucose solution should also be given by the rectum.

Failure to pass urine may in some cases be due not to suppression but to retention of urine, and in the latter event catheterization should be carried out twice a day.

Minor Reactions

Minor reactions have been attributed to a diversity of causes, including the use of dirty apparatus or old blood, or to the presence of minor incompatibilities which could have been eliminated by the application of cross-matching tests. The symptoms, e.g., fever, rigors, urticaria, hemoglobinuria, headache, malaise, may appear during or within a few hours of the transfusion and differ from the symptoms of hemolytic shock only in intensity. Treatment is as for hemolytic shock.

BLOOD DERIVATIVES

The scope of blood transfusion has been limited by three factors: the shortness of the time for which blood will keep in storage, the fact that in some pathological states blood must not be given, and the risk of accident due to mistakes in grouping. To overcome these drawbacks, workers have tried to find effective substitutes for whole blood.

Red Cells

Hedon in 1902 experimented with transfusion of red cells which had been washed and resuspended in saline solution. In 1929 Agote sent suspended red cells from Buenos Aires to Bordeaux. As red cells can be transfused without plasma, some authors then suggested that it would be better to give patients with chronic anemia a double amount of red cells in the given volume of fluid.

Various methods have been devised for preparing red blood corpuscles and concentrating them in a suspension. They may be suspended in saline solution at normal strength, slightly hypertonic saline 1.1 per cent, or Ringer's solution. In cases of red cell transfusion Mollison and Young (1940) report only 6.5 per cent of accidents from nonspecific protein shock.

Red blood corpuscles have been used in powder form, after being dried in the refrigerator and then resuspended in saline solution, glucose-serum or Ringer's solution (Naoji Kiguchi, reported by Grimberg, 1939). Kiguchi used dried blood 25 days old. By his method it is not necessary to group the bloods and, although accidents have occurred, none, he claims, have been serious.

Hemoglobin has also been used in Ringer's solution, but without great success.

Plasma and Serum

Experience in Great Britain seems to indicate that there is little to choose between these products. It should be recalled, however, that whereas serum has an average protein content of 7 per cent that of plasma is only 4 to 5 per cent owing to the addition of an anticoagulant solution. The protein content of reconstituted dried plasma and serum depends, of course, on the amount of fluid used. This, in the form of distilled water or normal saline, may be added in amounts sufficient to yield transfusion fluids of normal concentration or, if desired, of concentration up to four times the normal.

Indications for Plasma or Serum

These may be used in acute hemorrhage when blood is not available. Transfusion with plasma or serum is only a temporary measure, however; the patient needs hemoglobin to combat his anoxemia and for this purpose the presence of red blood corpuscles in the transfusion fluid is essential. If blood is available, but not in sufficient quantity, a transfusion of blood may be effectively supplemented by one of plasma or serum. A satisfactory proportion is two pints of plasma or serum to one pint of blood.

Both plasma and serum are now widely used in the treatment of shock, but here too the results are best when blood is used as well. If more than two pints of plasma or serum are injected they should be followed by at least a pint of blood. For further details see p. 138.

One of the chief uses of plasma or serum is in the treatment of burns. For the treatment of the primary shock the methods are those described in Chapter IX; but at a later stage the aim of treatment is to reduce the hemoconcentration which results from the loss of plasma, and either plasma or serum (without the addition of blood) should be given as long as this persists. From the time of injury the period may be up to 48 hours. Various formulas have been devised for calculating the amount of transfusion fluid required, and if reconstituted plasma or serum is used, it may be given at twice to four times the normal strength. An effective method is to begin transfusion when the hemoglobin reading is 10 per cent above the normal, giving 250 c.c. of plasma for each 10 per cent of rise. The first 500 c.c. should be given by a quick method, but drip transfusion (i.e., at the rate of 250 c.c. an hour) may be used for amounts over and above this. Concentrated plasma or serum may be given in proportionately smaller volume.

AN ARMY BLOOD TRANSFUSION SERVICE

The transport of adequate supplies of stored blood to the most advanced medical posts depends entirely on the general planning of the army medical services. Obviously, transfusion must be more successful if carried out in the battle area on newly wounded men than, after a variable time lag, in hospitals many miles back. The decision as to the type of organization, however, whether to have small medical units in the field or to concentrate the medical services in larger centers in the rear, rests with the higher command. Both types of organization were used during the Spanish War, the Republican Army Medical Corps preferring advanced posts, whereas Franco's armies, following the practice of the German Army Medical Corps, kept fully equipped medical centers in the rear. Thus, in the Republican army transfusion could be carried out in brigade posts, i.e., three steps farther forward than allowed for in the German system, as well as in every link of the organization back to the base hospitals (see Fig. 19).

Every classification post had a supply of stored blood; the medical officer prescribed transfusion but the operation itself was usually carried out by a senior orderly or nurse. In advanced No. 1 hospitals there was always kept a blood store big enough for fifteen transfusions; and here too the work was done by assistants under the orders of the chief of the surgical team. In No. 2 hospitals blood transfusion was in charge of a medical officer with three assistants; these hospitals kept enough blood for fifty transfusions. Every mobile unit had its transfusion staff working under the surgical team of the unit. The Barcelona Service had a special type of heavy lorries reserve depot, with enough blood for 100 transfusions, in charge of a medical officer with his assistants; every day it received fresh blood from the center, and cars supplied the advanced hospital and mobile units from it. If a unit needed blood urgently, an ambulance was sent to the nearest depot for supplies. Air transport is of course still more expeditious.

With this organization it was possible to deal with over a hundred transfusions a day, an average of ten for each surgical post. Moreover, the organization was economical in personnel, for the work could be carried out by trained though medically unqualified assistants (see p. 154). These took a course in the center and learned everything necessary about grouping, storing blood, the preparation of auto-injection containers, the keeping of records, and the first aid of post-transfusional accidents.

In advanced hospitals supplied with electricity the blood was stored in electric refrigerators; otherwise, the control center provided a paraffin refrigerator. The clearing station was provided with special heat-insulated boxes, some of wood and some of canvas, with a thick lining of cork and a chilled mixture of water and alcohol. In this type of box, blood from the Barcelona Service was transported for transfusion to Paris, Czechoslovakia and Switzerland.

The mobile units had electric refrigerators supplied from a dynamo worked from a car engine. The surgical trains also had electric refrigerators.

Records.—Transfusion data were recorded on special cards provided with every blood container, and at the base hospital the medical officer in charge had full clinical records of every transfusion. Patients could be traced to the different hospitals to which they had been evacuated. Every container could be traced from the blood bank, and records showed who transfused the blood, where and into which patient.

CHAPTER XII

ANESTHESIA IN WARTIME

The problems of anesthesia in wartime are here considered from the point of view of the surgeon at the side of the operating table rather than from that of the anesthetist at its head.

Under normal conditions the choice of the anesthetic appropriate to the individual case is safe in the anesthetist's hands, but in wartime the supply of good anesthetists is often inadequate, and the administration of the anesthetic may then fall to general practitioners or even to the nursing staff. In this event it is usually the surgeon who must decide not only whether the patient is fit for the operation, but also what form of anesthesia is most suitable, how long a period of anesthesia is needed, and the depth required at its various stages. The contribution made by the anesthetist is largely technical, and the whole question must be determined by the condition of the patient and by the requirements of the operation to be performed. I hope that the following suggestions, which are based on my own experience, may be of value to other surgeons who have to deal with war wounds.

Choice of Anesthetic

In modern warfare the need for an anesthetic may arise in the front line or in a raided city. Working conditions are very different in these two places, but in each the administration presents certain difficulties owing to three main common factors:

1. The large number of operations that may have to be performed simultaneously and the limited number of anesthetists and amount of apparatus available.
2. The diversity of the operations required and the varying condition of the patients.
3. The fatigue of the anesthetist after many hours of continuous work.

On the other hand, certain factors serve to differentiate the work of the anesthetist in the front line from that in the raided city, such as:

1. Apparatus must be easily transportable, owing to the mobility of modern armies.
2. Stocks may run out owing to the failure of supply services, and substitutes have to be used.

3. The anesthetic may have to be given by comparatively inexperienced doctors, owing to the heavy demand for anesthetists in the modern army.

From the individual point of view, the best anesthetic under peace or war conditions is, as Macintosh has pointed out (Macintosh and Pratt, 1939), that with which the anesthetist is most familiar. The skill of an anesthetist may be said to be in inverse proportion to the amount of anesthetic he employs to ensure operating conditions satisfactory to the surgeon. A really good anesthetist can use successfully a variety of techniques, but every anesthetist has a preference. When, however, operations have to be performed under war conditions, the best anesthetic is the one which is most easily administered and which ensures least harm if an overdose is given.

The anesthetic which fulfills these requirements most closely is ether. An excessive dose of chloroform may be extremely dangerous, owing to its effect on the cardiac musculature, and it should therefore never be used by the occasional anesthetist. Nitrous oxide, one of the best anesthetics, is unsuitable for general use in war conditions. The apparatus is complicated and an overdose is synonymous with anoxemia, a state particularly dangerous in shocked patients. Lennox and others (1935) have shown that, even in normal subjects, the central nervous system is easily damaged by an insufficient saturation of oxygen; and Quastel (1939) has laid stress on the irreparable lesions in this system produced by an anemia of only a few minutes' duration. In patients suffering from shock the effects of oxygen-lack are still more serious, not only on the central nervous system but also on the tone of the cardiac muscle, which largely depends on the degree of oxygenation in the coronary arteries. The administration of oxygen, in fact, forms the basis of any treatment of shock.

Nearly all the other general anesthetics, such as vinesthene, cyclopropane, avertin and most of the barbiturates, also require considerable experience in administration and are therefore not generally suitable in wartime. Evipan or pentothal, however, may be given in a single injection if the surgical operation can be completed in less than ten minutes.

Administration of Ether

In my own country ether was widely used in peacetime, and nurses were specially trained in its administration, with very satisfactory results. The apparatus most commonly employed was that devised by Professor Ombrédanne of Lyons, which is similar in principle and design to the familiar Clover's inhaler. It is efficient, simple and light, but has one disadvantage in that it is difficult to maintain a constant

concentration of ether. With some practice, however, an anesthetist is able, after the initial induction, to maintain a sufficient degree of unconsciousness and muscular relaxation by adjusting the control tap. In my hospital there was enough apparatus to provide anesthesia for all the regular operating tables. When the number of casualties was too great, ether was given by the open method.

Toward the end of his resuscitation treatment the patient should be given an injection of atropine to prevent undue secretion of mucus. Induction of anesthesia is started by placing the ether mask at a little distance from the face and gradually bringing it toward the nose and mouth. As soon as the depth of anesthesia justifies it, an airway is inserted or, in operations on the head and neck, an endotracheal tube is passed, preferably through the nose.

If the ether is given without undue hurry, the patient will take it easily and no other anesthetic will be needed. It is important to remember that in certain cases, e.g., patients suffering from shock, or from exhaustion after prolonged transportation, or under the influence of morphine, partial anesthesia is already present, and the amount of ether required may be less than half that needed for an operation of the same length in a patient not unduly depressed.

Professor Macintosh and his associates have recently devised an improved apparatus for the administration of ether. In this we have the best means at present known of controlling the amount of ether given to the patient; and indeed it is so dependable that by its means a specialist-anesthetist can supervise the anesthesia given by occasional anesthetists to as many as six or eight patients at a time. The Oxford vaporizer (Macintosh, Epstein, Mendelssohn, 1941) has the further advantage that it can, if necessary, be used to insufflate air or oxygen, a factor of considerable value if an overdose of anesthetic should be given, or if any other emergency should arise demanding artificial respiration.

Effect of Ether on Shocked Patients.—The administration of ether causes a slight rise in blood pressure, which is followed, after the termination of the anesthetic, by a sudden fall. Consequently, a relatively serious operation can be performed without any great risk from the anesthetic. But the subsequent fall of blood pressure when the anesthetic has passed off must not be forgotten, and resuscitation treatment must be continued after operation. If this is done, and if the patient has been treated by the biological technique and the affected limb has been immobilized in a plaster cast, the sense of relief, the lack of pain, and the absence of further disturbance of the wound will generally lead to a quick recovery from shock. The risks of the postanesthetic effect of ether must, however, be taken seriously into account, and the smallest possible dose should be administered. Fortunately the Ombrédanne apparatus or, better still, the Oxford vaporizer makes it possible to perform a relatively lengthy operation on a limb with a relatively small quantity of ether, and so to avoid the more serious complications of the postanesthetic period.

Cases in Which Ether Is Contraindicated.—There are two types of casualty for whom ether is contraindicated:

1. Those who need only a very short operation, e.g., a provisional incision of the wound, the reduction of a fracture, or the application of a plaster cast. In such cases ether is unsuitable, since the time required for induction is as long as that in which the whole operation can be performed; instead an intravenous injection of evipan should be given. A dose seldom exceeding 0.7 gram will enable a surgeon to finish all he needs to do, and the rapid detoxication permits prompt removal of the patient.

2. Wounded persons who urgently need an operation but who on account of severe shock are not fit for general anesthesia. In such cases local anesthesia should be used.

Local Anesthesia

Good local anesthesia may be obtained with a solution of 0.25-0.5 per cent procaine. If the operation is likely to take longer than an hour, and provided that the patient is not suffering from intense shock, it is advisable to add a small quantity of adrenaline (1 c.c. of 1 in 1,000 solution to every 100 c.c. procaine solution). If the wound is not very large and the amount of procaine solution administered does not exceed 150 c.c., it is preferable to use the 0.5 per cent solution, but where the amount needed is more than this (as, for instance, in cases of amputation of the thigh) the 0.25 per cent solution should be used. The infiltration should be made at some distance from the actual wound and contused tissues, and the operation should not be started until ten minutes later, in order that the full anesthetic effect may be obtained. The addition of a small amount of adrenaline to the procaine solution appreciably prolongs the period of insensitivity and diminishes the bleeding, with the result that the surgeon can work for a couple of hours without the sense of hurry which is so frequently present during long operations under inhalation anesthesia.

I have had considerable experience with local anesthesia for all types of surgery, and have employed it, in combination with infiltration of the splanchnic ganglia, in more than 700 abdominal operations, with uniformly good results (Trueta, 1935). Under war conditions the surgeon may find it difficult to spare the necessary time for a careful infiltration, but this difficulty can be overcome if he works at two operat-

ing tables and his assistants are trained in the technique, so that when he is nearing the end of his operation at the first table an assistant begins the infiltration at the second and no time is lost.

The value of local anesthesia in preventing shock is well known, but its beneficial effect on established shock has perhaps not received the attention it deserves. I had many cases in which even the most persistent resuscitation treatment failed to secure sufficient improvement in the patient's condition to allow the operation to be started. Shocked patients suffering from the effects of toxic absorption several hours after the production of the wound are often beyond the effective help of surgical operation without local anesthesia. In several such cases in my experience the local anesthetic produced a marked improvement in the patient's condition and made the operation possible. Meanwhile, resuscitation treatment was continued and the patient was then found to be receiving the full benefit of the plasma or blood transfusion. This improvement may be due to the action of procaine in suppressing the stimulation of sympathetic nerves in the region of the wound, the factor primarily responsible for the shock. In cases operated on under general anesthesia local infiltration with a weak solution of procaine-adrenaline helps to control bleeding. Such infiltration is particularly useful when the general anesthetic is gas and oxygen.

Regional Anesthesia

I fully agree with Atkins (1937) that regional anesthesia is not to be recommended for patients suffering from shock. An infiltration into important peripheral nerves, such as the brachial plexus (the Kulenkampf technique) or the sciatic nerve, is frequently followed by an immediate fall in blood pressure and other signs of shock. An infiltration of the peripheral nervous system appears to have a depressor effect on the nerve centers without suppressing the sympathetic stimulus.

Spinal Anesthesia

Even in patients not suffering from shock, spinal anesthesia has a depressor effect, and in shocked patients this technique is contraindicated. I have lost two patients on the operating table as a result of spinal anesthesia, and am convinced that the effect in man is exactly the reverse of that which Slome and O'Shaughnessy (1937) noted in cats. The object in giving any infiltrating anesthetic to shocked patients is to suppress sympathetic stimulation, but administering an anesthetic by the low spinal route does not achieve this effect, since anatomically the sympathetic trunks and ganglia are not contained within the dura.

ORGANIZATION OF THE ANESTHETIC SERVICE IN RAIDED CITIES

In view of the large number of anesthetics required and the ease with which the technique of administering ether anesthesia can be learned, special courses should be arranged for training additional personnel. General practitioners and experienced nurses provide the best anesthetists to work under specialist direction. When trained, they should be listed on the hospital's reserve staff in the same way as members of the resuscitation teams, whose work is also generally directed by a single specialist. A good supply of occasional anesthetists is thus readily available when required, particularly if, as with other services, they report for duty at every air raid. Senior surgeons should also train house surgeons and other assistants in the technique of local anesthesia.

One final and important point: supplies of ether and other inflammable anesthetics should be stored in small bomb-proof shelters.

PART II

ESSENTIALS OF WAR SURGERY

CHAPTER XIII

THE ESSENTIALS OF TREATMENT AND ORGANIZATION

The special features of modern warfare, and particularly the wide use of the aerial bomb, have introduced a great diversity into war wounds, and at the same time air attack on the civil population has necessitated new arrangements for the reception and treatment of casualties. The organization of the surgical services must be adapted to these varying requirements, but the actual treatment of any war wound, whatever the nature or scene of the battle in which it was received, should always be based on certain fundamental principles.

The biological treatment of wounds rests on the following five basic points or principles, each and every one of which must be applied to ensure the greatest possible success in the treatment of recently inflicted wounds.

1. Prompt surgical treatment.
2. Cleansing of the wound.
3. Excision of the wound.
4. Provision of drainage.
5. Immobilization in a plaster-of-Paris cast.

1. Prompt Surgical Treatment

The successful healing of a wound depends largely on the speed of treatment. The risk of serious post-traumatic infection is directly proportional to the interval between injury and operation. The work of the rescue parties, ambulance services, first-aid posts and resuscitation teams must all be organized in such a way as to facilitate surgical treatment with the minimum of delay. The shorter the period during which the casualty is left untended, and the shorter the time taken in transport to hospital, the earlier can resuscitation begin and the patient be ready for operation.

The value of such timely assistance has indeed been recognized since the earliest days of surgery; and it was no doubt this recognition which led to the organization of a rudimentary form of ambulance

service during the siege of Malaga by the troops of Ferdinand of Aragon in the 15th century, stimulated Larrey during the Napoleonic Wars to develop the ambulance on lines which were to form the basis of the modern system, and led Florence Nightingale to organize the first nursing units during the Crimean War.

During the early weeks of the War of 1914 to 1918, when the fighting was mobile, the lack of preparation in the arrangements for dealing with casualties in the Allied armies led to much disastrous delay in treatment, but with the development of trench warfare came improvements in the organization of casualty services. A continuous chain of receiving posts was organized, from the front line through the field ambulances and the casualty clearing stations, to the base hospitals in the rear. Unfortunately, it was never possible to provide any satisfactory organization for rescuing casualties who fell in "no man's land," and it was these which produced the highest mortality rate, owing to the delay before they received surgical assistance.

The experiences of the last war, and particularly Carrel's work, led to the common belief that eight hours represented the time limit within which wounds of the extremities must be treated to ensure recovery. This period may be considered as a reasonable average, but it by no means represents the safety limit in all cases. On the one hand, a patient who has received a bullet in the knee may still be in a good condition for radical operation, and even for primary suture of the synovial membrane, as long as 24 hours after injury. On the other hand, a patient who has been wounded in the thigh by an aerial bomb may be developing gas gangrene within four hours of his injury. (I have seen two such cases.) Thus, although the "eight-hour aseptic period" may be taken as a basis for planning the organization of the medical services in the front line, where conditions are difficult and the field of military operations is constantly changing, the army surgeon should always bear in mind the more urgent needs of those wounded by aerial bombs and high explosive shells, and remember that for them six hours represents the maximum time limit.

2. Cleansing the Wound

No antiseptic known is equal to soap and water for dealing with contamination in a wound. Even the best antiseptic is unable to remove "dirt," and the majority in fact fix the dirt in the tissues. Others increase the risk of infection by further destruction of the cells. Both liquor saponis olei cocois (B.P.C.) and sodium ricinoleate are more effective in getting rid of bacteria from wounds than are most of the noncaustic antiseptics. The staphylococcus is the only organism that has some resistance against these soaps. For the skin, iodine or a similar antiseptic should be used. At the end of the operation the wound

may be dusted with sulfanilamide. I never used sulfanilamide as a prophylactic in my country, where I treated over a thousand cases by closed plaster with almost uniformly good results, but there appears now to be sufficient evidence to justify its local prophylactic application.

3. Excision of the Wound

Excision of the wound is the keystone of the whole technique and the factor which permits the application of a closed plaster. WITHOUT PROPER EXCISION NO RECENT WOUND SHOULD BE ENCLOSED IN PLASTER EXCEPT FOR EVACUATION. This is a rule to which there can be no exception, and lack of appreciation of its vital importance is generally responsible for the failures which may occur with this technique as with all others.

To ensure proper excision, the wound must first be incised (the *débridement* of the French). In wounds caused by high explosives the extent of the damage in the deeper tissues, particularly the muscles, is often enormously greater than that in the skin and superficial layers, and consequently, unless the traumatic opening in the skin is considerably enlarged by incision, excision of the deeper tissues is very difficult and must generally be incomplete. After the initial incision of the skin and fascia and the excision of the dead portions of these tissues, the operation proceeds layer by layer into the deeper tissues, in successive stages of incision and excision, until the bottom of the wound is reached. The periosteum, however, must never be incised. Only a narrow strip of skin should be excised; excision of the fascia should be radical, and that of the muscles still more radical, but with the bone the surgeon must be as conservative as possible and should limit resection to fragments which have lost their periosteal connections or their muscular attachments.

4. Provision of Drainage

Dry gauze of a very fine mesh (similar to that of good quality bandages) should be used to provide drainage for a recent wound. The gauze is inserted without pressure into the intermuscular spaces, and a flat layer is laid over the surface. Where a deep and narrow cavity remains at the bottom of the wound, counterdrainage must be provided by the insertion of a piece of rubber tubing through an opening into the most dependent part of the cavity.

The next and final stage of the technique, the immobilization in plaster, is also designed to provide drainage. Good plaster of Paris is highly absorbent, and the direct contact between the dry gauze and the plaster covering the wound facilitates rapid absorption of the relatively small amount of discharge (mainly lymph and blood) which comes from a clean wound.

5. Immobilization in a Plaster-of-Paris Cast

With the provision of drainage the last stage in the surgical procedure is accomplished and the wound is now ready for protection. The only single expedient which will prevent initial absorption of toxic products from the wound, protect the granulation tissue, and newly formed epithelium from damage, and provide an effective barrier to secondary infection, is the plaster-of-Paris cast. This should be applied in direct contact with the skin, except at a few points over bony prominences. The plaster should be well moulded to the limb, particularly over the wound, in order to establish good contact with the drainage gauze and to maintain a gentle pressure on the surface of the wound, a factor which assists the progress of epithelization.

Summary of Technique

Here is a "five-point technique." All points are vital, but their successful application turns on Point 3: excision. Without proper excision, however faithfully the other points are fulfilled, the technique is worthless and may even be dangerous. Since excision is closely linked to and largely dependent on Point 1, early surgical treatment, this is also extremely important. If the operation is not carried out until six or eight hours after the time of the injury, the contaminated area may have become so extensive as to make excision a correspondingly serious operation. Point 5, immobilization in plaster, in its turn depends on Point 3, for unless excision is complete the treatment of a recent wound in a closed plaster, far from being beneficial, is fraught with serious danger.

Alternative methods for Points 2, 4 and 5—cleaning, drainage and plaster—might be substituted in certain injuries which are more frequent in peace than in war. In peacetime injuries drainage is not always necessary and the wound can often be closed by primary suture, whereas in war wounds primary suture is only exceptionally permissible. Relatively good immobilization can be obtained by many methods, e.g., continuous traction or the Thomas or Braun splint. Nevertheless, closed plaster, inasmuch as it provides many other benefits peculiar to itself, is in my opinion superior to all others for the treatment of recent wounds, always provided that excision has been properly carried out.

TYPES OF AIR RAID INJURY

The special features of modern war have enormously enlarged the field of possible casualties by bringing the civil population within the range of the enemy's attacks. It is particularly important that the

relative urgency of the main types of injury produced in air attack should be understood, always bearing in mind that *the condition of the wounded patient is more important than the wound.*

1. Wounds Caused by Heavy H. E. Bombs

These bombs are dropped with the idea of destroying massive buildings. They produce very severe wounds which if in the head, chest or abdomen are usually fatal, but if in the limbs may respond to immediate treatment. Proper treatment—namely, resuscitation and a major operation—can be carried out only in a hospital, and consequently the only possibility of saving casualties of this type is to get them to a hospital without delay. Transportation is in itself a problem, for shock increases with movement, and the patients must therefore be taken with great care and by the quickest possible route.

2. Wounds Caused by Light H.E. Bombs

These bombs are used with the specific object of producing casualties, and for this reason we in Barcelona (where they were used in Europe for the first time) called them "anti-personnel" bombs. They are used in attacks on aerodromes, on marching troops, and especially on the civil population in an attempt to inspire terror and demoralization in the face of an advancing army. Covered with a thin layer of light material, they make only shallow craters in the ground, but throw out thousands of small splinters, many no larger than a fingernail. Dispersion of these splinters is horizontal, and consequently the majority of the wounds occur in the leg, thigh or lower abdomen.

Patients so injured can generally be moved safely to more distant hospitals than patients in the first group, but the damage to the deeper tissues is nearly always far more extensive than the small wound in the skin would suggest. Many patients suffer from shock and severe hemorrhage. First aid outside the hospital is useless, for these victims must be treated by resuscitation as soon as conditions permit; and the efficacy of resuscitation mainly depends on the rapidity with which it is initiated. The best results are obtained when it is possible to operate within two hours. The fact that persons injured by this type of bomb are in the open should make it easier for them to be taken to a hospital within this time.

3. Injuries Caused by Incendiary Bombs

Many casualties are caused by the conflagration of buildings, particularly where these are largely built of timber. This was clearly seen in Spain, Poland, and Finland, as well as in Great Britain. Patients should be taken to a hospital immediately; but however good the organization of transport, there is often some inevitable delay while victims are extricated from fallen debris. When the hospital is less than one hour distant from the "incident" treatment in a first-aid post is useless; on the contrary, until the patient can receive proper treatment in a hospital it is better to leave his injuries untouched. The best dressing for the moment is his own burnt clothing, for any attempt to clean the burn and cover it with sterilized gauze in the first-aid post adds not only to the delay in providing proper treatment but also to the danger of further infection. Resuscitation is often needed, and cannot readily be provided at a first-aid post. If the nearest hospital is more than one hour distant, the burned area should be protected with sterilized plain gauze.

4. Crush Injuries Caused by the Collapse of Buildings

As a rule these injuries provide a surgical problem only when the buildings are small and constructed of light material. I do not know the exact numbers of people killed by falling masonry in Barcelona, but I believe that more than half our fatal casualties were due to this cause. The buildings of this city are so large (generally six floors high) and constructed of such heavy materials that very few who were crushed beneath them survived, the severity of their injuries, if the victims were not killed outright, precluding the possibility of surgical aid. In other towns, however, where the buildings were only two floors high and constructed of less heavy materials, many of the patients survived. All of them suffered severely from shock and were inevitably the last to be rescued, with the result that by the time they were extricated, they needed, so grave was their condition, intensive treatment such as could be provided only in a hospital.

5. Injuries Caused by Blast

Compared with other types of injury, these are not only fewer but also less serious. From the surgeon's point of view they present no problem, for the patients, unless also wounded, need no assistance beyond rest and some measure of resuscitation, and consequently need not be taken to a hospital until all the more seriously injured have been dealt with. They may have a certain amount of preliminary treatment, and above all shelter, at the first-aid post, while waiting for the ambulances to take them to a hospital for special treatment, if any. Many of these patients suffer from bronchial spasm, a kind of acute and transitory asthma, and perhaps also from arterial spasm; in addition they have microscopical alveolar and pleural hemorrhage. Zuckerman (1940), Falla (1940), and Hadfield and Christie (1941) have contributed to our knowledge of the effects of blast.

6. Minor Injuries

These include cuts by flying glass (when there is no serious hemorrhage) and also concussion and nervous excitement. It is with this type of casualty that the first-aid post should deal. Most of the patients are fit to go home after treatment and only a few need to be sent to a hospital.

PROBLEMS OF ORGANIZATION

It will be clear that all stretcher cases should be taken directly to the hospital and not to the first-aid post. Ideally, the first-aid post should be situated in the hospital itself, since more than 30 per cent of all casualties require operation. Any measure which tends to accelerate the admission of air raid casualties to the hospital contributes to the success of treatment, and all delaying factors should accordingly be eliminated as far as possible. Patients received in the hospital soon after injury are generally suffering from primary shock (that is to say, from the initial effect of nervous disturbance) or from a combination of primary shock and hemorrhage, conditions in which resuscitation treatment often quickly produces sufficient improvement to permit operation. When, however, patients do not reach the hospital for more than an hour after injury, they may be suffering from secondary shock, due either to persistent ischemia of the nervous centers or to absorption of the toxic products of tissue disintegration in the wound. Patients already suffering from loss of fluids in the injured limb are in a still worse plight and do not respond well to any form of resuscitation.

Successful hospital treatment therefore depends in no small measure on the speed with which casualties are admitted to the hospital, and this in its turn depends on the efficiency of the passive defense services in the bombed area. Individually, the surgeon is not responsible for failures due to bad organization of these services, for he cannot hope to give proper treatment to patients who reach the hospital either beyond help or at the best fit for operation only after many hours spent in combating shock, by which time serious infective complications will probably have set in. My observations on this matter are those of a surgeon who has suffered from the mistakes made in the original planning of a passive defense organization, and has seen the striking improvements which followed when these mistakes were rectified. The following scheme is based on the principle that speed is essential for success.

The Organization of Medical Services in a Raided City

The technical problems connected with the organization of rescue parties and of fire-fighting and ambulance services do not fall within my sphere, but the prompt conveyance of air raid casualties to a hospital largely depends on the efficiency of these services and on their collaboration with the hospital and other medical services. One illustration will serve to show the vital need for a unified control of these various organizations.

> A town is raided and a large number of casualties occur in a relatively small area. There are three hospitals in the district: hospital A is situated half a mile from the scene of the raid, hospital B one mile away, and hospital C two miles away. If there is no central control of the organization for transport of the casualties, the chances are that practically all the ambulances will take their patients to hospital A, since this is the nearest, and will continue to do so until the driver is told that this hospital is full. He will then proceed to hospital B, and only then will the surgeons at this hospital receive any patients; while in hospital C, the most distant, the surgeons will still be waiting. Meanwhile, at hospital A many casualties have to wait for hours before a surgeon is free to deal with them, although at a distance of only 15 minutes or so (distance should be reckoned in time rather than mileage) surgeons are standing idle.

I have on several occasions witnessed this pitiful state of affairs where there was no authorized person at the scene of the raid who knew the capacity of each hospital at any given moment and was able to direct transport accordingly. The organization of first-aid parties under an experienced surgeon, who is also in control of the ambulances at the scene of the raid, helps not only to provide some casualties with their most urgent needs, e.g., the application of a tourniquet or the immobilization of a limb, but also to ensure their appropriate distribution. This surgeon must, however, know at any given moment the available resources of beds and surgeons at the different hospitals, and this information can be satisfactorily supplied to him only through the central control office.

Organization in the Hospital.—To ensure smooth running of the work inside the hospital, the organization for dealing with casualties must be thoroughly efficient both in the grounds, for the control of ambulance traffic, and inside the actual building. Arrangements must be made for one-way direction of ambulances so that they may be unloaded without loss of time. Obviously, adequate numbers of stretchers, and especially of trolleys, are essential, but the secret of efficiency lies in perfect cooperation between all departments, and particularly between the staff responsible for the reception and sorting of casualties, those responsible for the resuscitation room, operating rooms and wards, and those responsible for discharge.

Classification of Casualties.—In the sorting room casualties should be divided into five main groups:

1. *Those Who Need Operation as Soon as Possible, Whether Resuscitation Is Necessary First or Not.*—The group includes patients with severe hemorrhage, open chest wounds, extensive bruised destruction, avulsion of limbs, and small penetrating abdominal wounds.

2. *Those Who Need Immediate Treatment But May Wait Until the First Group Has Been Dealt With.*—The group includes patients with compound fractures caused by small splinters, penetrating wounds of the joints, and wounds of the face.

3. *Those Who Need Immediate Resuscitation and Rest But No Operation, at Any Rate During the First Few Hours.*—The group includes patients with severe shock, small penetrating wounds in the chest, and crush injuries. These patients should be sent to the wards and resuscitation carried out there.

4. *Those Who, After Receiving First Aid, Can Be Transferred to a More Distant Hospital for Further Treatment.*—The group includes patients with penetrating wounds in the skull caused by small splinters, peripheral nerve injuries, and eye lesions.

5. *Those Who May Be Sent Home After Some Form of Minor Treatment.*—The group includes patients with minor injuries and simple fractures.

Sorting Room and Operating Room.—In the sorting room each patient should be provided with a record card or label of one of five different colors, according to the nature of his injuries and the treatment required. Efficient work in the sorting room will greatly increase the efficiency of the other departments; for without it patients who are unfit for operation will probably be taken to the operating room and those who need immediate operation to the wards. An experienced surgeon should be in charge in the sorting room, and it is a good plan for the senior surgeons of the hospital to take periods of duty there in turn, as a relief from the strain of continuous operating.

Resuscitation teams should start work on those patients who need immediate treatment: in the resuscitation room, in the wards, or in the operating room, according to the patient's condition and the urgency of his operation.

Each surgeon should work at two operating tables so as to avoid delay. While the patient on the first table is being operated on, the patient on the second table should be prepared and, at the appropriate moment, anesthetized, so as to be ready for the surgeon as soon as the first operation has been completed. Two surgeons working in this way can do as much as three working at single tables. Every hospital in a dangerous area should have at least one operating room underground

and protected against a direct hit. The degree of efficiency bears a direct relation to the sense of safety felt by the surgeon and his assistants, who must remain at the operating table in all circumstances.

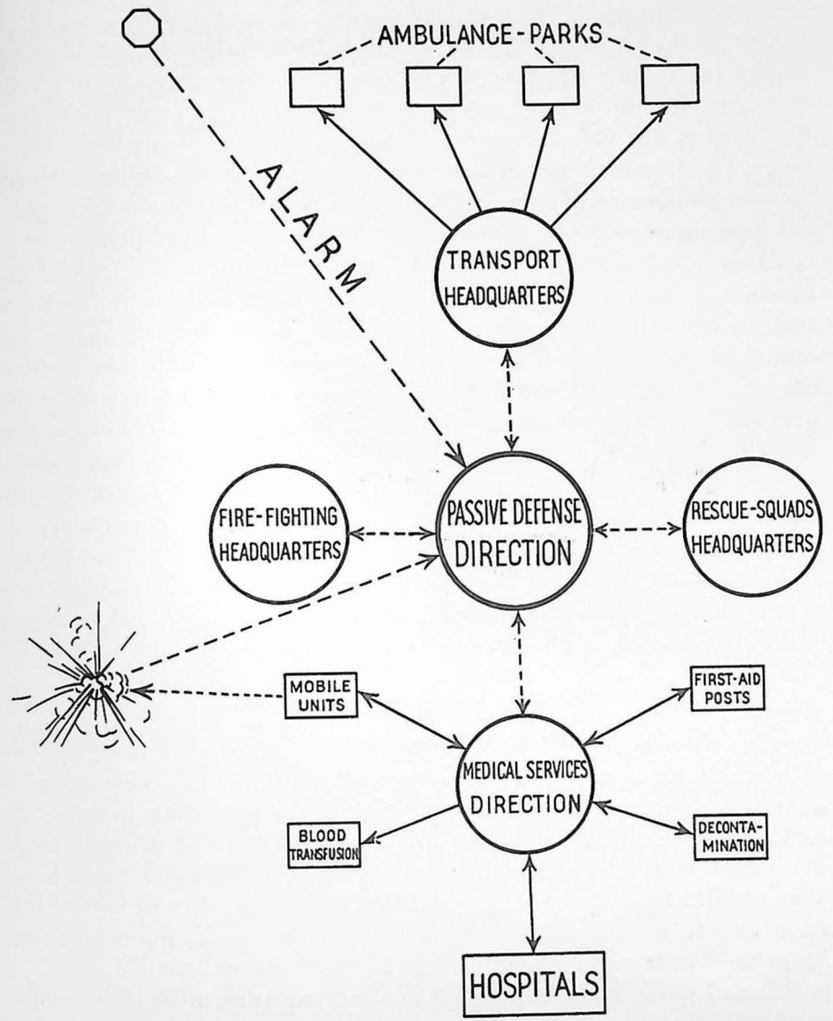


Fig. 18.—Organization of passive defense in a bombarded town, following the experience of Barcelona.

The Ambulance Service.—The ambulance depots must be connected with the central control office, and when casualties have to be conveyed to a hospital the ambulances which are sent to the scene of the raid should be under the direction of the surgeon who takes charge of the distribution of casualties. It is a great advantage to have a standard

type of stretcher throughout the organization, so that when the patient is unloaded he can be carried into the hospital without change of stretcher, a replacement stretcher being supplied to the ambulance at the hospital.

Fig. 18 shows the main structure of a passive defense organization. At the central control office is a representative of each of the five main services—demolition and rescue squads, transport, medical services, fire service, and statistics—each of which again has its own headquarters. The transport headquarters is in direct communication with the various ambulance depots, and is kept informed of the available number and movements of ambulances. The medical headquarters is in constant touch with the hospitals, having full information about the number of beds and surgeons available in each, and about the blood transfusion and other medical services. It is also responsible for the organization of first-aid parties. In each bombed district the medical officer in charge of these parties should not only have full authority over his own team but should also act as the representative of the central office, directing the distribution of casualties to the various medical centers on the information supplied to him through the central control office. The statistical headquarters, with its subsidiary departments of records, research and information, provides the means for developing and improving the whole organization in the light of experience, for it is here that the speed and efficiency of the various services are estimated and data collected on all aspects of the city's passive defense service.

The Time Factor in the Frontline

Surgical aid to casualties in the frontline is impeded by many factors and has to be adapted to varying conditions, but the main basis of success is to have the wounded patient on the operating table at the earliest possible moment. This is the only factor that counts, and is the objective at which the whole organization should aim. During the War of 1914 to 1918 the static condition of the majority of battlefields gave rise to a static system of assistance with a distant emergency hospital—the casualty clearing station. With the constantly changing position of modern armies, the surgical organization must be as mobile as the fighting forces and must follow them in advance and retreat.

In this connection, as in many others, the War in Spain provided much valuable experience. It was found that the casualties who most urgently needed surgical assistance had to be treated within a maximum of 5 hours—a requirement which resulted in the development of the "Three-Point Forward System" outlined in the following section.*

*For details of this organization the reader is referred to Major Douglas W. Jolly's *Field Surgery in Total War*, Paul B. Hoeber, Inc., 1940.

The Three-Point Forward System (see Fig. 19) was based on the distribution of assistance in three successive stations. The first was the casualty classification post, a center for collecting casualties, on which depended the smooth running of the whole organization. It was situated close to the front, on an average less than an hour from the fighting line. So great was the importance attached to the time factor in treatment that distance was measured by minutes and not miles.

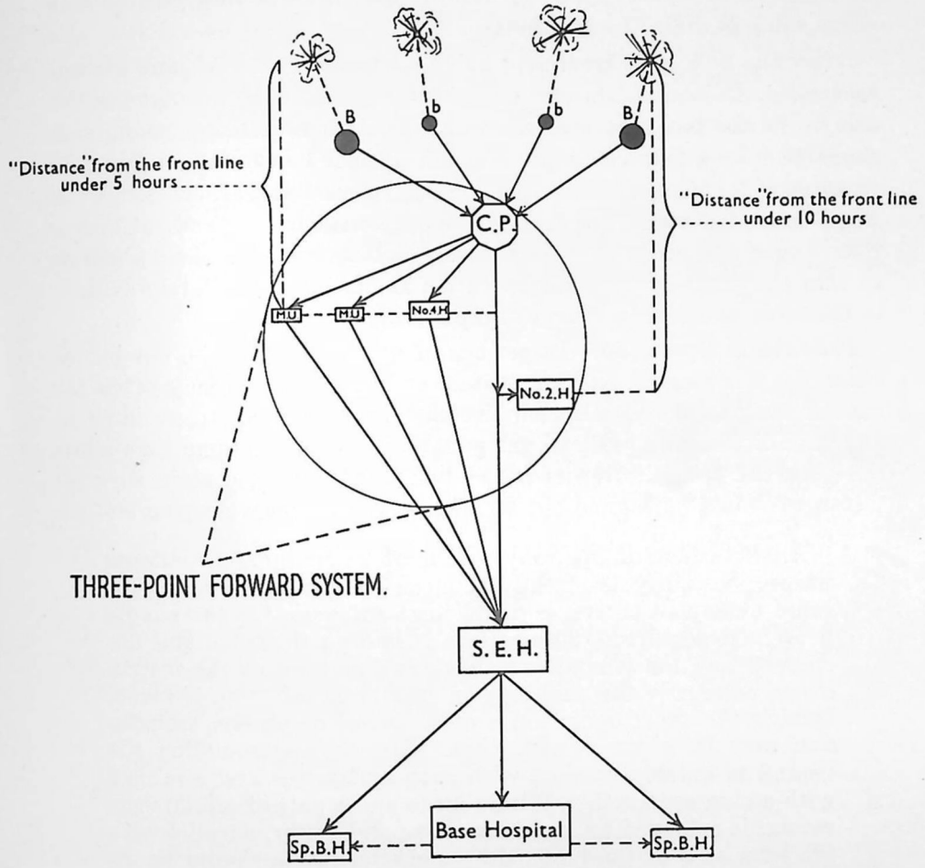


Fig. 19.—Organization of field medical services in a modern military medical corps, following the experience of the Spanish Republican Army.

The second step of the system was the No. 1 hospital, placed at a maximum of five hours from the front line. This was the center of treatment for the most urgent cases—hemorrhages (particularly cases in which a tourniquet had been applied), abdominal wounds, open chest wounds and serious bruised wounds in the extremities.

The last step of the system was the No. 2 hospital, at an average of ten hours from the frontline. Here the less urgent cases were dealt with.

During active military operations these surgical centers were assisted by self-contained mobile surgical units provided with everything necessary for dealing with the same type of urgent casualty as the No. 1 hospital. They had surgical lorries with operating rooms and sterilization apparatus, and so were in effect small mobile hospitals of great value in difficult conditions.

After the biological treatment had been tested at Teruel, and proved successful, Colonel d'Harcourt decided to extend it throughout the army. In the late stages of the war, by which time many young surgeons had been trained in the method, all No. 1 hospitals and mobile units used it; plaster casts were also often used for evacuation, even when wounded men were sent to the rear without any radical operation. Such casualties showed a distinguishing mark on their plasters, so that the pressing need for operation should be immediately evident to the medical officer in charge of the sorting room.

Provisional Operation.—In periods of great pressure, the number of casualties arriving at No. 1 hospitals and mobile units may often far exceed their capacity. In such circumstances, in order to avoid or at any rate diminish the risk of gas gangrene and at the same time allow time for the resuscitation required before operation, certain surgical measures should be carried out at the advance casualty clearing station.

> An injection of $\frac{1}{12}$ to $\frac{1}{6}$ grain of morphine for patients whose sensibility is already reduced by shock, or 0.5 to 0.7 gram evipan in others, is a sufficient analgesic for the simple procedure required. The patient is laid on the table and undressed and the wound examined, and as soon as the instruments are ready the analgesic or anesthetic injection is given. During the short operation a quick blood or plasma transfusion may be given (see p. 158). The skin surrounding the wound is quickly washed with soap and water and swabbed with a skin antiseptic. With a knife and a pair of scissors the wound is enlarged by incisions above and below, parallel with the long axis of the limb; the superficial fascia should be divided without hesitation. The wound is then dusted with sulfanilamide, a piece of dry gauze is inserted to keep it open, and the limb is immobilized by a Thomas splint or, better, a plaster cast. If the latter is used, a note should be made on the surface that excision has not yet been performed. The whole procedure will take a skilled surgeon less than ten minutes, and can be completed while the first resuscitation treatment is carried out. The patient is then ready for definitive treatment at a hospital some ten or twelve hours from the line.

When working under great pressure it is convenient to have at hand a number of muslin patterns (see Chapter XX) so that limbs requiring immobilization may be encased in plaster without delay.

Evacuation of patients with large wounds and fractures under plaster casts is very comfortable. In Spain the insistent demand of soldiers for such treatment was noteworthy. They knew that casualties evacuated in plaster suffered no pain, in contrast with those treated by any other method of immobilization. Local application of sulfanilamide powder definitely helps in these cases. In Great Britain this treatment was first tested during the evacuation from Dunkirk, with very satisfactory results.

The success of this technique depends only in part on the ability of the individual surgeon; its chief determinant is the efficiency of the military organization. The results are never satisfactory if different techniques are used by the various surgeons in charge of the treatment at each stage of the three-point forward system; or if these stages are not so disposed as to keep the time-lag within the prescribed limits.

CHAPTER XIV

ANTISEPTICS

Cleansing of the Wound

No advance in surgery has had such a profound influence as the institution of the antiseptic technique by Joseph Lister; indeed it is no exaggeration to say that the history of surgery can be divided into two eras, the pre- and the post-Listerian. The essence of Lister's greatness lies in the fact that he provided a solution to a problem which was as old as surgery itself but which even the most enlightened workers of the past had been unable to solve. Throughout history there had always been some surgeons who had realized that cleanliness, not only of the wound but also of the surgeon's hands and of the instruments he used, was essential for success. For over two thousand years, however, the truth of this observation, which today seems hardly worth mentioning, was recognized by very few. Hippocrates recommended boiled water and the cleanliness of the surgeon's hands and nails, and in doing so was laying the foundation stone of the aseptic technique as we know it today. One or two of the surgeons who immediately preceded Lister set the stage for his great discovery by refuting the old ideas of "poisons" in wounds and the "miasma" of the air.

It can hardly be claimed that the use of wine by Avicenna, of turpentine by Paré, or of acetic argile by the German surgeon Burrow in 1847 (see Volkmann, 1881), constituted antiseptic techniques, although all these substances have some antibacterial properties. The first genuine precursor of Lister was the Hungarian Ignaz P. Semmelweis (1818-1865), who published his first paper on antiseptics in 1848. Oliver Wendell Holmes (1809-1894) had come to conclusions similar to those of Semmelweis in 1843, and like him met with strong opposition from his colleagues.

Phenol.—It was to this sceptical world of medicine that Lister introduced the antiseptic technique as an essential element of surgery, and by his undaunted perseverance eventually succeeded in convincing his colleagues that this technique was the surgical weapon which they had been awaiting since time immemorial. Having heard of Pasteur's work on fermentation and heat sterilization, Lister tried to secure a similar sterilization by certain chemical substances. After trying zinc chlorides and the sulfites, he turned by a fortunate chance to carbolic acid, a substance which had been used for the sterilization of sewage.

In 1865 he used carbolic acid for the first time when operating on a patient in Glasgow, and in 1867 he published the results of two years' work in nine articles, one of which, now famous, was entitled "On the Antiseptic Principle in the Practice of Surgery." Like all innovations in science, these papers received much adverse criticism, a fact which is in striking contrast to the exaggerated use made of antiseptics in more recent times. Thomas Huxley was indeed right in saying, "It is a customary fate of new truths to begin as heresies and to end as superstitions."

It is unfortunate that Lister has been so widely misrepresented. In his outlook he was a true follower of Hippocrates, and his writings are full of ideas to which the great Greek physician would certainly have subscribed. For example, at the International Medical Congress held in London in 1881, he said, "I believe I happened to be the first to demonstrate that the tissues of a healthy living body have a power of counteracting the energies of bacteria in their vicinity and preventing their development." The attitude of the majority of his medical contemporaries, however, was still Galenist—that is to say, sceptical of the healing power of Nature—and in consequence, when after many years they were finally convinced of the efficacy of antiseptics, they took to using them simply as a new kind of "miraculous substance." Lister himself condemned this attitude when he declared (1881) that his object in establishing the antiseptic technique had been to help the body in its fight against bacterial aggression and not to substitute healing by artificial means for the healing power of Nature. How far from this criterion is the practice of many surgeons of our own day!

The goal toward which Lister was aiming was reached a few years later, when von Bergmann in 1886 introduced steam for the sterilization of instruments and developed the technique known today as asepsis, which in other words may be called "antisepsis outside the tissues of the body." The principles of aseptic surgery were quickly and universally accepted, and prevailed until the War of 1914 to 1918, when, after some months of new experiences, surgeons came to realize that war injuries could not be treated on the same lines as surgical wounds and, in an attempt to prevent the frequent infective complications, again took up antiseptics. Unfortunately the practice was carried too far, and distressing results followed the excessive use of phenol and strong cresol pastes.

Hypochlorite.—The studies of Alexis Carrel at this stage were therefore particularly opportune, and the adoption of sodium hypochlorite, which he recommended as the best antiseptic, led to an immediate improvement in results. The hypochlorite solution which Dakin prepared, though a comparatively active antiseptic, was relatively harmless to

the tissue cells, and it was to this factor that the better results were attributed. Today we are in a position to realize that its beneficial effect is largely due to other causes. In the first place the Carrel-Dakin technique, when used as recommended in continuous irrigation, causes very little interference with the wound (an important factor to which I believe the success of the much-discussed Bunyan bag is also largely due). Secondly, the hypochlorite solution has a valuable proteolytic capacity, which cleanses the wound and so makes bacterial reproduction in the dead tissues difficult.

After the war the use of antiseptics in treating wounds steadily decreased, and the majority of surgeons returned to the antiseptic-aseptic technique, applying antiseptics on one occasion—namely, during the operation—and closing the wound by primary suture where possible. When infection had already begun the Carrel-Dakin technique was still widely used.

Initial Antibacterial Treatment

Today one fact stands out clearly: all accident wounds need initial antibacterial treatment: that is to say, they must be protected from bacterial contamination or, where this is not possible, from bacterial colonization. Good antiseptics have a high potency against bacteria either on inorganic substances or on the skin, a tissue which has a great natural resistance to all external actions. In the interior of a wound, however, their effectiveness is very limited, for several reasons. First, the organic fluids, blood and lymph, alter the nature of most antiseptics and greatly reduce their bactericidal capacity. Secondly, the character of many wounds, and particularly their irregularity, makes it impossible for the antiseptic to be evenly distributed throughout every corner. Thirdly, antiseptics have a very poor selective capacity, discriminating little between different types of living cells; and consequently not only the bacteria but also the tissues suffer from their chemical action. Finally, antiseptics have little power of penetrating the tissues, and so cannot destroy bacteria where the natural defenses most need assistance inside the tissues. Even those antiseptics which have the greatest power of penetration, e.g., the aniline type, do not penetrate into the tissues to a depth greater than 2 to 3 mm.

Requirements of an Antiseptic

To be effective an antiseptic must fulfill certain conditions which depend not only on its own properties but also on the way in which it is used:

1. It should be applied before infection has begun, or, in other words, before bacteria have penetrated the tissues. In war wounds, and particularly in those caused by aerial bombs, four hours is the limit of time during which an antiseptic can be effectively applied.

2. It should be well distributed throughout the wound, penetrating every corner and pocket which may be contaminated. Enlargement of the wound and excision help to make this distribution possible.

3. It should not be toxic either to the tissue cells or to the body fluids.

4. It should be active against the majority of bacteria which contaminate wounds and should act in a single application.

5. It should be capable of resisting the inactivating effects of the body fluids.

The ideal antiseptic which fulfills all these conditions has not yet been discovered, as is clearly indicated by the constant succession of new antiseptics which in turn make their appearance on the market, only to disappear after a short period of trial. Nevertheless, it would be unjust to say that antisepsis has made no progress since the days of Lister's carbolic and Koch's mercury derivatives. The deep concern of surgeons in recent years over the action of antiseptics on the living cells of the tissues is proof of a definite advance. But the statement of Fleming in 1928 still stands: that the best antiseptics are the natural defenses of the body.

Action of Antiseptics on Living Tissues

Specialization in the different branches of medicine has brought many advantages, but has also had certain unfortunate consequences. One of the most regrettable of these has been the divergent approaches of the surgeon and the bacteriologist to the problem of infection. Happily, the wide gulf that existed in recent years is today becoming rapidly narrower as a result of mutual cooperation and understanding. The absence of early collaboration is clearly indicated by the methods of study of the action of antiseptics. To determine the action of an antiseptic the bacteriologist tests its antibacterial capacity *in vitro,* by observing its powers of sterilizing cultures and of preventing bacterial reproduction. To discover its toxic potency, intravenous, intraperitoneal or subcutaneous injections are made in experimental animals, particularly mice and rats, while recently the brains of rabbits and cats have also been widely used in the study of local toxic effects. Tissue cultures have provided bacteriologists with a better means of testing the effect on living cells, for by this method it is possible to observe the action of an antiseptic on the fibroblasts and leucocytes.

While all these laboratory tests are undoubtedly of great value, it must be remembered that when the tested antiseptic is applied to the living body its activity may be influenced by certain unknown factors, which do not depend only on the impeding action of the tissue

fluids. If it had been left to laboratory experiment alone to determine the properties of antiseptics and to recommend their use, Lister would never have effected the revolution in surgery which he achieved by his introduction of carbolic acid, a substance which we now know to be toxic to the tissues; nor would Morison have obtained his successful results with bismuth iodoform paraffin paste, for Garrod (1940) has shown that iodoform, the antiseptic basis of this paste, has no antibacterial capacity and is unable to impede bacterial reproduction even on its own surface. Fleming (1919) showed that wounds treated with bismuth iodoform paraffin paste contain more bacteria than other wounds.

There appear to be good grounds for suspecting that certain chemical substances stimulate the activity of the tissue cells and so may exert a favorable influence both on the granulation process and on the contraction of a wound, as Carrel (1921) found with turpentine. But undoubtedly the factor of greatest importance lies in the care exercised by the surgeon in his use of the antiseptic, and particularly in his avoidance of interference with the natural mechanism of healing.

Action of Antiseptics in Common Use

Many antiseptics that were commonly employed some years ago, e.g., the heavy metals, such as the mercury derivatives introduced by Koch, copper, silver, and zinc, have now fallen into complete disuse. The mercury derivatives, at one time widely used, have the great disadvantage that they coagulate the proteins, and are always completely ineffective in solutions sufficiently dilute to avoid this difficulty. Alcohols are not recommended for similar reasons. The halogens, such as chlorine, iodine, and iodoform, are in fairly common use, and iodine is undoubtedly one of the best antiseptics for the skin. The chlorines, like eusol and Dakin's solution, which are still employed in certain cases, are not strong enough to be effective in a single application and consequently involve repeated interference with the natural healing process. The Bunyan technique of the periodic bath avoids much handling of the wound, but precludes immobilization and its beneficial effects, which we now know to be essential for perfect healing. The oxidizing antiseptics are not very effective against bacteria, because the oxygen which they generate combines with organic substances, for which it has a greater affinity than for bacteria. For a long time it was commonly supposed that oxidizing antiseptics, and even oxygen itself, had a specific action against anaerobic infections, but they are now known to be ineffective against gas gangrene, and only the oxygen in the blood prevents anaerobic reproduction in the wounds.

Coal-Tar Derivatives do not coagulate the proteins, are nonirritant, and have a fairly quick bactericidal action. They have the disadvantage, however, that their potency is reduced by contact with the organic fluids, and thus they have only a short period of effective action.

Acridine Dyes.—Many of these anilines are on the market, the most widely used being acriflavine, euflavine, proflavine and rivanol. On the whole they are good antiseptics and in high concentrations are capable of quick action; when applied over a long period of time a more dilute form can be used. Garrod (1940) affirms that a concentration as low as 0.0001 per cent can still sterilize when allowed to operate for some time. Neither serum nor blood produces any marked change in their antibacterial properties, and it has been claimed that leucocytes stained with these acridine dyes have been seen to retain their amoeboid movements. These antiseptics are not, however, capable of effective action in a single application. Probably the most effective is proflavine sulfate in a concentration of 0.1 per cent in isotonic saline solution buffered to pH 6.2 (Russell and Falconer, 1940); while the most recent development of the acridine series is the 2.7 diaminoacridine hydrochloride, which appears to be the least toxic of all (Russell and Falconer, *loc cit.*: Manifold, 1940). The acridine antiseptics are effective against the hemolytic streptococcus but not against *Staph. aureus* or *Ps. pyocyanea.*

Antiseptics and Infected Wounds

The changes which bacteria undergo on contact with an active antiseptic depend on the properties of the antiseptic and its concentration. They are of three kinds; the bacteria may be destroyed, paralyzed, or deprived of their reproductive capacity. When an antiseptic is applied before the bacteria have penetrated into the tissues, the degree of contact established between the two opposing elements is merely a matter of technique, and any of the three effects can be produced. When, however, the antiseptic is applied to a wound in which bacteria are already colonizing, its contact, and therefore its action, are confined to those bacteria which are germinating on the surface of the wound and those which are extruded from the inner tissues with the discharge; consequently the effectiveness of the antiseptic is limited. Moreover, when infection is already established, those bacteria which survive the action of the antiseptic and retain their reproductive capacity give birth to a progeny which has a higher power of resistance, and which in its turn produces a still more resistant generation, with the result that in a comparatively short time the antiseptic entirely loses its effect, the bacteria having acquired a specific resistance to it.

These various factors, and above all, the constant interference with the body's own healing activities which repeated application of antiseptics necessarily involves, serve to explain the persistent failure of the antiseptic technique in dealing with infected wounds or in trying

to protect a wound from secondary infection. Clearly we should abandon antiseptics as a method of treatment for wounds in which infection has already been established, and rely on the biological action of the body's defenses, put in full activity by the surgeon's intervention. Fleming (1940) sums up the whole matter in two significant questions:

> 1. *Is it justifiable for the surgical pessimist who distrusts his own cleanliness to use antiseptics in an attempt to cover up his own deficiencies?*
>
> The only reasonable answer to that is that the surgeon should so improve his methods that he would cease to be a pessimist. All the antiseptics in common use are toxic in some degree to the human organism as well as to bacteria, and are to be avoided wherever possible.
>
> 2. *Is it possible by the use of an antiseptic to destroy an infection in a freshly inflicted wound before the bacteria have time to grow out?*
>
> In the last war, at a base hospital in France, I examined wounds which had been specially treated with carbolic acid, and compared them with others which had not been so treated. So far as the bacterial content went, the carbolic-treated wounds were worse than the others.

SOAP

In a chapter on antiseptics, soap deserves special mention, not only on account of its strong bactericidal action, but also because of the special property it possesses of being able to remove "dirt" from the surface of freshly made wounds. Lister is reported* to have endorsed the remark of a colleague that every good surgeon is, whether consciously or unconsciously, an antiseptic surgeon. "Scrupulous cleanliness," Lister continued, ". . . is an antiseptic means." In this sense soap is undoubtedly the best antiseptic, and it was clearly the efficiency of soap as a cleansing agent that led Lister's contemporary Lawson Tait, the great gynecologist, to oppose the use of carbolic acid. Tait was a very clean surgeon, who used soap and large quantities of water, and on the strength of his satisfactory results he carried out a violent campaign against the carbolic spray and other antiseptics. Tait was an "antiseptic" surgeon no less than Lister, but his method differed from Lister's in approximating more closely to the further development of the technique which we now call "asepsis."

During the War of 1914 to 1918 a number of French surgeons used soap for cleaning wounds, and their results appear to have been very satisfactory. Following a suggestion made by Sir Cuthbert Wallace, several British army surgeons used soap, and Dixon and Bates (1917) published the result of a series of 388 cases where it had been used.

*Forty-Eighth Annual Meeting of the British Medical Association, 1880.

Haycraft (1918) also used soap with very satisfactory results. Comparing the results with those of a series of similar cases in which eusol, hydrogen peroxide or bismuth iodoform paraffin paste had been employed, Dixon and Bates were convinced of the superiority of soap. They used a 2½ per cent solution in water of a soap containing 63 per cent of fatty acids, 4.6 per cent of combined alkalies and 24.6 per cent of water. The gauze used for drainage was soaked in this solution and changed every three or four days. These surgeons were surprised to find that there was no pus and that the muscles looked red and healthy; the treatment was not painful, and healing was obtained in a shorter time than with any other antiseptic.

My own experience was similar, and in many hundreds of cases I saw ample evidence that soap was superior to the common antiseptics, which achieve their effect solely by their chemical action. In the majority of cases I used coconut soap of low alkalinity, and found it to be neither painful nor irritant. Equally good results were obtained when soap was used to clean infected wounds. Other surgeons have reported similar successful results, but, in spite of the clinical evidence in its favor, soap is still commonly used only to clean the skin, while the disinfection of the interior of the wound is left to chemical antiseptics.

Soap as an Antiseptic

Koch (1881) was the first to point out that soap has a bactericidal action, and since then Reichenbach (1908) and many others have studied the various properties of soaps both *in vitro* and in experimental animals. Lamar (1911) found that unsaturated soaps will destroy pneumococci and streptococci, and believed sodium oleate to be the most active in this respect. Violle (1933) found the ricinoleates to be more active than the oleates, palmitates or laureates. Barnes and Clark (1934) showed that 0.004 per cent of sodium ricinoleate and 0.0004 per cent of sodium oleate were the minimum concentrations required to kill three different types of pneumococci.

Bacteria vary in their sensitivity toward soap, and, while all workers agree that the streptococci, pneumococci, meningococci, gonococci, and diphtheria and tubercle bacilli are extremely sensitive, some have found that the staphylococci, and to a lesser extent the coli-typhoid group also, are very resistant. Kolmer and his associates (1934), however, found that *Staph. aureus* is completely destroyed by exposure for an hour to sodium ricinoleate, while Bayliss (1936) showed that it is also destroyed by sodium abietate when the pH exceeds 8.6. Walker (1924-1925) found that a 1 in 50,000 solution of sodium laureate destroyed pneumococci, and that streptococci would not grow in the presence of even small amounts of sodium ricinoleate.

Vincent (1907) first demonstrated that soaps can neutralize bacterial toxins. Larson and Nelson (1924) found that several of the most powerful bacterial toxins were destroyed by ricinoleate as soon as enough of this had been added to the solution to reduce their surface tension below a certain figure. For example, guinea pigs given the equivalent of 100 minimum lethal doses of tetanus toxin and treated in this way showed no ill effects. Belin and Ripert (1937) found that the same toxin left for 90 minutes in a 1 in 10,000 solution of oleate or ricinoleate was completely inactivated.

It is clear, therefore, that the majority of the unsaturated soaps will destroy the bacteria most commonly found in wounds, and that they will also neutralize any of the powerful toxins that may be produced. The question then arises of the best type of soap to employ. Nichols (1920) showed that ordinary household soap in a concentration of 0.5 per cent has a powerful action on the streptococcus and pneumococcus. Walker (1926), who found that this soap was also active against the diphtheria bacillus, noted that the typhoid bacillus was destroyed by a coconut-soap solution at room temperature, and, moreover, that the effectiveness of all soaps was increased if the solution was warm. Sodium ricinoleate and the coconut soaps destroy the staphylococcus, and coconut soaps, to which my own experience has been largely confined, have the further advantage that they are very efficient in removing dirt. Sodium and potassium soaps differ little from one another in their bactericidal action, but the latter are more stable and produce a foam with smaller bubbles, for which reason they are commonly used for household and toilet purposes and particularly in shaving soaps. For cleaning the interior of a wound I prefer soaps which produce larger bubbles, such as the sodium soaps.

Effect of Soaps on Tissues.—Violle (1933) found that 50 c.c. of a 1 in 1,000 soap solution was not toxic when given intravenously to rabbits, and that local application of the same solution did not irritate the cornea. Stronger solutions, however, particularly of the acid soaps, were hemolytic and also tended to lower the blood pressure. My own experience of soap has convinced me that a 5 per cent solution of ricinoleate or coconut soap, with a pH no higher than 7.5, while very effective in destroying bacteria, particularly streptococci, does not damage or irritate the living tissue cells, and may even have a stimulating effect on healing. These soaps must be used in a concentration of at least 1 in 50, for, although a 1 in 50,000 solution of sodium laureate in water has an action equivalent to that of a 1 per cent solution of phenol (Walker, 1926), contact with serum greatly reduces their activity (du Noüy, 1922).

Effect of Soaps on Bacteria.—The mechanism by which soaps destroy bacteria has been widely discussed. It now seems clear that

soaps achieve their bactericidal effect not by their chemical action, as do other antiseptics, but by their physical properties. That is to say, their destruction of bacteria is accomplished neither by coagulation nor by lysis, but rather by a steady process of disruption, which is effected by a reduction in the surface tension of the bacterium. This process is considerably impeded by the presence of protein solutions such as blood serum. The fact that neutral soaps are as effective as alkaline ones disposes of the idea that they act only by reason of their alkalinity.

Soaps as Detergents.—Quite apart from their bacteriological properties, another factor which makes soaps invaluable in the treatment of wounds is their capacity for removing "dirt." This detergent action is again not due to their alkalinity, but to the fact that the power of attraction of soap for the dirt particles far exceeds the attraction of the tissues for them, and also that of the particles themselves for one another. This has been shown experimentally with particles of aluminum oxide, iron oxide, and silica. For the soap to fulfill its function as a detergent it must be able to reach the necessary interfaces, and for this reason it must be in colloidal solution, that is to say, it must be used in warm water.

Taking everything into account, its detergent action, its bactericidal and antitoxic capacities, and its lack of irritation of the tissues, I think that soap constitutes the ideal antiseptic for war wounds. In fact, I am personally so convinced of its value that I would be willing to use almost any variety of soap in preference to the best chemical antiseptic yet known.

Recent work has shown that useful substitutes for soap may be found among the group of substances known as detergents. Many of these combine strong bactericidal activity with useful cleansing properties, and are apparently harmless when applied to living tissues. One such substance is cetyl-trimethyl-ammonium-bromide, which has been shown to be very efficient both in removing dirt and in killing bacteria upon the skin (Barnes, 1942).

Soap in the Treatment of Wounds

The cleansing of the skin surrounding the wound and of the damaged tissues in the wound itself are two distinct processes. For the undamaged skin surrounding the wound a solution of about 5 per cent sodium coconut or sodium ricinoleate in warm water should be used. The temperature of the solution should be about 100° F. The skin is thoroughly scrubbed with a nail brush and several changes of the soap solution, and is then finally washed over with sterile water.

For cleansing the wound a similar but weaker soap solution is used, i.e., about 2 or 3 per cent. With a piece of sterile gauze or a soft

nail brush the wound is carefully and thoroughly washed, especially the muscles and cellular connective tissue; the soap solution is rinsed out with sterile water, and more of the solution is left in the wound until the actual operation. The surrounding skin may be treated with a chemical disinfectant to deal with any contamination coming from the wound. When the field has been isolated with sterile towels and the surgeon is ready to begin the operation, the soap solution is mopped up with sterile gauze and the wound is dried. In my country at the end of the operation a piece of gauze soaked in the solution was placed in the wound for a few minutes and was then replaced by a piece of dry gauze. I now prefer in such cases to use sulfanilamide powder instead.

Each time the plaster is changed the skin and the wound are cleansed in this way. If, on removal of the drainage gauze at the change of plaster, there is much discharge, it is a good plan to fill the wound with freshly made soap solution and pack it with sterile gauze soaked in the solution. This generally has a marked effect in reducing the discharge, and noticeably diminishes the smell.

Burns.—For cleansing burns the technique is the same, with one important modification. The whole procedure must be carried out with the utmost gentleness and care to avoid breaking the blisters. A brush must never be used, and the surface of the burn must be washed very gently with swabs of cotton wool. The normal skin surrounding the burn is treated as in a wound.

CHAPTER XV

CHEMOTHERAPY

The term "chemotherapy" is used to denote the treatment of infection by certain chemical substances whose action is chiefly manifested when they are introduced into the body. In its widest sense chemotherapy is an "antiseptic" method of treatment, although the chemotherapeutic substances cannot be considered as antiseptics if the term is confined to those chemical substances which directly destroy bacteria. All chemotherapeutic substances have an antiparasitic effect in the body at least as great as, and generally considerably greater than, that which they produce *in vitro*. They act, not by coagulation or by lysis of the bacteria, but by an as yet unknown action on the living body through which the destructive effect on the invading organisms is obtained. Admittedly the effect of certain chemotherapeutic substances—for instance Ehrlich's salvarsan—is commonly supposed to be due to direct bactericidal activity; but research workers have shown that salvarsan acts on the medium in which the spirochete lives, impeding its nutrition and thus interfering with its growth (Danysz, 1917). Of others such as the sulfonamide compounds, the view that the body plays a part in the action is more widely accepted, the problem having been more carefully studied in the light of modern biological conceptions.

Chemotherapy may be said to have been first employed in 1890 when Guido Baccelli introduced injections of quinine for malarial fever. The value of quinine in this condition had been known for some time, but until Baccelli's day it had not been used on a scientific basis or administered by injection. In recent years the field of chemotherapy has been enormously extended by the introduction of the sulfonamide compounds for the treatment of infections caused by the streptococcus-pneumococcus group and other organisms more or less related to it.

THE SULFONAMIDE COMPOUNDS

Jacobs and Heidelberger synthesized the first sulfonamide in 1917, but the technique of sulfonamide therapy was only established on a scientific basis by Gerard Domagk in 1935. Even before his first published account the antistreptococcal action of certain sulfone preparations was known. For instance, in my hospital in Barcelona we had before that date treated more than twenty cases of surgical streptococcal infection, many of them with complete success, with a French product, "sulpharsenol" **(sulfarsphenamine)**, which had been formerly used as

an antisyphilitic but was then coming on the market as an antistreptococcal agent. I well remember a particularly striking effect in a child of two suffering from a highly septic erysipelas. Unfortunately we did not know the exact dosage, or which of the two elements, the sulfonic or the arsenical, was the active part. In 1935 Tréfouël and others found that the activity lay in the sulfonamide nucleus.

In 1937, during the Spanish War, we received our first samples of prontosil and were able to use it in a number of cases of seriously infected war wounds. The results obtained by d'Harcourt, Folch and Oriol (1938), published during the war, were on the whole encouraging. I used it myself in seven cases of serious infective complications, but with less good results. Since that time, however, better knowledge of dosage, the use of new compounds, and increased experience have made it possible greatly to extend the use of the sulfonamide therapy in war surgery.

Action of Sulfonamide Compounds

It has been clearly shown that *in vitro* the bactericidal action of the sulfonamide compounds is inferior to that of the majority of even the weak antiseptics. Consequently, their use to maintain the sterility of organic substances, such as blood stored for transfusion, is entirely illogical. The beneficial action of the sulfonamides is developed in the living body, but the changes in the body to which they give rise, and by means of which they achieve their action, have not yet been clearly established. It has been suggested that they are more effective the greater the number of the specific antibodies in the blood (Collins, 1940); but McIntosh and Whitby (1939), on the other hand, deny that the natural defenses of the body make any contribution to their antibacterial activity. Recently Lockwood (1941) has shown that they prevent the use by the bacteria of the p-aminobenzoic acid which is essential to growth; the organisms thus die of starvation and are then ingested by the leucocytes and eliminated from the infected region. Several workers, including Finkelstein and Birkeland (1938), and Finklestone-Sayliss, Paine and Patrick (1937), have noted an increase in phagocytic capacity after administration of these compounds, a finding which at any rate does not conflict with Lockwood's observation.

At the same time, the p-aminobenzoic acid has an inhibitory effect on the action of sulfonamide compounds similar to that of peptones and proteolytic enzymes, and this fact may account for the increased resistance which bacteria seem to acquire to these compounds after the administration of several doses. There is clinical confirmation of the inhibitory effect of peptones and proteolytic enzymes on sulfonamide compounds in the fact that the latter are ineffective when applied to

wounds containing the products of tissue disintegration. Lockwood believes that the resistance of the staphylococcus to the sulfonamides is due to the intense local reaction produced by this organism, with a necrosis of the tissues which inhibits the antibacterial activity of the drugs. This appears to be a satisfactory explanation and might well account for their ineffectiveness in undrained abscesses, whatever the causative organism. Tunnicliff (1939) and Henschel (1940), working with tissue culture media composed exclusively of animal body fluids, showed that neoprontosil, in a concentration of 1 in 1,000, stimulates leucocytic migration in the rabbit's blood. One fact at any rate seems clear, namely, that the sulfonamide compounds have a bacteriostatic action in the tissue fluids.

Whatever the exact mechanism, the fact remains that these compounds act on the bacteria through the medium of the circulating fluids of the body, and are ineffective if these fluids do not reach the contaminated area and so come into contact with the bacteria. It is clear, therefore, that the full effect of the sulfonamide compounds in the treatment of traumatic wounds can be obtained only if the wound is completely free of all dead tissues and retained fluids, i.e., of any sort of organic foreign body, and if a good circulation is maintained.

Since the sulfonamide compounds are most effective in highly diffusive infections, e.g., streptococcal lymphangitis, their effect on the "spreading factor" has been investigated by Duthie (1941), but apparently with negative results.

Antibacterial Capacity of Sulfonamide Compounds.—

Sulfanilamide, Sulfapyridine, Sulfathiazole.—A comparative study of the effects of these three compounds on different infections has shown that they act with an intensity which varies with the causative bacteria. This is summarized in Table VIII which shows comparative values taken from the work of Reed and Orr (1941), McIntosh and Selbie

TABLE VIII

EFFECTS OF SULFONAMIDE COMPOUNDS IN VARIOUS INFECTIONS

	SULFANILAMIDE	SULFAPYRIDINE	SULFATHIAZOLE
Strep. pyogenes	3	2	3
Strep. viridans	2	3	2
Staphylococcus	0	1	2
Pneumococcus	0	3	3
Ps. pyocyanea	0	0	1
B. coli	2	2	3
Cl. tetani	1	2	2
Cl. welchii	2	1	2
Cl. septique	0	1	2
Cl. oedematiens	0	0	2
	10	15	22

In the table 0 stands for no effect, 3 for maximum effect, and 1 and 2 for values between.

(1941), Mayer (1938), Lawrence (1940), Melton (1941), Colebrook and Francis (1941), Hawking (1941), Whitby (1940), Thrower (1941), and from my own experience.

Sulfathiazole thus appears to be more effective than either of the other two compounds, whether it is administered orally or intravenously. For local application sulfanilamide has been found very suitable, owing to its diffusibility, but sulfathiazole in its soluble form seems to be even better (Hawking, 1941).

Administration.—The best way to give these drugs is either by the intravenous or by the oral route. It is important that there should be a high concentration in the circulating blood, i.e., not less than 5 mg. per 100 c.c. The initial dose, therefore, whether of the drugs themselves given orally or of their sodium derivatives (used for injection because of their solubility), should be high. Subsequently it may be reduced. For staphylococcal infection a constant concentration of more than 10 mg. of sulfathiazole per 100 c.c. is recommended.

Oral Administration.—For oral administration the sulfonamide compounds are prepared by the manufacturers in tablet form. The tablets should be powdered and given in milk or water.

Sulfanilamide (Prontosil Album; Streptocide; Proseptine; Prontylin).

Prophylaxis.—Eight tablets (4 grams) should be given at first, followed by 4 tablets (2 grams) in four hours' time, and then by 2 tablets (1 gram) every four hours day and night for 48 hours.

Treatment.—Eight tablets (4 grams) should be given at first, followed by 4 tablets (2 grams) in four hours' time, and then 2 tablets (1 gram) every four hours day and night for a period not exceeding 10 days. At the end of this time the drug must be discontinued, and if the infection is not yet under control, a course of treatment with a compound of another series should be started after an interval of at least 48 hours. The drainage of the wound should be improved, for failure of these compounds is generally due to an undrained inflammatory process and could in most cases have been prevented had surgical treatment been possible. Only patients who cannot receive surgical treatment should be treated with the intensity and persistence described above. As soon as the infection is under control, the dose should be reduced to 1 tablet (0.5 gram) every four hours, to be given until three days after the temperature has fallen to normal.

Sulfapyridine (M. and B. 693; Dagenan).—The dosage is similar to that of sulfanilamide, except that the initial dose is 6 tablets (3 grams) instead of 8 tablets (4 grams). If the patient vomits, it is advisable to split the doses and give them at shorter intervals, e.g., 1 tablet (0.5 gram) every two hours instead of 2 tablets (1 gram) every four hours.

If, however, the vomiting begins with the initial doses, it is difficult to continue the treatment, and the best plan is to change to sulfathiazole.

Sulfathiazole (M. and B. 760).—The dosage is the same as that of sulfapyridine. Vomiting is a less frequent complication.

Intravenous Administration of Sulfonamides

When oral administration is ineffective or impracticable, either because of gastric disturbance preventing absorption or because the patient is unable to swallow, the best alternative is intravenous injection

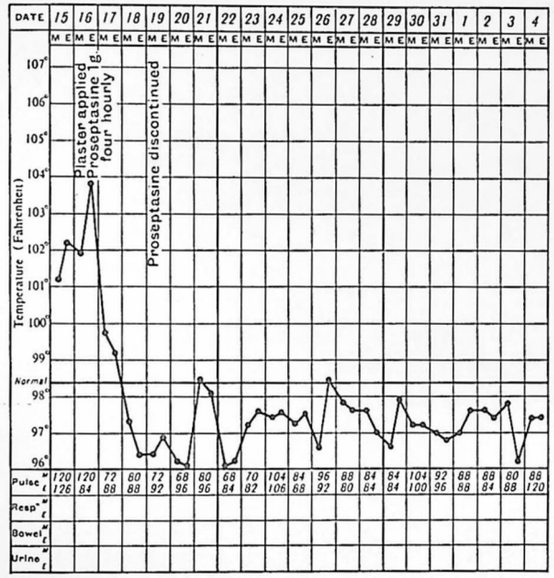


Fig. 20.—Rapid control of high temperature by the combined action of chemotherapy and immobilization in a plaster cast, in a patient suffering from streptococcal infection of a granulating wound.

of the sodium derivatives. Intramuscular injections can be given, but these are painful and produce some reaction in the cellular tissues; necrosis of the soft tissues and nerve lesions have been reported. The intravenous administration may be effected either by repeated injections or, better, by the continuous drip method. In the former case injections of 1 gram (one ampoule of M. and B. soluble [sulfathiazole]) in 20 c.c. of sterile distilled water or saline should be given every four hours. By adding the drug to a suitable quantity of saline or blood it can be administered by continuous drip in the same dosage, i.e., 1 gram per four hours. The latter seems to be a very satisfactory method and the best means of maintaining the drug in the blood at a constant level. As a prophylactic measure the administration should be limited to 48 hours,

but for treatment it may be continued for a total period of ten days, with the same dosage (1 gram every four hours day and night). As soon as the infection is under control, however, it is advisable to change from the intravenous to the oral route. Fig. 20 shows the effect of sulfapyridine in controlling a sudden rise of temperature.

Local Application of Sulfanilamide

In 1939 Nitti tested experimentally the local action of sulfanilamide, and Jensen, Johnsrund and Nelson reported the first clinical results after treating 41 compound fractures. The experimental work of Legroux (1940) at the Pasteur Institute and the papers by Colebrook (1941) have stimulated much discussion on the effect of sulfanilamide locally applied; nevertheless its value has not yet been fully determined. Experimental work in animals has shown that sulfanilamide is absorbed by the body when applied locally to the tissues of a wound. Thus, Reed and Orr (1941) found that after such an application the surrounding muscles, even those at some distance from the actual wound, may contain the drug in a high concentration. But the degree of concentration depends on the power of absorption of the tissues of the wound, and this is greatly diminished by certain local factors, such as the presence of a layer of coagulated fibrin, or of pus or dead tissues, or of a layer of healthy granulation tissue, which has a very low power of absorption.

War wounds, however, bear little resemblance to the ordinary type of experimental wound made in animals, and consequently the value of local application of sulfanilamide as a preventive should be assessed on clinical experience rather than on experimental findings, unless the latter are obtained from wounds closely resembling those of modern warfare. Directly after complete excision of the wound, when the dead tissues have been removed and the living tissues lining the wound are bleeding freely, absorption may be possible, and at this point a local application of sulfanilamide may render good service as a prophylactic. When after some days, however, the granulation tissue is well established, local application is not as effective, because the drug is not well absorbed, and its sphere of action is limited to the surface of the wound. The sulfonamides have little value as "antiseptics" in the more specific sense of the term, and at this later stage any suitable antiseptic is more effective.

The local application of sulfanilamide in wounds where local infection is already established is, in my opinion, worthless. It seems explicable only by the persistence of the antiseptic tradition. Antiseptics, even though at the best moderately efficient, are undoubtedly as effective as sulfanilamide in cleansing flat granulating wounds.

Moreover, the local applications necessitate changes of dressing and thus interfere with the healing process. Under the following conditions only are two or three days of local application of sulfanilamide justifiable: first, in the preparation of a healthy wound for skin grafting, because in these cases the damage to the epithelium caused by the change of dressings is only of secondary importance; and secondly, in a recently inflicted wound when for some reason operation must be delayed for more than eight hours.

Until recently the best drug for local application was sulfanilamide in its soluble form, the most commonly used being streptocide which is soluble in organic fluids. Lately, however, sulfathiazole seems to have taken its place, especially in America where it is more easily obtained.

Technique of Local Administration.—The amount of sulfanilamide powder required to protect a wound from infection varies with the size and depth of the wound, but the average appears to be from 10 to 15 grams. King (1941) has recently insisted that the drug must fill every corner of the wound. While not denying the general wisdom of this recommendation, I fear that it may lead to a misconception of the action of the drug, the emphasis on widespread distribution suggesting that it is an antiseptic with a direct bactericidal effect. Since the action is an indirect one, operating through the medium of the body fluids and in relation to the concentration of the drug in the tissues surrounding the wound, it depends far less than do antiseptics on physical contact with the infecting organism, and perfect distribution in the wound is not so vital as King's statement implies.

Colebrook (1941) has devised an insufflator with which the exact amount of sulfanilamide powder can be gauged, and although distribution even with this is still not very easy, it is undoubtedly more effective than by any other method (see Fig. 35). The difficulty lies in the hygroscopic quality of the drug, which makes the powder very compact. For this reason the powder should be kept absolutely dry.

Sulfonamide Compounds in the Treatment of War Wounds

All diffusive infective processes, and particularly the streptococcocal infections, should be treated with one of these compounds, always provided that the wound is also properly treated surgically. The satisfactory effect of immobilization combined with sulfonamide treatment in cases of streptococcal infection without either pocketing or cellulitis may be seen in the following case:

A boy of 16 had his left arm caught in a fan belt and was lifted off the ground. He had the lower epiphysis of the humerus dislocated and protruding medially through the skin; also a fracture of the forearm. At the Wingfield-Morris Orthopaedic Hospital, four hours after the injury, the wound (3½ in. by 2 in. in area) was excised and packed

with gauze; owing to the technical impossibility of a primary suture the fracture of the forearm was reduced and the whole upper limb placed in a plaster cast. Except for some slight temperature during the first ten days, the case followed a normal evolution, and the boy left the hospital two months after admission with the fracture of the forearm consolidated and the wound greatly reduced in size. The plaster was removed. In the convalescent hospital he was put into quarantine for scarlet fever, and some days afterwards he had a sudden malaise with sore throat followed by pain in the elbow joint, swelling of the fingers and hand, and a temperature of 104°. A course of proseptasine tablets was given for three days and a plaster applied. From the second day the temperature fell and on the third day it was normal (see Fig. 20); no other infective accident occurred. Hemolytic streptococci were grown from the wound.

If, however, the excision of the wound is incomplete, or if proper drainage is not provided, the effect of the drug is limited and often negligible. In fact, sulfanilamide is a potential source of danger in that it may encourage a surgeon to delay the necessary operation until there is evidence of a wider diffusion.

Lymphangitis.—In this condition the sulfonamides are undoubtedly of great value. The infection is widely diffused, and the initial focus may reveal no suppuration and is sometimes so small that surgical treatment is considered unnecessary. In such cases, and in erysipelas (also a highly diffusive infection) the effect of sulfonamide treatment may be very striking.

A soldier 36 years old was wounded by splinters in France on May 28, 1940. He had a penetrating wound in the abdomen which was explored, and a lesion was found in the omentum. The damaged part was excised and primary suture was performed without drainage. He also had a wound in the lower part of the upper arm, with the entrance on the inner side and the exit higher, close to the brachial artery but not involving it. There were signs of complete musculospiral section and a compound comminuted fracture of the humerus.

The wound was "superficially excised" and packed with vaseline gauze, and the arm was put in a plaster cast. Two days afterwards the patient was transferred to another hospital, where the plaster was immediately removed and complete immobilization applied in a shoulder spica. The wounds gave no trouble of any sort. He was sent to a third hospital on June 10 in good general condition. The plaster was too loose and the hand was not supported in a correct position; for this reason the plaster was removed on June 15 in spite of the lack of inflammatory signs at the site of the fracture. An antero-internal wound 2 in. by 1½ in. and a postero-external wound about 1½ in. in diameter in the lower third of the arm were found. Both were granulating, but an excessive amount of discharge came through the anterior wound. The wounds were cleaned and packed with vaseline gauze; a new plaster was applied fixing the wrist in dorsiflexion. The course was uneventful except for an excessive amount of discharge through the plaster and two short rises of temperature to less than 100°, which

were maintained only for a day each. The abdominal wound never gave any trouble. After a quiet evolution for three weeks the patient suddenly had a severe rigor lasting 20 minutes, and the temperature rose to 102.6° (see Fig. 21). He complained of headache but had no pain in the arm and no swelling of the hand and fingers, but some pain in the axilla. He stated that ten years before, while in India, he had had a severe attack of malaria, and that he had had one sudden rigor since returning to England. A lymphangitis was suspected. Sulfapyridine was administered, and on the second day the temperature fell to normal. The plaster was therefore not removed until July 8, a week after the final disappearance of the fever. He had at that time two small wounds surrounded by some edema and induration of the soft

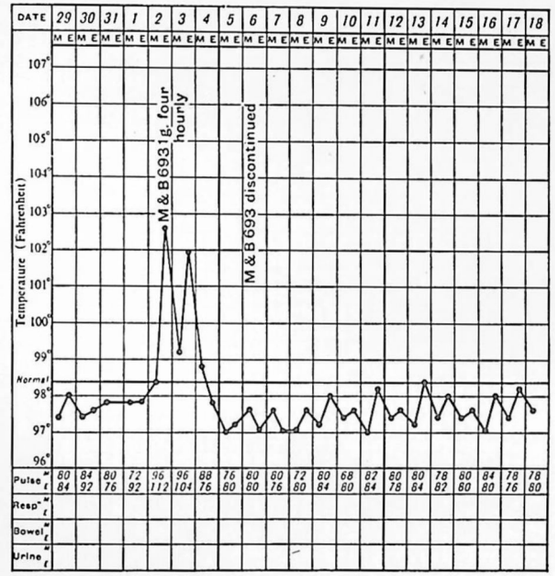


Fig. 21.—Sudden rise of temperature in a case of compound comminuted fracture of the humerus treated under plaster. Probable lymphangitis. Immediate control of the temperature by the administration of sulfapyridine. (M. and B. 693, sulfapyridine.)

tissues, and an elastic union of the fracture of the humerus. The wounds were granulating and some pus came out of the anterior one. A new plaster was applied, this time from hand to axilla. After three weeks the patient complained of a loose body inside the plaster near the elbow joint and, on removal of the plaster, two pieces of bone were found lying loose in the region of the wound on the anterior side. An additional small sequestrum was removed from the wound. The fracture was consolidated in good position. Two weeks afterwards the wound was healed. All the trouble was produced by the initial inadequate bony excision.

A man 23 years old sustained a compound fracture of the right tibia and fibula, together with several other lesions, in a collision on a motor-

cycle. The wound was cleaned, incised-excised and drained on correct lines. The leg was placed in an unpadded plaster from the toes to the middle third of the thigh. The postoperative course was uneventful, but the plaster was changed after 25 days on account of some slight discharge, which, however, was not copious or bad smelling. A second plaster was applied and the patient got up with crutches. Four days afterwards he felt uncomfortable, vomited and complained of pain at the fracture site, accompanied by chills and swelling and tenderness of the femoral glands. The temperature rose to 101.6°. There was no swelling of the toes. From the clinical picture he was clearly suffering from lymphangitis, and a course of proseptasine was given. From the second day the temperature fell to less than 98°, except for the evening of the fifth day. The drug was discontinued on the fourth day, on which the temperature was normal. The rest of the treatment was uneventful (see Fig. 22).

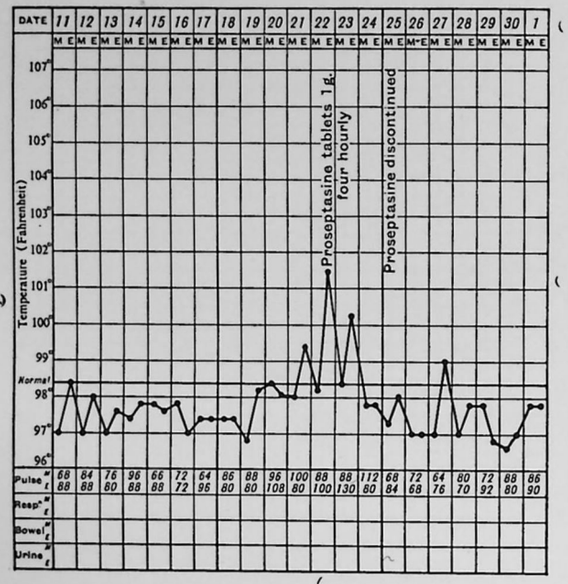


Fig. 22.—Immediate control of the temperature by the administration of proseptasine in a case of lymphangitis.

In this case of sudden general malaise the diagnosis of a lymphangitis was made easy by slight local pain, swelling of the regional glands, acute fever and lack of edema of the toes. The immediate response to sulfonamide treatment confirmed the diagnosis.

Abscesses.—In abscesses, on the other hand, the sulfonamides are entirely ineffective and the only treatment of any value is surgical. A member of the group may be administered after the operation to prevent undue bacterial absorption, but it will have no power whatever in combating the initial infection. The Chart shown in Fig. 26 is an example of this type of case.

Cellulitis.—The presence of necrotic tissues and pus, together with a tendency to diffusion, demands a combination of surgery with chemotherapy—or, perhaps I should say, of chemotherapy with surgery. The sulfonamides impede the diffusion, and the operation reverses the direction in which the bacteria and toxins travel.

Insufficiently Immobilized Fractures.—In some insufficiently immobilized fractures with profuse discharge, the granulation tissue is macerated and acquires a new power of absorption; this causes a persistent fever (100° to 101° F.). Sulfonamide compounds act only at the time they are administered; the correct treatment is to cut a window in the plaster and treat the wound locally with an antiseptic of the chlorine or acridine group, or better still with soap for three or four days, in order to reduce the discharge. The limb is then reimmobilized in a new closed plaster.

Sulfonamide Compounds and the "Biological" Treatment of Wounds

If a rise of temperature occurs in a patient whose limb is enclosed in a plaster cast, the most probable cause is a septic complication—erysipelas, lymphangitis, cellulitis, abscess, or unhealthy granulations. An immediate diagnosis must be made in order that the appropriate treatment should be given.

Erysipelas today is a rare complication of war wounds and one much less to be feared than in the preantiseptic age. Nevertheless, it may still occur under plaster. Its signs and symptoms are very similar to those of a highly septic lymphangitis, but include in addition a spreading sensation of local heat. A rise in the temperature of the plaster is commonly observed. The administration of one of the sulfonamide compounds is very effective.

Lymphangitis.—The rise of temperature is abrupt in lymphangitis, the patient feels ill at ease, and nausea and vomiting are frequent; there is no serious local pain but a painful inflammation of the regional glands (particularly in the axilla or groin), and edema is not at first apparent in the fingers or toes. A sulfonamide compound should at once be administered by mouth without disturbing the wound. The effect is often striking (see Figs. 21 and 22).

Cellulitis.—When cellulitis develops, the rise of temperature is more gradual. Local pain is severe and is accompanied by a feeling of tension in the region of the wound. Inflammation of the glands, on the other hand, is not so marked in the early stages, but the swelling increases after a short time; edema of the fingers or toes appears immediately. An initial course of one of the sulfonamides should be given immediately. If the patient experiences an increase in the area of tension, the plaster must either be removed or have a window cut in it without

delay, and appropriate surgical treatment must be given. After incision of the inflamed cellular spaces a new plaster should be applied, unless the area of inflammation is very extensive, when the new plaster should be deferred for a few days, lest the infection spread and necessitate early removal of the second plaster. Meanwhile oral administration of the drug should be continued.

When either lymphangitis or cellulitis is suspected but accurate diagnosis is impossible, one of the sulfonamides should be given for four or five days. If at the end of this time—and it is unwise to wait longer—there is no improvement in the clinical picture, a window should be cut in the plaster and the wound explored.

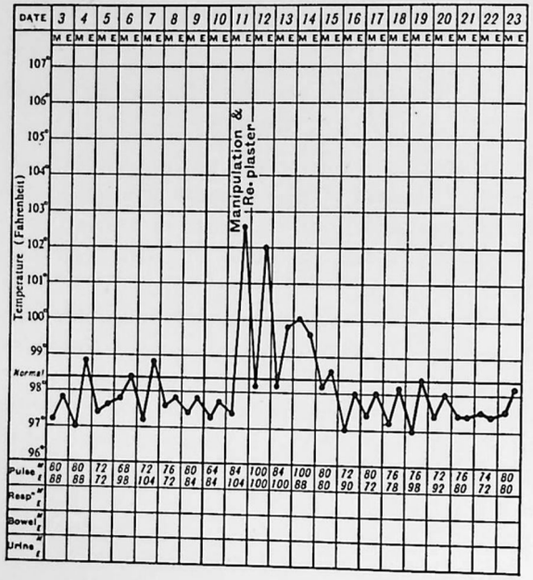


Fig. 23.—Compound fracture of tibia and fibula treated by cleansing, excision, drainage and plaster. Sudden rise of temperature after manipulation of the fracture to improve the position of fragments. Control of the temperature by simple immobilization in plaster.

Abscess.—The rise of temperature when an abscess develops underneath the plaster is progressive, but there is a daily fall; local pain gradually increases, but is never very severe; the feeling of tension is confined to the wound area, some regional glands are slightly painful, and there is little or no edema in the digits. The best treatment is to cut a window in the plaster, explore the wound, and provide better drainage. At the end of the operation the window should be closed. The sulfonamides are of no value in this type of localized septic process, and there is no object in using them in combination with a closed plaster (see Figs. 23 to 26).

A man 31 years old sustained a compound supracondylar fracture of the right femur; it was treated by excision, Thomas splint, and traction through a Steinmann pin placed in the tibial tubercle. He was transferred to the Wingfield-Morris Orthopaedic Hospital after nearly two months' treatment, with a shortening of 2½ inches and an osteitis of the tibia where the pin had been. Under general anesthesia with gas and oxygen, extension ice tongs were placed on the distal femoral fragment, the osteitis of the tibia was incised, and strong traction was applied. After four days, reduction of the fracture was very much improved; the ice tongs were replaced by a Kirschner wire passed through the inferior femoral epiphysis, and a plaster spica was applied. After six days the patient had a sudden rise of temperature accompanied by some pain at the site of the tibial osteitis. Sulfapyridine was administered every four hours, but after two days failed to relieve a tempera-

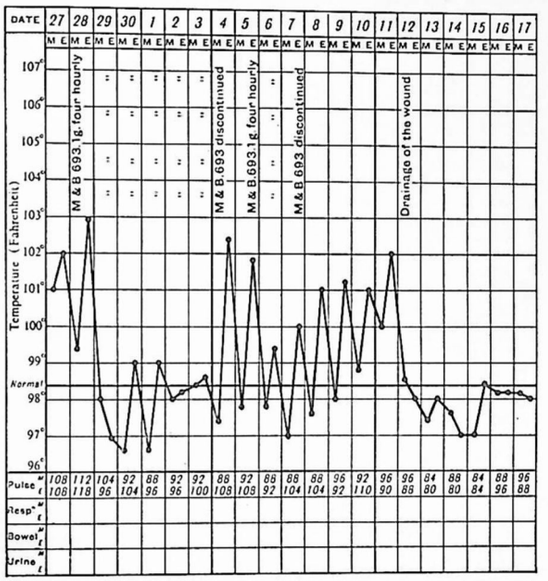


Fig. 24.—Transitory response to sulfapyridine in a case of infected compound fracture of femur. Definite control of the temperature after improving the drainage of the infected region when the patient was no longer under chemotherapy. (M. and B. 693, sulfapyridine.)

ture of 102°. A small window was cut at the anterior part of the upper tibial epiphysis and the dressing was changed; a small amount of pus (less than 2 c.c.) emerged. Next day the temperature fell to normal, and after two days the sulfapyridine was discontinued (see Fig. 25).

This is another proof of the failure of chemotherapy to control high temperature caused by retention of pus, and the immediate result of improving drainage.

A man aged 25 years was injured in a motorcycle accident on October 20, 1940, sustaining various injuries and a large laceration

with gross tearing of skin and muscle just above the front of the knee. Radiography showed fracture of the external edge of the patella with gross displacement. The skin of the leg and thigh was scrubbed with soap and water, the skin edges were excised and the traumatized tissue removed, together with loose bone fragments. The laceration, which involved the knee joint on the lateral side, was sutured with plain catgut. A dependent rubber drain was inserted on the lateral aspect, but not into the joint. A plain gauze dressing was applied and the wound left freely open. A plaster spica was put on. The patient was given sulfapyridine and the course was uneventful. At the change of plaster on November 14 the wound was found granulating well. On November 22 the new plaster was removed; the wound was found filled with granulating tissues and very clean. After the wound and the surrounding skin had been cleaned a dry dressing was applied and the leg fixed in a Thomas splint. A sample of the slight discharge found on the surface of the wound grew some colonies of hemolytic streptococcus. The wound was still 3 by 4 inches in area over the patellar region.

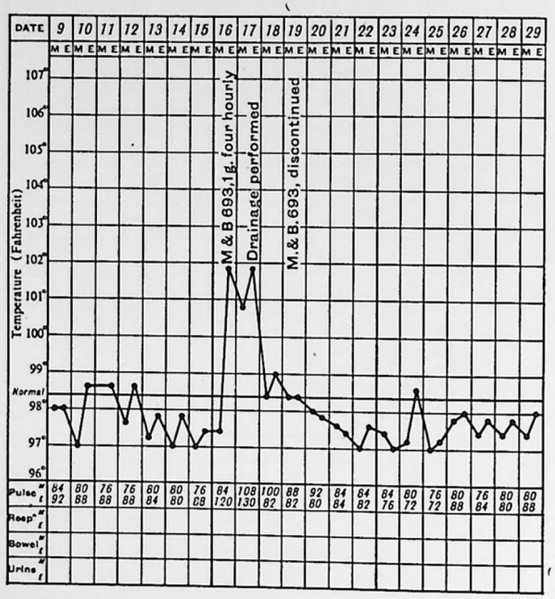


Fig. 25.—Immediate response to drainage in a patient suffering from infection caused by a Steinmann pin. A short course of sulfapyridine did not control the temperature until drainage was established. (M. and B. 693, sulfapyridine.)

After some days of cleansing the granulation tissue and applying sulfanilamide powder, a secondary suture of the wound was performed. The skin margins of the wound were excised and the granulations scraped off. The skin above and below the wound was mobilized with the help of two incisions about 4 inches long up the thigh at the inner and outer margins of the wound, and one short incision downward at the medial margin. The skin edges were approximated completely. There was slight tension where the flaps met in the center. A dry

dressing was applied and immobilization was secured with a posterior plaster splint. From the day of the operation a course of proseptasine in tablets was given.

In spite of the proseptasine the patient ran a temperature of 101° F. (see Fig. 26). After four days the dressing was removed, a very small collection of pus in retained blood was found in one of the corners of the suture, and a single stitch was removed; the rest of the suture was completely normal. The proseptasine was discontinued and the temperature fell to normal the same day. On January 11, 1941, the patient walked and flexed the knee 15°. After two manipulations under pentothal anesthesia he was discharged, flexing the knee to 90°, and flexion probably improved still further.

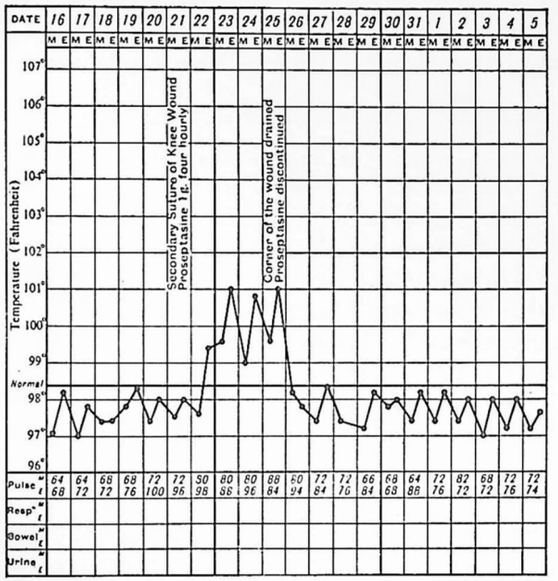


Fig. 26.—Complete failure of a course of sulfanilamide in a patient suffering from a small abscess containing 3 c.c. of pus, and from lymphangitis. Immediate response to the establishment of drainage.

The following facts are noteworthy: 1. The complete absence of articular reaction after a primary suture of the synovial membrane, in spite of the bony injury, hours after the production of the wound. 2. The absence of inflammatory reaction in the extensive wound of the soft tissues covering the knee joint. 3. The failure of the sulfonamide to control the temperature caused by a small pocketing, and the complete and immediate success after drainage of the collection. 4. The good result of a secondary suture.

Septic Absorption Through the Granulations occurs, with the development of pyrexia and other general signs of infection, in cases with profuse discharge in which the granulations are macerated by the

fluid and consequently lose their protective function. Treatment of such cases with a course of one of the sulfonamides is generally ineffective. Frequently, it is true, the manifestations of the infective process subside during the period of administration, but they reappear immediately the drug is discontinued. The only way to make sure of stopping absorption is to cut a window in the plaster over the region of the wound and treat the granulations direct with a mild antiseptic or a local application of sulfanilamide. When the discharge is reduced to the normal amount, either the window should be replaced or the granulations treated for a few days more, until the wound is ready for a skin graft.

It should be stressed that it is only in the last of these five types of infection that the local application of sulfanilamide can be of any help.

Sulfonamide Treatment of General Infections

The infections in which the sulfonamides give the best results are the so-called septicemias. These septic processes have a marked tendency to diffusion and give a consistent clinical picture of nervous and splanchnic impregnation (high fever, a dry skin, rigors, loss of appetite, great prostration, and in some cases delirium). They are generally due to a very small inflammatory focus in either an inaccessible or a concealed site. Where the site or type of the original septic focus prevents surgical treatment, chemotherapy provides our only resource and may have striking effects. From Herrell and Brown's (1941) study of a comparative series of patients treated with and without sulfonamide I have abstracted the following results (see Table IX), obtained in patients in whom pathogenic bacteria were persistently present in the blood and who showed a clinical picture of severe toxemia.

TABLE IX

RESULTS OF SULFONAMIDE TREATMENT IN SEVERE TOXEMIA

CAUSATIVE BACTERIA	TREATED WITH SULFANILAMIDE	RECOVERIES	TREATED WITHOUT SULFANILAMIDE	RECOVERIES
Strep. hemolyticus	38	25 (65 per cent)	61	18 (29.5 per cent)
Strep. viridans	39	7 (77 per cent)	2	1 (50 per cent)
Staph. aureus	27	15 (55.6 per cent)	29	10 (34.5 per cent)
Pneumococcus	15	5 (20 per cent)	20	6 (30 per cent)

Summary of Indications for Sulfonamide Compounds in War Surgery

Prophylaxis.—1. In all cases in which the complete surgical treatment of war wounds must be delayed owing to difficulties of transport, the number of patients to be treated, or the presence of shock, the sulfonamide compounds should be given at the earliest possible moment. Before the patient's admission to a hospital oral administration is the most convenient; after admission they may be added in soluble form to the fluids administered intravenously for resuscitation. After the provisional operation, i.e., incision of the skin and superficial fascia, a local application in powder form may be beneficial. Without the preliminary opening-up of the skin and fascia, however, local application of sulfonamide compounds will not be so effective, particularly in anaerobic infections.

2. Where early operation is possible and where excision of the wound has been complete, a local application of the drug seems to be a useful adjunct to the surgical technique.

3. A local application of the drug may contribute to the success of both grafting operations and secondary suture.

Treatment.—In an already established infection, treatment with sulfonamides should be general, not local. The wound should never be disturbed with the idea of destroying the bacteria by direct contact with the drug. In superficial wounds with suppurating granulations treated without plaster, it is better to use the drug for general treatment while applying a really active bactericidal substance, such as sodium coconut soap, to the actual wound. In serious cases it is advisable to give the drug intravenously in the early stages and, as soon as the infection is under control, to change to the oral route.

Minor Complications

Cyanosis.—Cyanosis due to the formation of sulfhemoglobin or, more probably, of methemoglobin (Collins, 1940), is characterized by a bluish coloring of the skin. It is a very conspicuous but not usually a dangerous sign. The best treatment is to give 0.5 Gm. methylene blue orally 3 times a day (adult dose). Drastic purgatives and saline purges should be avoided. In some really alarming cases bleeding, followed by immediate blood transfusion, was used by Durán Jordá in Barcelona.

Nausea and Vomiting often occur after the initial dose of sulfapyridine. In such cases the drug should be suspended for several hours and then restarted in fractional doses (i.e., 2 tablets every two hours instead of 4 tablets every four hours). If vomiting recurs, the drug should be discontinued, and after an interval of 48 hours another preparation (preferably sulfathiazole) should be administered. If, in spite of the change of drug, the vomiting begins again, this form of treatment should be abandoned, owing to the possible risk of agranulocytosis or hemolytic anemia.

Acidosis should be treated with sodium bicarbonate.

Dermatitis or Other Skin Eruptions may appear five to seven days after the beginning of treatment and generally occur at pressure points. Collins claims that this complication occurs in 7 per cent of cases, but I have seen only two cases among over 75 treated with these drugs. The surgeon, should, however, be on the watch for dermatitis, as it may be the first indication of a really serious complication. The drug should be immediately suspended and the patient made to take large quantities of fluid.

Drug Fever is often indistinguishable from the fever caused by the infection, and it is therefore difficult to decide whether the drug should be discontinued or not. Generally, however, the rise of temperature from this cause occurs after several days of normality and other signs and symptoms of infection are absent.

Headache and Dizziness.—These symptoms should not be lightly regarded, for they may be the forerunners of agranulocytosis, a serious complication. The patient should be made to drink large amounts of fluids, and if symptoms persist, the drug should be stopped and a leucocyte count made.

Hematuria occurs only with sulfapyridine and should be treated by the administration of plenty of fluids.

Serious Complications

Hemolytic Anemia, which may appear between the second and the fourth day of the treatment, is rare and generally not acute. It leads to jaundice and hemoglobinuria. Blood transfusion is of value.

Agranulocytosis.—Also a rare complication, agranulocytosis does not appear until eight or ten days have elapsed. Fever, headache, and a sore throat are often present, but the diagnosis is established by a leucocyte count. The only treatment known at present is blood transfusion and the administration of pentnucleotide.

As a precautionary measure, all patients treated with sulfonamide compounds should be made to drink large amounts of fluids, i.e., not less than 4 pints a day.

PENICILLIN

Recent work indicates that penicillin, a new substance, may also prove useful in combating a diversity of infections; it promises to be effective either as a local application or administered parenterally. It is extracted from the mould *Penicillium notatum,* as a brown, water-soluble powder. It is almost nontoxic to laboratory animals, and on

intravenous injection has little or no action on the cardiovascular or respiratory systems. Leucocytes exposed to a solution of 1 in 1,000 parts are not affected. It inhibits the growth *in vitro* of many bacteria; its action seems to be bacteriostatic rather than bacteriocidal. Given at the Oxford Department of Pathology to mice infected with *Strep. pyogenes, Staph. aureus* and *Cl. septique,* it has saved a very high proportion. Relatively large amounts may, however, be needed in the treatment of man. It has not yet been isolated in a pure form, and much work remains to be done on it (Chain and Duthie, 1939; Abraham and others, 1941).

CHAPTER XVI

WOUND EXCISION

ENLARGEMENT OF THE WOUND

The first stage in the operation on any war wound is enlargement or **incision.** This is an essential preliminary on which the effectiveness of each of the subsequent procedures depends. Unless an adequate opening is made in the skin and fascia and in the deeper structures, the second and most vital part of the operation—the excision of bruised tissues—cannot be carried out with sufficient thoroughness. Many war wounds are characterized by a small skin wound and extensive destruction of the deeper tissues. Even in larger wounds the injured muscles tend to disappear beneath the skin and superficial fascia, owing to the persistent retraction of muscular fibers ruptured by the projectile, so it is virtually impossible to excise them through the traumatic opening of the skin. Unfortunately this initial step of incision is only too often omitted, and the surgeon begins straight away with excision, with the result that many damaged tissues are retained, with the subsequent development of such complications as gas gangrene, cellulitis, or, at a later stage, osteomyelitis.

The line of the incision should be parallel with the long axis of the limb. Transverse incisions are unsatisfactory because they tend to damage important anatomical structures, are not suitable for drainage, heal slowly, and leave unsightly scars. Only in triangular wounds is a transverse incision, a cut towards each corner, permissible. The length of the incision varies according to the size and type of the wound and its location. Generally speaking, and excepting those cases where a large area of skin has been destroyed, it should extend beyond the wound on either side for a distance at least equal to the length of the wound itself. Small wounds in muscular regions, however, such as the thigh and arm, require longer incisions; while wounds caused by aerial bombs, particularly those of the smaller type which produce perforations of the skin and extensive damage in the tissues, need very long incisions—out of all proportion to the superficial wound (see Figs. 27 to 37). Where there has been very severe damage to the muscles, it may be necessary to extend the incision for wider inspection.

Technique of Incision

The skin surrounding the wound is carefully examined and the amount to be excised is determined. The skin, the cellular tissue, and

the superficial fascia are then cut with a sharp knife along the line which extends the wound both up and down in the longitudinal axis of the limb (see Fig. 29). The knife must be directed towards the edge of the wound from either end, and the incision made first on the proximal side with a cut from above downwards, and then at the distal side with a cut from below upwards. The knife is then exchanged for scissors, and the skin requiring excision is cut away along the edges of the wound

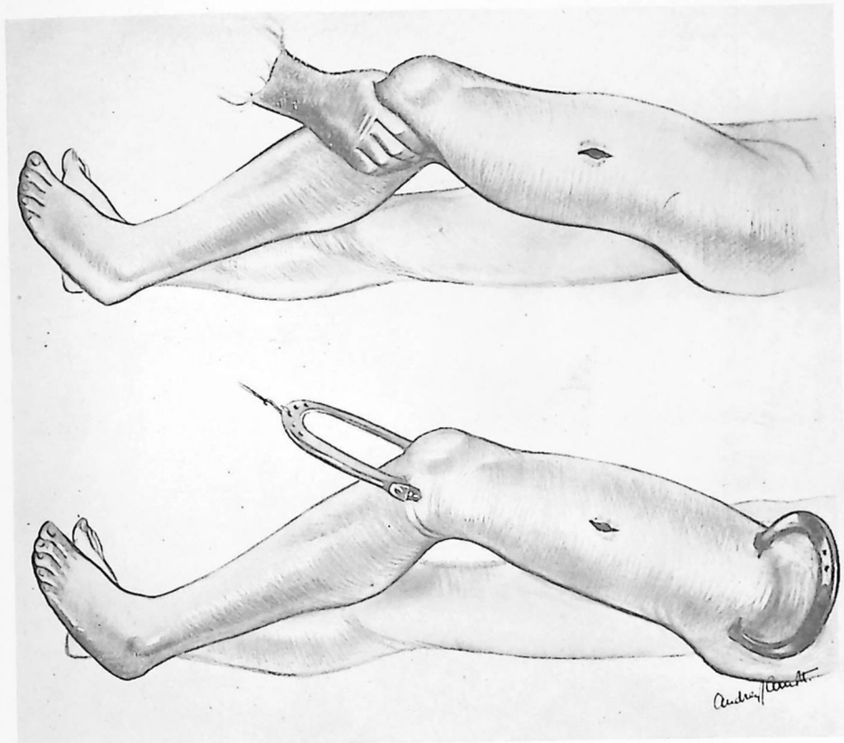


Fig. 27.—Excision of wound in a case of compound fracture of the femur produced by splinter. The thigh is placed under traction to bring the tissues into their normal arrangement and facilitate the recognition of anatomical structures. (See also Figs. 28 to 37.)

(see Fig. 30). In most cases it is enough to excise 3 or 4 mm. of skin from each side, but occasionally the lack of vascularity makes it necessary to remove a wider strip. I mention the excision of the skin at this point because this is a complementary part of the initial incision and is best carried out at this early stage of the operation, before the surgeon proceeds with his exploratory examination of the wound.

The wound must be carefully explored through each successive layer of tissues from the skin to the bottom of the wound, which generally

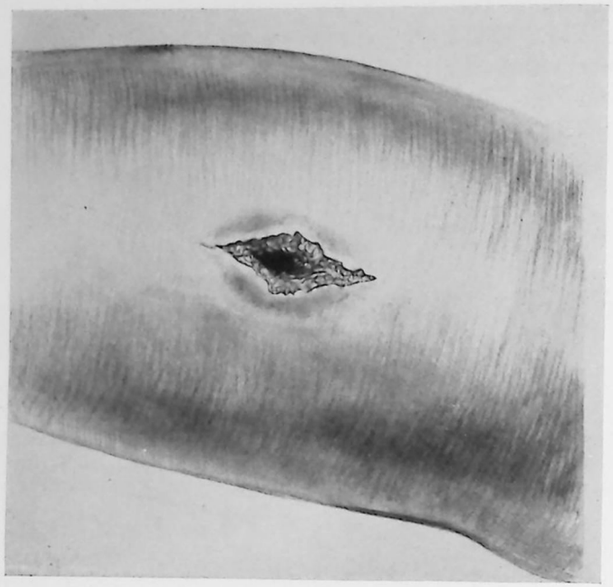


Fig. 28.—The same wound before operation; note the limited damage to the skin.

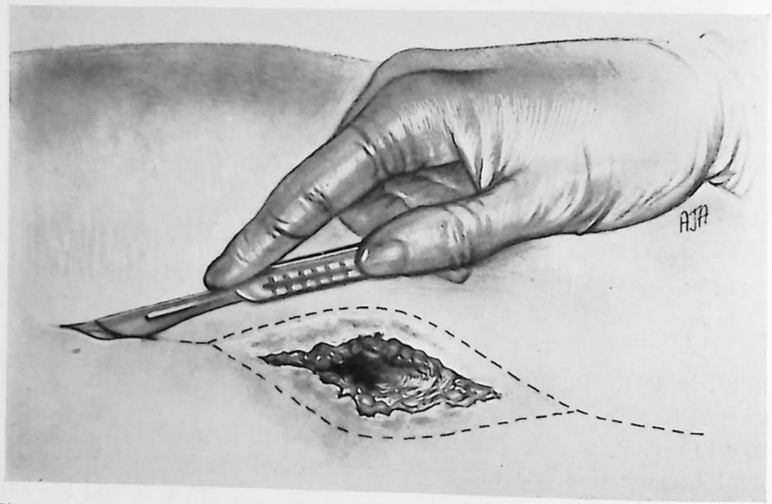


Fig. 29.—Exploratory incision of the skin. The length of the incision should depend on the type of injury and the region.

means to the bone, the most careful examination of all being made of the muscles. Thorough exploration of deep wounds is facilitated by separating the edges of the skin, either with fixed skin retractors or with aluminum retractors which can be adapted to the shape and depth of the wound. The examination of each layer is immediately followed by the excision of the dead tissues in that layer, and the operation continues plane by plane, in the sequence of incision, examination, and excision, until finally—if the wound extends to this depth—an unrestricted view is obtained of the bone.

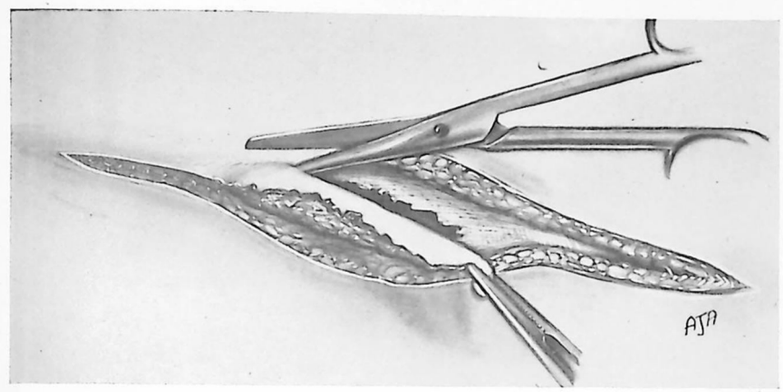


Fig. 30.—A narrow strip of the skin edge is excised with scissors or a knife.

Superficial aponeuroses require enlargement just as much as, if not more than, the skin, for they have little elasticity and so tend to increase the constriction of the muscles caused by traumatic edema. Consequently the surgeon should not hesitate to make a long incision in the superficial fascia with a knife or scissors; I prefer the scissors, as with them there is less risk of damaging the structures immediately beneath the aponeuroses (see Figs. 31 and 32).

In most wounds in muscular regions, such as the thigh, buttock and arm, the surgeon has to carry the incision to the deeper fascia, carefully dividing the muscles and taking special pains not to damage their supplying arteries and nerves. The muscle spaces must be opened up with a non-traumatic instrument, such as a Kocher spatula; the knife should be used only when the muscle must be divided. This stage of the operation is not difficult but must be carried out with care; thus, layer by layer into the deeper structures, the enlargement of the wound proceeds, followed at each stage by close inspection and the appropriate excision (see Fig. 33).

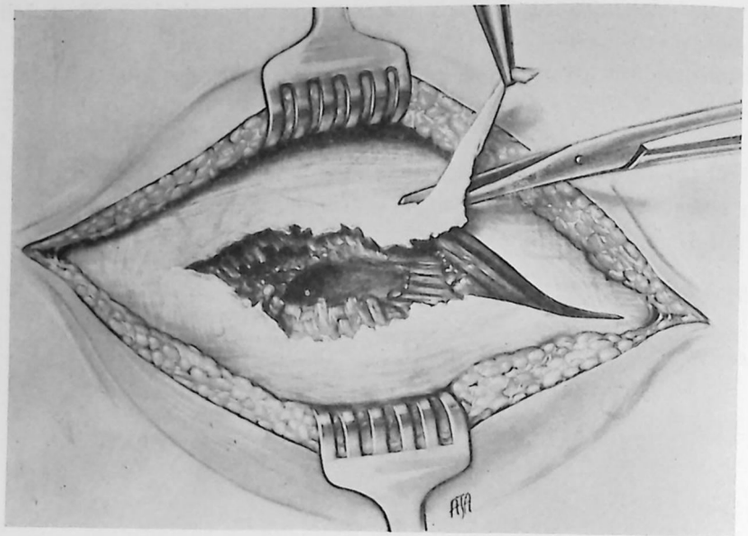


Fig. 31.—The skin is pulled apart with retractors. The fascia is widely incised-excised.

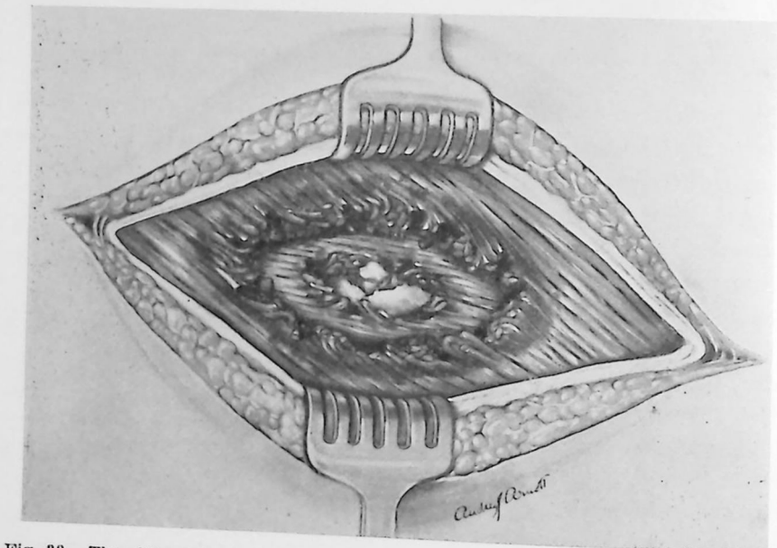


Fig. 32.—The skin and fascia are separated, facilitating exploration of the muscular damage. Hereafter it is better to perform the excision with scissors only.

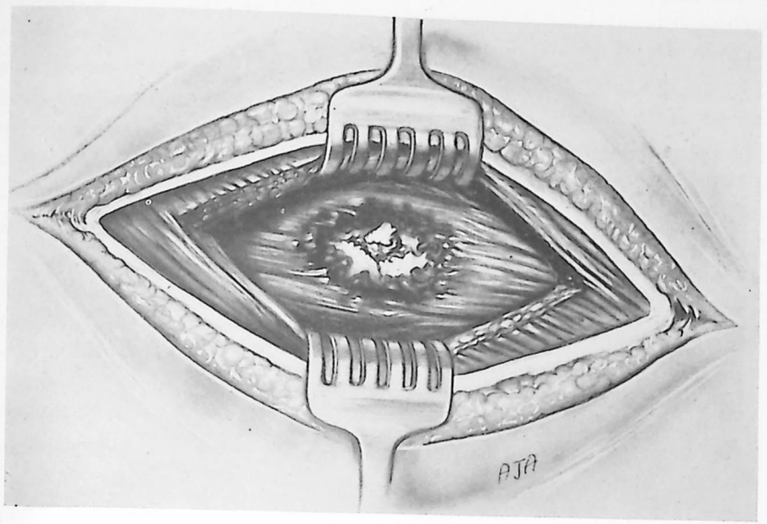


Fig. 33.—The first muscular layer has been clearly excised beyond the area of concussion. The deep muscle is now explored.

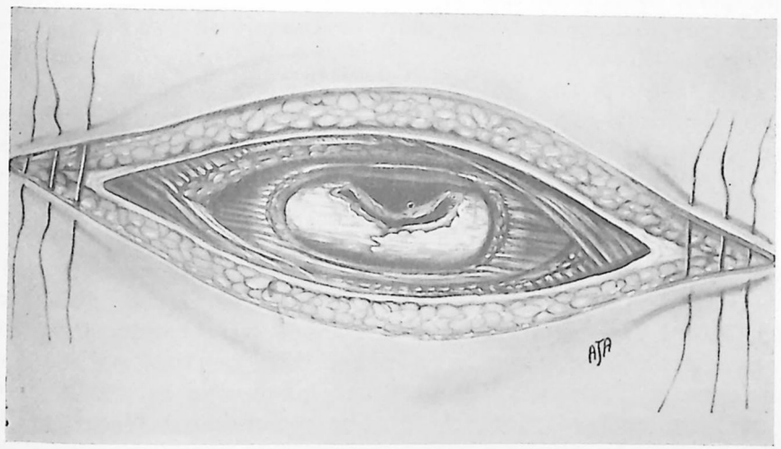


Fig. 34.—The deep muscle and fragments of bone free from muscular or periosteal attachments have been excised. The edges of the gap left in the bone by the removal of devitalized fragments are regular, and the bony marrow is cleaned. Some stitches are placed at the ends of the wound where the skin has been *incised* only.

The periosteum must never be incised. The connections between the deep muscles and the periosteum should as far as possible be left intact, for they are of great value in carrying nutriment to the bone.

In an irregular through-and-through wound, it is better to begin enlarging from the side of the bigger wound, which is ordinarily the exit wound. The greater destruction of tissues will be on this side. Having reached the bone from this side and after excising all devitalized tissues, the surgeon then proceeds with the operation on the side of entry. Thus the bone is exposed from both sides, and this often simplifies the excision of detached fragments (see Fig. 34).

The general rules for enlargement can be applied to wounds in all regions, with slight modifications in certain cases, as, for instance, wounds in the hand and the lower forearm. Here, in view of the functional importance of the tendons and the vital necessity of causing no damage to the tendon sheath, the range of the incision-excision must be more restricted; moreover, in these areas the absence of great masses of muscle, and particularly of long muscles, justifies a more limited operation.

EXCISION

The excision of all devitalized tissues is the basic factor in the treatment of war wounds. The patient's progress, good or bad, bears a direct relation to the skill and thoroughness of this excision. It is the most difficult part of the operative procedure, because the degree of tissue damage varies enormously and every wound has its special features. Obviously it is impossible to deal with every contingency that may arise; nor indeed is it necessary to do more than set out the general principles. It is only from direct teaching in the operating room by a surgeon experienced in the technique that the student can learn the necessary details and avoid the mistakes which any inexperienced surgeon is bound to make in his first cases.

I am convinced that the chief cause of the many surgical disasters of the War of 1914 to 1918, which gave rise to endless discussions on the infective properties of the Flanders soil, was that the technique of excision was not properly understood. The war in Catalonia provided us in Spain with the opportunity of proving, as I believe, beyond dispute the vital importance of proper excision. When the war began, the only experience which the vast majority of surgeons there had had was confined to peacetime injuries. These never show either the deep penetration or the extensive bruising and spasmodic ischemia that are found in war wounds, particularly in those caused by aerial bombs and high explosive shells; and consequently they require less extensive incision and excision, and in many instances can safely be

closed by primary suture. In dealing with their first cases of war wounds the Spanish surgeons not unnaturally applied the methods that have served so well in peacetime, with the consequence that their initial results were very bad. Quickly realizing that the treatment must be adapted to the special features of war wounds, they introduced radical changes into their technique and into the whole organization for dealing with casualties. This led to an immediate improvement in results, and the "antiseptic value" of wound excision was re-established on an even firmer basis than it had been in the later stages of the War of 1914 to 1918.

My observations both in Spain and in Britain have convinced me that a number of the infective complications which have occurred, particularly gas gangrene, have been due to insufficiently thorough excision, which in its turn was in most cases due to an inadequate previous enlargement of the wound. Among more than 200 cases of serious wounds (almost exclusively compound fractures) treated during the last two years by the staff of the Wingfield-Morris Orthopaedic Hospital, there has not been a single case of gas gangrene. The divergent results in different hospitals during these first two years of the present war might well give rise to another series of discussions on the infectivity or sterility of the soil in various parts of the country; whereas in fact the feature of supreme, if not sole, importance is the thoroughness, skill and care with which devitalized tissues are excised.

Technique of Excision

Excision alternates with enlargement, and in each successive layer of tissues is carried out immediately after the incision and examination of the layer. Only when the periosteum is reached does the surgeon cease enlarging and start immediately with excision of the devitalized tissue.

The general principles on which the excision of the various tissues should be based are as follows:

Skin.—We need to be very conservative with the skin, because this tissue has a very rich blood supply and a high power of resistance to infection. Apart from exceptional cases, not more than 3 or 4 mm. should be excised beyond the edges of the wound (see Fig. 30). Even in those areas where the skin is thin and has a relatively poor blood supply, as on the dorsal aspect of the foot, undue excision must be avoided. Secondary necrosis of the skin may often occur without giving rise to infective complications, provided that the underlying tissues are properly excised. Excessive excision of the skin deprives the wound—and, particularly important, the bone—of valuable protection,

and also necessitates skin grafts at a later stage. Scissors are the best instruments with which to excise the skin, being quicker than a knife and making a more even cut.

Cellular Tissue and Fascia.—The excision of the subcutaneous tissue must be bold and unsparing (see Fig. 31). This tissue is relatively unimportant, and the ease with which it is infected by hemolytic streptococci demands the radical excision of even those portions which have been only slightly damaged. The surgeon must keep a special lookout for the hematomas which form in this tissue; they are often small and very numerous and occupy the intermuscular spaces. They must all be excised, since they provide a good culture medium for anaerobic bacteria and, if not removed, will lead to infective complications.

Tendons.—Only ruptured and bruised tendons should be excised. Tendons in which the damage is confined to a limited area must be only partially excised, all fibers that can be preserved being retained. The degree of functional recovery after excision of one-half of the tendon fibers, particularly the extensors of the hands, is often surprising. With the flexors of the hand, however, the problem is more difficult, for here there is a serious risk of pyogenic infection in the tendon sheath; and so, notwithstanding its functional importance, the bruised sheath must be radically excised.

Nerves.—In dealing with damaged nerves the surgeon must adopt an extremely conservative attitude. Nerves are highly resistant to infection, and the loss of an undue length of one causes irreparable damage, for nerve transplantations in an area of scar tissue give very poor results.

Arteries.—Ideally, not a single artery that still functions as a blood channel should be destroyed. Unfortunately it is impossible to carry out excision without causing further damage to arteries, but great care must be taken to avoid cutting any artery that supplies either muscle or bone. Damaged arteries should be ligated if they are important, or clamped if this will stop the bleeding. Important arteries must never be sutured in the emergency operation. In some cases of traumatic aneurysm a suture may be used at a later operation after excision of the aneurysmal sac; but both end-to-end and lateral sutures of important arteries, performed in emergency war cases, are always failures.

Muscles.—Excision of muscles is the most important stage of the operation. Wound damage in muscles is of two types: first, bruising over a zone of destruction caused by direct action; and secondly, in a more remote area, vascular spasm in which the arterioles and capillaries are contracted as a result of traumatic stimulation of the sympathetic nervous system. In the first of these areas the blood supply has been completely interrupted and the muscular fibers cannot survive for more than a very short time. The excision in this area must, therefore, be radical (see Figs. 32 and 33). In the second area the muscles are still supplied with blood, but the amount circulating in them is reduced by the spasmodic action of the sympathetic nerves; and, when edema develops, the tension may still further decrease their nutrition with serious consequences. The wide area and indeterminate limits of the spasm make excision of all affected muscles impossible, and yet it is not sufficient to confine the excision exclusively to the bruised tissues.

The right course of action is to extend the line of excision to a point slightly beyond the limit of anatomical damage so as to include those portions of the muscle which are most seriously affected by the spasm. When a long muscle has been completely divided by a trauma, the tissues in the distal part require more drastic excision than those in the proximal part, owing to their greater loss of blood supply. Muscles should be excised with scissors. If in a relatively healthy area a muscle is cut with a knife, the individual fibers retract instantly, leaving an irregular plane of section, and clots tend to collect among the uneven ends. Scissors obviate this risk and make an even cut, causing a uniform retraction of the whole muscle.

Three signs guide the surgeon in the excision of muscles:

1. **Color.**—Ischemic muscles are always, even in the relatively early stages, darker than the normal muscle. In some cases, particularly when very little time has elapsed between the injury and the operation, the fibers retain their bright red tone and the only appreciable change in color will be bluish interstitial hematomas. The older the wound, the darker the color of the devitalized muscle, which in some cases turns completely black. In the area of spasm the affected muscles are often slightly paler than normal, but at an early stage no important change of color will be noticeable.

2. **Contractility to Mechanical Stimulation.**—Any muscle that has lost its power of contractility to stimulation with an instrument is either already dead or dying. With a certain amount of practice the contractile power of the muscular fibers can be assessed when the surgeon is excising with the scissors. Any piece of muscle that does not contract when cut in this way must be considered dead, and a further portion must be excised.

3. **Bleeding Capacity.**—Bleeding capacity is the most reliable indication of the vital condition of the muscles. After the first portion has been excised, the sectioned ends of the fibers must be carefully ex-

amined. If no blood appears at these ends, further portions must be excised until bleeding is observed. It must be remembered that the amount of bleeding from the normal muscle is in most cases only small, and that it is further diminished if the arteries are affected by traumatic spasm. A gentle oozing from the cut end is a sufficient indication that the right line of excision has been reached.

These three signs, taken in conjunction, indicate the vital condition of the wound. The difference of color between the healthy and the devitalized muscle guides the surgeon's hand in the initial excision, and the contractile capacity of the fibers and the bleeding from the sectioned ends indicate whether the excision is adequate. The area first excised is often shown to be insufficient by the subsequent tests of contractility and bleeding capacity, and a further excision parallel with the first is required. In the short muscles contraction, even under normal conditions, is almost imperceptible, and the surgeon must rely on the bleeding capacity.

Excision of Bone

The low resistance to infection, the porous character and the rigid structure of bone facilitate the onset of persistent pyogenic bacterial colonization. The cortex of the shaft is so compact that, when it is isolated from its original blood supply, newly formed vessels are often unable to penetrate it. The areas requiring excision must, therefore, be determined with the greatest care and accuracy, the line of demarcation between the portions that need to be retained and those that must be excised being very narrow. On the one hand, any piece of bone that is detached from the periosteum or muscular attachments must be removed (see Fig. 34); on the other hand, any fragment that retains its attachment to the periosteum or to the muscular insertions must be preserved, to avoid the risk of pseudarthrosis. The ends of the fragments must be evened with rongeurs and the pieces replaced in their normal position. At this stage sulfanilamide may be blown in with advantage (see p. 201 and Fig. 35).

Here, however, an important point should be borne in mind. If all the fragments can be preserved, and if each is replaced in exactly its normal position, there will be no possible outlet from the medullary cavity; and since this is invariably contaminated at the time of trauma and the bone has been deprived of its covering of soft tissues, particularly of muscles, both by the trauma and the excision, osteomyelitis is likely to develop. For this reason, it is wise in such cases to resect some of the most mobile fragments and so provide an opening for drainage from the medullary cavity.

In some cases, in spite of serious damage to the soft tissues, the bone has only a simple fracture with two fragments. Where the muscle damage is severe and the excision has to be very extensive, the bone will be left for a considerable period without any covering. Consequently, if in these conditions the ends of the fragments have lost their periosteum, it is advisable to resect a lateral portion of the cortex on each fragment, so as to prevent the retention in the medullar cavity of any contaminated fluid.

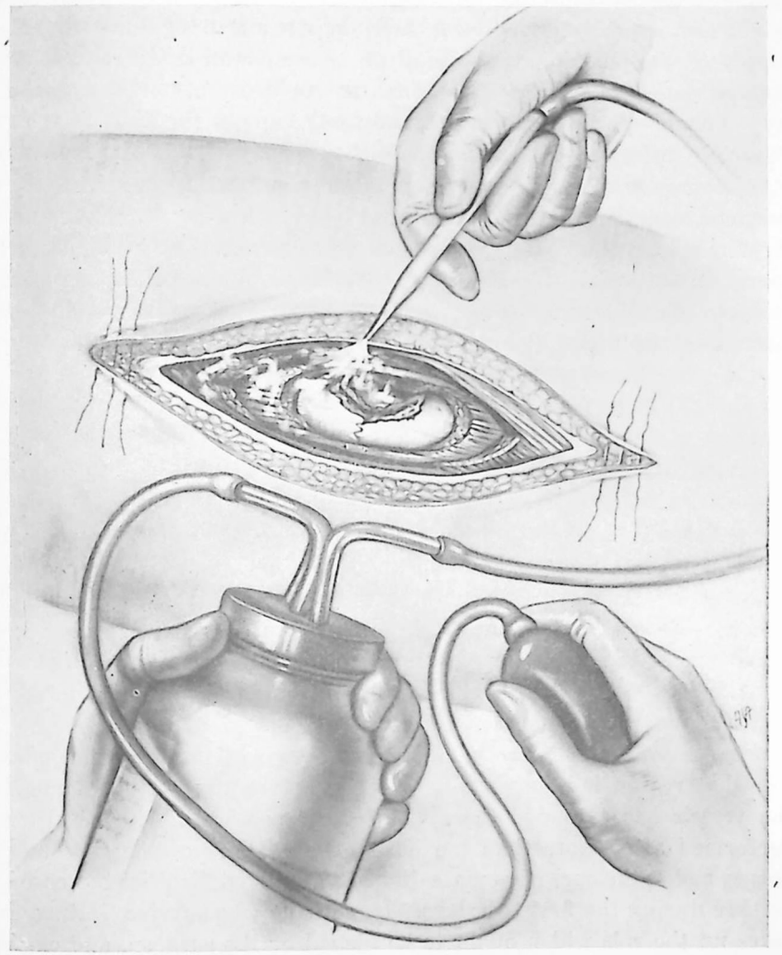


Fig. 35.—Sulfanilamide powder may be blown into the wound. The layer of powder should be thin and uniform.

Any portion of the periosteum that retains its attachment to the surrounding tissues must be scrupulously preserved. The periosteum receives all its blood supply through the surrounding tissues, and in its turn supplies the cortex which lies beneath it—especially the shafts of

long bones. Accordingly, if a piece of bone has to be excised, the cortex should first be separated from the periosteum, so that the blood vessels which supply the periosteum may be preserved intact to facilitate the formation of new bone beneath it.

Since the time of Duhamel, and more particularly that of Ollier, conservation of the periosteum has been recognized as a fundamental principle of surgical technique, but since good vascularity is essential for the production of callus, it is still more important to preserve the blood supply of the periosteum, especially in a compound fracture, where the greatest possible local vitality is needed to resist bacterial aggression. Any damage to this blood supply not only exposes the bone to the risk of serious infection, but also hinders the consolidation of the fragments.

In emergency work, especially after aerial attack against towns, previous examination of the fractured bone with x-rays is seldom necessary. On the contrary, the surgeon who systematically performs the operation with the x-ray film in view tries to approach the bone looking more to the radiograph than to the wound. The point which really matters is the direct examination of the wound. In articular wounds, on the other hand, an x-ray film is a great help.

Excision and Time

Obviously, excision is most effective in preventing infection when it is done early. No change in the vascularization of wounded tissues occurs during the first four hours after the production of the wound. After that, extension of the damage depends mainly on the degree of bruising and especially of crushing of the muscles. After four hours, infective anaerobic complications may develop if there has been great initial impairment of the blood supply, but in all war wounds after eight hours of injury inflammatory changes appear in variable degree and increase the area of devitalization. The cause of this secondary interference with the blood supply is progressive infective thrombosis. For that reason it is important to excise before any further damage in the vessels has extended the area of devitalization. When excision is performed after more than ten hours, the swelling of the surrounding tissues makes the operation more difficult, and the difficulties increase still further during the first two days. In patients who survive, Nature then takes up the role which ought to be played by the surgeon, and excision is brought about by sloughing and progressive suppuration.

Whether or not a delayed excision after 24 hours is justified, depends on the aspect and characteristics of the wound. The majority of wounds should be incised and explored whatever the time, and the surgeon should determine whether the wound needs excision or not. I personally do not accept the common view that a wound should never be excised

after the first 24 hours. The reason for this apparently conservative attitude dates back to the last war, when wounded soldiers died from septicemia after delayed excision. This was due to the massive absorption of pyogenic bacteria when the defensive barriers established round the wound were broken down. I have not lost any patient after delayed excision, even in the days before I used sulfanilamide, but I have always immediately immobilized the limb in a plaster-of-Paris cast. The success of the procedure appears, then, to have been due to immobilization. Patients operated on in this late period have a rise of temperature for several days, but this soon subsides with the marked decrease in absorption which the plaster effects.

The advantage of excision in these cases is that the wound is left without any favorable culture medium for bacterial colonization, the defensive mechanisms can act at full strength because the blood is supplied to all corners and pockets of the wound, and drainage can be established in the most convenient way. Even surgeons who object to late excision will not hesitate to perform thorough muscle excision, no matter how long a time has elapsed, when gas gangrene is developing; and to those who think the dangers of excision greater in pyogenic infections I recall the excision of bony tissue in osteomyelitis.

I do not pretend to lay down a general rule on this point, believing that every case must be considered on its own merits. If much inflammatory reaction results from infection without major tissue necrosis, operation must be limited to drainage after convenient enlargement, but all necrotic tissue should be eliminated to diminish the risk of complications. After 48 hours excision must be limited to the elimination of dead tissues without interfering with the layer of healthy tissues which surround the necrotic ones. A pair of scissors is the best instrument. An untreated patient who survives 48 hours without signs of anaerobic infection will probably escape gas gangrene.

CHAPTER XVII

DRAINAGE

The surgeon's chief concern in treating war wounds is the removal of foreign bodies from the wounds themselves or the surrounding tissues. During the War of 1914 to 1918 this surgical measure was directed largely to inorganic foreign bodies, such as bullets and pieces of shrapnel. Today, however, we know that these are of secondary importance compared with organic foreign bodies such, for instance, as pieces of clothing, splinters of wood, and, above all, pieces of devitalized tissue and collections of contaminated fluids.

The tissue fluids are powerfully bactericidal and very similar in composition to lymph. The purpose of their appearance in a wound is clearly defense against bacterial infection, for they are rich in antibodies, being in this respect inferior only to the blood itself. Once, however, the circuit which is comprised by the blood, the tissue fluids and the lymph is broken, the bactericidal capacity becomes progressively less. Consequently a wound, by breaking this circuit, collects tissue fluids as harmful as devitalized tissue. It cannot be too strongly emphasized that these fluids constitute a valuable defense against bacterial invasion only when they are confined to their proper place within the tissues; once they emerge from the tissues they immediately become a "foreign body" and as such must always be removed. The purpose of drainage is to prevent the retention of these fluids, which, in spite of their original defensive character, come to serve as an ideal culture medium.

There are two main methods of providing drainage for cavities and cellular spaces. In the first, known as dependent drainage, the fluids are evacuated by gravity; and in the second, drainage is accomplished by suction or aspiration, a method which is less commonly used but is often more effective. In ancient times drainage by gravity was the only method used. The drainage tube was first described by Pietro d'Argelata at the beginning of the 15th century, but it was used only intermittently in the subsequent periods until in the 19th century Chaissaignac again described it (see Billroth, 1871). Soon afterwards the use of drainage tubes was widely extended by the influence of Lister, who recommended the rubber tube as the best device. Surgeons later used a piece of striated rubber, cut in long, narrow strips and inserted in the

wound in the same way as the rubber tube. More recently Winnett Orr popularized the vaselined gauze pack as a means of draining wounds widely opened by incision.

These procedures are all based on gravity and require an opening at the most dependent part of the wound. This has serious disadvantages in war wounds, for in many cases it would be necessary for the surgeon to make new incisions outside the wound in an already much-damaged limb, and thus interfere with the nutrition of the tissues surrounding the wound. Moreover, with any of these methods some discharge is bound to be retained in pockets which are not at the most dependent part, and this will encourage bacterial reproduction. Drainage by gravity is undoubtedly the best method in infected wounds in which the discharge is copious, but drainage by suction leads to better results in wounds treated before infection has begun. Even a small amount of discharge is sufficient to allow bacteria to multiply, and consequently all wounds treated before infection should be kept absolutely dry. Drainage by suction will do this if properly applied.

A cavity with a narrow opening can be effectively drained by an aspirator or pump similar to those used to empty the pleura or stomach. A widely open wound, however, such as is produced by extensive excision, cannot be drained in this way, owing to the impossibility of obtaining the necessary vacuum, and the only satisfactory method of drainage in such cases is that afforded by the suction of a piece of highly absorbent gauze.

Plaster Drainage

The provision of adequate drainage, not only for the tissue fluids that have to be evacuated but also for the extravasated blood which fills every small corner of the wound, demands a special technique. The absorbent capacity of gauze, however high, is not unlimited, and consequently after a while it will be unable to absorb any further discharge. If the discharge is not to be retained in the wound, the gauze must be supplemented by some other substance still more absorbent than itself. Here the plaster cast provides one of its many advantages, for good plaster of Paris is very absorbent. It is important that the plaster should be applied in direct contact with the gauze, and its quality must be good; some brands on the market have little or no absorbent capacity. In treating compound fractures by the methods I describe, a nonhydrated plaster of Paris of the type called "alabaster" should be used, for this when set is highly absorbent, as indicated by the rapid dark staining of the outer surface of the cast.

This quick absorption of the initial blood and lymph exuded from the wound is of very great value; in fact, in my hospital in Barcelona

my assistants used to base their prognosis on the appearance of the plaster the day after operation. When the plaster was stained with blood at this early stage the patient nearly always made a good recovery. Moreover, if the exudate is rapidly absorbed the offensive smell will not appear, and when the plaster is changed the wound will be found dry and healthy.

In some deep wounds operated on towards the limit of the optimum time, i.e., between six and eight hours after injury, if the opening of the wound is situated on the upper surface of the limb, suction drainage is not sufficient to eliminate the discharge and must be supplemented by a form of gravity drainage applied to the bottom of the wound. In such cases the best method is to insert a narrow strip of striated rubber of appropriate size at the most dependent part, passing this out through a small incision in the skin. To avoid excessive saturation of the plaster by the discharge in cases operated on after more than eight hours, it is advisable to pass the external end of the rubber strip through a small hole in the plaster; the end is then covered with sterile gauze and cotton wool. As soon as this counterdrainage is no longer necessary (often after four to six days), the rubber strip can be withdrawn without interfering with the plaster, the small hole in the plaster being closed with plaster paste.

In wounds operated on before infection has begun and where the proper technique has been applied, suction drainage is so effective that unless a very close-meshed gauze is used, similar to that from which good quality bandages are made, the granulation tissue will grow through the mesh, making it difficult to remove the gauze when the time comes to change to plaster.

In infected cases, on the other hand, dry gauze is not so effective, because its capacity of absorption is not sufficient, even with the help of the plaster, to eliminate all the copious discharge; and so it acts as a "foreign body" and tends to be colonized by bacteria. The drainage afforded by a gauze pack coated with vaseline or paraffin, supplemented by a rubber tube to provide counterdrainage, gives better results.

Technique of Drainage

The first step in the provision of drainage is taken at the time of excision, when the surgeon should carefully study the lie of the wound and its special features, particularly its depth and irregularity, and should decide on the type and location of the drainage to be used and whether counterdrainage is necessary.

The easiest way of having the material for drainage ready for all possible needs is to sterilize a 6-inch bandage of good quality. From this

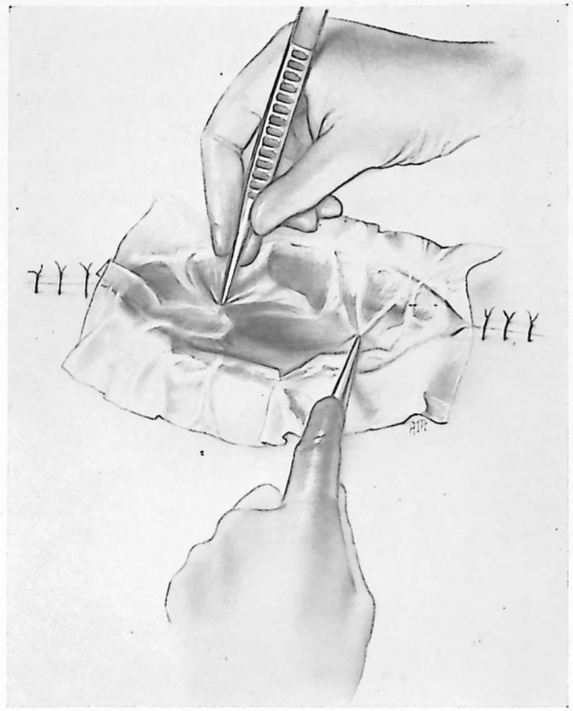


Fig. 36.—A layer of dry, close-mesh gauze, cut from a good quality bandage is applied to the depths of the wound.

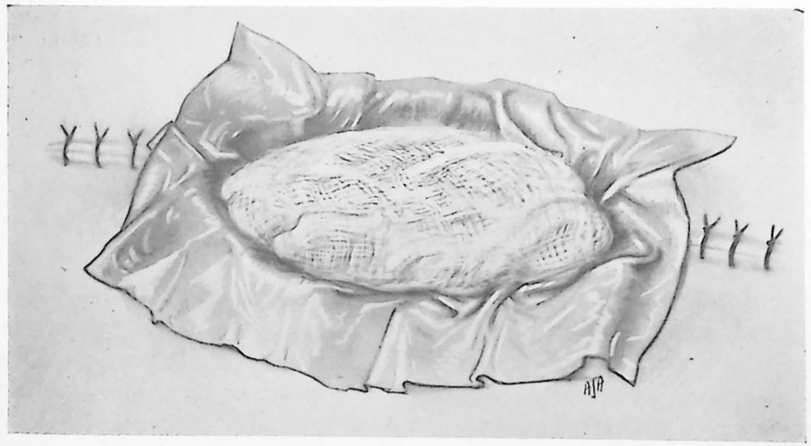


Fig. 37.—The cavity left by the excision of the bruised tissues is filled with a pack of ordinary gauze. This makes a prominence above the surface of the skin, and will be slightly compressed when the plaster is applied.

bandage is cut the first layer of gauze needed for drainage. This piece is cut much larger than the wound, put flat over the surface and pushed in with a couple of forceps (see Fig. 36). Then the concavity in the gauze is filled with ordinary sterile gauze until this reaches the level of the skin or, still better, above it (see Fig. 37). The application of the plaster cast in direct contact with the skin and gauze secures the absorption of the small amount of discharge which comes from a properly excised wound before infection develops. Not much pressure is necessary; the requirement is contact, not pressure.

Fig. 38.—Compound fracture of tibia and fibula operated on four hours after injury. Wound cleaned with soap and water; excised and drained with plain gauze. Fixation of the fragments with two Steinmann pins and application of plaster. Photograph taken one month after the operation. Note the plaster stained with blood. No discharge and no smell. (See also Figs. 39 to 41.)

In planning how and where to apply counterdrainage where this is indicated, while due consideration must be paid to gravity, the anatomical arrangements of the wounded region must also be very carefully taken into account. Counterdrainage must never be placed near a main artery or an important nerve; in a certain number of infected cases I have found that the proximity of the rubber to one of these structures has caused secondary hemorrhage. To prevent this it is wiser to insert a narrow strip of vaselined gauze instead of the rubber.

Counterdrainage

The best method of inserting a rubber wick for counterdrainage is as follows. The limb is placed in the position which it will occupy in the bed. A long and slightly curved forceps is passed to the bottom of the wound, and carefully and gently pushed down between the tissues, always being passed, if possible, through the intermuscular spaces so as to avoid damaging the muscle fibers, until finally it makes a

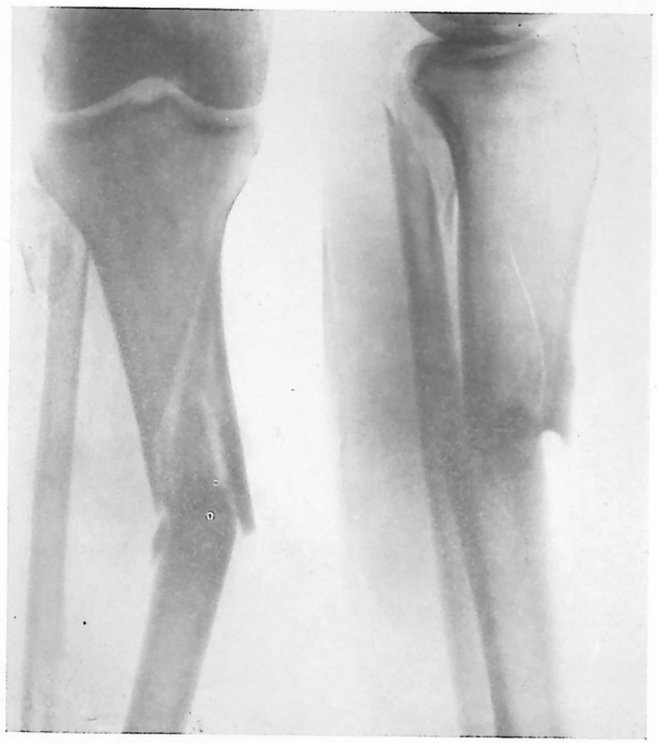


Fig. 39.—Radiograph of same case.

prominence on the skin on the dependent side. Here an incision is made in the skin and fascia and the forceps is pushed through. The tunnel thus made is slightly expanded by opening the forceps, which is then drawn back grasping one end of the rubber wick or vaselined gauze. The position of the wick should be such that it will be capable of draining off all the fluid without any assistance by manipulation or compression, for need of these is a sure indication that the drainage is not adequate. Occasionally a wound of irregular shape will require more than one wick to provide sufficient counterdrainage.

Orr's Technique

Orr's technique of vaselined gauze is satisfactory in infected wounds, which should first be incised and enlarged. The gauze, coated with vaseline, should be packed tightly into the wound so as to fill the whole depth and to keep the walls well apart. A flat layer of vaselined gauze is then laid over the packing, and finally the plaster is applied in contact with this layer. If the discharge is not unduly abundant I prefer to use paraffin rather than vaseline, since this, being more fluid, is more successful in penetrating to the corners.

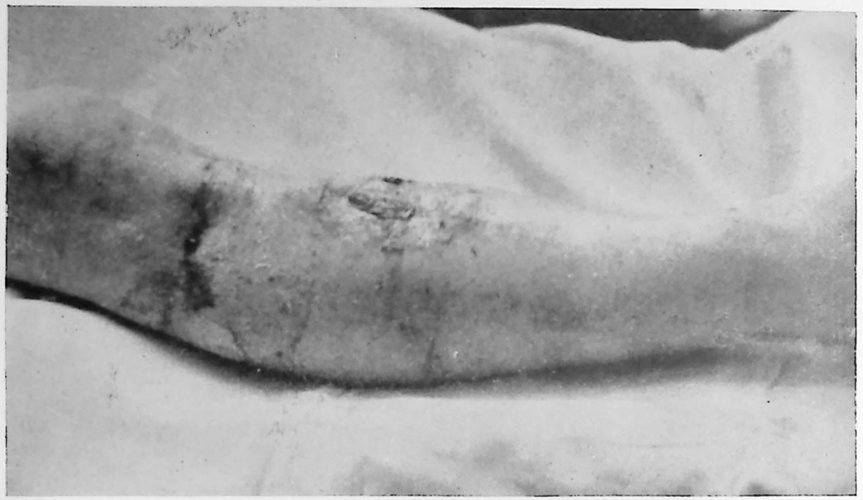


Fig. 40.—At the removal of the pins and first plaster, two months afterward, the wound is almost healed and the fracture is united by a callus still slightly elastic. A guarding plaster below the knee is applied.

Changing the Gauze

In normal circumstances a clean wound drained by dry gauze should not be disturbed during the early stages of healing, and the first drainage gauze and the plaster should be left in position for several weeks (4 to 6 on the average). If on removal of the plaster at the end of this time the drainage gauze, in spite of the close mesh, adheres to the surface of the wound, an application of peroxide for 10 to 15 minutes will enable the dresser to remove it without damaging the granulations or causing more than slight bleeding. In some instances, and particularly in fractures of the leg that have been pinned, the small amount of discharge and the absence of smell or any discomfort make it possible for the first plaster to be retained until the consolidation of the fracture is complete. It is not advisable, however, to leave the first drainage gauze in position for longer than 6 weeks, and in such cases, therefore, a window should be cut in the plaster at the end of this period and the gauze removed through it.

The new drainage gauze may be either dry or coated with paraffin or vaseline, according to the amount of discharge found on uncovering the wound. If the wound is dry or almost dry it is best to use plain gauze, for this and the fresh plaster used to close the window will quickly absorb the small amount of new discharge which a change of drainage always stimulates. When, however, the wound is still discharging, gauze with vaseline or paraffin, according to the special features of the wound,

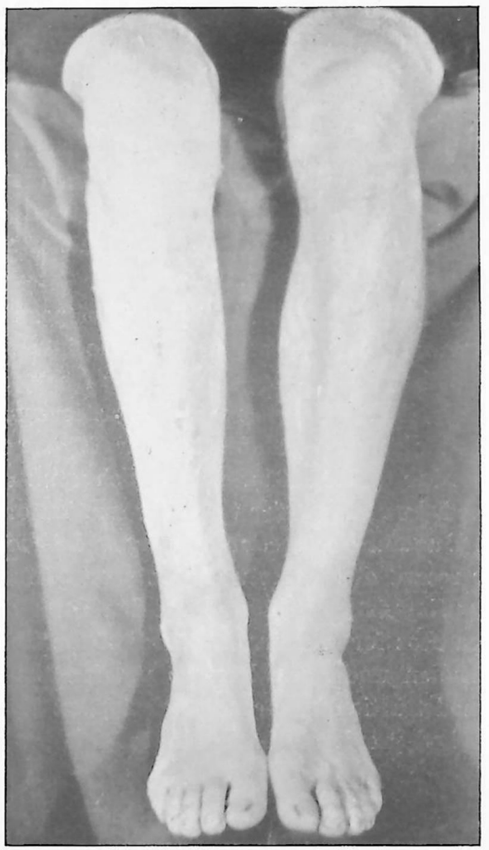


Fig. 41.—End result of case shown in Figs. 38 to 40. Photograph taken six months after injury.

should be used for the second drainage. If the wound is still deep I prefer paraffin, but when the granulations have nearly reached the level of the skin, it is better to use vaseline, as this is more persistent and has some favorable effect on epithelization.

Figs. 38 to 41 show one of the many examples of the evolution of a serious compound fracture when excision, drainage, and immobilization have been properly carried out.

CHAPTER XVIII

REDUCTION AND FIXATION OF FRACTURES

Whether in simple or in compound fractures, accurate restoration of the anatomical structure of the bone is a keystone of the patient's good and speedy recovery.

Reduction of fractures is obtained by traction, a fact which has always been recognized and on which special emphasis was laid by Guy de Chauliac, who as long ago as the 14th century described a device for maintaining such traction continuously. Traction in itself, however, will not secure a good position of the fragments: there must also be uniform tension of the muscles, for without this, traction causes deviation of the fragments owing to the different amounts of tension exercised by the various muscular attachments.

The first person to recognize the importance of posture in the treatment of fractures was Percival Pott (1769), who introduced a position of semiflexion of both thigh and leg for treating fractures of the femur. He used a double-inclined plane to relax the gastrocnemius and so prevent the backward displacement of the lower fragment. Some years later Robert Chessher (1750-1831), an English country surgeon, employed this method, but, except for the incorporation of the same principle by Gurdon Buck in his traction apparatus, I have been unable to find any further record of the postural treatment of fractures until its reintroduction by Zuppinger in 1906. Gurdon Buck devised the first really useful apparatus for reducing fractures of the femur: he applied a thick roller cushion under the knee to provide the double-inclined plane, and obtained traction by means of elastoplast affixed to the skin, a material which had previously been used for this purpose by Crosby.

Pin and Wire Traction

Traction effected through the skin was a great advance on previous methods, but in many cases it still proved inadequate. In 1897 Ransahoff introduced the "ice tongs" for skeletal traction, but it was soon abandoned. Early in the present century the Italian surgeon Codivalla described for the first time a method of traction by transfixion of anatomical structures. His apparatus consisted primarily of a narrow metal blade, which was inserted above the posterior tuberosity of the calcaneus and in front of the tendo achillis, and through which traction was applied. Before long two other systems embodying the same

principle were described, i.e., the Steinmann pin, published in 1911, and the Kirschner wire, which is better in certain cases.

Compound fractures need, if anything, even more perfect reduction than simple ones, owing to the importance of the local circulation in the fight against infection. The best means of obtaining good position is by the uniform pressure of muscles under traction, for these have a high splintage value. But in the treatment of compound fractures continuous traction has many disadvantages, some serious. The immobilization of the soft tissues is far from complete, the protection of the wound is inadequate, and the patient is necessarily confined to bed for a long period and requires much skilled handling, a particularly serious drawback in war conditions. During the War of 1914 to 1918 many hospital wards looked more like factory workshops than surgical centers, with Balkan frames over each bed and limbs hanging from a network of strings and pulleys and carrying numerous weights. In congested hospitals it was extremely difficult to give adequate supervision both to the wound and to the proper alignment of the fragments. Moreover, this cumbrous apparatus constituted a very serious obstacle to the evacuation of patients if and when this became necessary. A new technique was obviously required, one in which the beneficial effects of traction could be combined with complete immobilization of the limb, including the soft tissues, and a real protection of the wound, and which at the same time would facilitate immediate evacuation. All these requirements are provided when a plaster cast is used as a supplement to traction.

Plaster and Traction

Almost simultaneously Winnett Orr and Lorenz Böhler began to treat fractures by applying a plaster cast after reduction with a Steinmann pin or similar device, and including the pin in the plaster so as to immobilize this as well as the fragments. Böhler found that this technique involved little risk when the pins were absolutely immobile, and that the infective complications which sometimes developed at the site of the pin were almost always due to its incomplete immobilization. This technique was used mostly for simple fractures, but Orr applied it to infected compound fractures of the leg. Recently Anderson (1938) has been using a new method of external fixation based on a similar device employed by Lambotte (1913), transfixing the bone with pins from cortex to cortex and attaching a metal plate to each pair of pins; the plaster cast, which is a good substitute for lateral fixation, immobilizes the plates and pins, and consequently the fragments.

Unfortunately the Steinmann pin is not free from risk. I have myself seen enough local reactions (and, indeed, three cases of more serious

complications, two ended by amputation) to realize its limitations in compound fracture. The following is an illustrative case:

A man 41 years old was operated on for a compound fracture of the tibia and fibula and the wound was sutured. The leg was immobilized by traction through a Steinmann pin in the calcaneus. Considerable sepsis developed in the wound and round the pin, and eleven days afterwards the patient was admitted to the Wingfield-Morris Orthopaedic Hospital. The wound was drained and the calcaneus region opened up from both sides. A complete plaster was applied. The fracture of tibia and fibula healed correctly in normal time, but the osteomyelitis of the calcaneus, without giving rise to any general reaction, progressively destroyed the whole bone in spite of several operations. After many months of persistent suppuration, the ankle joint was stiff and the sinus persisted unhealed; the foot was painful and edematous. At that stage an amputation was decided on (see Fig. 42).

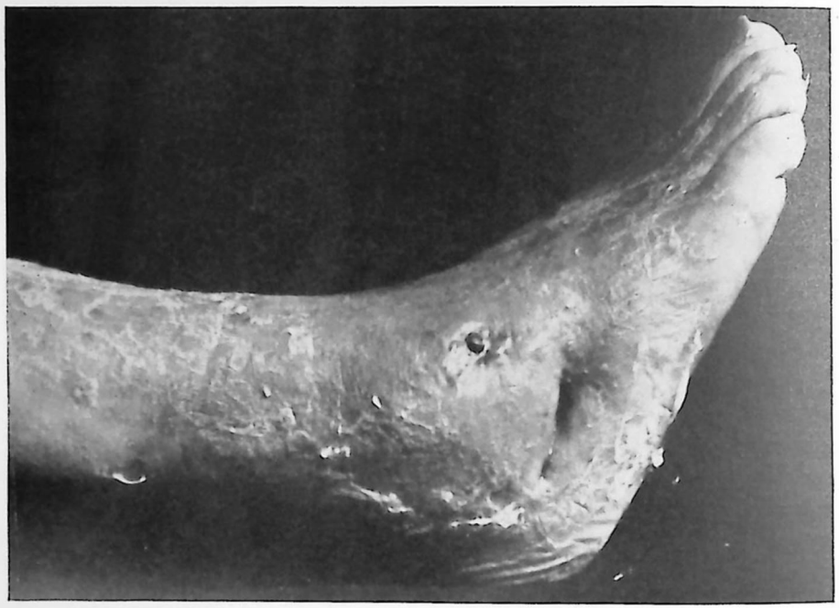


Fig. 42.—Osteomyelitis of calcaneus after the application of a Steinmann pin. After many months of treatment the foot had to be amputated.

There seems little doubt that the infection to which the pin is apt to give rise is due to the introduction of a "foreign body" of undue size; for it is well known that infection is less frequent when thin pins are used, provided they are completely immobilized. Strong traction, however, needs a strong pin, and the fractures which are in themselves most serious—those of the femur and tibia—are those which need the thicker pins. The Kirschner wire has an advantage over the Steinmann pin, in

that it permits strong traction with a relatively thin wire, but it also has the disadvantage that, in order to maintain the wire at tension, the "stirrup" has to be kept attached to it even after a plaster cast has been applied.

In my hospital in Barcelona I had a device, which I still use, to obviate this inconvenience. Inside the stirrup a simple form of clamp, to which is affixed a broad metal plate, is attached to the wire on each side of the limb. This plate is incorporated in the plaster (which naturally must be sufficiently strong at this level), and then, when the plaster is fully set, or preferably the day after its application, the stirrup is removed and the ends of the wire are cut off. The rigidity of the plates in the plaster is sufficient to keep the wire taut (see Figs. 43, 44, and 45). For further details see the description on p. 358.

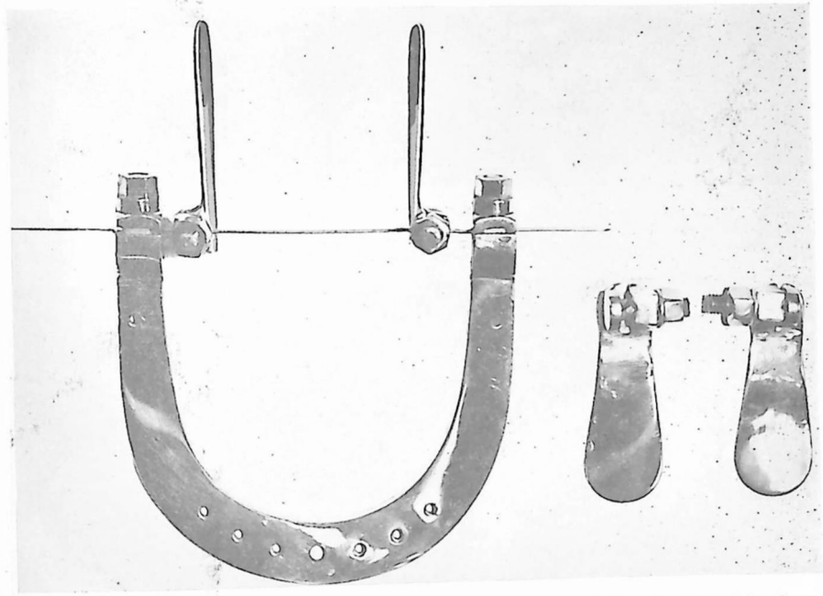


Fig. 43.—Plates fitted with a device similar to that which attaches the Kirschner wire to the stirrup: for fixing Kirschner wires to plaster casts. (See also Figs. 44 and 45.)

Operation Under Traction

All operations on war fractures should be performed under some kind of traction. This is an important rule which is only too often disregarded. Manual traction, with the hands of a trained assistant replacing the pin, is generally sufficient for fractures in the upper limb; but in a few cases, e.g., compound fractures of the head of the humerus, a Kirschner wire through the olecranon process providing traction, and

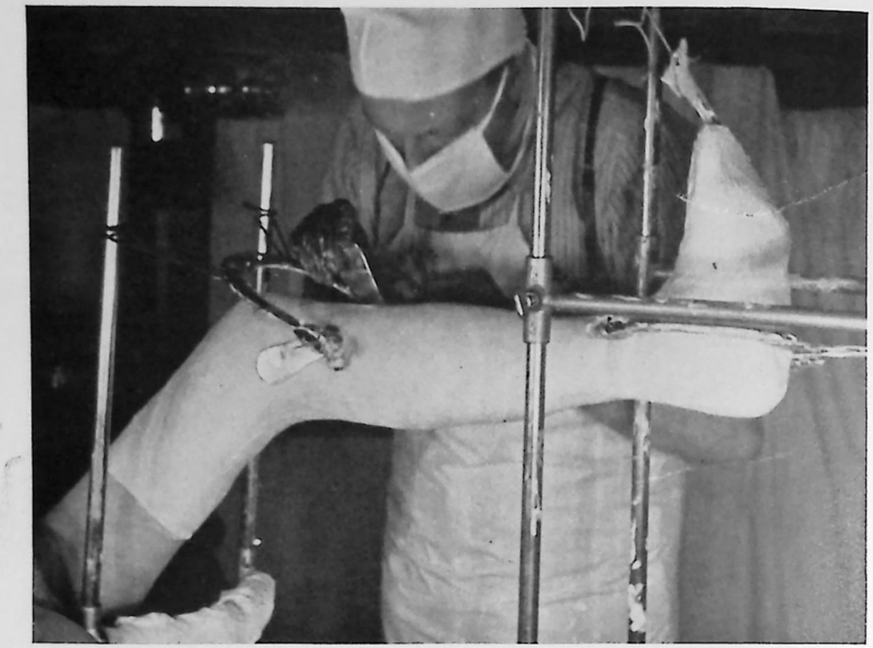


Fig. 44.—Traction is maintained by the stirrup, which tenses the Kirschner wire. Plaster is applied and, when it has completely set, the small plates are fixed in contact with its external surface.

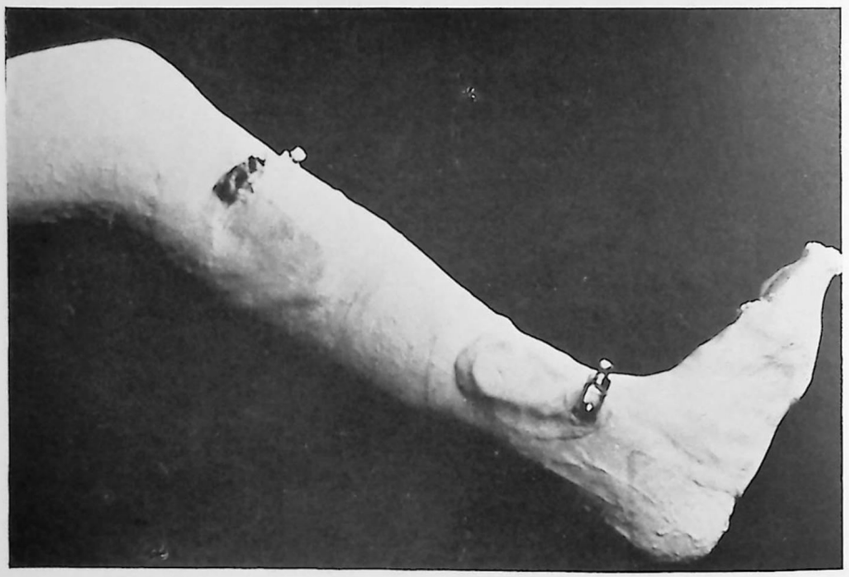


Fig. 45.—The plates are now fixed to the plaster with a few turns of plaster bandage. The stirrups are removed, the edges of the Kirschner wire cut, and the patient is free from external traction.

a strong bandage passed under the axilla and round the chest for countertraction, will greatly facilitate reduction, and particularly the application of plaster. In the lower limb, on the other hand, all compound fractures should be reduced under pin or wire traction, and the insertion of the pin or wire and its attachment to the traction apparatus of the orthopedic table (especially in fractures of the femur) should be the first stage of any operative procedure.

If an orthopedic table is not available, an extension apparatus of the Böhler type, which can be attached to any kind of table, should be used. If, however, either this apparatus or an orthopedic table is used for a fracture of the femur, some provision must be made for applying traction with the hip and knee joints in flexion. This can be done by a metal tube about 4 feet long, one end of which is fixed vertically in the traction apparatus of the table, while to the other end is attached the screw for foot traction found in most orthopedic tables. The patient is laid on the table with the pelvic support in position, the hip and knee are flexed, the appropriate degree of abduction is obtained in the thigh, and traction is applied from the screw at the upper end of the metal tube to a pin or wire passed through the superior epiphysis of the tibia.

In many cases of compound fracture caused by the high explosives of modern warfare the traumatic destruction of the soft tissues and the extensive excision which they require make it possible for the surgeon to reduce the fracture without much trouble. In fractures of the leg, particularly oblique fractures, the upward displacement of the plaster that commonly occurs is apt to cause overlapping of the fragments, and it is therefore advisable to insert a pin—or preferably a Kirschner wire—through the upper fragment of the tibia near the tubercle or to fix both upper and lower fragments, avoiding, however, the insertion of any pin in the calcaneus, owing to the danger of infection. In fractures of the femur there are various methods for preventing displacement of the fragments after reduction: Anderson's pins and plates, or a wire run vertically through the trochanter to fix the upper fragment and another through the lower fragment, or traction through the plaster by incorporating a small handle at the knee and suspending weights from this for the first month. It is, however, only those cases in which the wound is small and the muscles remain relatively intact which require these various forms of traction fixation. In the more serious cases, and particularly in fractures of the femur with much contusion of tissues, which require thorough excision and comminution, a good plaster-of-Paris cast and a proper degree of flexion in the hip and knee joints are generally sufficient to maintain the reduction. This technique is described more fully on p. 356.

The only cases which should be treated under traction without plaster are those in which the local condition of the tissues or the general condition of the limb when first seen is such as to render enclosure of the wound in plaster inadvisable owing to the risk of gas gangrene. This may occur in wounds of the thigh or leg. In wounds of the leg or thigh in which an arterial lesion endangers the circulation, it is wise to apply only skeletal traction at first, deferring the application of the plaster cast for a few days. In all other cases the limb should be enclosed in plaster immediately, while at the same time the beneficial effects of traction and postural treatment should be maintained. Detailed accounts of the methods of traction and immobilization most suitable for various types of injuries in the different limbs will be found in later chapters.

CHAPTER XIX

IMMOBILIZATION

Unlike most of the teachings of Hippocrates, the importance of rest was not "rediscovered" at the Renaissance, and, Magati's contribution apart, it was not until the last century, when John Hilton published his book *On Rest and Pain* (1863), that a complete study was made of its part in combating disease. In 1872 Ollier published the result of his treatment of war fractures by immobilization with plaster of Paris, and described rest as an essential therapeutic factor. About the same time Billroth (1871) was working on similar lines, using plasters with a window cut over the wound. Not, however, until the War of 1914 to 1918 was the vital importance of rest—and of rest in its best form, immobilization—universally accepted.

This great advance in surgical treatment was due largely to the work of Sir Robert Jones, who, appalled by the disastrous results of the early months of the war, introduced the splint which Hugh Owen Thomas (1886) had described in the last century and which had been almost forgotten in the intervening period. The immobilization afforded by the Thomas splint, in spite of its inadequacy for the soft tissues, produced greatly improved results and revealed once and for all the need for the best possible technique of immobilization. The other belligerent nations devised their own methods: the Germans took up the technique previously described by Billroth, using the windowed plaster (Schede, 1915; Braun, 1915, 1916); while the French used a combination of plaster and iron supports.

None of these methods, however, provided the complete immobilization afforded by the technique which Ollier had devised during the Franco-Prussian War; and it was not until after the War of 1914 to 1918 had ended that Winnett Orr introduced his epoch-making variant of Ollier's method, which immobilizes not only the bones but the soft tissues also. Orr recognized the value of rest as an antiphlogistic, and made this the basis of his treatment of osteomyelitis, immobilizing the affected limb by the only device which provides absolute and complete rest: a perfectly moulded plaster cast extending beyond the adjacent joint on both sides of the injured segment. In the treatment of traumatic wounds, complete immobilization is even more important than in osteomyelitis, since in these injuries, and especially in war wounds, the greatest risk to the patient lies not in the condition of the bone but in the infective complications which tend to arise in the soft tissues. To avoid these complica-

tions, absolute immobilization is necessary, a fact which was first brought home to me by my clinical experience in Barcelona and was subsequently proved by experimental research in Oxford.

THE EFFECTS OF IMMOBILIZATION

Until quite recently no one has known the actual mechanism by which the complete immobilization of a wound in plaster achieves its successful results against infection. Many theories have been advanced to explain the phenomenon. Albee (1933) believed that the beneficial effect of the Orr treatment was due to the production of bacteriophages in a wound covered by a closed plaster. Garcia Alonzo, among others, held that biological antagonism between different groups of bacteria makes it impossible for pyogenic organisms to colonize in plaster and that this slows up the septic process. In some cases, undoubtedly, bacterial incompatibility may diminish the numbers of pathogenic bacteria, but the success of the closed plaster cast must ultimately be attributed to immobilization and to this alone.

I have elsewhere referred to the experimental work of J. M. Barnes and myself which showed that obstruction of the lymph flow prevents the absorption of bacteria and their toxins (see p. 75). Our experiments also showed that rest produced by immobilization of the affected limb in a plaster-of-Paris cast has the effect of obstructing the lymph flow, in very much the same way as ligation of the lymphatic trunks.

Experimental Work on Lymph Flow

Interest in the part played by the lymph circulation in the absorption of substances from the tissues has led to a great deal of experimental work, particularly in recent years by Drinker and Field and their colleagues (see Drinker and Yoffey, 1941). These workers stressed the importance of muscular activity, and indeed of any kind of movement, in determining the rate of lymph flow in the limbs. They put a cannula into a lymphatic vessel in the leg of a dog and found that no lymph flowed from the cannula as long as the dog was at rest, but that as soon as the limb was moved, the lymph appeared and continued to flow as long as movement was maintained. It has also been found that the flow of lymph from a limb with an inflamed paw is greater than that on the normal side (Lassar, 1877; Field, Drinker and White, 1932).

J. M. Barnes and I carried out a number of experiments in dogs to confirm these observations (1941), cannulating one of the main lymphatic trunks lying alongside the femoral vessels in the thigh and ligating the remainder. In a normal limb at rest there was no detectable flow over a period of thirty minutes. Passive movement produced an immediate flow, which could be considerably increased if the muscles

were stretched by hyperextending or acutely flexing the limb; manual compression of the muscles produced no flow at all. The greatest lymph flow over a period of thirty minutes was brought about by active muscular contractions produced by faradic stimulation of the nerve, the limb being allowed to pass through a full range of movement. If, on the other hand, the same stimulation was continued after the whole limb had been immobilized, the flow stopped almost completely.

Having confirmed that the lymph flow is stopped by complete rest, we next tried immobilizing the limb in a plaster cast, and found that under these conditions only a very small amount of lymph appeared through the cannula; in one animal the volume was nine times less than when the leg was freely moved. The efficiency of the plaster cast was further proved by experiments in which we injected snake venoms and bacterial toxins into the limbs of rabbits immobilized in plaster and obtained results very similar to those of our earlier experiments in which the lymphatics had been ligated. With tetanus toxin the results were particularly striking, for, while the control rabbits all died in an average of less than 4 days, those which had been immobilized in plaster survived for over 11 days, the majority at death showing no signs of tetanus.

Effect of Immobilization on Inflammation

Inflammation produces an increase in lymph flow that coincides with the development of edema. The lymphatics in an edematous area, far from being occluded by the pressure of the swollen tissues, have been seen to be widely dilated (Pullinger and Florey, 1935), and our experiments confirmed these observations. In animals with edema following burns, and in two animals with a generalized edema of one leg (one of them associated with an abscess in the thigh), there was always a greatly increased lymph flow on movement. When, however, after scalding the foot, we prevented edema by immediately applying a small plaster, the lymph flow was markedly reduced. But although enclosure in plaster of a recently scalded foot will prevent swelling and so reduce the lymph flow far below the amount observed in a foot left free to swell, the flow is still considerable. Our investigations showed that this flow can be further reduced if some incisions are made over the inflamed area.

IMMOBILIZATION IN CLINICAL PRACTICE

From our findings, first, that the immobilization in plaster of a limb, with or without inflammation, greatly reduces the flow of lymph and thereby reduces the absorption of foreign substances from a wound, and secondly, that in cases with no inflammation the arrest of the lymph flow effected by plaster immobilization is almost as complete as that secured

by ligation of the lymphatics, it follows that immobilization in plaster provides one of the most effective measures for preventing bacterial and toxic diffusion, and so constitutes one of the most valuable localizing agents at our disposal.

Clinical observations fully confirm the evidence of experimental findings. Some patients whose wounds are immobilized in a closed plaster cast have fever for the first day or two after the injury, but it subsides as the beneficial effect of the plaster makes itself felt, and a fresh rise of temperature may be observed only after each change of plaster, indicating that some diffusion has occurred in the short period of interrupted immobilization.

It might be argued that the application of a splint would achieve a similar effective arrest of the lymph flow, but this is not so. None of the existing splints provide more than a relative fixation of the extremities. The best of them, the Thomas splint, which combines some degree of lateral fixation with traction, immobilizes the bones but does nothing to protect the soft tissues either from uncontrolled external pressure or from the movements caused by muscular activity. Complete and absolute rest for the muscles and protection from external disturbance are provided only by the plaster-of-Paris cast. A windowed plaster as used by Billroth is, in my opinion, better than a splint, but it has the serious drawback that the region of the wound—which is just the area that most needs rest and protection—is left uncovered and exposed to the disturbance of inflammatory swelling. In some cases treated in this way I have seen complications due to the poor circulation and the absence of uniform compression. One such case will serve as an example.

A man aged 45 years sustained a compound fracture of the right tibia and fibula on June 27, 1940, when he was thrown from his motorcycle which had struck a car. He was operated on within two hours of being wounded, and 2000 units of antitetanic serum were given. There was a wound 3 in. × 2 in. over the lower third of the tibia on its internal aspect, with ragged edges and the underlying muscle extremely lacerated. A second small wound, ½ in. in diameter, lay 1½ in. distal on the outer side of the leg. There was comminution of both bones at the level of the fracture. The skin and wound were cleaned with soap and water, and the skin edges and muscles were excised. A free fragment of tibia was removed. Gauze was applied over the wounds and the leg was put in plaster after reduction by manual traction, which was considered sufficient. X-ray examination five days afterwards showed that reduction was incomplete. During the first three weeks the temperature, except for one evening when it rose to 100° after a new injection of antitetanic serum followed by some anaphylactic reaction, was below 99° F.

On July 8 the plaster was removed and the fracture manipulated under general anesthesia. The wounds looked healthy and had a slight, clean discharge. A new plaster was applied, and a small window was

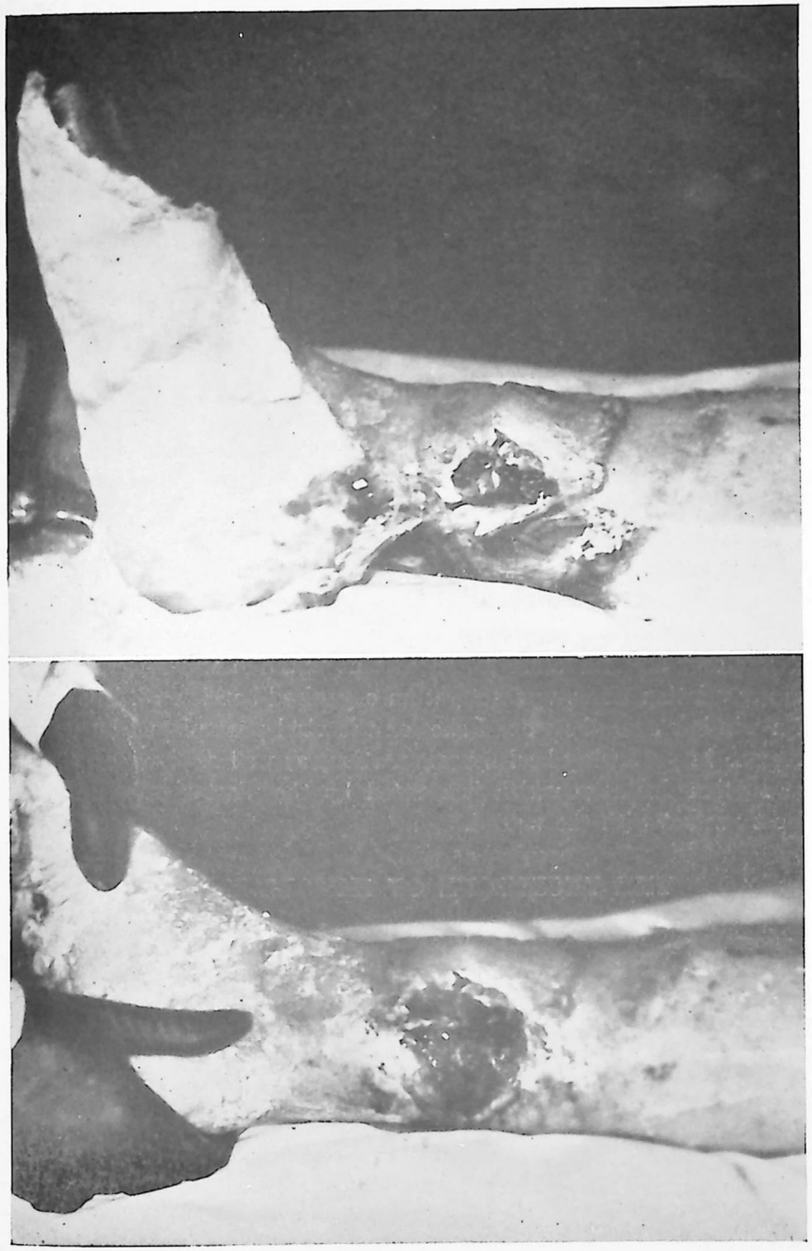


Fig. 46.—*A*. Compound fracture of tibia and fibula treated by plaster covering only the posterior half of the wound. Note the marked edema corresponding with the window. The uncovered area of the wound was sloughing and suppurating.

B. When the plaster was completely removed the part of the wound covered with plaster was found clean, granulating well, and free from edema.

cut over the anterior half of the big wound to obtain samples of the discharge for research purposes. The part of the plaster corresponding to the window was reapplied and maintained in position by an ordinary bandage. After that day the wound discharged more, and, on removal of the plaster after three weeks, the part which had been covered by the window was found edematous and sloughing, and the surrounding skin showed a dermatitis, whereas the posterior area, which was completely covered and compressed by plaster, showed very healthy granulating tissue with only slight discharge; the edges of this part of the wound were flat and clean. A very definite line existed between these two areas. The other wound, which was completely covered by plaster, was granulating well (see Fig. 46).

On December 16, the fracture was completely consolidated but a small sequestrum was seen on the x-ray film, and was removed under pentothal anesthesia. New plaster was applied from toes to knees, after packing the little wound with dry gauze. A fortnight later the plaster was cut off and the sinus appeared to be healed. There was clinical and radiographical union but still another small sequestrum, which, after some localized inflammation, was removed two months later. After that, movement of the knee ranged from 0° to 110° and of the ankle from 0° to 35°, and the patient was transferred to his unit.

The points to be stressed in this case are: 1. The excision was carried out without enlargement of the wound, and as a consequence the removal of devitalized bone was incomplete. 2. The reduction was not satisfactory, and therefore a second manipulation was necessary when the granulation tissue was not yet an organized barrier. 3. The cutting of a window over the wound showed the vital part played by uniform pressure in producing healthy granulations as well as the good effect of the suction drainage which is exerted by the plaster when this is in direct contact with the wound.

THE TECHNIQUE OF IMMOBILIZATION

To provide perfect immobilization a plaster cast must include not only the joints on either side of the wound, but also the segments of the limb beyond these joints. For example, to immobilize the leg the plaster should include the foot and extend to the upper third of the thigh. The same principle applies to joints: for instance, the knee should be immobilized in a plaster which includes both the foot and the hip. In order that the surgeon may satisfy himself about the condition of the enclosed limb, at least the last phalanges of fingers and toes should be left uncovered. Edema, any change of color in the skin, loss of movement or warmth in the digits will thus be readily detected and serve to confirm any general signs and symptoms of complications. It is more difficult to provide proper immobilization for wounds in the hand or foot without enclosing the fingers or toes in the plaster. A good method is to include part of the digits and to fix the rest with traction, that is to say, to make them immobile but visible.

Padding and Its Drawbacks

Some surgeons cover the whole limb with a layer of padding before applying the plaster. The reason given is that with muscular atrophy the enclosed limb soon shrinks, and that consequently, if a proper degree of immobilization is to be maintained, an intervening layer of some resilient material must be placed between the plaster and the skin. This is a great mistake. In the first place, a thick layer of padding definitely reduces the immobilization. Secondly, any padding between the plaster and the gauze covering of the wound (it should be remembered that I am speaking only of wounds and compound fractures) reduces the absorption of the plaster, and the wound is thus kept wet with the fluids which exude from it. The absorbent capacity of the padding is quickly exhausted, and the saturated material provides an excellent medium for the growth of bacteria as well as producing a most offensive smell. If, apart from the protection of a few bony prominences, the plaster is applied without an intervening layer of padding, the limb is more effectively immobilized, the wound is kept dry and less susceptible to infective complications, and the smell is far less unpleasant.

Owing to the dependent position of the upper extremity even in bed, muscular atrophy never constitutes a serious problem in wounds of the arm, forearm and hand. In leg wounds, however, the best method of ensuring close contact between the limb and the plaster is to make the patient walk about on a Böhler iron as soon as the condition of his wound permits. Walking may be allowed after the first change of plaster if the wound is well filled with healthy granulation tissue and the risk of infection is considered to be over. Where the patient's progress is so satisfactory that the plaster can be left in position until the consolidation of the fracture or the healing of the wound is complete, the patient may be allowed to walk about a month after the injury, the exact period depending on the severity of the lesions in the soft tissues. Patients with fractures fixed by pins or wire may walk sooner than others, owing to the better immobilization of the bones.

During the first days of walking the patient must be carefully watched for any sign of pyrexia, edema of the toes, or sensations of heat or pain in the wound. The slight swelling of the whole limb and the better muscular nutrition afforded by the exercise lead to a greater tension in the plaster and so to better immobilization of both the soft tissues and the bones. When a patient suffering from a wound in the lower extremity has to be kept in bed for a long period, owing to multiple lesions or other factors causing a serious general condition, it is a good plan, after keeping the plastered leg raised for a period not exceeding a month, to move the limb into a lower position for a short but gradually increasing period two or three times each day. This alteration in position must, however, be made without moving the patient from his bed.

CHAPTER XX

PLASTER-OF-PARIS TECHNIQUE

The immediate precursor of our modern plaster-of-Paris technique was the use of bandages freshly stiffened with starch—a method perfected by the Belgian surgeon Seutin (1840) in the first half of the last century, and later adopted in most of the surgical centers in Europe (see also Putti, 1939). The starch bandage was reinforced by splints consisting at first of strips of thick pasteboard and later of thin laths of wood, which were attached by bandages soaked in starch paste. This bandage was not very rigid, however, and had the further disadvantage that it required 24 hours to harden; it was therefore abandoned when the possibilities of plaster of Paris were discovered.

The plaster dressing as it is now used was first described in 1852 by a Dutch surgeon, A. Mathijsen, but did not become widely known until some years later (see Monro, 1935). Mathijsen's plaster dressing was composed of roller bandages very similar to those in common use today, but various modifications have been introduced since his time, the most important being that of Pirogoff. This surgeon, finding himself without any of the necessary bandages during the Crimean War, used various kinds of material cut in the shape of splints and provided with a stiff coating by being drawn through a thin plaster paste. After the war Pirogoff elaborated his method and evolved a special form of the plaster technique, cutting coarse sailcloth to a definite pattern shaped to fit the limb and soaking it in plaster paste before application. Since Pirogoff's day there have been other modifications of a similar type.

From early days, too, surgeons have varied in their methods of applying the plaster dressing, some using an underlayer of padding to protect the skin, others placing the plaster in direct contact with the skin.

Since plaster of Paris was first used in the treatment of fractures, therefore, almost every possible *modus faciendi* has been tried. The successive "rediscoveries" of the various adaptations of the general method have, however, failed to provide any substantial improvement on the earliest forms of the technique. For his institution of the plaster cast, surgery undoubtedly owes Mathijsen a debt of gratitude no less than those which it readily acknowledges to Jackson, Long, Morton and Simpson for anesthetics and to Lister for antiseptics.

The value of plaster of Paris to the surgeon is its property of crystallization, or "setting," when it dries after being mixed with water.

This feature was first observed by Lavoisier in 1765, and a special study of the substance was made by van't Hoff and his school at the beginning of the present century. Plaster of Paris will absorb a great deal of water, far more than is required to make it crystallize—a point which must be borne in mind when a plaster cast is applied, for unless the surplus water is removed before the crystallization begins, the plaster will not be sufficiently compact. The plaster supplied for surgical use is 90 to 95 per cent calcium sulfate, the chief impurities consisting of calcium carbonate, ferric oxide, aluminum silicate and sometimes pyrites. So long as these impurities are present only in small quantities, their influence on crystallization is negligible.

The process of crystallization can be retarded by sodium phosphate or small quantities of glycerine or starch, or it can be accelerated by the addition of one part of potassium silicate or alum, in saturated solution, to the water used to make the paste. Warm water also hastens the setting of the plaster.

PRINCIPLES OF APPLICATION

The general principles of applying plaster-of-Paris casts for the immobilization of fractures are based primarily on the fixation of the portions of the skeletal system which lie nearest to the skin, i.e., the epiphyseal regions, the foot, the anterior superior iliac spine, the lateral part of the thorax, and in some cases the crest of the tibia. The pressure applied to the bone through the soft tissues is responsible only in part for the general fixation process; the support given by the plaster to the soft tissues, particularly the muscles, is just as important. As orthopedic surgeons have come to use plaster more and more for the immobilization of limbs affected by every kind of pathological condition as well as fractures, there has been an increasing tendency to follow the old method of protecting the skin and bony prominences with some form of padding, cotton wool, or stockinette. This padding is used with a twofold object: first, to prevent constriction and consequent ischemic effects; and secondly, to protect the skin overlying the more superficial parts of the skeleton in order to avoid the formation of sores.

These complications have occurred with sufficient frequency to justify the unwillingness of many surgeons to apply the plaster in direct contact with the skin. In most cases, however, careful investigation will show that the real cause of these sequelae lies, not in the skin-tight fit of the plaster, but in a faulty technique of application; either the plaster has been put on too tightly, or else the position of the limb has been altered before the plaster has set. Among the thousands of plasters

which I have myself applied without any padding, I have seen only one serious complication. This was after an operation for a fracture of the lower end of the humerus. I found that reduction was most satisfactorily maintained with the forearm in semi-extension, and I therefore applied the plaster with the limb in this position. Before it was dry, however, an assistant, not realizing that there was a special reason for this position, moved the forearm to form a right angle with the humerus, and consequently produced a severe compression followed by Volkmann's ischemic contracture, which was fortunately corrected by an immediate arterial sympathectomy. Slight constriction will also tend to occur when a plastered limb is kept low, for edema is readily produced and increases the pressure of the plaster.

There has been much discussion whether the plaster increases in volume on setting, and many surgeons have believed that constriction is due to this cause. Rugh (1904) investigated the supposed change, using a dynamometer similar to that used to measure pressure of the hand, and found that in every case the dilation produced was less than $\frac{1}{25}$ inch and that contraction never occurred. This shows that there is no ground for the argument that a plaster applied directly to the skin without padding tends to cause constriction. Apart from the prevention of possible friction in a few areas, among them the great tuberosity of the calcaneus, the anterior superior iliac spine, the lumbar spinal processes, and the sacrum, there is nothing to be gained by separating the plaster from the skin. In fact, a plaster applied in direct contact with the skin effects a more complete immobilization and thus holds the fragments of the bone more firmly in position than does one which is placed over an intervening layer of padding.

Moreover, the absolute immobilization of the limb that can be obtained by careful application of a skin-tight plaster, provided that there is some protection over the bony prominences, prevents any slight displacement of the skin underneath the plaster, and thus averts the sores commonly produced by this cause. That the sores which occur underneath plaster casts are in many cases caused by friction due to incomplete fixation is clearly shown by the conditions under which the commonest of all such ulcerations is produced, namely, that which appears in the lumbo-iliac region. Despite the routine protection of this area with several layers of padding, sores often develop here underneath spica plasters. On the other hand, sores in this region are very rare when the plaster covering it is part of one which immobilizes the trunk, as in fractures of the spine, even though this plaster exerts a considerably greater pressure than the hip spica. In other words, the more complete immobilization of the bony prominences of the spine prevents ulceration of the skin.

In almost every case the lesion is first seen in the superficial layers of the skin, and only in the later stages is the whole integument destroyed; the damage is clearly produced by severe scraping combined with some pressure.

Sores produced by excessive pressure, causing an area of ischemia in the whole skin, are rare and arise from one of two causes: the poor general condition of the patient or faulty technique. The most common mistake is to apply undue pressure with the thumb when moulding the plaster over a small but marked bony prominence (e.g., the head of the fibula or the internal epicondyle of the humerus). The late appearance of sores under a plaster that has given no trouble throughout a long initial period, and the development of skin lesions accompanying general infective processes, are well known. With the type of sore due to ischemia there is a necrotic sloughing of the whole thickness of the skin over an area immediately surrounding a bony prominence.

It will be seen, therefore, that a protective general padding is of limited value in preventing sores, and in some cases actually increases the risk, since the less complete immobilization which it often involves promotes friction of the skin by the protective material, which quickly becomes compressed and hard beneath the plaster. The best material for protective purposes is white adhesive felt $\frac{1}{4}$ inch thick; the adhesion of this to the skin prevents friction. To protect a marked bony prominence, such as the posterior iliac spine, it is a good plan to cut a number of slits in the piece of felt radiating from the center, so that there is a snug fit round the protuberance. For patients who must be kept in bed for a long period, it is particularly advisable to use felt cut in squares of three inches.

In war injuries there is a further and still more important reason for omitting a layer of padding beneath the plaster. Compound fractures operated on late and immobilized in plaster, whether with or without a window, are apt to produce a copious discharge which saturates the cotton wool or other protective material, producing maceration of the granulations and an offensive smell which necessitates premature change of the plaster.

For these various reasons skin-tight plaster is strongly advocated for compound fractures. Those few areas of the body which require some slight protection from direct contact with the plaster will be indicated later when the casts for the different regions are individually described.

METHODS OF PLASTERING

As in the days when plaster of Paris was first employed for surgical purposes, two methods of application are in use today: the plaster-

bandage and the "pattern" techniques. Each has its individual advantages and disadvantages.

Advantages of the Plaster-Bandage Technique.—

1. The application of plaster bandages requires no special knowledge other than that possessed by the general practitioner. Moreover, students can be quickly trained in the technique, owing to its similarity to that of the ordinary roller bandage.

2. The material, being uniform, varying only in size, is very easy to apply.

3. The fact that plaster bandages can be made up in advance and stored up for future use results in saving of time in the preliminary preparations.

4. The pressure of the plaster can be reinforced over those areas which carry the greatest weight merely by making additional turns of the bandage.

Disadvantages of the Plaster-Bandage Technique.—

1. An ample supply of prepared bandages has to be kept in store.

2. The application of the bandages, particularly for shoulder and hip spicas, takes up a fairly considerable time. In wartime, when considerable numbers of casualties are admitted to a hospital at the same time and have to be dealt with in quick succession, surgeons must necessarily work at speed and can ill afford the 20 to 25 minutes which are required for applying, for example, a thoracobrachial plaster by this method. Moreover, even at the end of this time the operating table is not free for the surgeon to proceed with the next case, for the patient must be left until the plaster has set. All compound fractures must be plastered on the table on which the surgical procedures have been carried out. The patient who needs a thoracobrachial plaster has probably suffered a serious injury and undergone a long and severe operation, and so the considerable extra period of general anesthesia is an added risk.

3. The procedure is always messy. However careful and skillful the worker, it is virtually impossible to apply a plaster bandage without spilling the plaster over the table and floor. If the operating room is to be spared this mess, the patient should be moved to the plaster room before the plaster is applied, but that will still further increase the time taken.

Advantages of the Pattern Technique.—

1. There is no need to keep a stock of prepared bandages, which in time of great pressure, as after heavy raids, might become exhausted.

2. The technique is relatively quick, for more than half the procedure—the preparation of the materials—can be carried out by an assistant while the surgeon is still operating, and the plaster can be applied on an orthopedic table without any alteration in the skeletal traction used during the operation. A thoracobrachial plaster can be applied by this method in about 8 minutes.

3. The method is clean, and the whole application can be completed without more than a few drops of paste being spilt on the floor. Hence there is no need to move the patient out of the operating room for the plastering process.

4. Radiographs through the uniformly thick and dense pattern plaster are not marred by the patchiness so often produced by radiography through plaster bandages.

5. The plaster sets uniformly, taking on a similar consistency throughout, and is therefore not subject to the exfoliation which not infrequently occurs with the bandage technique.

Disadvantages of the Pattern Technique.—

1. The technique requires a certain amount of specialized knowledge and takes somewhat longer to learn.

2. Some time must be given up to the preparation of the plaster just before its application.

In my opinion, each of these two techniques has its special indications. For immobilization of the elbow, the forearm and the foot, the plaster-bandage method is the most suitable; for the shoulder and arm (thoracobrachial plaster), the leg and the wrist I prefer the pattern technique. For the hip spica there is little choice between the two.

The Plaster-Bandage Technique

Instruments and Materials

The instruments commonly employed are:

1. Several plaster cutters.
2. A saw.
3. A magnified glove stretcher for opening the plaster after cutting.
4. Benders.
5. Scissor-like cutters for soft plaster.
6. Strong scissors for cutting felt.
7. Strong scalpels, generally second-hand from the operating room.
8. Wire cutters.
9. Indelible pencils.
10. A tape measure.
11. A pint measure.
12. Pails.
13. Bowls of several sizes, some very large.

The materials required are as follows:

1. Plaster of Paris, known as "superfine plaster."
2. Book muslin, 32 threads to the inch, stiffened with starch, not sized.
3. Wool bandages.
4. White felt, ¼ inch thick.
5. White adhesive felt, ¼ inch thick, backed with zinc oxide.
6. Malleable iron wire, 10-20 s.w.g.
7. Flat strips of malleable iron, 2 ft. × ⅜ inch × ⅛ inch.
8. Kramer wire, 3¼ inch × 24 inch and 3¼ inch × 40 inch.

The plaster and the plaster bandages are kept in airtight containers in a dry place.

Preparation of Bandages.—The muslin from which plaster bandages are made is supplied in rolls about one yard wide and twelve yards long. This is torn into strips of various widths and lengths ranging from 6 inches by 4 yards to 3 inches by 2 yards. From each strip of muslin the outer three threads are withdrawn; if this is not done these threads tend to fray and hamper the bandaging process. The strips are then loosely rolled into a bandage.

The method of converting these strips into plaster bandages is best learned by observation and practice. On a smooth board the bandage is unrolled foot by foot, passed through a heap of dry powdered plaster, which is lightly rubbed into it, and re-rolled as the plaster bandage. About 12 to 15 inches of the muslin strip lies exposed on the board at a time. Care must be taken to ensure that just the right amount of plaster is rubbed into the muslin, and again that the proper amount is retained in the mesh and left on the surface of the material in the re-rolling process. The rolling must be done very evenly and at a moderate tension; if the roll is too tight it will not absorb the water, and if too loose much of the powder will come away before, during, and after the soaking process and the bandage will tend to run out in a "tail" when applied.

Soaking.—All materials and utensils must be ready. The probable number of bandages needed should be laid out on a tray. This is an important point, because if bandages are taken from the storage container with a wet hand, drops of water will inevitably be spilt on the other bandages and render them useless. Plenty of warm water should be set out, in two deep basins for small plasters and two pails for large ones. A smooth board about 3 ft. by 2 ft. should be readily available for plaques.

When all preparations are complete, the first two rolls of bandages are gently lowered into the water. There are a right and a wrong way of handling the bandage during the soaking process. The roll should be gently let down to the bottom of the basin or pail in the horizontal

position and left there undisturbed until all bubbling has ceased. It is then lifted out clear of the water, still horizontal, and is gently squeezed from the two ends; it must not be wrung. By this means unnecessary loss or disturbance of the plaster is avoided. If, on the other hand, the bandage is let down into the water or removed from it in the vertical position, or if it is handled carelessly, much of the plaster either escapes altogether or becomes unevenly distributed through the muslin and the bandage is consequently spoiled. The squeezing is intended only to remove the surplus water, and the bandage should be applied while still dripping wet.

Application.—The characteristic virtue of the plaster bandage is its combination of great flexibility while being applied and strong rigidity when fully set, and the period between these two stages is of critical importance. The limb must be placed in exactly the required position before the plaster is applied, and this position must be strictly maintained throughout the whole of the application. If the position is altered at any stage, even while the final layers of the plaster are being applied, unsuspected ridges will be formed among the inner layers, which will not only cause pain but will also tend to produce sores or ischemia. The comfort and well-being of the patient depend on the smoothness of the inner surface of the plaster and on its accurate and comfortable fit round each bony prominence. A plaster cast that has a perfect external appearance may have a sharp ridge inside. The position of the limb, therefore, should never be altered during the application of the plaster. If the position is found to be wrong, the plaster must be stripped off and reapplied after the correct position has been obtained.

It is advisable whenever possible to apply a plaster with the limb completely immobilized by continuous traction on the orthopedic table on which the surgical operation has been performed. If a fractured limb is held in position by hand, slight movement is almost inevitable, particularly in the plaster-bandage technique, for with this the hands of the assistant holding the limb must be moved from time to time to allow the bandage to be applied, and the comparatively long time consumed in the application favors the possibility of movement from the original position.

"Loop" and "Draw."—Two movements can be used to ensure that each turn of the bandage lies evenly and to allow changes in the direction of the bandage: first the "loop," by which a 2- to 3-inch loop of the plaster bandage is thrown back, after which the run of the bandage is easily redirected; and secondly the "draw," by which one edge of the bandage is drawn back a little while the run is redirected. It is advisable to make frequent use of one or other of these two devices in applying the innermost layer of a skin-tight plaster, in order to avoid

all risk of causing a small ridge or unevenness by greater tension of one edge of the bandage. If during the earlier stages of applying a plaster bandage a loop or draw is made as each turn covers any bony prominence, and if the plaster is well rubbed in and moulded to exaggerate, if anything, the depression surrounding the bone, there is little risk of undue compression.

The Outer Layers.—Once the first few layers of the plaster bandage have been carefully applied in this way, we come to the application of the layers which form the outer structure of the cast. The method here is somewhat different and is based on the sole principle of providing additional strength where this is needed. The process consists no longer of bandaging in the ordinary sense of the term; indeed, great care must be taken to avoid the slightest pull. One method is to unroll the bandage rapidly on the actual surface of the existing plaster, for this eliminates the risk of tension involved when the roll is held away from the surface.

In certain areas, such as the dorsum of the foot and the anterior aspect of the elbow, the initial layers of the plaster bandage are sufficient support and require no reinforcement, while the region of the upper abdomen and lower ribs in front need never be enclosed in plaster at all. The plaster cast for the lumbar region is made of plaques, well moulded to the body and possibly held in place temporarily by a few turns of bandage round the upper abdomen, the bandage being cut and turned back from this region before the plaster has fully set. On the whole the best method of reinforcing the inner layer of the plaster cast is by plaques, which are prepared by one or more assistants while the inner layers are being applied.

Plaques.—Plaques for reinforcing plaster casts are made out of ordinary plaster bandage. The smaller plaques are made from the smaller bandages, i.e., those that are used for the forearm and hand; while for strengthening casts over the thorax and the back of the pelvis, broad plaques 2 feet square are made from several bandages of a larger size. The plaster bandage is soaked in the ordinary way and is then moulded backwards and forwards over a smooth board, being unrolled naturally along the board in one direction and then lifted and unrolled by hand in the other, then laid down and run along the board again, lifted and unrolled by hand, and so on. This process is carried out much more easily and quickly if an assistant places a finger at each end of the plaque as the bandage is unrolled and the layers are laid out on the board.

The plaque is laid carefully over the casing made by the plaster bandage and is rubbed into it, being held in position by a further bandage where necessary. It can either be left flat or gathered into round

ropes or oval bars to form trabeculae. The surgeon places the reinforcement just where the plaster requires additional strength, e.g., for a long spica of the groin, both in front of and behind the hip.

Patching.—If, in the course of wear, a plaster cast requires strengthening at any point, it can be patched either with bandages or with plaques. Such a patch will not, however, adhere to the original plaster unless the surface is slightly softened with new plaster paste. The technique of doing this is as follows. The portion to be patched and the area immediately surrounding it are scratched and roughened with a saw or rasp; some fairly thin plaster paste is rubbed well into the roughened area, and the bandages or plaques are applied before the paste has had time to set.

The Pattern Technique

Since the first description of this technique by Pirogoff (1864) its main principles have remained unchanged; but the materials employed for the patterns and the design of the patterns themselves have been frequently modified. In Catalonia we used a thick, soft flannelette with a wide mesh; in France the school of Calot and in England John Croft employed ordinary gauze. I have recently adapted the technique current in Barcelona, using the muslin material ordinarily employed for plaster bandages and increasing the number of layers to compensate for the thinner material.

Preparation of the Patterns.—Measurements of the part to be immobilized are taken on the uninjured limb, from 5 to 10 per cent being added to allow for shrinkage of the fabric. These measurements are marked on the muslin, which is spread out on a table, and the appropriate number of layers are then folded up. Next the design is pencilled on the top layer of the muslin, and the pack is cut out. The number of layers required varies with the size and weight of the part to be immobilized. The quantities given below refer to the requirements for an average-sized adult. There are five patterns for the limbs; these are suitable for all cases and vary only in size.

The Plaster Cream.—The proper amount of hot water (temperature approximately 100° F.) is poured into a shallow basin. Plaster powder in the prescribed proportion (for details see "Regional Plaster Techniques" below) is quickly sprinkled over the surface of the water until it is no longer absorbed. The mixture is then stirred and rubbed into an even cream. Held at one end, the pattern, complete with all its layers, is passed into the mixture, where, while still immersed, it is loosely rolled up. Finally, the roll is lifted out of the basin and gently squeezed (it must not be wrung) to remove any excess of liquid. The pattern is then ready for application.

Application.—Without loss of time the pattern is spread out over the injured limb and moulded to the surface. Care must be taken that all the layers correspond and that no ridge is formed. Some turns of ordinary bandage are used to hold the pattern in position and a thin layer of plaster cream is spread evenly over the surface. Before the plaster has set the pattern must be well moulded round the epiphyseal regions and other bony prominences and over the area of the wound, care being taken that smooth pressure is made with the whole hand and not with the tips of the fingers only; this is to secure uniform and wide pressure on the selected points.

REGIONAL PLASTER TECHNIQUES

The Hand

No padding is required in either the bandage or the pattern technique.

Bandage Technique.—The plaster extends from the heads of the metacarpals to one inch below the bend of the elbow. Plaster bandages measuring 3 in. × 2 yards are used, from one of which a plaque should be made. This plaque is applied to the palmar region and forearm with the hand in dorsiflexion. Two or three bandages of the same length and width are used to hold the plaque in position. The thumb should be placed in slight abduction and opposition. The end of the plaster at the elbow must allow complete flexion of the forearm without making any pressure on the skin; if the plaster is too long the upper edge must be turned back before setting.

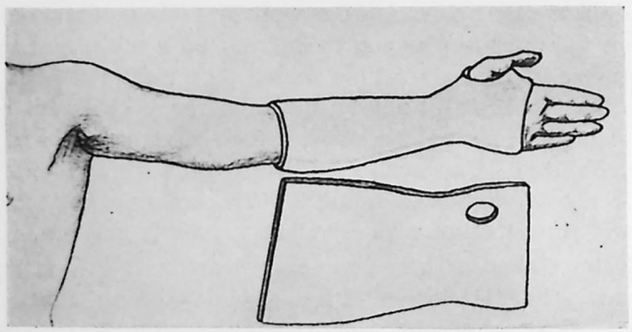


Fig. 47.—Plaster pattern for immobilization of wrist.

Pattern Technique.—

Materials required: 6 layers of muslin
½ pint of water to ¾ pint of plaster

The extent of the plaster and the position of the hand are the same as in the bandage technique. The pattern (see Fig. 47) is slightly narrower at one end; an inch and a half from this end, and near one of the long edges, a hole about the size of a half dollar is cut out for the thumb. A single plain gauze bandage is used to hold the pattern in position.

For simplicity and rapidity of application and for perfect fit, this technique is preferable to the bandage technique in this region.

Wrist and Forearm

The hand should be in 45° of dorsiflexion, the forearm in 90° of flexion. The degree of rotation of the hand depends on the level of the fracture: if the fracture is in the lower end of the radius and ulna,

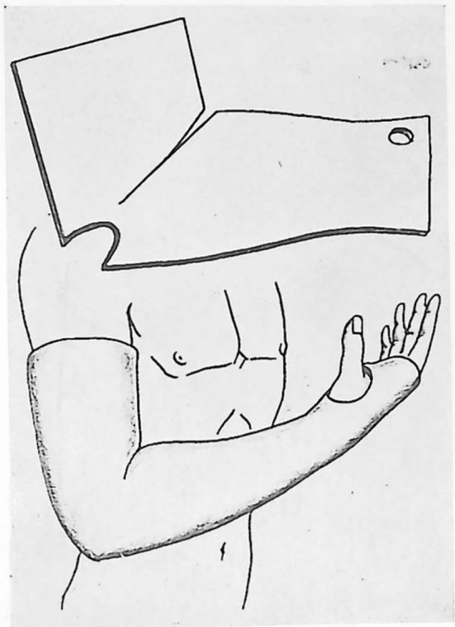


Fig. 48.—Plaster pattern for immobilization of forearm.

the wrist should be in pronation, but this position must never be forced. For other fractures the hand must be immobilized in a degree of supination determined by the level of the injury: for a fracture in the middle third of the forearm, the hand should be in a midway position, and for one in the upper third in moderate but not extreme supination.

In thin persons, or in patients suffering from sepsis with toxic absorption, the internal condyle of the humerus must be protected with a square of adhesive felt to prevent undue pressure at this point.

Bandage Technique.—A plaque is made with a single bandage, 4 in. × 4 yards, to stretch from the heads of the metacarpals to the humeral insertion of the deltoid, and is applied to the posterior part of the

arm and forearm. With the hand in pronation the plaque supports the palmar region, and with the hand in supination the dorsal region. Four plaster bandages of the same type are rolled on to make a strong plaster.

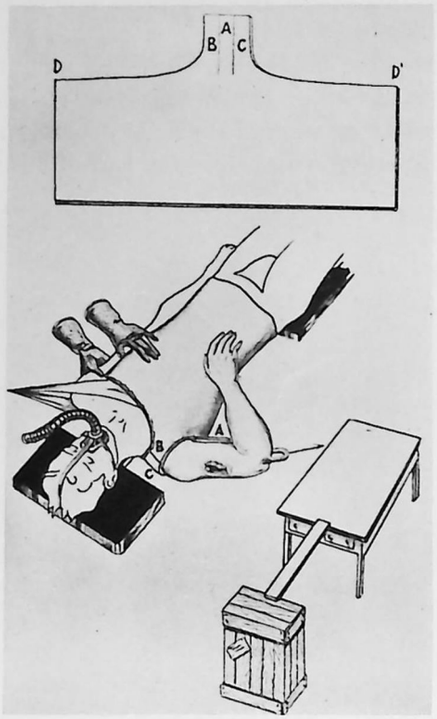


Fig. 49.—Shoulder spica. Thoracic pattern. *A*. Part corresponding to the axilla and inner aspect of the arm. *B* and *C*. These two parts are superimposed over the suprascapular region.

Pattern Technique.—

Materials required: 6 layers of muslin
1¾ pints of water to 2 pints of plaster

The design of the pattern for the wrist and forearm is similar to that for the hand, but it has an extra part to include the elbow and arm (see Fig. 48). This extra part is drawn at right angles to the forearm, and its width corresponds to the circumference of the arm. A cut is made in the center of the anterior angle to facilitate application, and a curved indentation is made in the posterior angle, which corresponds to the position of the olecranon. The plaster is applied to the lateral aspect of the limb and fixed in position with an ordinary gauze bandage.

The pattern technique has no appreciable advantage over the bandage technique in this region, and the simplicity of the latter explains its general acceptance.

Elbow, Arm, and Shoulder

The elbow cannot be completely immobilized without fixation of the shoulder, and for this the "thoracobrachial" plaster is required. This is the most complicated of all plasters and, as it includes a large part of the body and the upper limb fixed in abduction, must be strong and yet not too heavy. For this region the use of bandages, by which the plaster is difficult to fit and takes a long time to apply, is greatly inferior to the pattern technique. I shall therefore confine myself to a description of the latter, by which with practice the thoracobrachial cast can be applied in less than ten minutes.

Fig. 50.—Shoulder spica. Brachial pattern. This is applied immediately after the thoracic pattern. In fitting the pattern to the elbow, the superimposition of the layers of muslin increases the resistance of the plaster.

Thoracobrachial Plaster: Pattern Technique

This plaster consists of two different parts, one embracing the thorax, and the other immobilizing the shoulder, arm, forearm and wrist. These two parts will be described separately.

Pattern for the Thorax.—

Materials required: 10 layers of muslin
2½ pints of water to 3¾ pints of plaster

The width required is the maximum circumference of the thorax (plus 5 per cent to allow for shrinkage of the muslin) and the length is from one inch below the anterior iliac spine over the shoulder to the spine of the scapula (see Fig. 49). When the layers of muslin have been prepared, the rectangle is folded in half so that the two shorter edges D—D′ come together. From one of the edges, at a point 6 to 7 inches from the fold, a curved line is drawn to the lateral edge at the

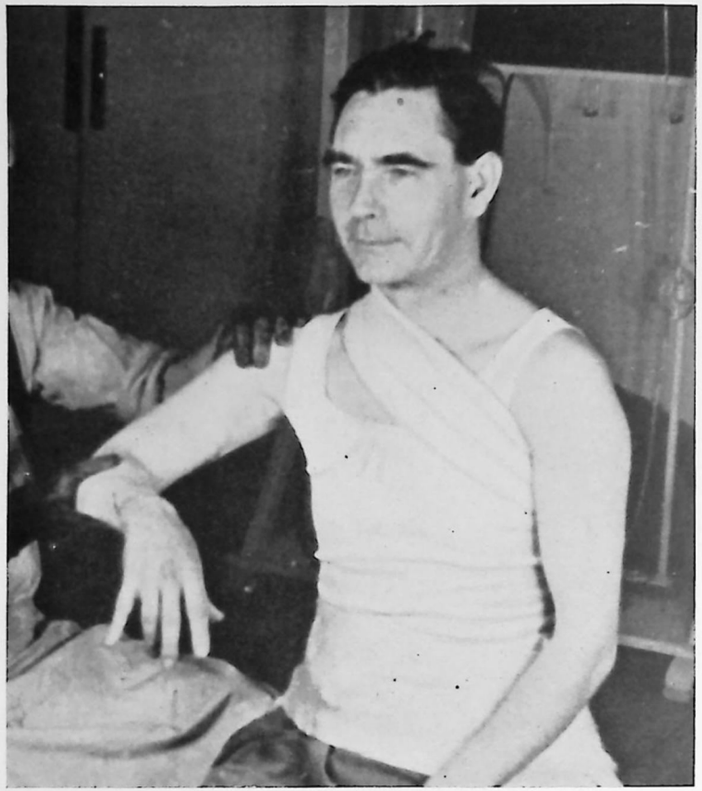


Fig. 51.—Shoulder spica. Padding with felt. (See also Figs. 52 to 57.)

level which will correspond to the axilla of the uninjured side (B—D and C—D′). From the same edge, and about 2½ inches from the fold, another line is drawn, this time parallel with the fold and ending one inch below the level of the axilla (B—A and A—C). When cut out the pattern presents the appearance shown in Fig. 49; the flap A forms a strong support for the arm in the axillar region.

Pattern for the Limb.—

Materials required: 10 layers of muslin
2 pints of water to 3 pints of plaster

The length is taken from the heads of the metacarpals to the base of the neck, with the forearm extended, and the width from the circumference of the arm. Measurement of the girth of the forearm is not necessary, because the proportions are very constant; in its proximal part it is slightly larger than the upper arm, and in its distal part it is smaller by two-fifths.

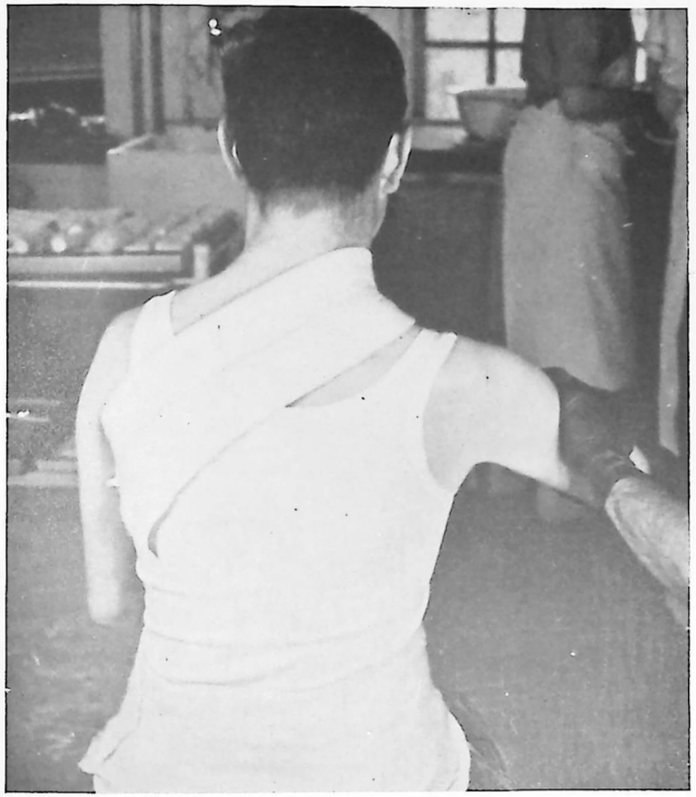


Fig. 52.—Padding of back.

This pattern has a different design from that described for the forearm, owing to the need for reinforcing the plaster at the elbow. It is drawn in a straight piece, with a long cut into its anterior face at the level corresponding to the bend of the elbow (see Fig. 50). As the pattern is placed on the arm with the elbow in flexion, the two edges of this cut overlap each other at the point where extra strength is needed. The part corresponding to the shoulder is butterfly-shaped; and at the level of the axilla a cut is made on each side to enable the plaster to be applied smoothly round this area.

Protection of the Skin (see Figs. 51, 52).—

In order to protect the skin from the upper edges of the plaster, a band of felt 4 inches wide should be passed round the base of the neck on the injured side to the axilla on the opposite side, where the two ends are stitched together. The lower 3 inches of this band will be covered by the plaster and the remaining inch turned back over its edge. A similar band should be used to protect the anterior superior iliac spines and lumbar region. In thin or toxemic patients the internal condyle of the humerus should also be protected.

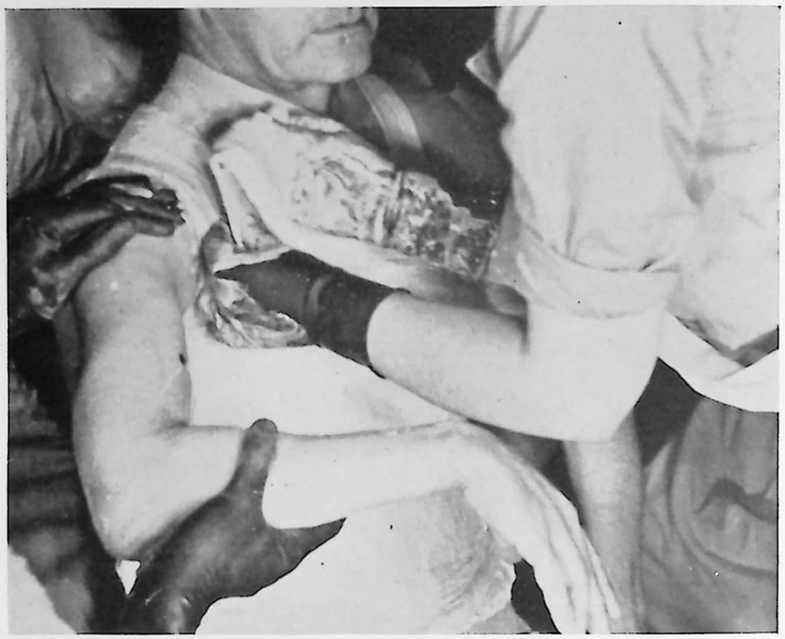


Fig. 53.—The anterior flap, corresponding to the suprascapular region, is superimposed on the posterior.

Application.—

The best position for the patient is sitting on a stool. Obviously, however, a patient cannot easily be held in a sitting position under general anesthesia, and in such cases a special operating table is required for the application of the plaster. If this is not available an improvised support can be devised (see Fig. 49). The patient's head and pelvis are supported by two separate tables, and a bar, preferably of iron, some 40 inches long, 3 inches wide, and 5/16 inch thick, is placed as a bridge to carry the patient's spine. An assistant should steady the patient by holding the uninjured shoulder.

The thoracic pattern, having been duly prepared and soaked in the plaster cream, is the first to be applied. The two flaps for the supraclavicular and suprascapular regions respectively, and the flap for the axilla must be placed carefully in position (see Fig. 53); and over the iron bar the plaster is well moulded to the body, particularly over the iliac spines and the upper edges of the ilia. A fine plain gauze bandage is used to hold the pattern in position. Meanwhile an assistant or nurse

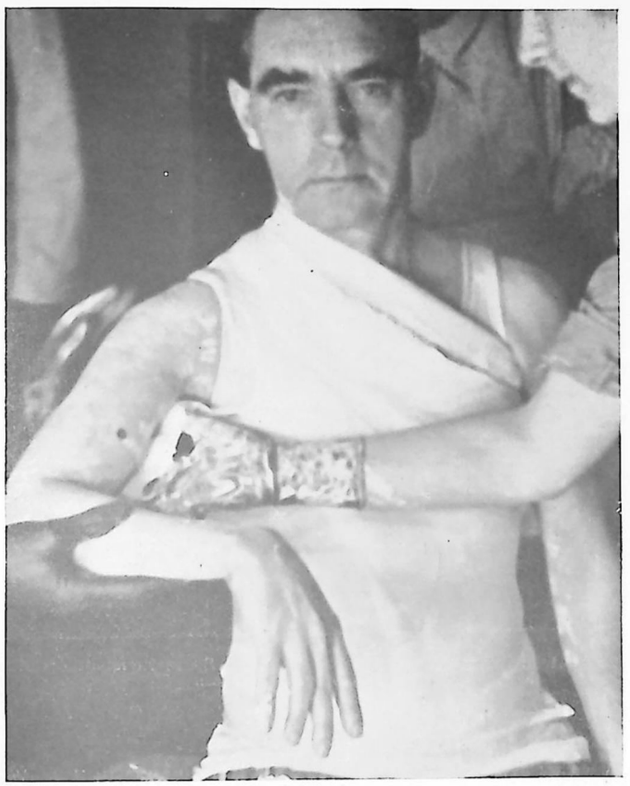


Fig. 54.—The flap corresponding to the axilla is applied to the inner aspect of the arm.

has prepared the plaster cream for the limb pattern and soaked this in it. The limb pattern is now applied immediately, the part for the shoulder being placed over the shoulder flaps of the thoracic pattern (see Fig. 54). Care must be taken that the flap for the axilla in the thoracic pattern is well covered by the corresponding portions of the arm pattern. The pattern is held in position by an ordinary gauze bandage (see Fig. 55). Finally the iron bar is withdrawn from inside the plaster by traction towards the patient's head (see Figs. 56 and 57).

The immobilization of the different types of fractures of the humerus and the various positions of the arm required are dealt with in Chapter XXI.

Fig. 55.—The pattern for the arm is being applied. Some turns of ordinary bandage fix the plaster in position.

The Foot

Some protection, preferably of felt, should be placed round the leg below the knee to prevent friction of the skin from the upper edge of the plaster. If traction is to be applied, the whole ankle region must be protected; if not the only padding required on the foot is over the tuberosity of the calcaneus.

Bandage Technique.—Plaster bandages can often be easily applied in this region. The best method is to prepare a plaque with a single bandage, 6 in. × 4 yards, spanning the distance from the toes over the heel to just below the back of the knee. This is applied to the plantar and posterior aspects of the foot and leg. A cut must be made into both edges at the level of the heel to avoid the formation of ridges and

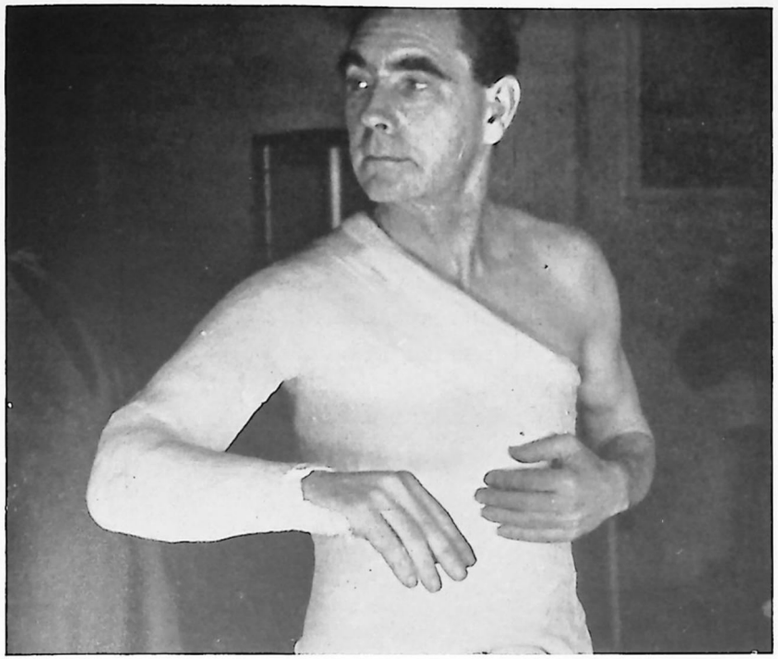


Fig. 56.—Thoracobrachial plaster completed. Anterior view.

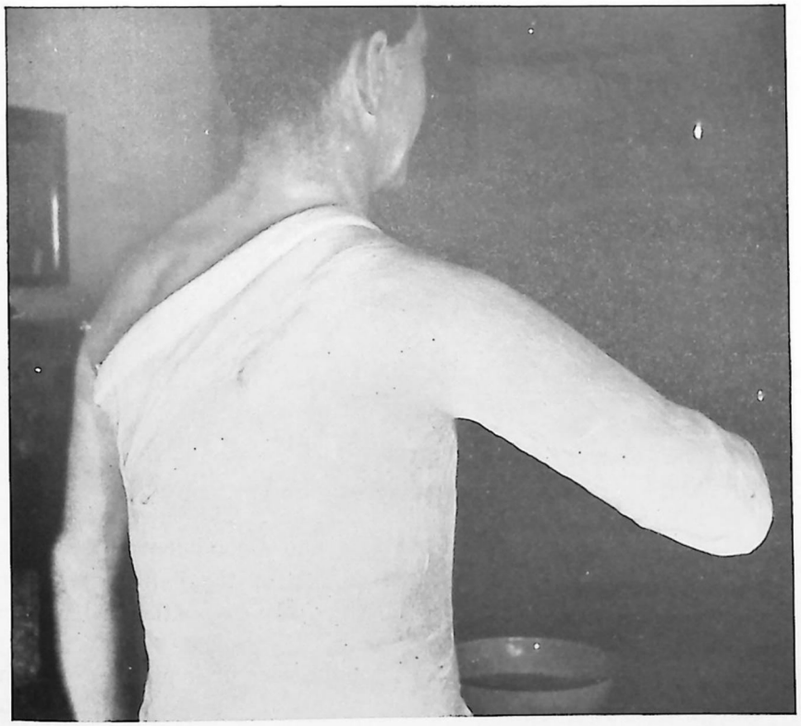


Fig. 57.—Thoracobrachial plaster completed. Posterior view.

consequent pressure points. Four or five plaster bandages of the same width and length are rolled on and moulded carefully over the ankle and heel. Care must be taken to avoid retraction of the toes in flexion, which is very liable to occur when the tips of the toes have no proper support.

Pattern Technique.—

Materials required: 8 layers of muslin
1 pint of water to 1¾ pints of plaster.

The length is measured from the tips of the toes to the heel and thence to the back of the knee. The maximum width of the pattern is the circumference of the leg at the calf; below this point the pattern narrows to the malleoli, and then widens out again.

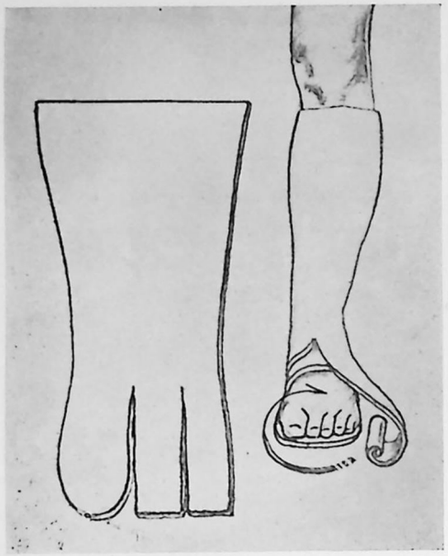


Fig. 58.—Pattern for immobilization of the foot and ankle. The foot is placed between the straight straps. The curved lateral strap covers the heel and plantar region. (See also Figs. 59 to 63.)

Into the lower end of the pattern two cuts about 12 inches long are made, dividing this end section into three flaps, two of which are of equal width and the third slightly wider (see Fig. 58). The pattern is applied so that the foot passes between the first and second flaps, which thus cover both malleoli. The remaining portion of the pattern is passed round to the back of the leg so that the third flap covers the heel and sole of the foot, where it is held in position by the two side flaps which are now rolled round the foot. If a Kirschner wire or a pin is exercising traction on the calcaneus or lower epiphysis of the tibia, the first and

second flaps pass in front of the wire and the third behind it. The whole pattern is held in position by ordinary gauze bandages.

The pattern technique is simple and quick, and is undoubtedly preferable to the use of bandages for limbs immobilized under continuous traction, if only because of the difficulty of passing the bandage between the foot and the traction apparatus. Moreover, when position is being maintained by manual traction, better fixation is obtained because the hands need only be moved once to permit application of the pattern.

The Leg

The rules for protection of the skin are the same as those described above in the technique for the foot. In addition, however, a piece of felt should be placed over the patellar region.

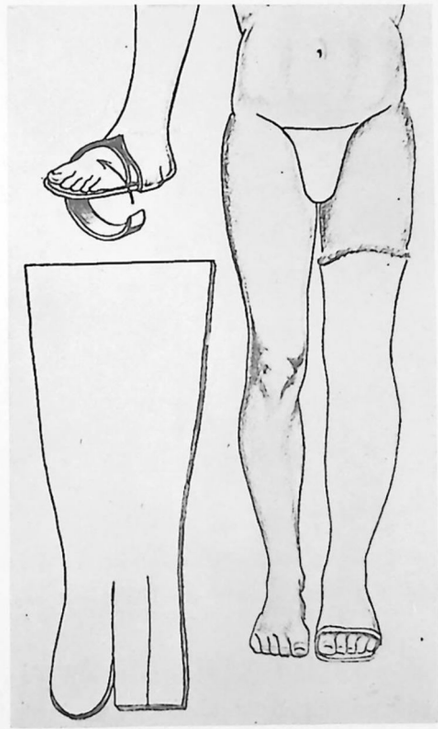


Fig. 59.—Pattern for immobilization of the leg.

Bandage Technique.—Using two 6-inch bandages 4 yards long, a plaque is made extending from the middle of the thigh, over the back of the heel, to the toes, and applied to the plantar and posterior aspects of the foot and leg, as described in the technique for the foot. It is

fixed in position with seven or eight plaster bandages of similar size, and with a 4 in. bandage for the foot.

Pattern Technique.—

Materials required: 10 layers of muslin
2 pints of water to 3 pints of plaster

This pattern is similar to that for the foot, described above, except that it extends to the middle of the thigh (see Figs. 59 to 63).

For the leg, as for the foot, the pattern technique is preferable to the bandage technique when traction is required.

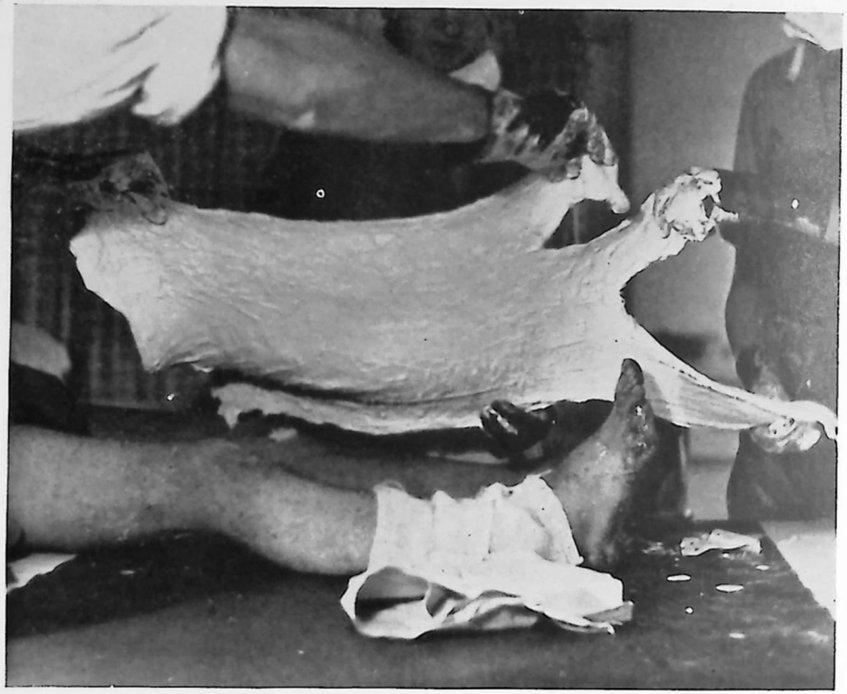


Fig. 60.—The pattern soaked in the plaster cream is spread out over the leg, and the foot is placed between the narrow strips.

Knee, Thigh and Hip (Hip Spica)

In both bandage and pattern techniques protection should be provided over the anterior superior iliac spines and sacrum, round the knee, and over the calcaneus.

Bandage Technique.—A plaster bandage 6 in. × 4 yards is rolled in a figure of eight round the pelvis and groin. A two-bandage plaque is applied round the pelvis and held in position by another 6-inch bandage. One single-bandage plaque is applied to the back of the buttock, thigh and knee, and another to the front of the pelvis and groin; these are held in position by two circular bandages. When the hip has been fixed, plaster bandages are rolled on from the groin to the middle of the calf, and a plaque of 6-inch bandage is applied posteriorly from the middle of the thigh to the lower third of the leg, and held in position by two more plaster bandages. The knee having been thus fixed, a plaster bandage 4 in. × 4 yards is rolled round the ankle and foot, and a posterior-plantar plaque extending from the thick of the calf to the toes is applied and secured by another 4-inch circular bandage.

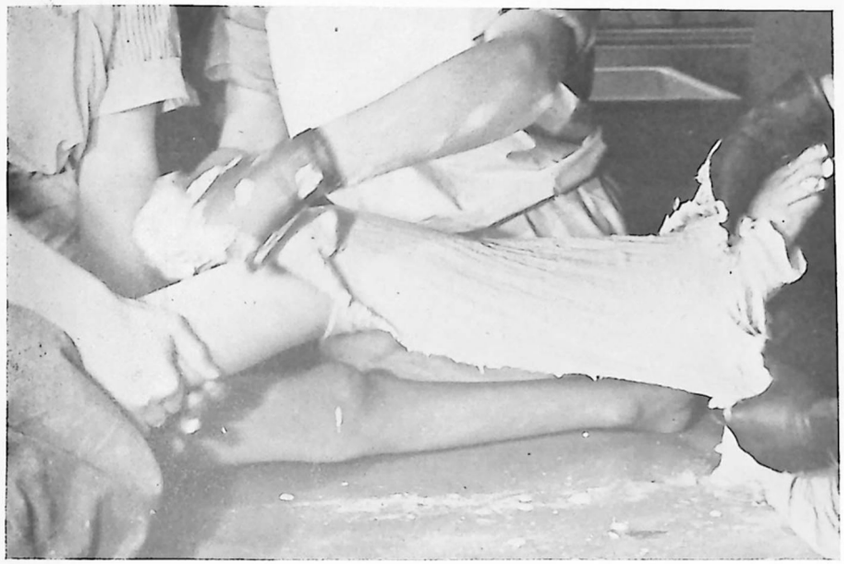


Fig. 61.—The plaster pattern is spread out, carefully avoiding the production of ridges.

Pattern Technique.—The pattern consists of two parts, one embracing the pelvis and the other the thigh, leg and foot. These two parts overlap 4 to 6 inches at the groin (see Fig. 64), where an angle is cut out to facilitate application. A curved indentation is made opposite this angle, so that the pattern can be smoothly fitted round the buttock. This overlap of the two parts provides extra strength at the most vulnerable region of this plaster.

Materials required
for each part: 10 layers of muslin
2½ pints of water to 3½ pints of plaster

For the pattern for the pelvis the length required is from the ninth rib to one inch below the groin, and the width is the circumference

Fig. 62.—Some turns of ordinary bandage hold the pattern in position.

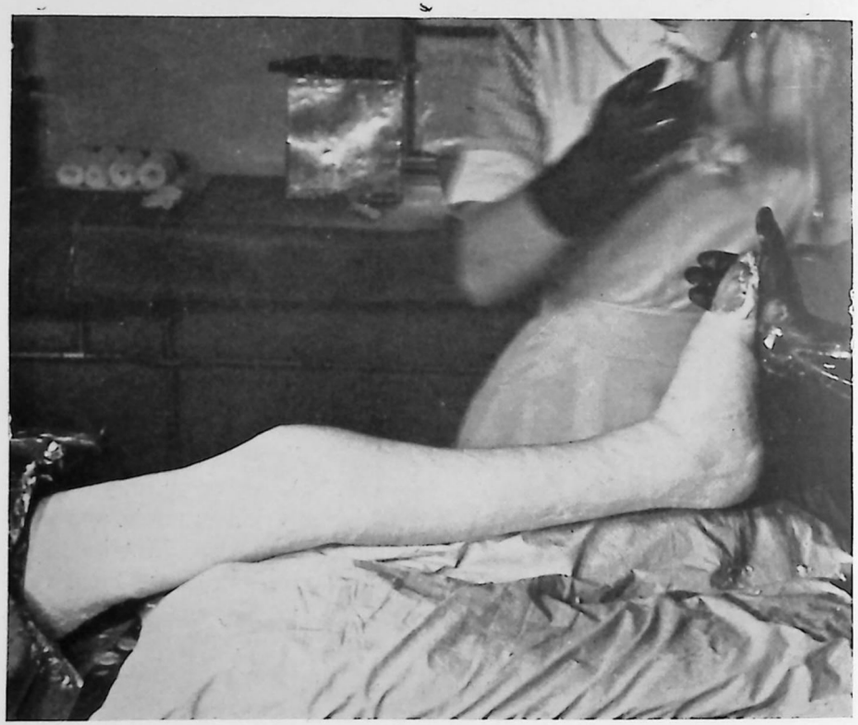


Fig. 63.—The final product.

of the pelvis. For the pattern for the leg the length is taken from the anterior superior iliac spine to the toes, and the width from the circumference of the thigh at its widest part.

The pattern for the pelvis is the first to be applied (see Fig. 65) and is held in position by two ordinary gauze bandages. Care must be taken that it should be very well moulded over the anterior iliac spine on each side and over the groin area. Application of the leg pattern should follow without delay, before the pelvic plaster has time to set

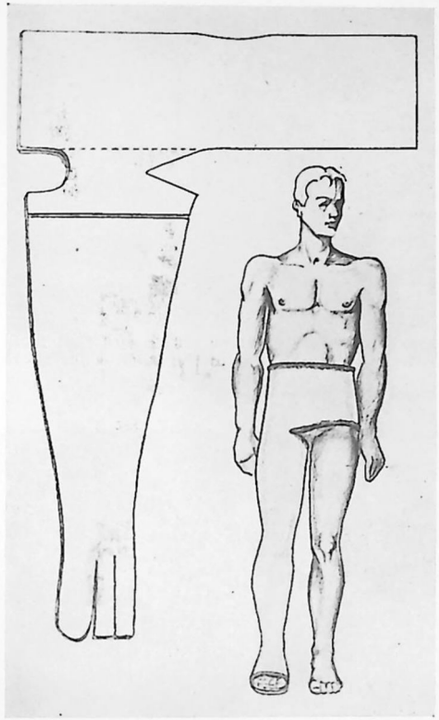


Fig. 64.—Groin spica for adults. The plaster pattern is cut in two pieces: one for the pelvis and the other for the thigh and leg. They are superimposed at the groin. (See also Figs. 65 to 68.)

(see Figs. 66 to 69). The upper end is laid over the groin and trochanteric portions of the pelvic pattern, care being taken that the cuts for the groin and buttock in each pattern correspond exactly. The lower portion of the leg pattern is applied as described above (see p. 270). If traction is exercised by means of foot pieces, the pattern ends at the level of the malleoli and the foot is subsequently immobilized with plaster bandages.

In this case the pattern technique has the advantage of taking only half the time required for application of the bandage technique.

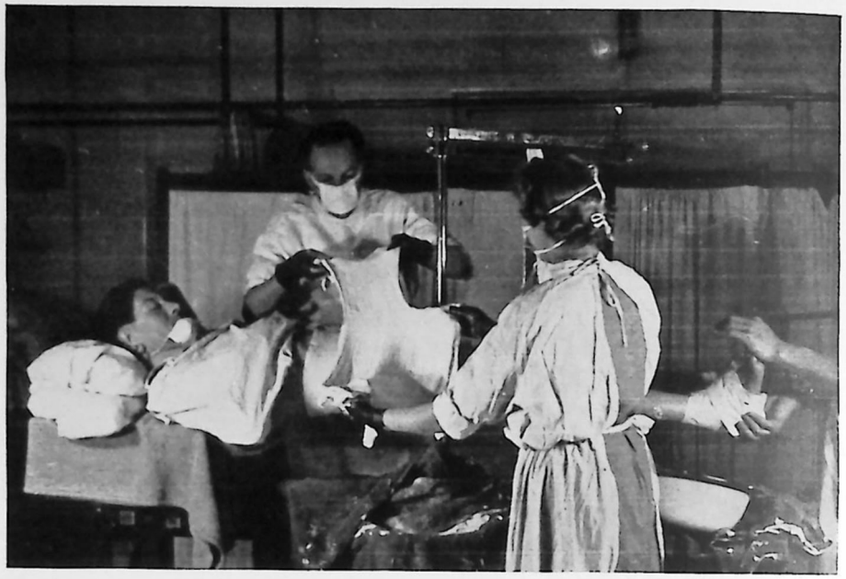


Fig. 65.—After the bony prominences of the pelvis and foot have been protected with felt, the pattern corresponding to the body is placed in position.

Fig. 66.—The pattern for the limb is spread out and placed in position.

Fig. 67.—The pattern is held in position by some turns of ordinary bandage.

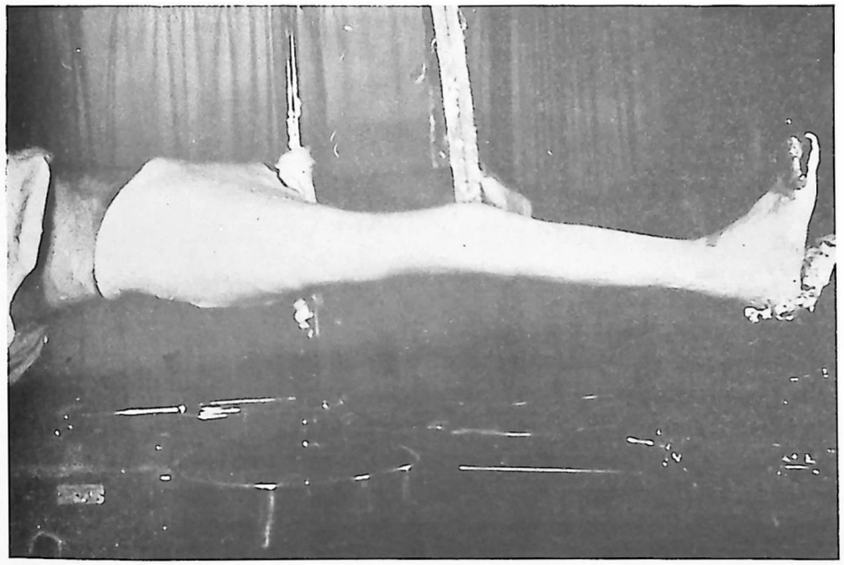


Fig. 68.—The final product.

Fig. 69.—Long groin spica to immobilize a transtrochanteric fracture. Plaster made by pattern technique. Although it is a light plaster, the photograph shows its good condition after ten weeks of wear.

COMPLICATIONS UNDER PLASTER

One of the major difficulties in introducing the biological technique of treating war wounds has been to convince surgeons that the complications are not only far fewer than with any other but also more easily detected. The old demand to examine the wound directly in order to estimate the progress of healing has been one of the greatest obstacles to the general acceptance of this technique. Fortunately, any complication which may arise in the wound immediately produces general repercussions and other direct signs that allow the surgeon to make a prompt diagnosis. In the following pages I shall describe the most important and commonest of the complications which may occur in wounds treated under plaster casts, estimating the importance of the signs and symptoms and suggesting their interpretation.

Fever.—Many patients with wounds encased in plaster show a rise in temperature for two, three, or four days after the operation. This fever varies with the characteristics of the wound, the time of the operation, and the technique. It is a sign either of a local fight against bacteria or of reabsorption of blood in an extensive zone of local shock (see p. 145). In the great majority of cases it lasts for two or three days and then decreases rapidly. A rise in temperature alone need not mean that something wrong is happening beneath the plaster. In some cases a more persistent fever may occur, and the administration of one of the sulfonamide compounds may help in diagnosis. A fever that disappears after a short course of chemotherapy is not a sign of complication in the wound, but probably reflects the ordinary local fight that goes on before the layer of granulation tissue can protect the wound from absorption. Patients treated prophylactically with sulfonamide compounds are generally free from this initial rise in temperature, and so are those who are operated on under the optimal conditions of time and technique without chemotherapy.

Absence of fever is the main sign that a perfect evolution will follow. The patients who remain afebrile are also those who never have an offensive odor and whose first plaster can be kept in position for six or eight weeks if need be.

Most of the patients who have had an initial period of fever after the operation have a transient rise in temperature each time the plaster is changed, very similar to the first bout but shorter. This is due to absorption of bacteria and toxins as a result of the slight damage done to the granulations by the change of dressings and of the movement of the tissues during the fitting of the new plaster.

A sudden rise in temperature shortly after operation, accompanied by an increase of pain and swelling of fingers or toes, is a sign of an infective complication in the wound. The commonest cause is cellulitis, due either to the operation having been performed too late or to an inadequate incision into the cellular spaces having allowed blood and lymph to collect. A course of one of the sulfonamide compounds should be given immediately (see p. 205).

A similar picture may be shown by patients whose progress has been satisfactory for some time after the operation. Such patients have usually had some excessive discharge, and the problem is whether better drainage or treatment for lymphangitis is required. If the first, chemotherapy is useless, but a window in the plaster or, still better, its division into two halves allows the necessary operation to be performed; if the latter, sulfonamide compounds administered by mouth rapidly control the temperature.

The remaining possible cause of early fever is gas gangrene; but fever is not the most important sign of this complication, which with

very few exceptions affects only wounds of a lower limb (see Chapter VII). Suspicion should be aroused at once by a rapid pulse, pain with an increasing sensation of heat and tension in the wound, edema, cold and difficulty of movement in the toes, slight excitement during the first few hours, and the general characteristics of the wound at the time of the operation.

In case of doubt it is better to cut a small window without delay, not over the wound itself but over the skin proximal to the wound, to see the degree of tension of the thigh or leg. The plaster should be removed only if the skin is pressing against it. In over 1,300 cases I have treated with plaster I have had only one case of gas gangrene, and that was diagnosed early by the discomfort caused by the increasing tension of the limb under the plaster.

Another type of patient has a moderate but persistent fever for several weeks. This is due to osteomyelitis, for which the only treatment is drainage of the affected bone.

The Pulse.—The pulse is important only in relation to the temperature. An increase of pulse rate together with some rise of blood pressure may be the first sign of gas gangrene.

Pain.—One of the most striking features of the treatment of wounds under plaster is the absence of pain. This is so constant in the biological treatment that pain has a diagnostic value far greater than in any other technique. Pain, or even discomfort, in the wound is a sign that something is amiss. Pain has a special significance in a patient who has previously been perfectly well. When pain accompanies fever in a patient who has been under treatment for more than a week, the most probable cause is either cellulitis or pocketing of the wound due to insufficient drainage. Swelling of the regional glands and edema of the toes and fingers, and in gas gangrene the sensations of tension and heat, which both increase with great rapidity, facilitate diagnosis.

Edema.—Edema of the toes associated with a rise in temperature and inability to move toes and fingers is typical of an infective complication.

Profuse Discharge.—Though not a real complication, profuse discharge is one of the events which may induce the surgeon to change plasters too often. In a fracture especially, the removal of the plaster increases the risk of losing the reduction, damages the granulation tissues, and gives rise to absorption. On the other hand, some plasters become softened by a copious discharge with resulting impairment of immobilization. For this reason, and also because a profuse discharge is a nuisance and there is danger of absorption through the granulations, treatment is desirable.

The best measure is to prevent the suppuration by proper operation at the appropriate time. When a granulating wound more than two

weeks old has a copious discharge, it is desirable to wait as long as possible and, before changing the plaster, to cut a window in it, examine the wound, and search for osteomyelitis. If this is present, the limb should be radiographed and the operation performed after cleansing the wound in the manner described in Chapter XIV. The second plaster may certainly be left on the limb very much longer than the first, and by the time it is changed, probably the whole wound will be granulating and the bone covered. If suppuration is still profuse, the wound should be cleansed with soap and water solution and dried, the granulations soaked in tincture of iodine (which decreases the excessive moisture by coagulating the superficial layer), and vaseline gauze and a new plaster applied.

The excessive discharge of some wounds treated under plaster causes the most serious drawback of the biological treatment: offensive smell. As this may be strong enough to constitute an argument against the use of plaster for wounds, the problem merits discussion in some detail.

THE PROBLEM OF OFFENSIVE SMELL

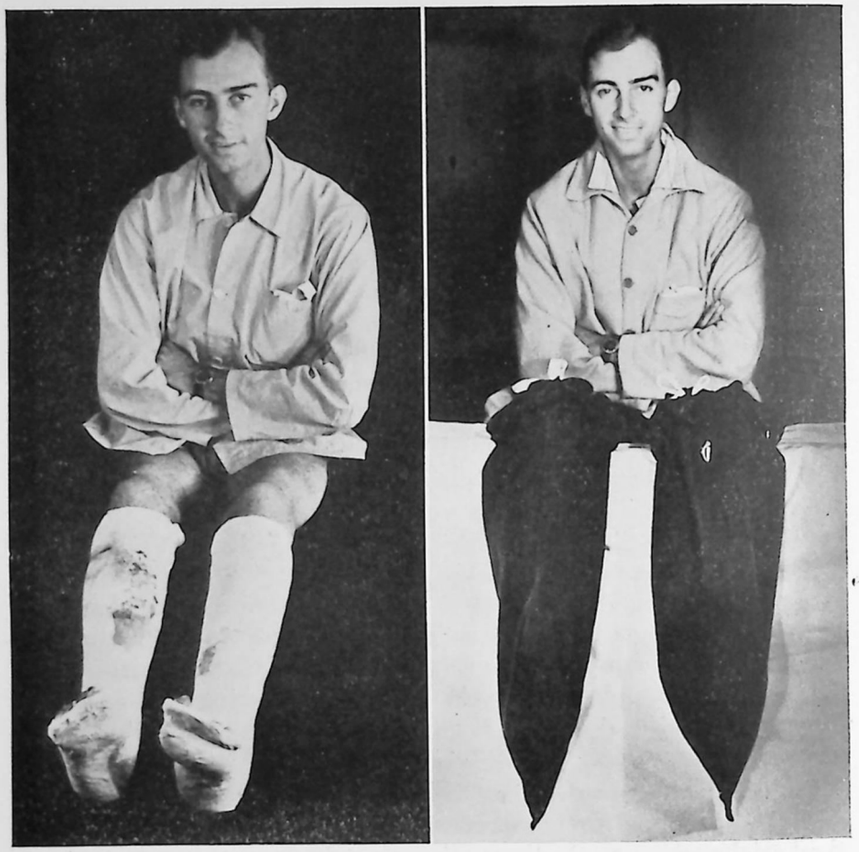
It has been widely declared that bad smell is inseparable from the treatment of wounds under plaster casts. This is true when, as a result of delay or improper surgical technique, wounds are not encased until colonization of bacteria has begun to take place. Among the bacteria which multiply in the wound are many anaerobic saprophytes, and it is these in particular which produce the offensive smell. Pus is profuse, and plasters stained with the discharge smell abominably.

On the other hand, in many cases—which are precisely those which follow the least eventful course—the wound produces an inoffensive smell or none at all. Bacteriological examination in these cases shows practically sterile wounds, and only dry and black clotted blood stains the inside surface of the plaster. Thus the best way to combat smell is to prevent it by a proper operation at the proper time. Once pus has formed in the wound, smell is inevitable and may even interfere with treatment. Many plasters are changed too soon owing to the offensive discharge which soaks them; this constitutes a risk, especially in cases of compound fracture.

Several measures to combat the smell have been devised, but none so far has been uniformly successful. Yeast has been recommended by the Leriche school on the theory that yeast feeds on the necrotic tissue. I treated a few cases with this ferment but found no appreciable difference. The difficulty of procuring enough yeast adds to the inconvenience of this method, and is a reason that experience with it is so meager. Wallis and Dilworth (1941) recommend lactose, to modify the conditions of bacterial growth and thus decrease the number of

anaerobes. I have tested this technique in three cases of offensive smell without observing any change.

Connell (1940) recommends a paste called "zipp," consisting of zinc oxide 1 part, iodoform 2 parts and liquid paraffin 2 or 3 parts. This is a modification of Rutherford Morison's Bipp, but seems to be less irritant and less likely to cause iodoform poisoning. I have seen only a few cases in which it was used, chiefly in soldiers from Dunkirk, and I was not unfavorably impressed with its effect on the smell, even though it added the unpleasant odor of iodoform. Some bad smell, however, persisted in spite of the "zipp."



A. *B.*

Fig. 70.—Infected compound comminuted fracture of both legs, caused by aerial bomb. Admitted to the Wingfield-Morris Orthopaedic Hospital six weeks after the wound. Drainage was performed, sequestra were removed, and both legs were encased in plaster and tied up in bags to confine the smell. The photographs were taken after four months of treatment in plaster.

A. Short plasters to allow flexion of the knees, showing some discharge.

B. Protective bags covering the smelling plasters.

Seddon and Florey (1942) have approached the problem from another angle: that of "isolating" the plaster by covering it with a specially prepared linen bag impermeable to gases. When all the plaster can be included, e.g., on leg or forearm, and the bag is tightly closed, this device undoubtedly does diminish the smell (see Fig. 70). Plaster spicas, however, cannot usually be completely enclosed.

Apart from the best antidote, a clean operation within six hours of the wound, I recommend the avoidance of too frequent changes of plaster merely because of the bad smell. Though it seems strange, many cases with evil-smelling plasters, that are kept in position for several weeks, make a very good recovery, and the smell decreases with each change of plaster. If, however, smell and discharge persist despite renewals of plaster, the cause in nine cases out of ten is osteomyelitis, which should be treated by removal of the necrotic bony tissue and free drainage of the cavity. It is better, however, to wait until the temperature rises and some direct signs of osteomyelitis appear before removing the plaster. As long as smell is the only sign, the plaster should be left alone.

Gissane (1939) recommends a few drops of chlorinated eucalyptus dropped on the plaster several times a day. I have had no experience with this procedure; it might perhaps help in cases treated at home.

CHAPTER XXI

PRIMARY AND SECONDARY SUTURES

PRIMARY SUTURE

Wounds have been treated by immediate and primary suture intermittently since the early days of surgery, but it was not until the fourteenth century that the method was fully described by Pietro d'Argelata as a definite principle of surgery. Since then it has been employed from time to time, but the frequency of serious infections (the "irritations" of olden days) discouraged surgeons from using it as a general practice. Primary suture first became a regular procedure in the treatment of traumatic wounds after the discovery of antisepsis by Lister, for in many cases the antiseptic technique enabled it to be applied without bad results. The general position remained essentially unaltered until the War of 1914 to 1918, when the majority of surgeons began to treat war wounds on lines similar to those they had used for peacetime injuries. This led immediately to disastrous results, and it was not long before surgeons came to realize that a drastic revision of surgical technique was needed. The vast numbers of casualties in the early months of the war provided surgeons with ample opportunity of determining the value of their techniques and improving their methods.

Milligan (1915), Tabuteau (1915), Lemaitre (1916), and others showed that the essential factor in the treatment of war wounds lay in the excision of dead tissues. When the importance of this principle had been recognized with a very marked improvement in results, primary suture, which had been temporarily discarded, again made its appearance. The reason for this is obvious. Many surgeons with long and wide experience of peacetime surgery had adopted the new methods of wide excision and drainage, without any enthusiasm, and when further improvements in technique made possible the use of primary suture with less risk, they gladly took up this new development, for it approximated more closely to the technique they had used before the war. As a result of numerous failures, however, there followed an immediate reaction, and primary suture was condemned from all the main surgical centers of the Allied armies, particularly from the Académie de Chirurgie de Paris. That the practice was supported rather by prejudice than by sound judgment is indicated by the changed attitude of a number of French surgeons, including Professor Tixier, who, having strongly advocated the technique during the War of 1914 to 1918, now emphasize its serious risks.

Drawbacks of Primary Suture

A number of factors militate against primary suture as a routine procedure in war wounds:

1. The need for excising a wide area of dead tissues, which makes it very difficult for the surgeon to draw the edges of the skin together without tension.

2. The presence in most cases of an area of concussion surrounding the wound which must be kept entirely free from tension if gas infections are to be avoided.

3. The invariable appearance of edema in the area of concussion and spasm, which makes it all the more necessary that the soft tissues should retain their maximum elasticity and capacity for distention.

4. The frequent delay before surgical treatment can be given, due either to the requirements of military operations or to the poor general condition of the patient.

5. Factors concerning the surgeon himself: the difficult conditions under which he has to work, the large number of casualties with which he has to deal, fatigue, and frequently inexperience.

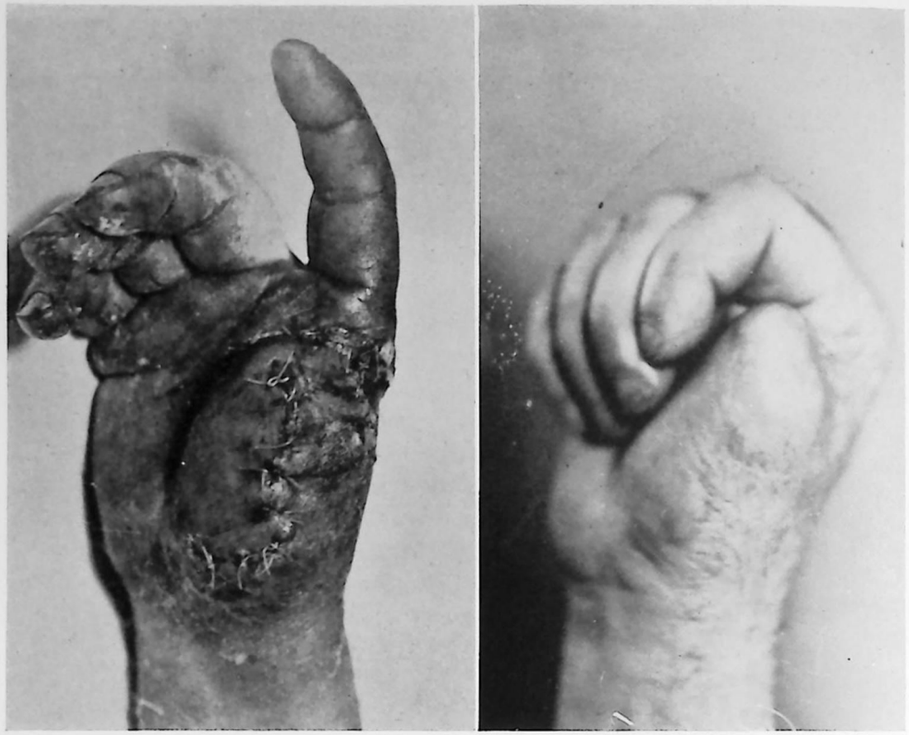
For these various reasons primary suture should be used only in exceptional cases. The definition of these cases is not easy, however; if only because it is never easy to express in brief terms the solution of a large problem which has been arrived at by personal experience over a long period. A useful though rough classification is into two groups: cases in which primary suture may be used, and those in which it should never be used.

Cases in Which Primary Suture May Be Used.—

1. Articular wounds operated on within 24 hours of injury, in which, after careful excision, it is technically possible to appose the edges of the synovial membrane. In these cases the skin and aponeuroses must generally be left open. Only when the operation is performed at a very early stage, i.e., within 6 to 8 hours of the injury, and when the amount of skin requiring excision is so small that a suture will not cause the slightest tension, can the whole wound be completely closed. Even so, in most cases it is preferable to avoid suture of the skin. If the skin is stitched up, the sutures must never be continuous but always of the separate stitch type, so that blood and lymph can escape between the stitches.

2. Wounds in tendinous regions, as in the ankle and foot, and wrist and hand. In wounds of these areas the risk of gas infection is very small; healing by granulation leads to disastrous functional results; and even slight infection of widely open wounds often leads to sloughing of the tendons. For these reasons, primary suture may be used

with advantage for wounds of this type in all cases in which it is technically possible and the conditions, especially time and cleanliness, are satisfactory (see Fig. 71).



A. *B.*

Fig. 71.—*A.* Primary suture in a lacerated wound of the hand, caused by the explosion of a hand grenade four hours before.

B. Good functional result, due to absence of fibrosis in tendons and cellular spaces. This is the great advantage of primary suture in a tendinous region. A small bone graft inserted in the stump of the first metacarpal gave a better grip.

3. In a few cases primary suture may be allowed after an elaborate suture of nerves, in order to protect them from infection and possible interference by granulating tissues. These cases, however, are very rare in war surgery.

4. The majority of lacerated wounds of the skin, without serious damage to muscles (e.g., those caused by glass splinters in bombed towns), operated on within eight hours.

Cases in Which Primary Suture Must Never Be Used.—

1. Wounds in muscular regions. The greater the amount of muscle involved, the greater the risk of primary suture. For example, a deep wound in the middle third of the thigh should never be closed by primary suture.

2. Wounds in areas which receive blood through a single main artery. The best examples are wounds at the back of the knee and in the anterior aspect of the arm. Primary suture applied after excision in these areas adds to the risk of constriction, and consequently increases the risk of gas gangrene.

3. Wounds in which it has been necessary to ligate the main local artery, e.g., ligature of the anterior tibial artery in a wound of the anterior aspect of the leg.

4. Wounds not operated on until after six to eight hours from the time of injury (with the exception of the articular wounds mentioned above).

Technique of Primary Suture

When work has to be carried out at very high pressure, owing to the large number of casualties which have to be dealt with in a relatively short time, primary suture must be confined to the most exceptional cases, that is, to selected cases of articular wounds. The primary suture of the surgical wound made in the incision-excision procedure is, however, another matter. Here the long deep incision, made to facilitate exploration and proper excision, must be reduced after the excision has been completed. If this is not done, an excessive amount of fluid will be lost through the long opening, the wound will tend to gape, the muscles will prolapse and healing will be very slow. The suture of this incision should be with separate stitches, to facilitate the natural evacuation of blood and lymph. It should begin at the extreme ends of the incision on each side of the wound, and should end at the outer limits of the excised area. The size of the opening that is left will therefore correspond to that of the original wound plus the enlargement produced by the excision. To extend the suture to the area where the tissues have been excised would only lead to still further restriction of circulation in the ischemic area, and so expose the patient to the risk of serious complications.

The most suitable material for sutures is either flax or very fine silk. Catgut has the disadvantage that it is quickly macerated by the lymph and prevents the wound from drying.

It must be remembered that only the skin should be sutured; no stitches should be made in the fascia or muscles. This rule applies equally to the closure of enlargement incisions, in which, if the superficial fascia were sutured, all the benefit of the release of internal tension provided by the incision would be immediately lost—with serious consequences to the patient when the inevitable edema followed.

SECONDARY SUTURE

The careful studies made by Carrel at Compiègne during the War of 1914 to 1918 enabled him to lay down the principles of secondary suture. The great advantage of deferring suture is the avoidance of

the risks which accompany it at the first operation. Secondary suture also encourages rapid healing.

In the later stages of the last war three conditions were considered necessary to justify the closure of a wound by secondary suture (see Fraser et al., 1918):

1. That not more than two bacteria per microscopic field should be present.
2. That it should be possible to apply the suture without causing undue tension in the tissues.
3. That the edges of the skin should be clean and healthy.

Secondary suture should preferably be carried out about eight to twelve days after the injury. After this period the wound becomes too sclerotic and it is extremely difficult, if not impossible, to draw the walls together. In contrast to the requirements of primary suture, the apposition of the tissues in the deeper parts of the wound is more important than that of the skin edges. When an area has been excised, it is very risky to close the skin without first closing the space in the depth of the wound. Suture of the skin alone would leave an already mildly septic cavity incompletely closed, and thus lead to infective complications, particularly cellulitis.

Technique of Secondary Suture

General anesthesia is preferable, so as to avoid the increased tension in the tissues produced by the infiltration of a local anesthetic. The wound is first washed out with a 5 per cent solution of soap (e.g., sodium ricinoleate or 1 per cent solution of C.T.A.B. detergent (see p. 193) and water, changing the solution five or six times. The surrounding skin is sterilized with an alcoholic solution of iodine or other skin antiseptic, and the field is isolated with sterile towels. The sutures should be made with a very long and strong curved needle; and stout catgut or other suture material, such as flax, should be used. The needle is introduced into the skin on one side of the wound about half an inch from the edge and is passed through the tissues to the bottom of the wound. Great care must be taken not to include any important anatomical structure in the suture. From the bottom of the wound the needle is reintroduced into the deep tissues on the other side, and is passed up until it emerges through the skin, again about half an inch from the skin edge. A piece of thin rubber tubing one inch long is passed over one end of the suture to take the pressure from the skin when the suture is tied. A second stitch is similarly inserted at a distance of about one inch from the first, a third at the same distance from the second, and so on.

When all the stitches are in position, the wound is dried and dusted with sulfanilamide powder, and the stitches are tied. Only moderate tension should be used, just enough to appose the edges. In between

each of these strong and deep stitches a superficial suture of fine quality is inserted. Finally, a dressing of sterile gauze and cotton wool is applied with a moderately tight bandage, and the limb is placed on a plaster splint that covers about three-quarters of its circumference. The region of the wound itself must not be covered with plaster, because in a certain number of cases subsequent inflammation makes it necessary to remove the stitches. The large plaster splint provides an adequate measure of immobilization and at the same time facilitates immediate reopening should this become necessary.

During the War of 1914 to 1918 secondary suture was widely used, and failures were far less frequent and less serious than those of primary suture. Some surgeons also described a form of secondary suture which they called "delayed primary suture," in which the suture was applied three or four days after the wound, when the danger of gas infection was largely over. This early use of secondary suture is not to be recommended, however, for although gas gangrene does not often appear after three or four days, pyogenic infections commonly do, closure of the wound at this stage greatly assisting their onset and rapid diffusion. Moreover, edema is still present, the circulation is deficient, and the local defenses, particularly the layer of granulating tissue, are not fully developed. At this stage rest forms a vital part of the natural defense mechanism of the body and interference may be dangerous. After about ten days of normal progress, secondary suture applied to wounds that show only a few bacteria per microscopic field produces results which are on the average sufficiently successful to justify its use. The introduction of sulfanilamide powder has increased the scope of secondary suture.

In the treatment of a wound enclosed in plaster, whether or not a fracture is involved, the sutures are applied through a window cut large enough to permit easy access. When the suture is finished and the dressing has been applied, the window is laid back over the wound and held lightly in position by a few turns of ordinary bandage. The window can be quickly opened for the removal of stitches, if infection makes this necessary. With the biological treatment, however, secondary suture is seldom necessary or even possible, since that portion of the wound which can be closed by apposition of the edges, i.e., the region of the incision, has already been sutured at the first operation, while in the area of excision, which has been left open, the gap is generally too wide for a suture to be made without causing tension. I prefer to leave the area of excision to heal by granulation, as with this method there is a better chance of avoiding the risks which accompany all war wounds.

When the cavity of the wound is being filled up with granulations the surgeon can decide whether or not a skin graft is needed to complete healing.

CHAPTER XXII

SKIN GRAFT IN WAR SURGERY

Only one aspect of this important subject can be discussed here; namely, the skin graft as it concerns the general surgeon rather than the specialist (e.g., in the plastic surgery of war), and in particular its application as a means of completing or accelerating the healing of war wounds treated in accordance with the principles described in this book.

OBSTACLES TO REPAIR OF SKIN

In epithelization, we have the final stage of the natural reparative process. The epithelium gradually advances from the edges of the skin over the granulating tissue, while at the same time the wound contracts, until finally, in most cases, the whole surface is covered. Several factors, however, interfere with this normal healing process.

1. **Lack of Natural Healing Capacity.**—In some regions retraction of the wound is limited by the comparative immobility of the skin, with the result that the area of granulation tissue is too extensive to be covered by the new epithelial cells growing from the wound edges. For this reason the process of epithelization is generally less effective in wounds at the back of the knee and the lower third of the leg than in wounds of the thigh.

2. **Friction of the Skin.**—In general, wounds on the extensor side of the joint heal more slowly than those on the flexor side; and, in general, wounds in articular regions show less active healing than those in the diaphysial areas. This is still true when plaster is used, because this, however carefully applied, inevitably allows some minor muscular contractions, which lead to a slight superficial friction of the skin, particularly over bony prominences.

3. **Extensive Area of the Wound.**—Once the contraction of the wound has stopped, the newly formed connective tissue fixes the edges of the skin to the periphery of the wound, with the result that it cannot cover any gap that still may remain at this stage between the edges of the epithelium.

4. **Presence of Hypertrophic Granulation Tissue.**—Hypertrophic granulation tissue is one of the most frequent causes of delay in healing. The epithelium can advance over the surface of the granulations only if they are at the same level or slightly lower; it cannot surmount the obstacle of hypertrophic granulations. In a wound on which the granulation is very prolific, the epithelium is at all points

growing along the floor of the valleys between the hills, just as a river makes its course along the deepest part of the ravine. Hypertrophic granulation provides a great impediment to healing, and the more prolific the granulation the less the capacity of the epithelium to cover the wound.

5. **Excessive Discharge.**—An excessive discharge from the wound macerates the newly formed epithelial cells and decreases the activity of the cells at the edges of the skin.

6. **Infection.**—Streptococcal infections destroy the new, labile epithelial cells and damage those at the edges of the skin, thus impeding the formation of new epithelium. A pyocyaneus infection has a similar but less marked effect.

All these factors, operating singly or in combination, obstruct the final process of healing, and when present in any considerable degree indicate the need for a skin graft. In many cases, however, the decision to graft must be deferred until the natural healing process has been in operation for some time. Only when the surgeon can see at once, either by the extensive nature or the particular site of the wound, that complete natural healing will be slow and difficult, can the need for a skin graft be foretold at the time of the first operation. For instance, it may be taken as a general rule that (except for the thigh) a wound larger than two inches in diameter when the excision is completed will need a skin graft.

THE TIME TO GRAFT

The proper moment to graft war wounds, in general terms, is when a substantial layer of healthy granulation tissue has been established. By this stage the risk of infection is past, the bone is protected by newly formed tissues, and the cavity produced by the loss of muscles and fascia has been filled in. When a closed plaster cast has been used, the graft should be made when the first plaster is changed, i.e., two to three weeks in a wound without a fracture, four to five weeks in one with fracture.

This refers to wounds operated on before infection which have run an aseptic course. In septic cases, when Winnett Orr's plaster technique (see p. 37) has been used to combat the infection, skin grafting should be deferred until the final stage of treatment, first because infection impedes the survival of the graft, and secondly because, even if the graft should be successful, it will interfere with the drainage of the cavity. As, however, excision does not form part of Orr's technique, insufficient epithelization never constitutes a major problem when it is used.

TECHNIQUE OF THE SKIN GRAFT IN WOUNDS TREATED BY CLOSED PLASTER

The skin graft was first used in 1847 by the American surgeon F. H. Hamilton. In 1869, two years after he had demonstrated the parasitic properties of skin, Reverdin of Geneva introduced the so-called Malpighian graft, 2 to 6 mm. in size. The technique of skin grafting was improved by Karl Thiersch of Munich, professor of surgery in Erlangen, who in 1874 described the method which has since been known by his name, but with which Ollier's name should also be associated, for this great French orthopedic surgeon had already described a method exactly similar in 1872. The "pinch" graft, consisting of a small conical graft of skin about half a centimeter in diameter, is generally attributed to Staige Davis (1919). More recently the grafting of small pieces of skin was greatly improved by my own teacher, Manuel Corachán, who in 1933 published an account of the technique with which he had obtained highly successful results. Since 1917 the chief exponent of the whole-thickness living graft in the form of tubed pedicle flaps has been Sir Harold Gillies, to whose school the progress of modern plastic surgery has been so largely due.

Preparation of the Wound for Grafting

An extensive wound that has been treated by a closed plaster cast is ready for grafting just before the cavity has been filled up with granulation tissue to the level of the skin. Wounds in which the bone is suppurating or is not covered by granulation tissue must not be grafted. In a great many cases the wound is ready for a graft when the first plaster is changed, and that opportunity should be seized. At this stage the wound is often covered with discharge, and although in many cases the infection in this is relatively low, some preliminary measures to clean and dry the wound are required. Where the discharge is very copious, it is advisable to cut a window three to five days before the plaster is changed and prepare the wound through this. The wound should be washed each day with a 5 per cent soap and water solution (preferably of sodium coconut soap) and subsequently dusted with sulfanilamide powder.

In some wounds treated by plaster the granulations are so firm and the superficial layer of connective tissue covering them is so resistant that it is advisable, before applying the graft, to scrape away the superficial covering and make the granulations bleed slightly so as to ensure adequate nutrition for the graft. In other cases this is unnecessary, for the mere removal of the gauze covering the wound makes the granulations bleed freely, a fact which indicates that the wound is ready for grafting. In cases in which skin grafting has been unduly

delayed, the skin edge surrounding the wound may be sclerosed and the plane of its line of section be at right angles to the surface of the skin; in such cases a narrow strip should be excised from the edge at the time of grafting to facilitate the advance of the epithelium. Hypertrophic granulations must be scraped until their level is that of the surrounding skin. The following case is an example of the troubles caused by excessive delay in grafting a wound.

A man of 41 was injured by an aerial bomb on August 16, 1940. He had a large wound in the back of the left calf and a large portion of the gastrocnemius was missing, but the circulation in the foot remained good. Operation was performed four hours after the injury. Most of the gastrocnemius was excised after the wound had been cleansed with soap and water. The fascia covering the soleus muscle was intact. The small sciatic nerve was also intact, but hanging and extending halfway round the calf. After complete excision ordinary dry gauze was applied flat on the wound, and the leg immobilized by a plaster cast from the toes to the upper third of the thigh. The postoperative course was completely uneventful, the lack of pain and pyrexia through the treatment by plaster being specially noticeable.

On October 5 the plaster was removed under pentothal anesthesia and the skin cleansed with soap and water. The gauze used for drainage was found invaded by the granulations, which were growing among the mesh. When the gauze was removed, great damage to the granulations was produced, and many strands were left buried in the wound. A new plaster was applied. On November 9 the plaster was removed and the wound was found granulating well although many strands of gauze were still being eliminated. The leg was put up in a Thomas splint and saline dressing was applied to the wound. On November 25 a Corachán skin graft was placed on the wound. On December 11 the dressing was removed and the whole area was found epithelizing well. Only a small area the size of a half dollar on the inner and upper aspect was slightly greenish and not yet covered with epithelium. The wound was cleansed with saline and vaseline gauze was applied. To avoid any movement the leg was put in plaster, and the patient was discharged from the hospital.

On removing the plaster three weeks afterwards the wound was found covered by a greenish slough; all the skin graft was destroyed; the granulations were fibrotic; and some strands of gauze still had to be removed. On April 8, 1941, the granulations and edges of the wound were excised. A Bunyan bag was applied and the wound was irrigated with Milton solution. On April 24 the wound was found clean and the bag was accordingly removed. On May 31 pinch grafts were applied after excision of the wound and granulations; the wound and grafts were covered with sulfanilamide powder. On June 14 half the grafts were found destroyed by new sloughing. On June 30 the wound was almost completely healed except for a small area at the upper margin. A few days afterwards the patient discharged himself from the hospital. He came back on August 7 with the whole scar broken down and an area of inflammation surrounding it. After treatment in bed for a month he was discharged to a plastic surgery hospital.