AN EXPERIMENTAL STUDY OF THE OPERATIVE TREATMENT OF FRACTURES.

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During the last twenty years ever-increasing attention has been given by surgeons to the operative treatment of fractures. This has resulted from various causes. Amongst them may be mentioned the Workmen's Compensation legislation, which has directed notice to the unsatisfactory functional results produced by the older methods; the advent of the *x*-rays, showing how very seldom anatomical accuracy of apposition is attained by splint treatment; and the general advance of aseptic surgery, which has made a direct attack upon the broken bones a justifiable undertaking. There has thus come about such a general consensus of opinion that many cases of even simple fracture require an open operation, that it is not necessary to argue this proposition. But there still remain the important questions to be answered: In which case is operative treatment demanded: and In which will the non-operative give a perfectly satisfactory result? It is exceedingly difficult to answer these questions, with any approach to accuracy, from clinical evidence alone. The circumstances of clinical observations vary so enormously, that comparison of the results of different methods of treatment is almost impossible. Some of the more important of these varying factors are: the age and health of the patient; the site and anatomical condition of the fracture; the length of time that has elapsed before treatment was undertaken; the period between the termination of the treatment and the recording of the result; the skill and the attitude of mind of the surgeon in the method employed. It is only by experiment that these variables can be replaced by constants, and a true estimate made of the factors which underlie success or failure of operative methods.

My primary object in taking up this research was to determine the comparative merits of the different methods of operative fixation of fractured bone fragments, as judged by the organic union produced by them. In particular, I wished to ascertain whether the rapidity and firmness of repair were the better promoted by intramedullary pegs or by external plates and screws. But one inquiry has led on to another, and the appearance of Sir William Macewen's epoch-making work upon the growth of bone has given me a fresh stimulus to examine the source and method of formation of callus.

Before describing my own work, a few words are necessary in relation to similar work done by others. In the broad meaning of the term, the experimental study of bone injuries and bone growth in the lower animals is dealt with in a vast body of literature, which it is difficult even to catalogue, and almost impossible to epitomize. The three burning questions of the origin of callus, the role of the periosteum, and the viability of bone-grafts, have dominated this literature to such an extent that scarcely any other topic is mentioned. Havers, in 1692, whose name has ever since been identified with the vascular canals of the bone, described the periosteum as simply a connective tissue, limiting and vascularizing membrane; but his work, apart from mere speculation, was purely anatomical and microscopical. A less remembered observer, Antoine de Heyde, in 1684, published the first experimental observations on fractures, having worked with frogs, and having come to the conclusion that callus was formed by calcification of the blood, extravasated round the broken bone ends. It was, however, in the middle of the eighteenth century (1739–1743) that the first systematic work on this subject was carried out by Duhamel, who was the originator of the modern generally accepted theory of the function of the periosteum. In his view the periosteum became thickened and succulent round a fracture, and by pushing this new tissue in amongst the fragments, it formed the callus. He it was who founded the term "cambium layer" of the periosteum which is now in every-day use in German literature. Eighteen years later, Troja produced experimental necrosis, and described the new bone formation between the dead bone and the periosteum. A century after Duhamel, after many less remembered works and discussions on the subject had appeared, came the great work of Ollier (1867), which remains to-day as the foundation of all our exact knowledge of bone growth. Ollier's work was so thorough and careful, that his conclusions have attained an almost unassailable position. He proved the regeneration of bone from periosteum in every possible way, and ever since his day the periosteum has been regarded as the most important vital tissue of the bone. Nearly fifty years have elapsed since Ollier's treatise, and during this period practically the whole of modern surgery has arisen. Very many works have been written dealing with fractures, experimentally produced, but these have chiefly concerned themselves with the structure and origin of callus. More recently, the practical question of filling bone defects by grafts of dead or living bone obtained from various sources has absorbed the attention of workers, who have sought to examine experimentally this method of bone re-construction. The most notable contributions to this part of the subject have been those of Barth (1893) and Axhausen (1898). The former showed that large living bone masses, when transplanted, lost their vitality, and acted in the same way as a piece of dead bone, i.e., as a mere splint or scaffolding on which new bone is laid down. The latter proved that certain areas of transplanted living bone retained their vitality and acted as centres of new bone formation. Every practical worker on the subject has moreover endorsed the opinion that a living bone of the same species gives much quicker, stronger and more certain results than dead bone, or than that taken from another species.

It was in 1911 that Macewen produced a little simple work entitled, "The Growth of Bone," in which he showed, by a few most convincing experiments, that bone growth can and does take place quite independently of the periosteum, and that the periosteum is in no way essential for bone growth. As a deduction from these observations, the author would once more revert to the view of the periosteum taken by Clopton Havers in the middle of the seventeenth century, viz., that it is chiefly a vascular limiting membrane.

But in all the literature of this subject I have been unable to find any detailed account of experimental observations on the operative treatment of fractures. There have been papers by Rossi, Roncali, Potârchâ, whose titles suggest that they may have a bearing on this aspect of the question, but unfortunately they are not accessible in this country. Bum, Forlini, Bergel, Pochhammer and Schmieden have made experimental observations of the influence of passive congestion or the application of fibrin or blood-clot in the hastening of fracture repair. All the other papers deal with the formation of callus, or the rôle of the periosteum or medulla in experimental fractures. At the end of this article I have given references to all these papers, classified according to their subject matter.

A GENERAL DESCRIPTION OF THE METHODS EMPLOYED AND THE MATERIAL USED.

I began with the idea of using dogs, cats, and rabbits as subjects of my experiments, but was very soon led to modify this plan. The use of dogs is not only expensive, but it involves many unnecessary difficulties when a number of animals have to be kept under observation at the same time; and up to the present I have not employed any of these animals. Nineteen rabbits were used, but the frailty of their bones made them difficult to deal with, and splintering of the shaft is liable to take place. Further, the fact that in the leg bones the fibula of the rabbit is not a separate bone, but only a slender ossicle which is fused with the tibia at its lower end, makes it difficult to fracture the tibia without at the same time breaking the fibula.

The tibia of the cat is in every way most suitable for an extended series of experiments. It is stout and strong, it has a medullary cavity $\frac{1}{8}$ in. to $\frac{5}{32}$ in. in diameter, and can be drilled in various directions without breaking. The fibula, moreover, is a separate bone, which, whilst allowing free manipulation of the tibia, nevertheless serves as a splint in helping to maintain the tibial fragments in position. Of my 100 experiments, 81 have been on cats, and 19 on rabbits; 65 on the tibia and 35 on the femur.

As regards the operative technique, it may be well to describe here the general plan which has been followed, reserving the description of special methods until later.

The animals were anæsthetized by a laboratory attendant with open ether, and then tied to a warm table by the four paws. The thigh or leg was shaved after washing with etherial soap, bathed with spirit and ether, and after drying, painted with 10 per cent iodine solution. A towel with a median slit was placed over the animal, and the edges of the slit secured to the area of operation by a few stitches. No lotions were used, the swabs were all dry, and the general technique was exactly as in an ordinary surgical operation, including, of course, the use of dry-sterilized gowns and gloves. The majority of the actual operations were carried out single-handed, though occasionally a retractor was held by an assistant through the towel. It was very seldom necessary to ligature a vessel. Drainage of the wound was never done, the fascia and skin being closed separately by fine continuous catgut stitches. The wound was dressed by a small fragment of gauze smeared with 10 per cent iodine in collodion. About a week after the operation this gauze came away, and the wound required no further attention. No attempt was made to fix the limb in any way after the operation, the animal being simply placed in a roomy cage upon clean hay.

The conditions of my licence required me in every case to divide the bone by a saw or forceps through an incision in the soft parts. This was done in most cases by a fine fret-saw, making an incision as nearly as possible at 45° to the long axis of the bone.

Fixation by Short Plates and Screws.—In modern surgical practice, the method of fixing fractures which has become most popular is that of "plating." A short steel plate is used, and this is screwed on to the outside of the bone by short screws which hold the dense bone, but do not penetrate the medullary cavity. I endeavoured to carry out this principle in animals, but without any success.

The plates used were $\frac{3}{4}$ in. long, $\frac{1}{8}$ in. wide, with two holes at either end. The screws were $\frac{3}{16}$ in. long. In order to ensure a good position of the bone, the holes were drilled, then the saw-cut made part way through the bone, the plates were screwed into position, and the division of the bone was completed. In this way a firm fixation was always made in a perfectly good position. But in all nine experiments—two cats (tibias), two rabbits (tibias), five rabbits (femurs),—the bone-ends became disunited within the first week, with more or less angulation and deformity. This was due in every case to the screws coming out. Usually both screws came out from one fragment and the plate remained firmly fixed to the other; but sometimes all the screws were out and the plate was loose among the muscles.

Examination of the bones from these cases shows that the screw-holes become enlarged, so that whereas the screws hold tightly at the time, later the same sized screw will drop loosely into the hole. The whole muscular force of the leg acts upon the grip between the screw-thread and the bone, and the latter quickly gives way by a process of absorption.

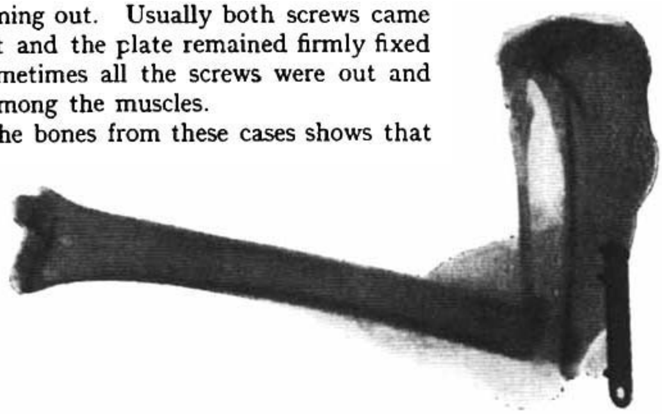


FIG. 285.—Skiagram of rabbit's tibia, 21 days after plating. Screws have come out of the lower fragment, and the plate protruded from the wound.

A second undesirable feature of this series of experiments was the tendency to sepsis, with occasional extrusion of the plate. In three cases there was a septic discharge from the wound, and in a fourth, though the wound was healed, there was periostitis, and a large abscess cavity among the muscles. This marked tendency to sepsis as compared with other methods, is due to the combination of a great irritation caused by free movement of the displaced fragments, with the presence of a foreign body. That it is not due to faulty technique is shown by the fact that in other methods where the same procedure was observed, there was very little sepsis. That it is not due simply to the presence of foreign bodies is evident by the fact that, in the next series, where very much larger plates and pins were used, it did not occur once.

Thus two facts are demonstrated clearly: (1) That short plates and screws, in the absence of external splint fixation, rapidly become loose; (2) That when the fixing agents are once loose amidst the displaced fragments, sepsis is very likely to be set up.

Of course the circumstances of these experiments are not the same as in human surgery. The size of the bones is such that very small screws have to be used. The co-operation of the human patient with the use of external splints, will make the loosening of the plate much less likely. But if the application of splints is necessary after the plating of a fracture, this method will be liable to some of those very evils of the splint treatment which the operation is intended to avoid; that is to say, the muscles and joints will suffer from long immobilization. Moreover, in spite of the use of splints, it will often be found in human surgery that the plates and screws do become loosened. This may be demonstrated by the x-rays, and is proved by those frequent cases where, weeks after the healing of the wound, a sinus is formed, leading down to loose plates and screws.

Fig. 286.—Skiagram of rabbit's femur (No. 26), 21 days after plating. Screws have come out from lower end. Mal-union.

Fig. 287.—Rabbit's femur (No. 28), 31 days after plating. The screws have come out from the upper fragment. Note the quantity and density of the callus.

The general pathological features of this series may best be described by a few skiagrams and drawings.

Fig. 285 is a skiagram from a rabbit's tibia (No. 23), twenty-one days after operation. The plate remains firmly fixed by the upper screws. There is marked angular deformity.

Fig. 286 is a skiagram of a rabbit's femur (No. 26), also twenty-one days after operation. There is marked overlapping of the fragments, and the screws have both come out from the lower fragment and are lying loose in the soft tissues. Healing was aseptic.

Fig. 287 (No. 28) is a rabbit's femur, thirty-one days after operation.

The screws have become displaced from the upper fragment, and the bone is united with marked angular deformity by callus, which is exceptionally dense for this period. Healing was aseptic.

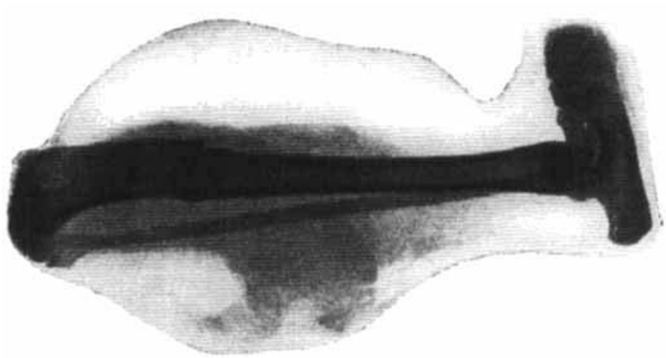


FIG. 288.—Cat's tibia, 19 days after plating. Screws have come out from upper fragment, and have been discharged through the wound.

Fig. 288 (No. 32) is from the tibia of a cat, nineteen days after operation. The screws have come out from the upper fragment and have been discharged from the wound, which has become septic.

It may be noted that in these four examples, both the tibial cases became septic. This is not due to any difference of technique, and in fact the tibia is much easier to plate than the femur. I believe that the sepsis is the result, and not the cause, of the loosening of the screws. It is evident from this series that the screws do rapidly become loose in all cases under the given conditions. Directly a little movement is possible between the screw and the bone, and between the bone ends, there is a great outpouring of tissue secretion, both fluid and cellular. If the source of irritation and the fluid collection lies just under the skin, the wound will probably be opened by the mere tension of the fluid, or by the direct pressure of the plates and screws (e.g., see *Fig.* 285). Once the wound is open for the fluid discharge, septic infection of the whole area is inevitable. This point is of great importance, and I shall refer to it again later.

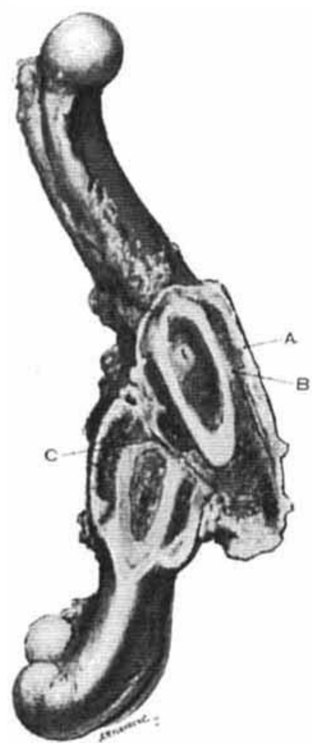


FIG. 289.—Rabbit's femur (No. 25), 42 days after plating. Mal-union with great angulation. A section has been made through the line of junction to show the structure of the callus.

A, Peripheral cartilaginous callus. B, Ossified callus next to the bone. C. Line of fracture where callus is still cartilaginous.

Fig. 289 is a drawing of a rabbit's femur (No. 25), forty-two days after operation, the wound of which had healed without sepsis. The plate fixation had given way very soon after the operation. It shows the great callus excess usually produced in conditions in which the raw bone ends have much mobility; that is to say, conditions of mechanical irritation. Each broken fragment is covered in by an exuberant callus mass, which has ossified next to the bone, but peripherally remains cartilaginous. The line of fracture is still distinct.

Fig. 290 is a drawing from the same case as *Fig.* 286, i.e., a rabbit's femur twenty-one days after operation (No. 26). It shows, as in the last specimen, the lateral union of the fragments by the callus excess, the plate still being firmly screwed to the upper portion, but the screws having come out from the lower.

FIG. 290.—Rabbit's femur (No. 26), 21 days after plating. Screws have come out from the lower fragment. Mal-union with lateral displacement.

Fig. 291 is a drawing from the same case as *Fig.* 287, i.e., a rabbit's femur thirty-one days after operation (No. 28). It presents the same callus excess as the last two cases, and the same arrangement of ossified and cartilaginous areas, the cartilage remaining chiefly at the periphery and at the line of fracture.

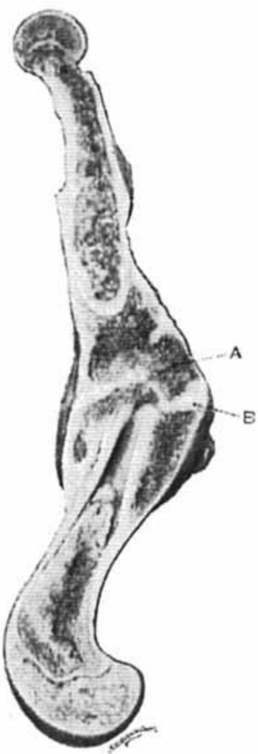


FIG. 291.—Rabbit's femur (No. 28), 31 days after plating, cut down the centre to show union.
A, Ossified callus. B, Callus which is still cartilaginous at the line of fracture.

The next two specimens show the formation of a false joint. It is most difficult to say exactly what circumstance determines in any given case, whether a mal-united fracture will heal by callus excess, or whether non-union with a false joint will occur. The pathological factor is clearly whether much active callus is formed, or whether there is merely fibrous union, allowing free play of the bone ends; but the conditions which determine whether much or little callus is laid down may be various. Three such circumstances are, the degree of mobility, the interposition of soft parts, and the tendency of the bone to callus formation as influenced by blood-supply or the age of the bone. In the cases now under consideration, the only constant difference between those in which there is mal-union with callus excess, and those in which a false joint occurs, was the age of the animals, as judged by the junction of the epiphyses. The young bones, in which the epiphyses have not yet joined, all formed callus excess; but the older ones, whose natural growth had ceased, formed false joints.

Fig. 292 is a rabbit's tibia (No. 24), thirty-three days after the operation. Healing was aseptic. The bone ends are widely separated, and lie in a large cavity which was partly filled with fluid and partly with fibrin. The soft tissues are matted together to form a strong fibrous capsule. Both bone ends are bare and their edges rounded, whilst the screw-holes are enlarged and smoothed away, the plate and all four screws lying loose in the cavity of the joint. The *x*-rays show that both epiphyses have fused with the shaft.

FIG. 292.—Rabbit's tibia (No. 24), 33 days after plating. All the screws have come out. There is an early stage in the formation of a false joint. The ends of the bone are becoming rounded off. The screw-holes are enlarged and their edges rounded.

FIG. 293.—Rabbit's femur (No. 27), 38 days after plating. There is a perfect false joint, of which the upper fragment forms the ball and the lower the socket.

Fig. 293 is from a rabbit's femur (No. 27), thirty-eight days after operation. Healing had been aseptic. A very perfect new joint is seen between the fragments. The lower end of the upper portion of bone is smooth, rounded, and covered by fibro-cartilage, and it rests in a socket on the front and outer side of the lower fragment, this socket being made up by the saucer-like edge of callus to which the fibrous capsule of the joint is attached. It will be noted that here there is no callus excess, and the epiphyses are fused to the shaft.

Table I.—RESULTS OF NINE EXPERIMENTS WITH SHORT PLATES AND SCREWS.

No.	DATE	ANIMAL AND BONE	PERIOD DAYS	REPAIR	ANATOMICAL RESULT	REMARKS
23	17/5/11	R. T.	21	Large mass of callus. Lower screws out. Upper screws firm	Great angulation	Plate protruded from wound
24	17/5/11	R. T.	33	All screws out; screw holes enlarged and rounded. Some necrosis of both ends. False joint	Angulation and overlapping	
25	17/5/11	R. F.	42	Firm callus union. Upper screws out	Angular displacement and overlapping	
26	17/5/11	R. F.	21	Callus union. Screws out from lower end	As above	
27	19/5/11	R. F.	38	All screws out. False joint	Angulation and over-riding	
28	19/5/11	R. F.	31	Upper screws out. Firm callus union	Overlapping and angular displacement	
31	19/5/11	C. T.	7	None, fibula fractured. Screws out from upper fragment	Good position	Sepsis
32	7/6/11	C. T.	19	Upper screws out. Early callus union. Necrosis of upper end	Angular overlapping and displacement	Sepsis
36	9/6/11	R. F.	37	Wires broken; plates loose. Large abscess cavity. Periostitis	Great deformity	Wound healed soundly, two plates and perforating wires

SUMMARY.—Under conditions employed the method was quite useless. In every case the screws came out from one or both fragments. In four out of nine, sepsis complicated matters. In three of these, the plates lay just beneath the skin. Plates used were $\frac{3}{4}$ in. long. Screws were $\frac{3}{16}$ in. and $\frac{1}{32}$ in., with metal thread.

Long Plates and Perforating Pins.—It was quite evident that the short plates held in place by short screws which only penetrated one side of the dense bone, were (apart from splints) quite unable to retain bones in position. I therefore tried some much longer and thicker plates, and fixed these in position by pins, technically known as " cotter " or " split " pins, which perforated the entire thickness of the broken shaft. In one case the plate used was 2 in. long and $\frac{1}{16}$ in. thick, but in the other it was only $1\frac{1}{2}$ in. long and $\frac{1}{32}$ in. thick. They were not flat, but in cross-section formed one quarter of a circle $\frac{5}{16}$ in. in diameter. The pins were $\frac{1}{16}$ in. thick, and after being thrust through the plate and the bone, the split ends were turned back, so as to keep the pin and plate in position.

It was only necessary to do a few of these experiments, all of which were on tibias of cats, because the method was uniformly successful. In none was there any sepsis, the wound healed by first intention, and the animals used the leg freely during and after the second week. The periods of observation varied from four to six weeks. In three of these experiments the healing of the bone was quite ideal. The callus was of the minimum amount, and true bony union was evident from the fourth week onwards.

Figs 294 and 295 show four of these specimens, by the *x*-rays and after dissection.

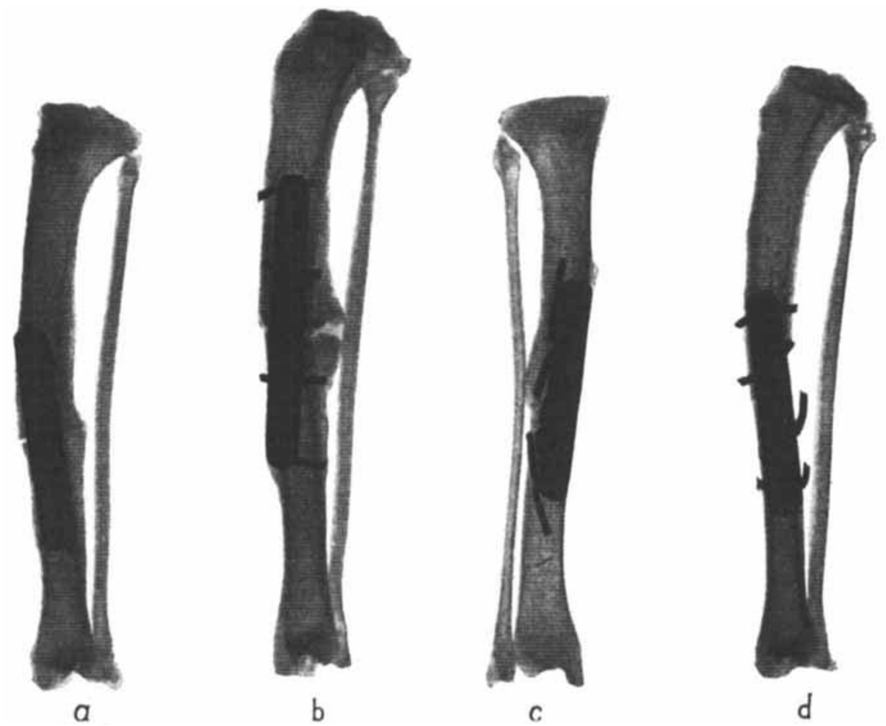


FIG. 294.—SKIAGRAM OF FOUR CATS' TIBIAS UNITED BY LONG PLATES AND PERFORATING PINS. (*a*). No. 54, 28 days after operation. (*b*). No. 48, 34 days after operation. (*c*). No. 53, 42 days after operation. (*d*). No. 52, 42 days after operation.

(*a*) Is No. 54, twenty-eight days after operation. The seat of union is already firm bone, and the medullary cavity is filled with dense internal callus. Of external callus there is only a thin layer, which partly covers in the plate.

(*b*) Is from No. 48, thirty-four days after operation. This was the specimen in which the longer (2 in.) plate was used. Here, although with a longer plate immobility must have been more assured than in the others, there is some callus excess, the line of bone union is not complete, and there is a wide area of cartilage in the callus mass.

(*c*) Is No. 53, forty-two days after operation, and in *Fig.* 295 the specimen is shown cut down the centre. Complete and perfect union has taken place, with very little external callus. Internal callus is firm, and the dense bone of the shaft is thickened on its medullary aspect, above and below the fracture. The plate has been removed, and there is perfect solid continuity of the two halves of the bone.

(*d*) Is from No. 52, forty-two days after operation, and it affords a rather startling contrast to the other members of this series. Although, as regards

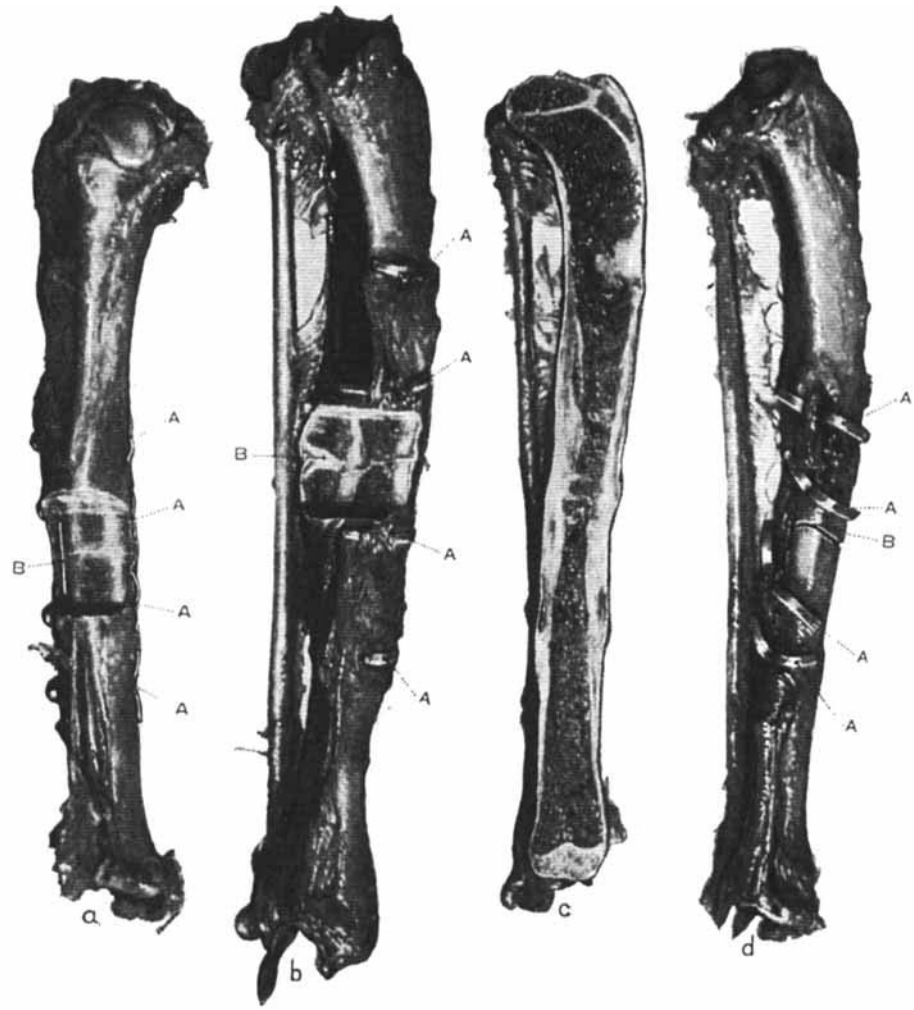


FIG. 295.—FOUR CATS' TIBIAS UNITED BY LONG PLATES AND SPLIT PINS. (*The same as Fig.* 294.)

(*a*). No. 54, 28 days after operation. A piece of bone has been cut out to show the union. A, Ends of split pins turned over. B, Edge of the plate.

(*b*). No. 48, 34 days after operation, a piece having been cut out to show union. A, Ends of split pins. B, Wedge-shaped cartilage in the callus at the line of fracture.

(*c*). No. 53, 42 days after operation, cut down the centre, after removal of the plate and pins. There is perfect union. No external callus, visible as such, a short plug of internal callus and a notable thickening of the dense bone of the shaft some distance above and below the fracture.

(*d*). No. 52, 42 days after operation. No callus, no union. A, Ends of the pins. B, the line of fracture, the edges of which are quite sharp-cut.

function, this animal had been just as well as the others, the wound having healed by first intention and the limb being used freely, yet, nevertheless, the specimen shows a complete absence of callus or any repair, the ends of the bone having undergone an aseptic necrosis up to the nearest pin on each side. The animal was young, and the epiphyses were still separate from the shaft. The only circumstance that appears to be different in the condition of the operation between this and the three other similar experiments, is the fact that the ends of the pins have been left rather long and have been turned transversely, so as partly to surround the bone. This is shown best in the skiagram (*Fig.* 294, *d*). The effect must have been to keep the periosteum and soft parts at a distance from the bone, thus hindering the vascularization of the cut ends.

The importance of this exceptional result is great, in view of the fact that in human surgery many observations have been made that the operative treatment of fractures is accompained by a much-delayed bone repair. It has been customary to attribute this to an immobility which has deprived the bone of the usual stimulus of friction and movement. The present experimental evidence does not support this, because it has been shown that in all the other cases rapid and perfect bone union has occurred when the fragments have been absolutely fixed.

It has been assumed that bone tissue must either be living, with full vitality and reproductive activity, or else necrosed and cast off as a sequestrum. But it seems certain from many observations, that bone may be in an intermediate state, in which circulation and tissue change come to a standstill for the time being, to be re-activated at a later date. Such is the condition of things when a large piece of bone is transplanted from one situation to another. The greater number of its cells die, but later on it is penetrated by other bone-cells and takes on the appearance of new growth. There has been much discussion as to the nature of the bone in this intermediate state. Some say frankly that the bone is dead; but this seems unreasonable in view of the fact that within a short time it is certainly alive and growing. Others say that it merely forms the scaffolding tissue into which cells penetrate and build up new bone. But whatever may be the nature of this latent period, it would seem that it is this period through which the ends of the broken bones pass in these exceptional cases, when treated by operative methods. Aseptic necrosis, or suspended vitality of an injured bone, may be caused by any manipulation, and it usually affects the ends of the broken fragments, being determined most probably by an interference with the blood-supply. It will naturally cause a very great delay in the union of a fracture.

If the method of operative fixation is one which lasts but a short time, e.g. by plates and screws, the fracture will become displaced long before union occurs. On the other hand, if the fixation is of a more permanent character, the delay in the vital action of the bone tissue is of no great matter, because the limb can be used for its full functional activity whilst the delayed repair is going on. One fact, however, stands out clearly in comparing these two methods of plate-fixation; the mere size of the plate has nothing at all to do with its liability to set up inflammation, which may cause its extrusion. A large plate firmly fixed will remain in place indefinitely, whilst a small plate which becomes loose, will set up irritation which leads to its being thrown off. Firmness of fixture is the dominant

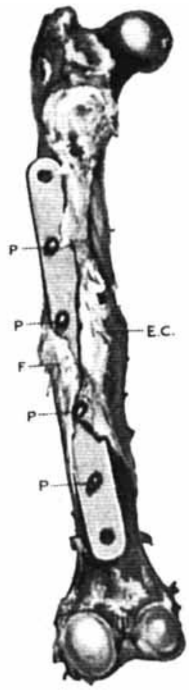


Fig. 296. Fig. 297.

Fig. 296.—Skiagram of a cat's femur (No. 92), 53 days after fixation by double plates and split pins.

Fig. 297.—Drawing of the same femur as Fig. 296. P, Heads of pins. F, Site of fracture. E.C, External callus growing over plate.

factor which determines most often whether a plate will remain in position, or become loose.

Nickel-plated steel has no irritating effect upon the tissues; but if a plate is attached to a bone in such a way that slight but constantly recurring movement is permitted, it will cause mechanical irritation, bone absorption, fluid collection, sinus formation, and finally, sepsis. It will be a mere chance in the latter case whether the plates have done any good at all. If they have held the bone in position until union has occurred, their ultimate removal may be a matter of comparative indifference; but if, as is so often the case, they give way before bone repair has taken place, they are worse than useless, because they hinder repair and often bring about sepsis.

An experiment (No. 92), done at a much later date, may be placed with the foregoing. It is illustrated in *Figs.* 296 and 297. A cat's femur was fixed between two flat plates, and the latter joined together by means of four split pins, which perforated the whole thickness of the bone. The skiagram gives a good representation of the arrangement. Healing was good and function perfect, and the animal was killed fifty-three days later. In the drawing (*Fig.* 297) is seen how the external callus is growing over and enclosing the plates.

Table II.—Results of Operations with Long Plates and Split Pins.

No.	Date	Animal and Bone	Period Days	Repair	Anatomical Result	Remarks
48	22/2/12	C. T.	34	Firm. Callus in some excess growing over the plate. Cartilage at the site of fracture	Good	Good function. Plate was 2 in. long and $\frac{1}{16}$ in. thick
52	2/5/12	C. T.	42	No union. Very little callus	Good	Good function. Plate 1½ in. long $\frac{1}{16}$ in. thick
53	2/5/12	C. T.	42	Firm bony union. Minimum of callus	Good	Good function. Plate as in last
54	16/5/12	C. T.	28	Firm bone union. Small amount of callus	Good	Good function. Plate as in last
92	11/9/13	C. F.	53	Firm bone union	Good	Good function. Double plates

SUMMARY.—In all cases the four holes for the pins were bored in the bone before it was divided. This accounts for the uniformly good result anatomically. The pins were ordinary split or cotter pins, $\frac{1}{16}$ in. in diameter, passed through the whole thickness of the bone and the ends turned back and cut short. The plate, which was nickel-plated steel, formed one quarter of a circle $\frac{5}{16}$ in. in diameter. In every case functional and anatomical perfection was gained. In an actual fracture there would be the important factors of accurate adjustment and the ultimate fate of the place to be considered. Note the remarkable contrast between 52 and 53 as regards union. In the last case, 92, double flat plates were used.

Outside Metal Collars.—In this group are included seven experiments, all of them being on the cat's tibia. In four, the material used was aluminium plate; in one, steel plate; in one, magnesium plate; in one, aluminium-bronze wire. When metal plates were used they were cut out of thin sheet, wrapped round the bone fragments, and then secured by wire. As far as possible the periosteum was raised from the bone, and the plate secured between the two structures. In three of the experiments the fixation was insecure, and one end of the bone became dislodged from the embrace of the metal collar. There are therefore only four for consideration. In all of these the same course of events is seen, although in different stages.

Mechanically, the collar is a good method of fixation, and the position and function of the limb appear to be quite normal; but the process of repair is delayed and weak even after a long period. At first sight it seems as though the ends of the bone grasped by the collar had undergone necrosis, but closer examination shows that this is not so.

When the collar is removed, the underlying bone is "bare," in the sense that it has no soft tissue covering it; but in the early stages it is rough and pitted, from the exudation of the granulation tissue that is to form the external callus, although the periosteum is quite excluded.

Fig. 298 *a* is a cat's tibia (No. 10, ten days). There is almost no naked-eye evidence of repair, but no necrosis. The surface of the ends of the bone is roughened by very early granulation (callus) formation. *Fig.* 298 *b* is from No. 14 (twenty-five days). There is well-marked callus formation, chiefly present beneath the plate, between it and the bone. Also there are both internal and intermediate callus, but these for the most part are not derived from, or attached to, the actual ends of the fragments, which appear in part to be bare, in a state of necrosis or suspended vitality. The vital union, therefore, is incomplete. These two specimens (*Fig.* 298) show well the early stages of external callus formation, derived solely from the bone when the periosteum is excluded.

Fig. 299 is from No. 9 (fifty-two days), and shows a most interesting specimen. The bones have united in good position. The steel plate is covered in by a layer of periosteum. A thin layer of callus lines the deep surface of the periosteum outside the plate, and this is best marked at the two ends, where the periosteum is close to its bony attachment. There is also a distinct thin layer of external callus on the outer surface of the bone beneath the plate. At the site of fracture a feeble repair has taken place, by cartilaginous tissue. The dense part of the shaft of the bone has been almost entirely replaced by an open spongy tissue, there being the thinnest possible shell of compact bone left. It is evident in this case that the closely encircling plate has interfered with callus formation on the outer surface of the bone, and that, as if to make up for this, the medullary circulation being good, the bone activity in the form of osteoporosis and bone reconstruction has proceeded with unwonted vigour in its interior.

From a practical point of view the method is of doubtful value. It clearly interferes with the chief agent of repair, viz., the external callus. If the collar is put on so rigidly as to act as an efficient immobilizing splint, it prevents the laying down of external callus; if it is put on loosely, so as to allow a callus layer on its interior, it will permit movement, and this often leads to displacement.

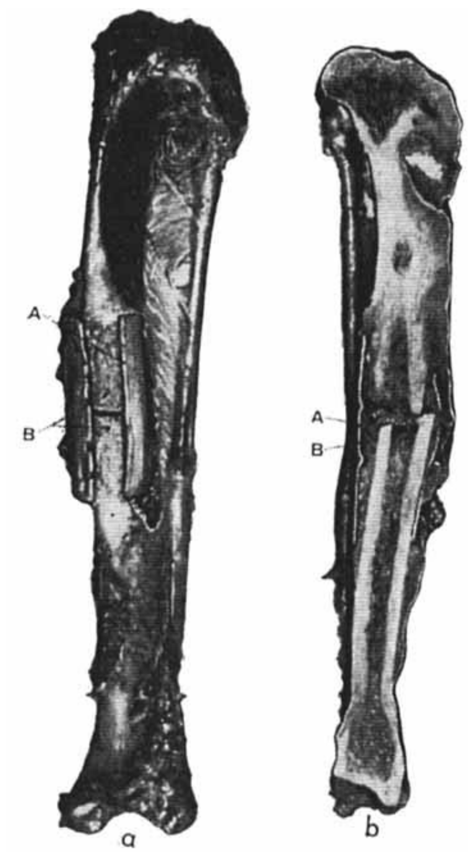


FIG. 298.—TWO CATS' TIBIAS TREATED BY METAL COLLARS.

(a). No. 10, 10 days after operation. Aluminium plate, A, has been cut open to show bone ends. B, The outer surface of these is rough and pitted by the granulations of early callus.
(b). No. 14, 25 days after operation. Specimen is cut down the middle, without disturbing the aluminium plate (A). There is abundant external callus (B) formed beneath the plate, independently of the periosteum.

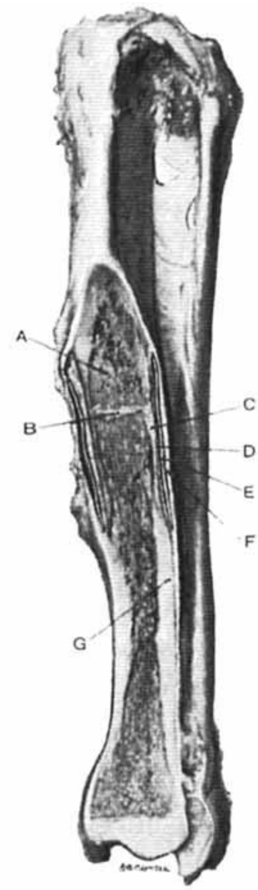


FIG. 299.—Cat's tibia (No. 9), united by steel plate, 52 days after operation. There is very slight external callus, and the deep layer of periosteum is ossified. A remarkable development of internal callus occupies the marrow cavity and the place of the dense bone. A, Internal callus. B, Cartilage still present at line of fracture. C, the much thinned dense bone. D, External callus. E, Steel plate. F, Ossified periosteum. G, Thickening of the dense bone below the fracture.

Table III.—RESULTS OF EXPERIMENTS WITH ENCIRCLING METAL COLLARS.

No.	Date	Animal and Bone	Period Days	Repair	Anatomical Result	Remarks
4	6/4/11	C. T.	1	None	Lower end had escaped from collar. Fibula fractured	Died, cause undetermined
9	26/4/11	C. T.	52	External periosteal callus outside plate deficient at one area. Ossified only at the edges. Union of bones by cartilage. Remarkable internal reconstruction	Good	Excellent function. Steel plate and wire
10	26/4/11	C. T.	10	None, but bone ends rough. Early callus	Good	Aluminium plate. Wound broke open, exposing plate
11	28/4/11	C. T.	13	Plate largely eroded Early periosteal callus, lower fragment. No union	Good	Magnesium and wire. Good function. Skin became sore
14	1/5/11	C. T.	25	No bony union. Ends partly necrosed. Early callus growing over ends of collar	Good	Aluminium and wire. Excellent function. Fibula thickened opposite fracture
42	19/6/11	C. T.	28	Firm callus union. Tibia fractured	Overlapping and angulation	Wire only. Upper end escaped

SUMMARY.—Mechanically, the method is good. If properly carried out, the bones are kept in good position and good function results; but the natural union is delayed greatly, the bone ends may undergo necrosis, and there is a marked tendency to opening of the wound with exposure of the plate. Very instructive as to the origin of callus.

Intramedullary Pegs (Bone).—In seven experiments I used pegs made of bone or ivory; but as these were only $\frac{1}{8}$ in. to $\frac{5}{32}$ in. in thickness, they were not strong enough to stand the strain put upon them, and in every case the peg was snapped. From a practical point of view, therefore, this series can be dismissed with few words. It is evident that the muscular force which comes into play after a fracture is considerable. It is evinced also by the fact that when the lower leg was the seat of the operation, the fibula usually was also fractured. But the specimens from this series illustrate very well some of the features of repair in the case of mal-united bones, and also afford examples of the formation of false joints.

Fig. 300 shows, in its early stage, the process by which the mal-position of the fragments is minimized by a filling up of angles and concavities with callus. (*a*) is from No. 5 (seventeen days). Displacement is not complete, so that the ends of the fragments are still in apposition, but with some lateral deviation.

The angles between the side of one fragment and the end of the other are filled with callus; this has not formed at all on the surface of the fragments, which are left jutting out. The useful result of this arrangement is clear: the filling up of angles restores the bone to something of its original form, and supports the strain thrown upon it in the original axis. The interesting point arises, however, as to the factors which cause this purposeful remodelling of the bone architecture. The simplest explanation would be that the lateral displacement of the fragments, as seen in *Fig.* 300 *a*, strips off a portion of periosteum, and causes a blood-space, triangular in longitudinal section (shown by the letter A), bounded by three surfaces: (1) The outer surface of one end, (2) the cross-section of the other end, and (3) the deep surface of the periosteum. Into this blood-space both the raw bones pour cells which form callus. Where the bone juts out beyond its fellow, the periosteum remains tightly bound to it, and no exudation or callus-formation occurs.

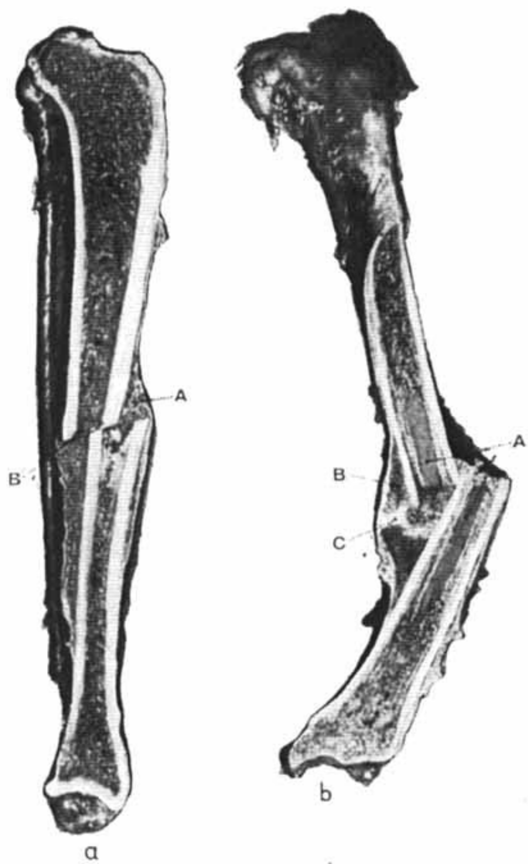


FIG. 300.—TWO CATS' TIBIAS, SHOWING MAL-UNION AFTER MEDULLARY BONE PEGS HAVE BROKEN.

(*a*). No. 5, 17 days after operation. A, Early callus filling up the angle between the fragments. B, fracture line.

(*b*). No. 6, 44 days after operation: A, Broken bone peg. Mass of callus on the concavity only. B, Ossified callus next to the bone. C, Cartilage still remaining at the site of fracture.

Fig. 300 *b* shows No. 6 (forty-four days). Union has occurred with marked angulation, the concavity of which is filled by callus, partly cartilaginous and partly ossified. That part of the callus which is first formed and is liable to least movement is in the angle between the periosteum and the bone. This is ossified. The part opposite the site of fracture, where movement has continued longest, is still cartilaginous. Here again, the filling up of the concavity of the fracture by callus seems to be determined by the fact that it is at this site that the periosteum is loose and allows exudation. In general terms, therefore, it may be said that in irregular fractures with mal-position, the deposit of callus is determined by an absence of tension, which favours the exudation of bone cells from the ends of the fractured bones.

In *Fig.* 301 *a* and *b*, are seen two specimens of femurs of rabbits showing the formation of false joints: *a* is after thirty-two days, and *b* after forty-seven days. In both there is abundant callus formation, showing that in these cases it is the excessive displacement and mobility which cause the non-union, rather than any absence of reparative capacity. In this respect these cases contrast with the two specimens already figured (*Figs.* 292, 293), in which a

FIG. 301.—FEMURS OF TWO RABBITS, SHOWING THE FORMATION OF FALSE JOINTS AFTER THE GIVING WAY OF MEDULLARY BONE PEGS.

(*a*). No. 15, after 32 days. There is abundant callus formation, especially from the upper end. A, Upper fragment of the broken peg. B, Cavity of the false joint. C, Cavity from which the lower half of the peg has fallen out.

(*b*). No 20, after 47 days. Here, too. there is abundant callus formation. A, Broken peg. B, Fibrous capsule of the false joint.

scantiness of repair associated with the age of the bones seems to determine the condition. In one respect, however, all the four specimens of false joint which I have encountered in these experiments are similar: they all occurred in either the femur or the tibia of a rabbit; that is to say, in a part of the limb where there is only a single bone (the fibula is only a rudimentary spicule in the rabbit). This would show that free mobility is an important factor in the production of this condition. As to another factor, often cited as a cause of false joint, viz., the interposition of the soft parts, none of my experimental cases showed any evidence of this.

Table IV.—RESULTS OF SEVEN EXPERIMENTS WITH INTRAMEDULLARY PEGS—BONE.

No.	DATE	ANIMAL AND BONE	PERIOD DAYS	REPAIR	ANATOMICAL RESULT	REMARKS
3	6/4/11	C. T.	5	None	Peg broken Good alignment	Died, cause unknown
5	12/4/11	C. T.	17	Early callus filling angles	Peg broken. Slight lateral displacement	Slight skin suppuration
6	12/4/11	C. T.	44	Firm callus union. Callus partly cartilage, partly bone	Peg broken. Marked lateral displacement. Fibula fractured	Good active movements
7	21/4/11	C. T.	15	Early callus union	Peg broken. Displacement and overlapping	Some suppuration
15	5/5/11	R. F.	32	Extensive cartilaginous callus with false joint	Peg broken. Marked overlapping	
19	12/5/11	R. F.	45	Inflammatory process has overshadowed any healing	Peg broken out from one end of shaft. Extreme displacement	Osteo-periostitis. No apparent ill-health or pain
20	12/5/11	R. F.	47	False joint with well-marked fibrous capsule	Peg broken. Marked displacement	

SUMMARY.—Mechanically, the method was a failure, because the bone pegs always broke. In three cases there was some suppuration, and in one this was of a serious character. Great displacement, excessive callus, and a tendency to the formation of a false joint were exhibited in the union when the fixation had given way.

Intramedullary Pegs (Decalcified Bone).—These experiments, five in number, met with no success. The peg always gave way and displacement occurred. For practical purposes, therefore, nothing more need be said. Two of the specimens call for comment.

Fig. 302 *a* shows No. 12 (twenty-nine days); there is a large callus mass filling up the angle between the fragments. In this it is easy, even with the naked eye, to trace two stages: (1) Just outside the dense bone of the shaft is a narrow irregular zone of ossification; (2) All the rest of the callus is of a semi-cartilaginous consistency, having originated from the bone.

Now, the ossified portion is the oldest part of the callus, and therefore the position of the ossification points to the originating point of the callus. This, in the specimen, has clearly been from the outer surface of the bone, and not from the deep surface of the periosteum.

Fig. 302 *b* shows No. 39, which is one of the cases of almost entire absence of union with which one is occasionally confronted in bone repair after operation. It is a cat's tibia (twenty-eight days). The skiagram shows practically as much as the specimen itself. The position has been well maintained by a few turns of aluminium-bronze wire outside the periosteum, which embraced the two obliquely-cut ends; but there is not a trace of any kind of callus or

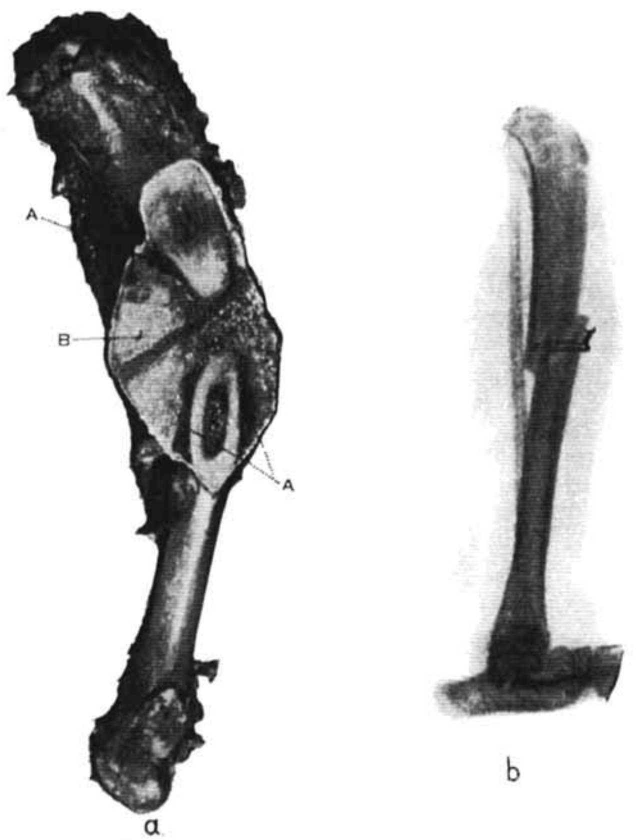


FIG. 302.—TWO CATS' TIBIAS, SHOWING MAL-UNION AFTER THE USE OF DECALCIFIED BONE PEGS.

(*a*). No. 12, after 29 days. A large mass of callus is present, chiefly in the concavity of the fragments. A, Ossification of the callus taking place from the surface of the bone. B, Wedge-shaped cartilage under the periosteum.

(*b*). No. 39, after 28 days. Skiagram showing the encircling wire and the displacement. There was no callus.

reparative material. The ends of the fragments of bone beyond the wire are necrosed. The section of the bone and the insertion of the peg must have injured their deep blood-supply, whilst the wire interfered with the surface vessels. There is probably a third factor in the matter. I have constantly found that specimens in which aluminium-bronze wire has been used show marked green discoloration of the tissues, and it is likely that this copper absorption may hinder tissue growth. The specimen is most significant as to the origin of the reparative material from the cut surface of the bone.

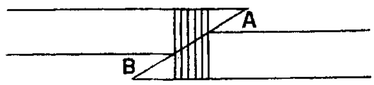


FIG. 303.

The experiment is represented by the diagram (*Fig.* 303), which shows that the obliquely-cut bone ends have slid into the position shown. In normal circumstances healing would occur by the angles A and B being filled by callus. Now the sides of these angles formed by the cut bone is dead, and the other side of the angle is the outer periosteal surface, hence no callus is formed.

Table V.—RESULT OF FIVE EXPERIMENTS WITH INTRAMEDULLARY PEGS—DECALCIFIED BONE.

No.	Date	Animal and Bone	Period Days	Repair	Anatomical Result	Remarks
8	21/4/11	C. T.	28	Callus well marked. Upper end of lower fragment is necrosed	Great overlapping. Fibula fractured	Marked displacement within few days
12	28/4/11	C. T.	29	Union by excessive callus. Necrosis of upper end of lower fragment	Great overlapping. Fibula fractured	Cat well and lively
17	9/5/11	R. T.	10	No union, but no necrosis	Overlapping and angular displacement	Leg put up in plaster
21	12/5/11	R. T.	38	Firm union by external callus	Overlapping with angular displacement	
39	19/6/11	C. T.	28	No union, but position maintained by wire. Necrosis of both ends	Good position	Good function

SUMMARY.—In the absence of other means of support, the method is useless, because the decalcified peg at once snaps.

Intramedullary Pegs (Gelatin and Catgut).—The pegs were made by running gelatin into moulds in which were strands of No. 1 chromic catgut. By this means the pegs, which were hardened in formalin, were prevented from becoming brittle. Only four experiments were performed, all on cats' tibias. The gelatin softened too quickly to allow of any real fixation by this means. Wire, which was used to introduce the pegs, was also wound round the oblique fractures, and it was evidently this wire more than the intramedullary splint that kept the bones in position. In two specimens, No. 34 (twenty-two days) and No. 40 (twenty-eight days), there is no repair of any sort near the fracture. The encircling wire has produced necrosis of the ends of the bones in just the same way as in No. 39 of the last series.

Fig. 304 *a* shows No. 41 (twenty-eight days); there is early union by external callus in good position, but there is no bony union, and part of the ends appears necrosed.

Fig. 304 *b* shows No. 33 (forty days); there is a further stage of union by thick spongy external callus, which is partly ossified, but this is not firm enough to prevent considerable movement between the fragments.

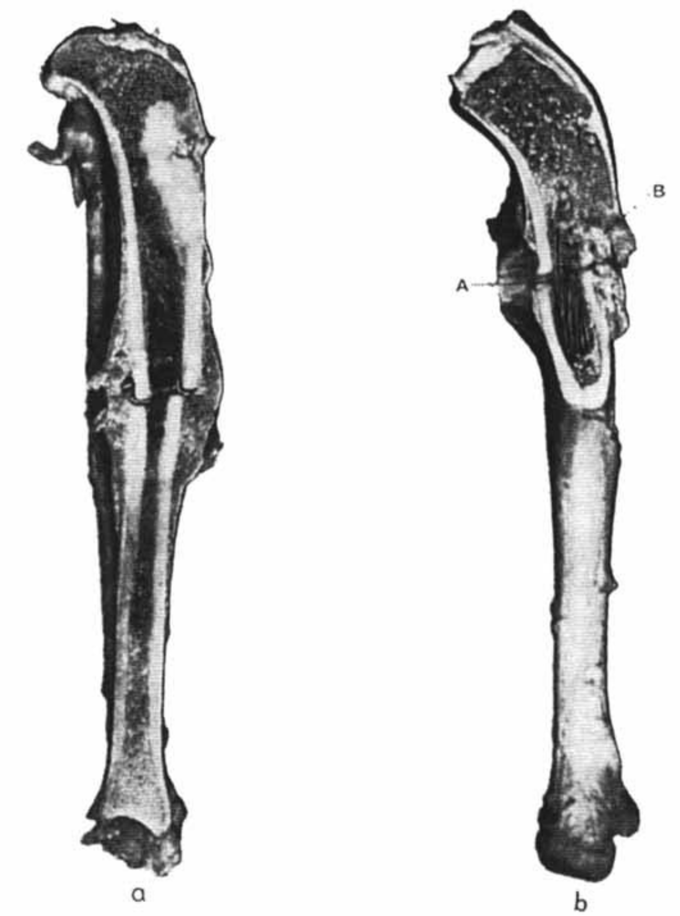


FIG. 304.—TWO CATS' TIBIAS AFTER THE USE OF MEDULLARY PEGS MADE OF CATGUT AND GELATIN.

(*a*). No. 41, after 28 days. Union by external callus. Actual bone ends show partial necrosis.

(*b*). No. 33, after 40 days. A, Remains of catgut peg. B, External callus. Here, too, the actual cut surfaces of the bone show but little repair.

I account for the failure of, or weak, union in these cases by the fact that both intramedullary and periosteal means of fixation were used, thereby interfering with the blood-supply of the bone ends, both from within and from without.

Intramedullary Pegs (Horn).—I only tried horn (which has been spoken of so highly by Rehn) on one occasion. It behaved just like bone or decalcified bone; that is to say, it broke, and allowed great displacement of the fragments. It is evident that it would only be of use when supplemented by external splints, and therefore I did not think it worth while to pursue the matter.

Table VI.—Results of Five Experiments with Intramedullary Pegs—Gelatin (4), Horn (1).

No.	Date	Animal and Bone	Period Days	Repairs	Anatomical Result	Remarks
				Gelatin.		
33	7/6/11	C. T.	40	Union by abundant callus, not by bone. Fibula fractured	Good. The wire had kept the ends in apposition Catgut unaltered	Wire used round oblique division
34	9/6/11	C. T.	22	Almost no repair, even callus absent. Necrosis of ends held by wire	Good, kept by wire	Wire round oblique section
40	19/6/11	C. T.	28	No repair. Ends held by wire necrosed	Good, held by wire	Wire round oblique section
41	19/6/11	C. T.	28	Slight callus repair. Necrosis of ends	Good	Wire round bone section
				Horn.		
45	8/2/12	C. T.	28	Slight callus. No bone union. Fibula fractured	Overlapping. Peg broken	Displacement evident in second week

Summary.—As far as these few cases go, it is evident that absorbable pegs cannot alone hold the bone until union occurs. The effect of the wire in holding the bones together, but in causing necrosis of the bone ends, is important as showing the effect of interference with the periosteal blood-supply.

Intramedullary Pegs (Metallic Magnesium).—As is well known, metallic magnesium is readily disintegrated and absorbed in the living tissues. It seemed, therefore, worth while to try the effect of this metal when used as an intramedullary peg; and the experiments, which were six in number, produced most interesting results.

In four, the femur was the bone used, once of a cat and three times of rabbits. In all of these great displacement occurred, three times from the breaking of the peg, and once from the breaking of the shaft of a rabbit's femur. In these three there was the same excess of callus and new bone that is seen in the tibial specimens, and in two of them (Nos. 22 and 30) the condition was one of periostitis with the formation of abscess cavities. Even in those two specimens where the process was less severe (Nos. 29 and 38), there is a great periosteal thickening of the bone running some distance along the shaft in both directions. The two experiments on the cats' tibias are the best illustration of the results of this method. In both, the anatomical position and the function were good, but there was great excess of callus.

Fig. 305 *b* shows No. 37 (fifty-five days). At the seat of fracture there is spindle-shaped thickening of the bone to about double its natural size. This consists of well-ossified callus, by which the bone is firmly united. In the marrow cavity is seen the disintegrated remains of the peg in the form of opaque whitish masses, interspersed with red material (blood-clot and tissue cells).

Fig. 305 *a* shows No. 35 (sixty-six days), the union is not so good, and the fibula has undergone fracture. Here, too, there is a great callus mass, by which the tibia and the fibula are united to one another. Practically none of the metallic peg remains as such. In the callus there are some islets of cartilage.

FIG. 305.—TWO CATS' TIBIAS AFTER THE USE OF MAGNESIUM PEGS.

(*a*). No. 35, after 66 days. A, Remains of the peg. There is fracture of the fibula and great callus excess in both bones.
(*b*). No. 37, after 55 days. A, Remains of the peg. B, Excessive external callus, firmly ossified.

It is evident from these specimens that magnesium is rapidly disintegrated and absorbed from the medullary cavities of bones. This disintegration is too rapid to allow reliance to be placed on such pegs as the sole means of fixation; but in the process of its absorption, the magnesium evidently acts as a most powerful stimulant to bone-formation. Indeed, it acts as an irritant which may so stimulate the bone as to cause a definite periostitis. This property makes the use of magnesium pegs undesirable in the treatment of ordinary fracture. But it seems to me that if one had to deal with an old un-united fracture, where bone-formation is in abeyance, the method would offer very great advantages, and I should be inclined to adopt it if occasion offered.

Table VII.—Results of Six Experiments with Intramedullary Pegs—Magnesium.

No.	Date	Animal and Bone	Period Days	Repair	Anatomical Result	Remarks
29	19/5/11	R. F.	31	Excessive callus, in which is one small cavity with clear fluid. No bony union	Extreme overlapping, rotation, and angulation. Peg in advanced disintegration	Peg fitted loosely and soon broke. Wound healed well
30	19/5/11	R. F.	42	Exuberant callus and marked periostitis, especially of upper fragment. Several cavities filled with putty-like matter	Great displacement and deformity	Wound healed well. Peg broke
35	9/6/11	C. T.	60	Excessive callus union. Superficial part shows small septic cavity with slight necrosis	Good position. Slight angulation. Fibula and tibia embedded in large callus mass. Peg disintegrated	Wound sore. Good function
37	14/6/11	C. T.	55	Spindle-shaped callus mass. Firm union by this. Slight local aseptic necrosis	Excellent	Good function and healing
38	14/6/11	C. F	55	Excess of callus. Periostitis	Great deformity	Bad function. Peg broke
22	12/5/11	R. F.	38	Upper fragment has split. Periostitis with large abscess	Great deformity	Magnalium rod. Fair function

Summary.—The metal is too soft and easily broken to be relied on, unless supported by another appliance. The great stimulation of callus formation is the outstanding feature.

Intramedullary Pegs (Steel).—Having found that none of the foregoing pegs were rigid or strong enough to be reliable for experimental purposes, I tried solid pegs made of nickel-plated steel. These were of different thicknesses, from $\frac{1}{8}$ in. upwards, varying by $\frac{1}{64}$ in., and $1\frac{1}{2}$ in. long, pointed at both ends. Some were provided with a fixed cross-piece at the centre and inserted into one fragment, and the other fragment was brought over the projecting half. This was the easiest method in the case of the femur. When working with the tibia, it was impossible to separate the ends of the bone enough for this manœuvre, and a different one had to be adopted. The pegs were perforated by a fine hole transverse to their long axis at the centre. The sides of the pegs were grooved along their whole length, and the ends of the transverse hole opened into the grooves. A fine steel wire was threaded through the peg, and its ends were laid along the grooves. The peg was then completely pushed into one fragment, the two fragments brought into line, the ends of the wire pulled upon, and the peg thus drawn up into the other fragment, so that the half peg lay in each half of the bone. The ends of the wire were then twisted together and cut short.

The number of these experiments was seven. Every one succeeded, as judged from the point of view of function. In one case (No. 47, *see Fig.* 307 *c*) a rabbit's femur was split by the peg at the moment of introduction. This led to a badly comminuted fracture, which was encircled by wire. With the exception of this case, all gave a good anatomical result.

As regards the reparative process, a very marked difference was observed in the behaviour of the femur and the tibia. In the former there was some tendency to callus excess ; in the latter, repair was distinctly sub-normal.

Fig. 306.—Skiagram of Bones after the Use of Steel Medullary Pegs.

(*a*). Cat's femur (No. 43), after 42 days.
(*b*). Cat's femur (No. 44), after 42 days.
(*c*). Cat's tibia (No. 51), after 14 days.
(*d*). Cat's tibia (No. 56), after 34 days.

There were four experiments on the femur (two cats, two rabbits). In both the cats' femurs (Nos. 43 and 44), seen in *Figs.* 306 and 307, *a* and *b*, the period of observation was six weeks. In one, repair was complete, by a firm external callus and union of the bone ends. In the other, there was rather more callus, but this was partly cartilaginous opposite the line of fracture, and bony union was not complete. In both the rabbits' femurs there was firm though excessive callus, and bony union at periods of thirty-four and forty-three days.

The specimen in which there was the firmest and earliest union was the comminuted case (No. 47, *Fig.* 307 *c*). The peg lies in a comparatively large central cavity, round which there is a shell of new bone nearly ¼ in. thick, evidently the result of callus-formation and ossification round each bone splinter as a centre. This specimen affords evidence of the activity of the bone itself in the process of repair. Instead of repair occurring only from the cut surfaces of the bone, it took place from every separate fragment.

The tibial experiments (*Fig.* 306 *c* and *d*, *Fig.* 307 *d* and *e*) appear at first sight to be even more successful than the femoral. In each of the three cases the bones were in perfect alignment, and the limb was of perfect function ; but on cutting open the bones, the process of repair is seen to be defective.

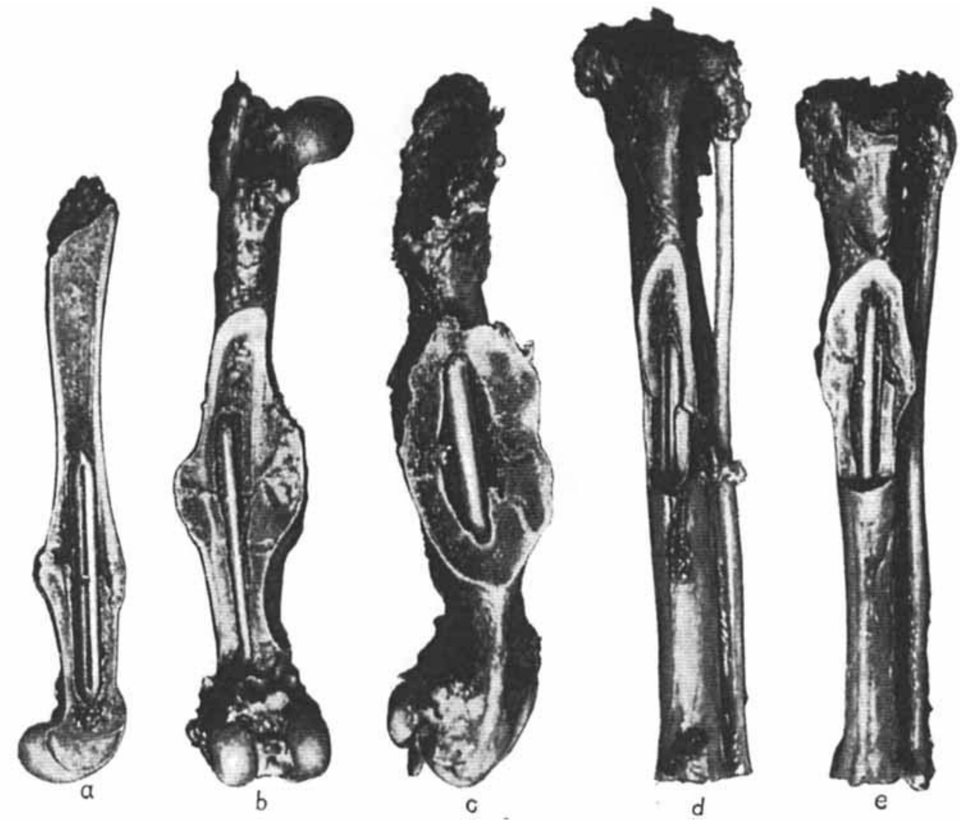


FIG. 307.—BONES AFTER THE USE OF MEDULLARY STEEL PEGS.

(*a*). Cat's femur (No. 43), after 42 days. Firm union by ossified external callus.
(*b*). Cat's femur (No. 44), after 42 days. Firm union, with some excess of external callus. This is still cartilaginous at the line of fracture.
(*c*). Rabbit's femur (No. 47), after 34 days. Bone was splintered by the insertion of the peg, and the parts were surrounded by wire. The peg lies in the centre of a cavity whose walls are formed by a thick layer of new bone formed from the splintered bone.
(*d*). Cat's tibia (No. 51), after 14 days. There is no evidence of repair.
(*e*). Cat's tibia (No. 56), after 34 days. Union is chiefly by external cartilaginous callus.

Figs. 306 *c* and 307 *d* show No. 51 (fourteen days.) The animal was unhealthy, and died at the end of a fortnight. There was no callus and no repair.

Figs. 306 *d* and 307 *e* show No. 56 (thirty-four days) ; there is moderate callus and early bone union, with the formation of some cartilage at the point of fracture.

In No. 50 (forty-two days) there is no repair visible; the ends of the bone appear to be cut clean and not rounded off, and there is neither effusion nor callus surrounding the seat of fracture. In this case, both ends of the bone had to be bored to take the $\frac{1}{8}$-in. peg, which fitted tightly. Probably in the course of the operation, the periosteum was raised from the bone ends to some extent, and thus the actual cut surfaces of bone were rendered avascular.

Several points are clear. In all, there was anatomical and functional success. In those cases (the femurs) where the peg fitted loosely, there was good union, but callus excess. In the cases (the tibias) where the peg fitted tightly, the repair was delayed. In none of these cases was there any inflammatory or septic complication. This latter fact shows the tolerance of the bones towards foreign bodies of comparatively large size, provided that they be firmly fixed and not chemically affected by the tissues.

Table VIII.—RESULTS OF SEVEN EXPERIMENTS WITH INTRAMEDULLARY PEGS—STEEL.

No.	Date	Animal and Bone	Period Days	Repair	Anatomical Result	Remarks
43	25/1/12	C. F.	42	Callus rather excessive. Bone union	Perfect	Peg with fixed cross-piece. Perfect function
44	25/1/12	C. F.	42	Excess of callus, centre of which is cartilage. Bone not united	Perfect. Peg had slipped too far into lower fragment	Peg with wire. Perfect function
47	22/2/12	R. F.	34	Callus excess. Peg lies in centre of a cavity	Deformity. Angular and rotation	Bone splintered and surrounded by wire
49	7/3/12	R. F.	43	Callus excess. Firm union	Good. Peg had slipped too far into lower fragment	Good function
50	2/5/12	C. T.	42	No callus. No union	Good. Peg very firm	Excellent function
51	2/5/12	C. T.	14	Very slight callus. No bone union	Good	Animal never fed properly. Died
56	16/5/12	C. T.	34	Moderate callus. Early bone union	Good	Died of diarrhœa

SUMMARY.—Of the above, No. 47 must be regarded separately, as an accident converted it into a comminuted fracture. All the rest did well. None showed sepsis. The repair is remarkably different. In three femurs the callus is in some excess. In the three tibias it is less than normal, and repair seems to be delayed. Functional and anatomical excellence in every case.

Intramedullary Pegs (Wire Spirals).—One objection to the non-absorbable form of intramedullary peg is that it leaves a large foreign body inside the bone, and if at any time inflammation or sepsis occurs, it will be very difficult to remove it, and the removal will endanger the continuity of the bone. I have endeavoured to meet this by the construction of wire pegs of longitudinally placed strands surrounded by circular turns, and so made that by leaving the end of the wire outside the bone, the whole peg could be removed by pulling on this end. I may say that in this experimental work I have not been able entirely to succeed, simply because the size of the bones is so small that the spiral cannot be made sufficiently rigid, and the wire is so thin that very often it breaks when pulled upon. In two cases I have succeeded in removing the peg without disturbing the fracture, and I think that with bones having a marrow cavity which will take a $\frac{1}{4}$-in. or larger peg, it is perfectly possible.

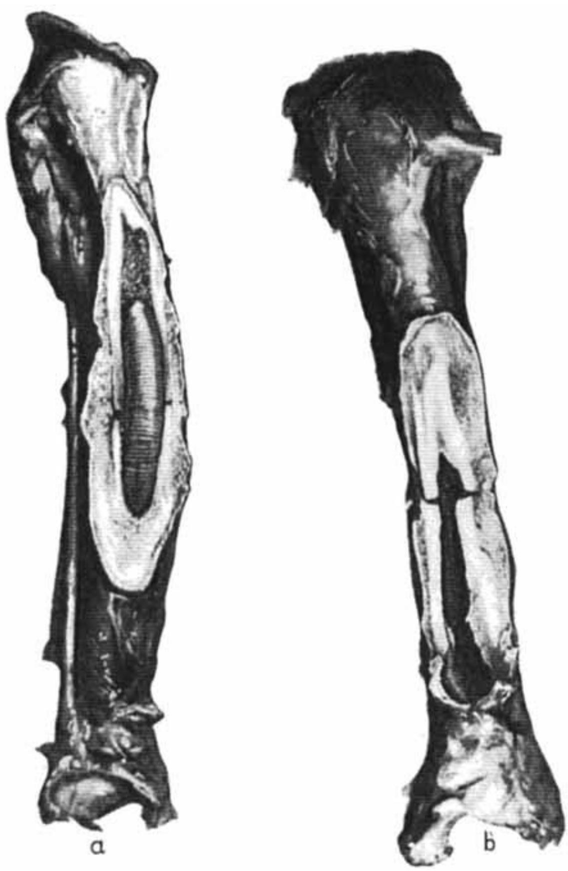


FIG. 308.—TWO CATS' TIBIAS AFTER UNION BY A WIRE SPIRAL INTRAMEDULLARY PEG.

(*a*). No. 64, after 28 days. The peg is still in position. Great periosteal thickening.

(*b*). No. 77, the peg has been removed by unravelling before the specimen was dissected. There is great periosteal thickening. In both cases sepsis occurred, and in both the actual bone ends show no sign of repair.

However, these specimens, apart from the immediate object with which they were undertaken, show some points of interest. In nearly all there was marked angulation from a bending of the peg, and in four out of six there was some sepsis. This latter is of interest in its origin. The technique was exactly the same as when using the solid pegs. Why then was there so much greater liability to sepsis ?

The answer to this is found, I think, in the fact that the bones were allowed too free mobility. This produces an excessive effusion, which leaks through the wound, and this leakage causes a contamination from the skin, whilst the copious effusion in the tissues gives an ample soil for the growth of bacteria. The sepsis was trivial, but nevertheless quite important enough completely to modify the aspect of the case.

In all cases there was great thickening of the bones, with excess of callus. This was brought about partly by the over-stimulation of mobility, and partly by the inflammatory irritation.

Fig. 308 *a* is from No. 64 (twenty-eight days). The wire spiral is still in position, and the great periosteal thickening is well shown.

Fig. 308 *b* is from No. 77 (fourteen days), and shows the fracture in good position and undisturbed by the removal of the wire, which had been drawn out before opening the bone.

I think a comparison of the experiments with solid metal and those with wire spiral pegs affords the most convincing demonstration that imperfect fixation, and not the presence of a foreign body, is responsible for both callus excess and the formation of a septic sinus; for in all respects, except that of the rigidity of the peg, these cases were similar. In the one series there was never any sepsis, but in the other it occurred generally.

Table IX.—RESULTS OF SIX EXPERIMENTS WITH INTRAMEDULLARY PEGS—WIRE SPIRALS.

No.	DATE	ANIMAL AND BONE	PERIOD DAYS	REPAIRS	ANATOMICAL RESULT	REMARKS
61	13/6/12	C. F.	15	Callus in concavity	Extreme angulation	Deformity within first week. Spiral bent
62	27/6/12	C. T.	43	Bone thickened by periostitis. Callus union	Angulation. Fibula fractured	Slight sepsis in wound
63	27/6/12	C. T.	43	Callus union	Angulation Fibula fractured in two places	
64		C. T.	43	Periostitis. Firm callus union	Angulation. Fibula fractured	Slight wound sepsis
66		C. T.	14	Necrosis of one end. No union	Some angulation	Wound sepsis
77		C. T.	28	Periosteal callus. No union	Slight angulation	

SUMMARY.—In no case was the result satisfactory. It is not possible to construct wire spiral pegs of this size with sufficient rigidity.

Transfixion and Extension Apparatus.—All the foregoing methods of operating upon fractures involve a direct attack upon the seat of injury. It is a matter of great importance to compare with these a method which fixes the broken bones without the exposure of the site of fracture,—a method which, whilst maintaining extension, does not rigidly fix the broken ends to one another. For practical purposes this is important, because it illustrates the principles of extension so widely used in human surgery; and on theoretical grounds it is important, because it gives, as no other method can, the stages in repair, uncomplicated by displacement of, or interference with, the parts concerned by any foreign bodies. The method I adopted was as follows: The tibia was perforated at either extremity through minute skin openings by holes which were two and a half inches apart. In order that these should be exactly parallel with one another, the drills were guided by openings in a metal block perforated by parallel holes at the proper distance. Through the holes in the bone were passed two round rods 1 in. long and ⅛ in. thick, cut at each end with a screw thread for a nut. Then the bone was divided by the fret-saw about the middle through an incision. The latter is closed in layers, and the parts are clamped into position by placing thin steel bars 2½ in. long on each side, so as to take the ends of the transverse bars. The rectangle thus formed is fixed by four nuts and washers.

This method proved to be simple and very efficacious. The animals ran about with the steel frame in position, and in only one case (the first, when I had not got the suitable drills) was there any sign of inflammation round the transfixion holes. Two cats of this series died of distemper (Nos. 58, 65). In one of these no repair was evident at the end of eighteen days, but in all the other

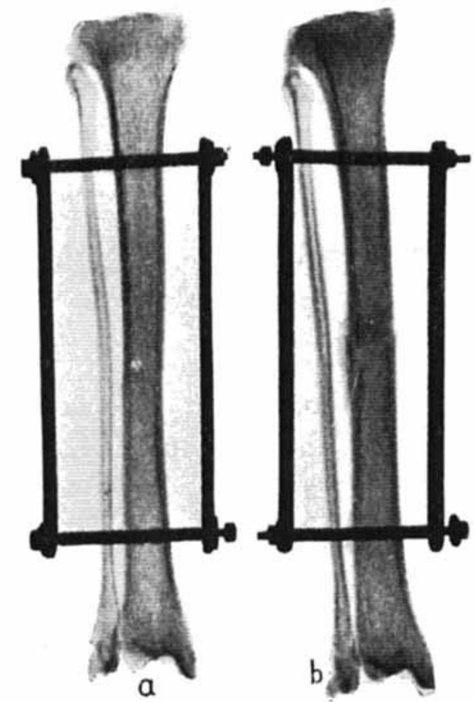


Fig. 309.—Skiagrams of Cats' Tibias treated by Transfixion.
(*a*). No. 65, after 7 days.
(*b*). No. 57, after 14 days.

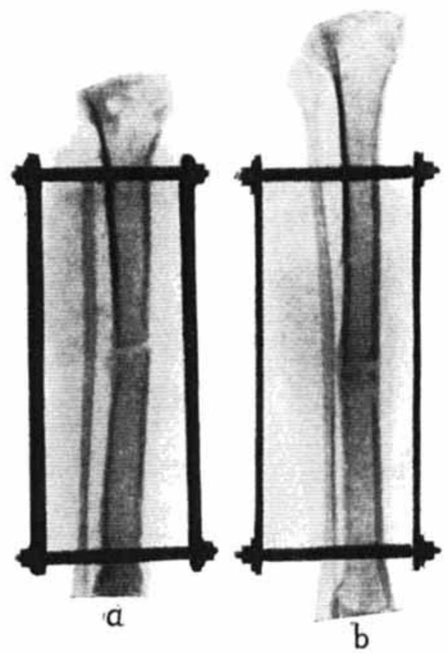


Fig. 310.—Skiagrams of Cats' Tibias after Transfixion.
(*a*). No. 60, after 57 days.
(*b*). No. 59, after 71 days.

five cases, repair proceeded regularly. It will be convenient to describe these five in the order of the length of period during which they were under observation.

Figs. 309 and 310 are skiagrams showing some of the specimens at intervals varying from seven to seventy days. They show how well the position of the bones is maintained, and how little irritation occurs at the site of perforation.

Fig. 311 *a*, No. 65 (seven days), shows merely a small quantity of blood-clot beneath the periosteum and in the marrow cavity.

Fig. 311 *b*, No. 57 (fourteen days). There is a layer of external callus, about the same thickness as that of the compact bone beneath. The callus is uniformly calcified, and extends about ¼ in. above and below the fracture. Inside the marrow cavity there is a very definite internal callus plug in the upper, but not in the lower, fragment. The line of bone-division is still clearly defined. There is a curious islet of cartilage in the marrow cavity of the upper fragment, about half an inch from the fracture.

Fig. 312 *a* shows No. 55 (twenty-one days). The same condition is seen as in the last case, except that the external callus is distinctly cartilaginous. The same difference is seen as in the last specimen, between the upper and lower fragment, in respect to the presence of internal callus in the former and its absence in the latter.

Fig. 312 *b* shows No. 60 (fifty-seven days). The bone is firmly united, and only a linear trace of the fracture can be seen on naked-eye examination of the section. There is a small amount of external callus and a solid internal callus. This and the following specimen represent the most perfect union that I have ever attained in experimental operations.

Fig. 312 *c* shows No. 57 (seventy - one days). Exactly the same conditions are found as in the last case, i.e., a solidification of the fracture, together with a minimum amount of external and internal callus. It is especially interesting, as showing the complete absence of irritation at the two points where the bone is perforated and in which steel bars have been resting for over ten weeks.

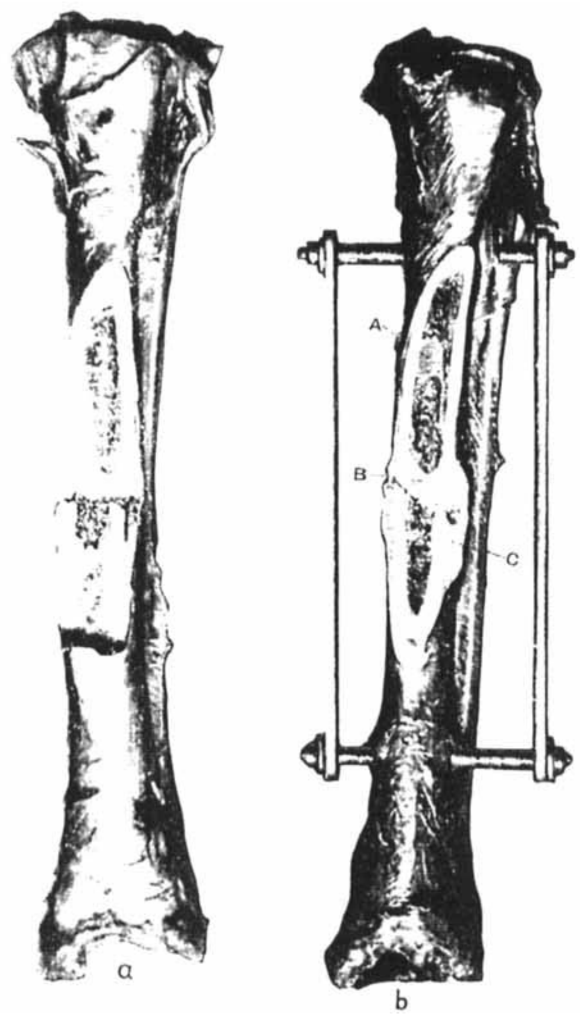


FIG. 311.—CATS' TIBIAS AFTER TRANSFIXION.

(*a*). No. 65, after 7 days. The ends of the bone have a small quantity of blood and granulation tissue between them. (*b*). No. 57, after 14 days. Early ideal repair. A, Islet of cartilage present in the medulla far from the fracture. B Internal callus present only in the upper fragment. C, External callus.

There can be no doubt, as far as the evidence of these experiments goes, that this method of indirect fixation of the fracture gives a more perfect union of the bones than any direct method that I have performed. It may be objected that the experimental conditions, in which fixation is provided for before any displacement has taken place, are much more favourable than can be attained in human surgery. But on the other hand, in every one of these cases the periosteum has been divided and the bone cut by a straight smooth saw-cut, both of which conditions are unfavourable to repair in comparison with those obtaining in simple

FIG. 312.—CATS' TIBIAS AFTER TRANSFIXION.

(*a*). No. 57, after 14 days. A, Internal callus present only in the upper fragment. B, External callus.
(*b*). No. 60, after 57 days. Perfect internal and intermediate callus.
(*c*). No. 59, after 71 days. Perfect union by means of a minimum of callus.

fractures, when the periosteum is often not severed, and in which the jagged bone-break gives a far better surface for repair.

The small quantity of callus formed is noteworthy, and is associated, no doubt, with the absence of friction between the bone ends.

Table X.—RESULTS OF SIX EXPERIMENTS WITH TRANSFIXION APPARATUS.

No.	Date	Animal and Bone	Period days	Repair	Anatomical Result	Remarks
55	16/5/12	C. T.	21	Early callus	Angulation. Fibula fractured	Faulty technique. Boring difficult Soft parts torn. Wound suppurated
57	30/5/12	C. T.	14	Firm callus union	Excellent	Good technique. Good function
58	30/5/12	C. T.	18	No repair, callus or bony	Excellent	Good function. Never well. Died of distemper
59	30/5/12	C. T.	71	Bony union. Minimum callus	Excellent	Good function from 2nd week
60	13/6/12	C. T.	57	Bony union. Minimum callus	Excellent	Good function
65	27/6 12	C. T.	7	Early stages of repair	Excellent	Cat never well. Would not feed. Died of distemper

SUMMARY.—Every case did well except the first, in which the technique was at fault. The good anatomical result, the repair with so little callus, and the early functional recovery, are very notable.

COMMINUTED FRACTURES.

The use of the transfixion apparatus described in the last section rendered it comparatively easy to undertake the study of comminuted fractures. The technique of these operations was the same as the last, except that the bone was crushed by a forceps for a distance of about ½ in., instead of being divided by a fret-saw. After this had been done, one of three different courses was pursued :—

(1) *The fragments and periosteum were left in situ ;* or (2) *All the loose fragments were removed, but the periosteum left*; or (3) *The broken bone was surrounded by a thin aluminium plate, which excluded the periosteum from the fragments.*

In all cases the soft parts and skin were closed over the site of fracture. It will be convenient to describe the results of each class separately, before discussing the merits of this method for the treatment of severely crushed bones.

1. **Fragments and Periosteum Left in Situ.**—There are three cases in this series (shown in *Fig.* 313 *a*, *b*, *c*), all of them being cats' tibias. The period of observation was twenty-eight days in two cases and forty-two in the third. In two (Nos. 67 and 72) the position was well maintained, and except for some thickening of the bone in No. 72, the bones were restored to a close approach to the normal form. The functional results were uniformly good. The animals after the first week used the injured limb quite freely, and often ran without any appreciable limp.

The union in all these cases was firm and solid, the fragments being embedded in callus. In fact, these cases exhibit the most rapid and firm union of any experimental fracture that I have seen.

Fig. 313 *a* shows No. 67 (twenty-eight days). There is firm union in good position without callus excess. There seems to have been a posterior splinter

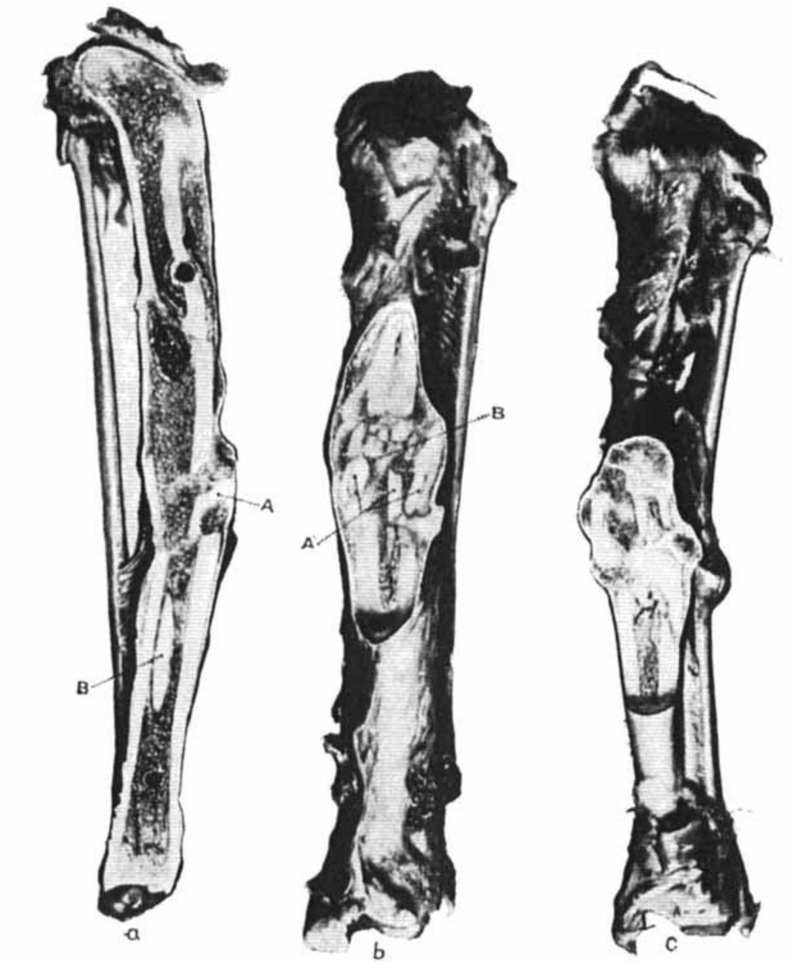


FIG. 313.—THREE CATS' TIBIAS, COMMINUTED. FRAGMENTS LEFT IN POSITION.
(*a*). No. 67, after 28 days. A, One of the fragments. B, A fragment which has slipped down into the marrow cavity.
(*b*). No. 72, after 28 days. A, Small fragments of bone. B, Callus growing from these fragments.
(*c*). No. 68, after 42 days.

of bone left connecting the main fragments, which would therefore have served to keep the parts more firmly fixed than in those cases where there was complete solution of continuity. In the upper fragment the medullary cavity is filled by a firm mass of callus extending about half an inch from the fracture. This is less marked in the lower fragment.

Fig. 313 *b* shows No. 72 (twenty-eight days). There is a large, spindle-shaped mass at the site of injury. The line of the bone is well preserved. The thickening consists of all the fragments welded together in firm callus which is in an advanced stage of organization, so that there is solid union of the fracture. In this mass, surrounded by the periosteum, there is no distinction between external and internal callus ; but the dense fragments of bone can be distinguished from the intervening callus with its more open structure. There is, in fact, a strong and solid union.

Fig. 313 *c* shows No. 68 (forty-two days). There has been some fault in the upper transfixion hole. Either this was made too large, or else it became enlarged by inflammation ; but the result has been that fixation was not secure, and the fibula has fractured and the bones are angulated. There is the same solid mass of bone fragment embedded in callus as in the preceding specimen.

Table XI. Three Experiments on Comminuted Fractures with Transfixion Apparatus. Fragments and Periosteum Left in Situ.

No.	Date	Animal and Bone	Period Days	Repair	Anatomical Result	Remarks
67	5/9/12	C. T.	28	Firm welding of fragments in callus	Good, with some thickening	Cat ran freely one week after operation
68	5/9/12	C. T.	42	Firm welding of fragments in callus	Angulation. Fibula fractured. Upper pin-hole too large	Good function
72	19/9/12	C. T.	28	Firm callus mass embedding all the fragments	Good	Walks well

Summary.—The result was good. Repair firm, with a tendency to callus excess and bony thickening. Repair is quicker and better than in those cases where either periosteum or fragments are removed.

2. **Fragments Removed.**—There were four experiments upon cats' tibias. In one the lower transfixion hole had been made through the front surface of the bone, and the transfixion bar had worked loose. In this the fibula had broken and the tibia was angulated. In all the others the anatomical result was good. The functional condition was not so good as in the last series, and the animals appeared reluctant to place their weight on the leg, so that although they could walk, this was with a marked limp.

As regards repair, all the specimens show the same general condition, with remarkably little difference according to the period (varying from three to six weeks). To the naked eye, the longitudinal section shows that the continuity of the bone is restored with great exactness ; but the material of repair is merely fibrous or cartilaginous callus, with but little evidence of ossification.

Fig. 314 *a* shows No. 69 (twenty-one days). There is marked angulation. The whole space between the bone ends is occupied by a mass of fibro-cartilage which merges into the structure of the dense bone by a callus of firmer texture.

Fig. 314 *b* shows No. 70 (forty-two days). The restoration of the form of the bone is almost exact, but the gap between the bone ends is filled by cartilaginous callus.

Fig. 315 *a* shows No. 71 (twenty-one days). The alignment is good. The gap between the bones is not completely filled to the same thickness as the shaft.

FIG. 314.—CATS' TIBIAS. COMMINUTED FRACTURE. FRAGMENTS REMOVED.

(*a*). No. 69, after 21 days. A, Ossified callus on the surface of the lower fragment. B, Fibrous callus in the middle of the gap. There is one small piece of bone in this gap, but from its firm texture and sharp outline it is evidently a fragment which has been left, and not a new formation.

(*b*). No. 70, after 42 days. Callus is ossified where it touches the bone ends, but cartilaginous in the centre.

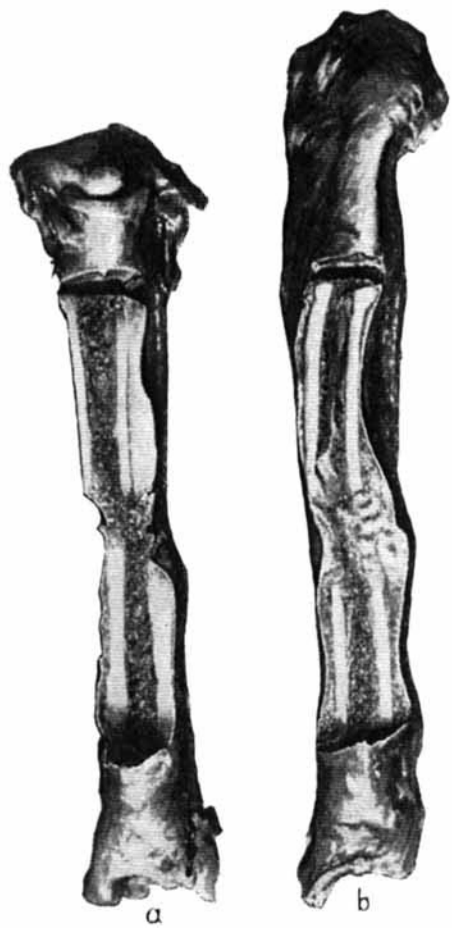


FIG. 315.—CATS' TIBIAS. COMMINUTED FRACTURES. FRAGMENTS REMOVED.
(*a*). No. 71, after 21 days.
(*b*). No. 73, after 28 days.

Fig. 315 *b* shows No. 73 (twenty-eight days). The union has a very solid appearance, but it consists of cartilage, in which there are a few islets of a more calcified material.

An interesting fact in this series is the great contrast afforded by the x-ray pictures and the naked-eye appearance of the specimens. In the one (*Fig.* 316) it looks as though there was nothing filling up the gap between the ends of the bone, whilst in the other, continuity appears to have been completely restored.

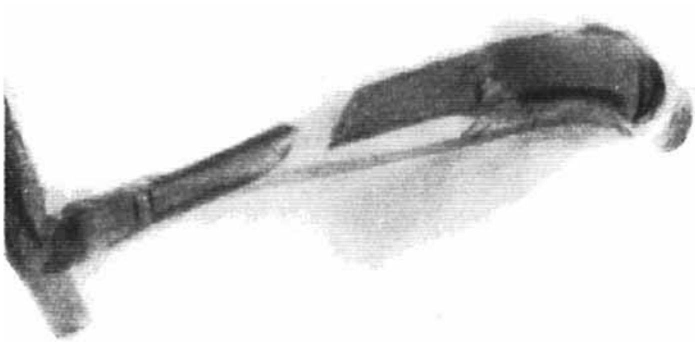


FIG. 316.—Skiagram of cat's tibia (No. 70), 42 days after comminution and removal of fragments. Contrast the apparent absence of repair with the drawing of the same specimen in 314 *b*.

Table XII. FOUR EXPERIMENTS ON COMMINUTED FRACTURES WITH TRANSFIXION APPARATUS. REMOVAL OF LOOSE FRAGMENTS.

No.	DATE	ANIMAL AND BONE	PERIOD DAYS	REPAIR	ANATOMICAL RESULT	REMARKS
69	12/9/12	C. T.	21	Definite solid mass of soft callus between the two ends	Angulation. Fracture of fibula	Limped badly. Upper pin only caught edge of tibia and had broken out
70	12/9/12	C. T.	42	Union by solid mass of calcareous callus, not rigid	Good	Walked with a limp
71	12/9/12	C. T.	21	Union by solid callus and by a splinter of bone	Good	Apparatus became unscrewed
73	19/9/12	C. T.	28	Restoration of bone by callus which is partly cartilage	Good	Walked badly

SUMMARY.—Cartilaginous and fibrous callus is rapidly formed and replaces the lost bone; but ossification is long delayed.

3. **Exclusion of Periosteum.**—In this series there were only four experiments, and of these, two are of no value. In one (No. 74), the animal died the day following the operation, from some undetermined cause; and in the other (No. 76) sepsis occurred, and all the fragments underwent necrosis.

The remaining two specimens, Nos. 78 and 75, were of periods of thirty-five and forty-two days respectively; in both there was a good anatomical result, and in one (75) the animal walked well.

Fig. 317 *a* shows No. 75 (forty-two days). The bone is in good alignment. The small fragments are joined to one another and to the upper half of the bone by firm callus, but there is still some mobility possible between the fractured fragments and the lower half of the bone. There is very definite advanced internal callus present between the small fragments and the upper half of the shaft. Between the dense bone and the plate there is a thin layer of soft material like lymph, but no callus. The periosteum is in a very different condition in different parts of the longitudinal section. On the left, it appears to be perfectly unchanged, neither thickened nor ossified. On the right, it presents a definite firm layer of tissue about $\frac{1}{16}$ in. thick. At each side this layer is continuous with the shell of external callus on the outer surface of the main halves of the bone; here it is thicker, and is certainly ossified. In the centre, the periosteal bridge is thin and soft. Between the ends and the centre there are transitional areas of cartilage. This structure shows that the subperiosteal callus layer is being laid down in the angle of junction of the periosteum and bone, and not by the whole of the deep surface of the periosteum.

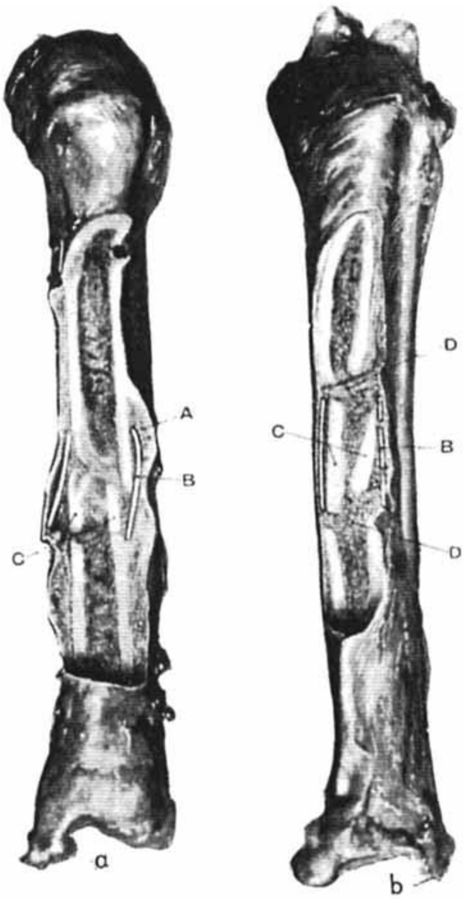


FIG. 317.—CATS' TIBIAS. COMMINUTED FRACTURES, SURROUNDED BY ALUMINIUM PLATE.

(*a*). No. 75, after 42 days A, External callus growing from the angle between the bone and the periosteum. B, Plate. C, Separate fragments of bone.

(*b*). No. 78, after 35 days. B, Plate. C, Separate fragments. D, Internal callus at junction of the comminuted part with the main parts of the shaft on either side.

Fig. 317 *b* shows No. 78 (thirty-five days). It reveals a rather tardy union of the bones, and there is distinct mobility between both the main parts of the bone above and below, and the comminuted portion in the centre. This latter exhibits a marked thickening of the fragments. No external callus is visible outside the metal plate, and the periosteum appears to be quite unchanged. There is some internal ossified callus at the junction of the comminuted part with the main parts of the bone on each side. Both these specimens show that the comminuted fragments are the centre of active reparative changes, although isolated from the periosteum. At the same time these changes are much delayed, and their vigour impaired, by the periosteal exclusion.

Table XIII. FOUR EXPERIMENTS ON COMMINUTED FRACTURES WITH TRANSFIXION APPARATUS, WITH EXCLUSION OF PERIOSTEUM.

No.	Date	Animal and Bone	Period Days	Repair	Anatomical Result	Remarks
74	19/9/12	C. T.	1	None	Good	Died, cause not found
75	3/10/12	C. T.	42	Fragments appear to have grown together, but there is little union with bone beyond fracture. No external callus	Good. Slight angulation	Walked well. Aluminium plate
76	3/10/12	C. T.	21	No union. All fragments necrosed	Good	Sepsis
78		C. T.	35	Union of fragments to upper pair of main shaft. Periosteal callus growing over plate from the edges	Good	Walked badly

SUMMARY.—It is clear that vitality and repair are preserved, but that callus formation, and therefore effective rapid union, is greatly delayed when the periosteum is separated from the seat of fracture.

In considering this series of eleven comminuted fractures, there are several important conclusions to be drawn.

From the practical standpoint it is evident that the method of indirect fixation of the ends of the bone, leaving the site of fracture untouched, is a good one. It is a method which will be of great utility in dealing with both compound and comminuted fractures in surgical practice. The length and alignment of the bone are accurately preserved, and at the same time the joints above and below the fracture can be exercised from the very first. It combines the advantages of the methods of extension with those of the methods of early massage and movements.

Next, as to the origin of the reparative callus. This is seen to arise from the bone itself rather than from the periosteum. When there is much raw bone surface, the callus forms from many centres and is rapidly matured. Where the bone fragments are removed, callus is poured out into the periosteal tube, chiefly from the cut ends of the bone ; but it is a much slower process. When the periosteum is excluded, union by callus still occurs, but the field of repair, being shut out from the vascular supply of the periosteum, produces its callus slowly and in small quantities.

As every fragment in a comminuted fracture is a focus of repair, it follows that every fragment ought to be retained in the interests of quick and firm union. But where mobility rather than strength is required, as in the neighbourhood of a joint, it will often be better to remove loose fragments, lest excessive callus cause joint fixation. Any direct operative attack upon a comminuted fracture will involve the risk of interfering with the vitality of the fragments, and therefore lessening their ability to act as a centre of repair.

Indirect Fixation of the Femur.—The method of indirect fixation by transfixion of the bone, which is so excellent in the case of the tibia, cannot be applied without modification to the upper part of either limb, because in both cases the upper portion of the bones (humerus and femur) cannot be transfixed, or rather, a transfixion rod cannot be brought to the surface, because in the one case it would lie in the axilla, and in the other in the perineum.

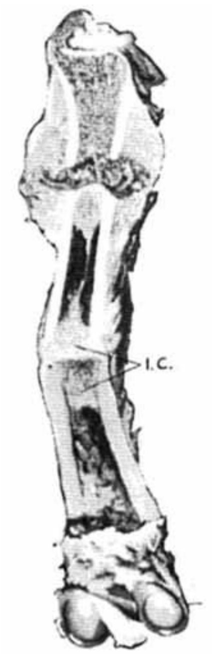


FIG. 318.—Cat's femur (No. 82), forty-two days after operation. Treated by unilateral screw fixation. There is much angulation, and a great thickening round the upper screw-hole. I. C, Internal callus.

I thought to solve this difficulty by unilateral transfixion. Two screws were passed into and through the femur, one just below the trochanters and one just above the condyles. Each was provided with a rim or shoulder which held firmly against the bone surface when the screw was driven home tightly. After dividing the bone between the screws, the soft parts were united and the ends of the screws left protruding beyond the skin. These were then fixed to a steel bar by nuts.

Much to my surprise all four of these experiments failed to give a satisfactory result. That is to say, in three out of four, one screw came out of the bone and gross deformity resulted, and in the only one in which the apparatus remained in place, very considerable angulation resulted. In two cases the screws were fixed at a slightly divergent angle to the longitudinal bar, so that the tension of the muscles should tend rather to pull the bones more firmly on to the screws; but the result was no better.

These screws were one-eighth inch in diameter, with a stout thread, and yet within much less time than is occupied in consolidation of the bone, they generally worked loose. This is in accordance with what has been stated above as to the reaction of metal screws tightly driven into hard bones.

Fig. 318 is from experiment No. 82, a cat's femur forty-two days after operation. There is a marked angulation in a posterior direction, with much callus thickening round the upper screw-hole. Natural callus is well developed, but union is not yet osseous.

TABLE SHOWING THE RESULTS OF UNILATERAL FIXATION OF THE FEMUR.

DATE	NO. OF EXP.	PERIOD DAYS	ANATOMY	HEALING	REMARKS
5/6/13	81	14	Gross deformity	Good internal callus	Upper screw came out
5/6/13	82	42	Some angulation	Union chiefly by internal callus	Apparent success
26/6/13	87	21	Gross deformity	Internal callus only	Upper screw came out
28/8/13	90	14	Gross deformity	None	Upper screw came out

SUMMARY.—These failures show that a single bone cannot be kept in good position by an apparatus which holds it by two points only without exercising continuous extension.

Regeneration of Bone after Subperiosteal Removal of a Portion of its Entire Thickness.—The transfixion apparatus having proved itself such an excellent device for studying the repair of simple and comminuted fractures, it seemed a good method for observing the repair which occurs when a piece of the entire thickness of the bone is removed.

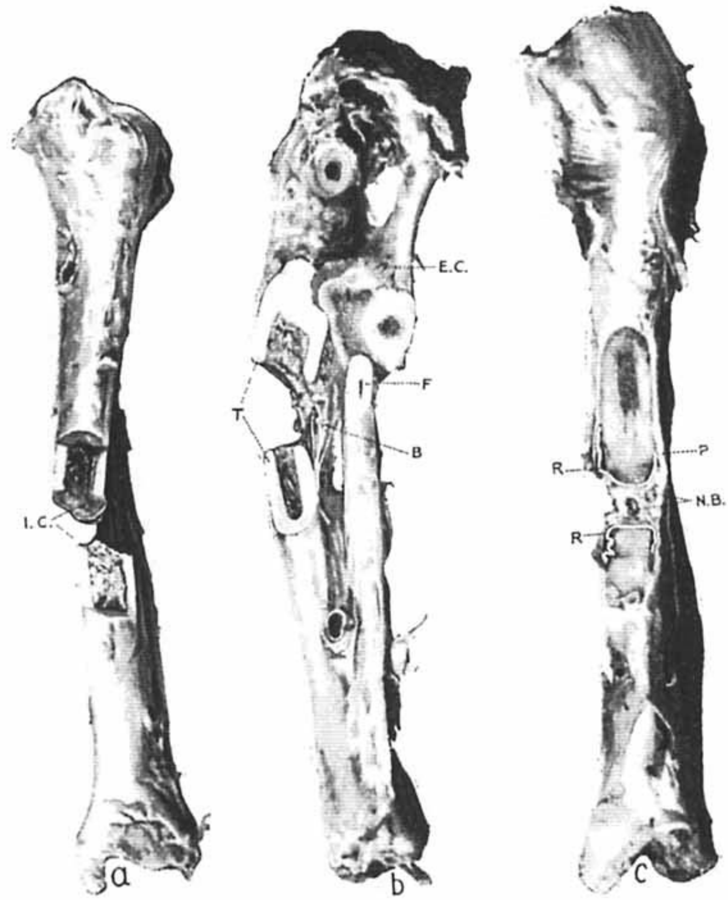


FIG. 319.—CATS' TIBIAS AFTER SUBPERIOSTEAL REMOVAL OF A PORTION OF THE SHAFT IN ITS WHOLE THICKNESS.

(*a*). No. 80, after 14 days. Internal callus best developed in upper fragment. Nothing in gap. I, C, Internal callus.

(*b*.) No. 79, after 35 days. Fibula has broken. In the tibial gap there is no new bone, but round the fibular ends there is a big mass of new bone. T, Tibial ends. F, Fibula. E. C, External callus. B, Bridge of soft tissues only in the gap between bone ends.

(*c*). No. 85, after 42 days. The ends of the bone have been covered in by rubber tissue; but in spite of this the gap is filled by callus, both cartilage and bone, derived from the periosteum. P, Periosteum. R, Rubber tissue. N. B, New bone in the cartilaginous callus mass.

In all cases the cat's left tibia was the subject of the experiment, and a section of the bone, about half an inch in length, was removed subperiosteally by means of two saw-cuts. There were five experiments in this group; in the first three, the cut ends of the bone were left bare, and in the last two they were covered in thin rubber, tied on with a fine wire.

Fig. 319 *a* is from No. 80, fourteen days after the operation. There is seen a healthy and fairly vigorous formation of internal callus from the upper fragment, and much less from the lower. Otherwise there is no trace of any callus or reparative material between the bone ends. The callus mass growing from the upper fragment is very sharply defined, and gives the impression of merely forming a cap for the bone end, rather than a bridge that is going to stretch across the gap.

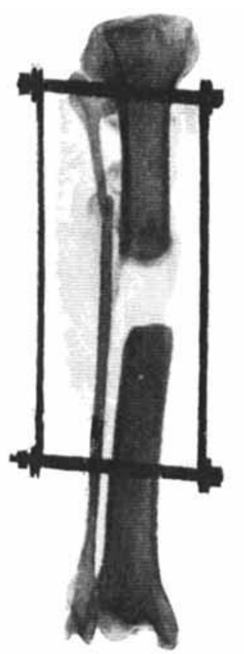


FIG. 320.—Cat's tibia (No. 79). Skiagram of specimen shown in 319 *b*. There is complete absence of bone in the gap after 135 days.

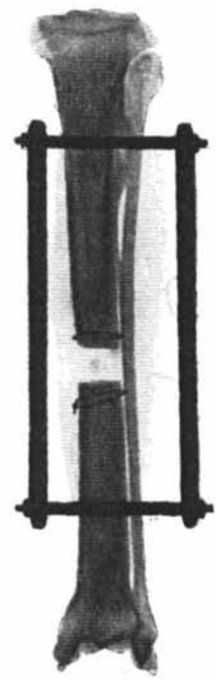


FIG. 321.—Cat's tibia (No. 85). Skiagram of the specimen shown in Fig. 319 *c*. Two nodules of bone are seen in the gap.

In *Fig.* 319 *b* is seen No. 79, thirty-five days after operation, and here too there is a perfectly clear interval between the cut ends of the tibia, with no suggestion of new bone or callus. In this case, the fibula has fractured and the exuberant callus formed round the broken ends of the fibula would have been more than enough to fill the gap in the tibia. Thus there is a striking example of the absence of callus when bone ends are not in contact, and the exuberance of callus formed by broken bone ends which are allowed some movement against each other.

In the three cases, Nos. 79, 80, and 83, there was no trace of callus being laid down by the periosteum, and much less pouring out of callus from the cut bone ends than I expected. In the two cases 84 and 85, I wished to eliminate this last factor, and for this purpose a small fragment of rubber tissue from a glove was tied over the cut ends of the bone. In both these there was found perfectly normal internal callus formation beneath the rubber tissue, proving that such callus is derived from the bone and its marrow cavity, and not from the periosteum. In No. 85, however, a surprise was in store. The specimen is illustrated both by skiagram and by drawing (*Figs.* 321 and 319 *c*). There is here unquestionably an advanced callus formation between the rubber-covered bone ends and the periosteal sheath This is chiefly cartilaginous, but there is a well-marked bone nodule in its centre, which is dense enough to show in the skiagram. It is impossible to avoid the conclusion that in this case, at any rate, the periosteum has laid down the new bone.

TABLE SHOWING RESULTS OF THE SUBPERIOSTEAL REMOVAL OF A PART OF THE WHOLE THICKNESS OF THE BONE.

DATE	NO.	PERIOD. DAYS	ANATOMY	HEALING	REMARKS
15/5/13	79	35	Fibula had broken	Internal callus in upper fragment. Nothing in gap. Callus excess round fibula	Good function
15/5/13	80	14	Good position	Internal callus in upper fragment	Died—cause unknown
19/6/13	83	7	Good position	No repair	Good function. Died—cause unknown
19/6/13	84	7	Good position	Early stage of internal callus under rubber	Rubber tied over bone ends
19/6/13	85	42	Good position	Internal callus in both ends under the rubber, and a a mass of cartilaginous and bony callus formed from periosteum in gap	Rubber tied over bone ends. Good function

SUMMARY.—From a practical point of view, this small series of cases shows that in the majority of cases bone is formed very scantily or not at all from bone ends which are separated from one another by a considerable gap.

Regeneration of Bone when a Part only of the Thickness has been Removed.—These four experiments were undertaken in connection with the subject of bone transplantation, which cannot be discussed in any detail here. The skiagrams are merely shown to illustrate the rapid repair which takes place when a part only in the thickness of the shaft is removed. The anterior border of the tibia was exposed, and a piece 1 in. long sawn from the bone, so as to remove about half its entire thickness. This piece was then split into two equal parts, and one was grafted whole and the other after minute subdivisions, under the fascia lata of the thigh. In all cases the grafts lived. The whole graft seemed to remain unchanged, whilst the comminuted graft formed a bone mass of some size.

Figs. 322, 323 and 324 show the tibia after intervals of twenty-eight, sixty, and sixty-three days, and in the last two it will be seen how completely the gap in the tibia has been replaced.

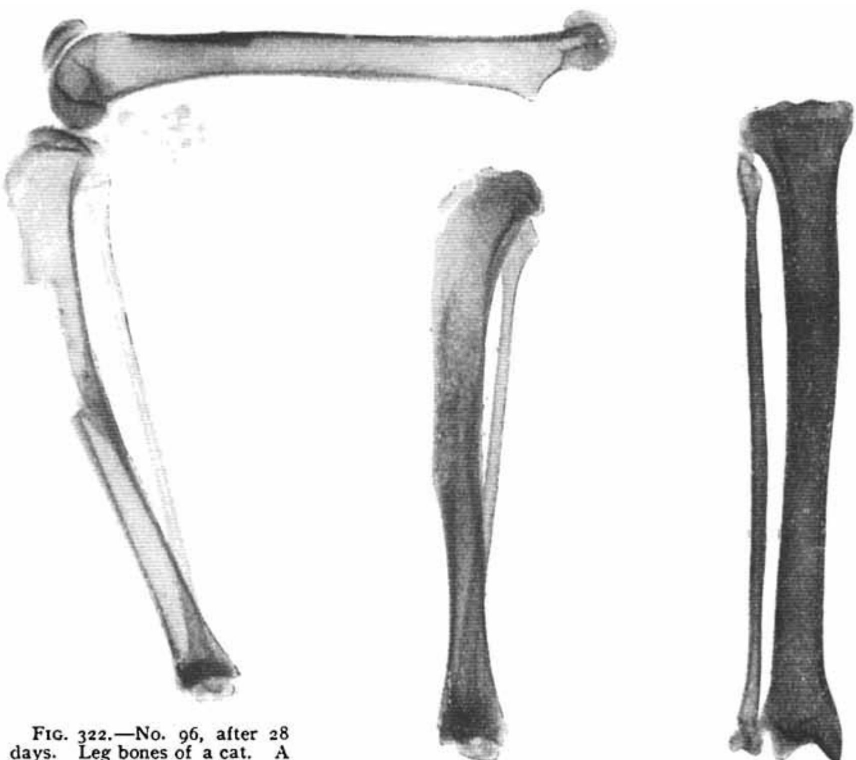


Fig. 322.—No. 96, after 28 days. Leg bones of a cat. A piece has been removed from the tibia and grafted in two parts in the thigh—a single piece and a number of chips.

Fig. 323.—No. 94, showing regeneration of the cat's tibia after 60 days.

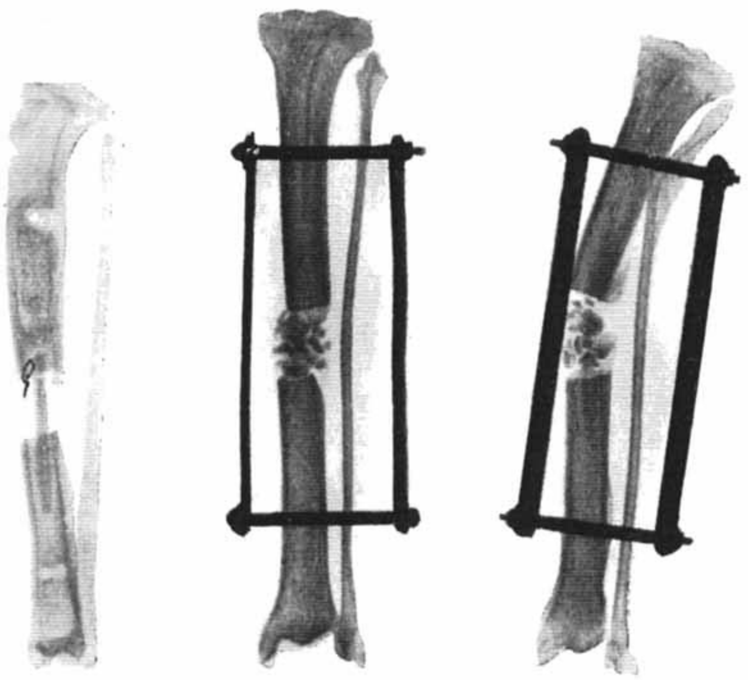
Fig. 324.—No. 91, showing regeneration of tibia after 63 days.

Table of Experiments on Removal of a Part of the Thickness of a Long Bone.

Date	No.	Period Days	Remarks
12/9/13	96	28	Gap is partly filled with cartilaginous callus. There is new bone formed in the marrow cavity
12/9/13	95	60	Gap is almost completely filled with bone of normal density
12/9/13	94	60	Gap completely filled with bone of normal density
28/8/13	91	63	Gap is filled with bone, and the marrow cavity somewhat encroached upon by new dense bone

Summary.—A large defect in the bone, affecting only half its thickness, is rapidly made good, probably by regeneration from the raw bone surface left.

Experiments in Filling a Bone Defect by a Single large Piece or by many small Chips.—These experiments are at present only three in number, and therefore not very conclusive, but they are interesting as far as they go. In all cases the leg was put up in the transfixion apparatus. In the first case, the gap in the tibia was made good by a rod cut from the opposite leg bone and thrust into the marrow cavity of both bone ends. After forty-nine days the specimen (*Figs.* 325 *a* and 326 *a*) shows a good solid union. The bone as a whole gives a feeling of perfect solidity. The graft is embedded in callus which is chiefly cartilaginous, and there is certainly a structural continuity between this



a *b* *c*

FIG. 325.—SKIAGRAMS OF CATS' TIBIAS, WITH FRAGMENTS GRAFTED.
(*a*). No. 86, after 49 days. Single graft in the form of an intramedullary peg.
(*b*). No. 88, after 15 days, showing separate fragments.
(*c*). No. 89, after 70 days. The chips are still quite discrete.

callus and the graft. Whether the callus has grown from, or merely grown into the graft, is impossible to say.

Figs. 325 *b* and *c* and 326 *b* and *c*, illustrate the two specimens in which a piece of the tibia was cut out and then replaced after crushing up into small pieces. The skiagrams are remarkable for the great similarity between (*b*) after only fifteen days, and (*c*) after seventy days. Both the drawings show that the particles of bone are embedded in callus, but in neither is any solidity attained. In (*b*) the callus is only cellular, in (*c*) it is partly cartilaginous. The manner in which some of the particles remain clean cut and apparently inert, forms a very sharp contrast to the condition of affairs in which the bone was merely crushed but the particles were not removed from their bed (*see Fig.* 313, *b* and *c*).

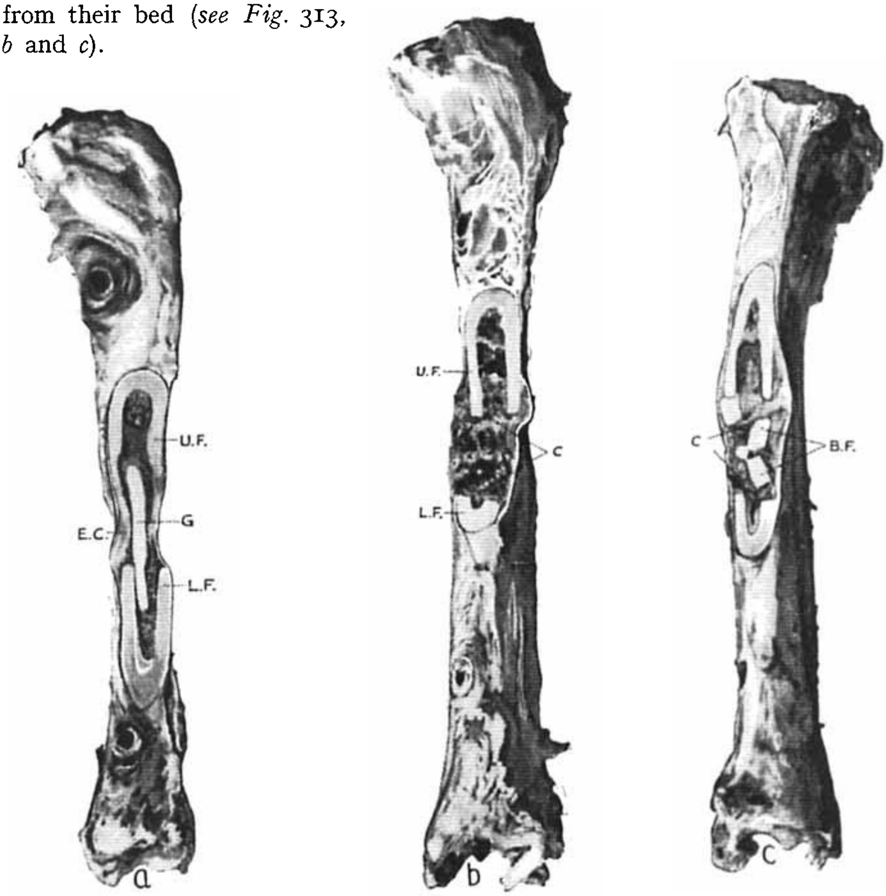


FIG. 326.—SAME SPECIMENS AS IN FIG. 325.

(*a*). No. 86, after 49 days. A graft from the opposite leg lies firmly growing into the ends of the bone and surrounded by a cartilaginous callus. U. F, Upper fragment. L. F, Lower fragment. E. C, External callus. G, Bone graft.

(*b*). No. 88, after 15 days, the grafted bone chips lying embedded in early callus. U. F, Upper fragment. L. F, Lower fragment. C, Callus with loose bone chips.

(*c*). No. 89, after 70 days. Except that the callus is cartilaginous, there is not much advance over the previous specimen, many of the chips being still quite distinct. C, Callus. B F, Bone fragments.

TABLE OF RESULTS AFTER GRAFTING BONE IN A DEFECT.

DATE	No.	PERIOD DAYS	REMARKS
26/6/13	86	49	A single piece of bone used to fill the defect. Solid union
15/7/13	88	15	Gap filled with bone chips. Chips lay embedded in cellular callus
15/7/13	89	70	Gap filled with bone chips. Chips lie in cartilaginous callus, but there is no solid union

SUMMARY.—From these few experiments it appears that a large piece of bone firmly fixed to living bone acts better as a bone graft, than small chips lying loosely.

GENERAL DEDUCTIONS BASED UPON THE ABOVE EXPERIMENTS.

It now remains to examine the series of facts above recorded, as a whole, and to discuss their bearing upon the practical problems of the operative treatment of fractures and the theory of bone repair. The task of applying these deductions to the practice of clinical surgery I propose to take up at an early date, being content here with inferential or occasional references to human fractures.

It seems necessary, however, to point out the chief conditions in which animal fracture experiments fail to represent the conditions found in the human subject. Perhaps the most important of these is the fact that there is no interval between the infliction of the injury and the operation undertaken for its repair. Thus, the overcoming of the contraction of the muscles and the difficult problem of the arrangement of the fragments in a natural position are not dealt with. The use of external splints and bandages is impracticable, and the co-operation of the patient, apart from the mere instinct of resting a painful limb, is not available. The animals, being quadrupeds, can more readily move the limb without bearing weight upon it, than is the case when the leg of a biped is injured.

I was not allowed, by my licence, to break the bones, and therefore the experiments are only concerned with clean-cut bone division, and not the jagged injuries of natural fractures. And lastly, the longest time of observation in any of my experiments was seventy-one days, so that the remote results of the operative treatment cannot be estimated from them.

I.—Factors Determining the Success of Direct Operative Treatment of Closed Fractures.

(*a*). *The Permanent Burying of Foreign Bodies.*—There are many to whom this appeals as the chief factor in the situation. Rather than bury foreign bodies of an unabsorbable nature, they would submit the patient to almost certain anatomical and functional mal-union, or avoid these by methods involving the most tedious delay. Is it possible to determine experimentally whether there is any foundation for these fears of the foreign body in the treatment of fracture ? As far as the evidence goes, and for the comparatively short periods of observation, these experiments show that indifferent aseptic foreign bodies do no harm. My justification for this statement is as follows. If a foreign body be harmful, then the more foreign body the greater the harm. But all the experiments with the long steel plates and pins (*see Figs.* 294, 295), and all those with steel intramedullary pegs, in which, relative to the bones, a very large mass of metal was used, were successful anatomically and functionally, and in none was there evidence of injury to the tissues. In all the cases where only a small quantity of foreign body was buried, viz., the short plates, small screws, wire, etc., there was evidence of anatomical and functional failure, and in most of them there was grave tissue inflammation or suppuration. Of course, the good result from the big plates and the bad result from the small, are due to the fact that one is mechanically efficient and the other not, but the fact that the best results were obtained in those cases where the largest foreign bodies were used, is significant of the tolerance of the tissues.

Another circumstance pointing to the same conclusion is, that in many cases when short plates were used, the plate remained firmly fixed to one fragment (*see Figs.* 285, 286, 287, 288) after disunion of the other end had taken place, and after the parts had come to rest. In such cases, if there was always an effort on the part of the tissues to cast off the foreign body, all the screws would certainly be loose after four to six weeks.

(*b*). *Mechanical Efficiency of Fixation.*—This is the most important factor necessary for success. Long plates and perforating pins, or intramedullary pegs of a strong material, gave almost uniform success. Any method of fixation which left a weak and shaky junction was always a failure. Bone has the physical properties of neither wood nor metal. It will not allow a screw to bury its thread in its substance; neither will it maintain for long a thread that has been tapped into its substance if the surface of this thread is subject to continuous tension. Hence it is that any method which depends chiefly upon the bite of a screw into the bone is mechanically inefficient. It is the same principle as that of the tightly-tied ligature in the soft parts, which quickly cuts its way through them until tension is relieved.

It has been widely held that no fixation of the bones in the treatment of fractures is necessary at all. The further assumption has naturally followed, that the object of operative interference will be attained if the minimum of fixation is carried out. A strand of wire, one or two staples, or a short plate and a few screws which for the moment hold the bone ends together, are regarded as doing all that is necessary. This assumption is a fallacy. Healing can only take place when the tissue tension has reached stable equilibrium. If no operation be performed, the parts soon adjust themselves, so that tension is at an end, and in this position union takes place. When a mechanically efficient fixation of the bones has been made, all the muscular force of the limb or the effects of gravity or leverage cannot move them; hence, here again there is nothing to delay healing. But if the bones are tied together by anything which does not hold them firmly and strongly, then movement will constantly take place, and muscular tension will ever be acting upon the healing tissues, instead of being borne by the fixation apparatus.

The relatively great force which fixation apparatus has to withstand is shown very well by the experiments with ivory and bone pegs, in every one of which the peg was snapped across.

To leave the parts alone to adjust themselves by natural laws, or to fix the parts mechanically so that they can withstand all the possible strain that can be put on them, are both reasonable methods; but to tie the parts together loosely or weakly is a fatal compromise which is much worse than either.

Bones left to natural repair will, after finding tension equilibrium, heal by granulation. Bones firmly and accurately fixed will heal by first intention. Bones weakly joined by a method which allows more and more movement between them will not join at all, or their junction will be long delayed.

(*c*). *Sepsis: Its Origin and Significance.*—The attainment of asepsis has quite rightly been laid down as a *sine qua non* in the operative treatment of closed fractures; but the difficulty of its attainment has probably been misunderstood. It has been generally assumed that when metal structures, e.g., plates, screws, or wire, lie at the bottom of a septic sinus, this complication is due to some technical error, infective material having been implanted in the wound during the operation. But I think there is another explanation of the matter. In the above experiments, exactly the same technique was used in the same place and same circumstances throughout. And yet in one series, e.g., the short plates and screws, or the bone and absorbable pegs, there was a very high proportion of sepsis ; whilst in another, e.g., the long plates or the steel pegs, there was not one infected case. This cannot be explained by one group all being done at the same time, because for the most part varied experiments were done on the same day. It seems to me there are three circumstances which conduce to sepsis, quite apart from errors in the aseptic technique of the operation : (1) the mobility of the foreign body used and the bone fragments ; (2) the superficial position of the foreign body; and (3) the action of an irritant foreign body upon the tissues. Contrast, for example, the following groups of cases :—

Cases where there was much Mobility		Number of Experiments	Number of Septic Cases	
Short plates and screws		9	4	
Bone pegs		7	3	
Spiral wire pegs		6	5	
	Total	22	12	more than half
Cases where there was no Mobility				
Long plates and transfixing pegs		5	0	
Steel pegs		7	0	
	Total	12	0	none

Then, as to the position of fixing structure. This is much more likely to cause sepsis if it is superficial, e.g., in the tibia rather than when deeply buried in the thigh. Thus. in the above-mentioned twelve septic cases, ten were tibias and only two femurs. The influence of a chemically-irritant foreign body is seen in the action of magnesium. In the pegging operations with this substance there were four septic cases in six operations.

These facts prove that sepsis must depend on something other than errors in the operative aseptic technique. That entire series of operations can be done without a single septic case must be evidence that the technique is good, and when a high proportion of sepsis arises, this is probably post-operative in origin. The mobility of the fragments, together with a loose foreign body, cause a great outpouring of fluid round the fracture. This fluid will soon find its way through the recently sutured wound, and especially so if the loose body lies just underneath the skin (*see Figs.* 285 and 288). The escape of this fluid opens the wound and forms a sinus, which quickly becomes infected from the skin surface. This is a reasonable explanation of the occurrence of sepsis in so large a proportion of cases where there is mobility, a superficial position of the mended bone, or an irritating foreign body. In other words, sepsis is the result of faulty fixation, and not its cause, in the majority of cases.

(*d*). *Delayed Union.*—There is a good deal of clinical evidence that the operative treatment of fractures is accompanied by delay in union. But in this simple problem there are really many factors. Only to mention one of these: probably many cases are treated in such a way that the materials used for fixation, whether screws or wires, become loose in the manner already spoken of. In such a case repair can hardly begin until the parts have acquired a position of equilibrium, and as the tension of the muscles slowly overcomes the artificial fixation, the bone ends gradually slip over one another until a stable position is assumed. Naturally all this will delay union, and much more so if the process of undoing of the fixation leads to suppuration in the way described in the last section.

All cases should be put aside, therefore, in which fixation was mechanically inefficient, because in these we can never be sure whether a certain result is due to the fixation or to its failure. Of my cases of simple closed fracture with immovable fixation, two series only are suitable for the consideration of this question, those with long plates and transfixing pins, and those with steel intramedullary pegs. In each of these series there is one case in which, after the lapse of a relatively long time, there was no appearance of union. (No. 52, cat's tibia, *Fig.* 295 *d*, 42 days after operation, long plate and split pins. Perfect wound healing and good position and function. No. 50, cat's tibia, steel peg, 42 days, good position, healing by first intention and excellent function). So that in these series, including twelve cases altogether, two show delayed union apart from any other complication. This is positive evidence supporting the contention that operative fixation causes delay in union. It is most difficult to go further than this, and explain why these exceptional cases occur. If it was the absolute fixation preventing the bone ends rubbing upon one another, then it would surely occur more often than once in five times with the long plates and split pins.

Bier and his school have suggested that it is the hæmostasis and the clearing out of blood-clot which in operative treatment of fractures causes delay in union; but in my experiments the fractures were quite fresh, and there were no blood-vessels tied or constricting bandages applied, so that there must always have been blood surrounding the fracture.

The most probable explanation that occurs to me is the mere interference with the blood-supply of the fractured bone ends. In the shaft of a long bone there are three sets of vessels: those in the periosteum, medulla, and the Haversian canal system. When any operation is performed on these parts, there is the probability that the periosteum is raised from the bone, which will temporarily divert the first set; and if the marrow cavity is extensively bored, then the second set will also be more or less destroyed. Thus there will be left only the third, that is, the small vessels in the dense bone itself. It is easy to understand that under these circumstances the blood-supply will be so poor that there will be a delay in healing. In both the specimens I have referred to this explanation would be satisfactory. The bone ends are perfectly healthy, but merely indolent.

There then arises the further question as to the ultimate result of this delayed union. If the bones are firmly fixed by prostheses which actually take the place of either internal or external callus, the result from a practical point of view is negligible. That is to say, the function of the limb is just as good in every way as if union of the bones had occurred, and in a further period of time the indolent bone ends will grow together. This line of argument supplies another reason for making the union mechanically firm, and of such a character that it will support the bone in good position for an indefinite time.

(*e*). *Comparison of Periosteal and Intramedullary Methods of Fixation.*—For this purpose, we have again the same two series of cases for consideration, viz., those in which long plates with transfixing pins, and those in which steel intramedullary pegs, were used. Practically, these two groups have both given the same results—a firm lasting fixation, good union in the majority of cases, an absence of sepsis, and uniformly good function. In both there has been one case of delayed union.

The advantages of the long plates with transfixion are, that their application interferes but little with the marrow cavity, and that they can be removed if necessary without disturbing the bone union. On the other hand, they are more difficult to apply accurately if there is much displacement of the bone, and they require a long incision, with an exposure of the bone on two opposite sides.

The advantages of the pegs are, that with the proper instruments they are easier to apply than plates, and will require only a small incision; they will, when applied, automatically ensure the correct alignment of the bone. But for general use there are many drawbacks. They require an extensive sacrifice of the medullary cavity, and a large series of different-sized pegs and borers; they cannot be used if the bone is at all splintered or comminuted; and they cannot be removed without danger of re-fracturing the bone.

II.—On the Indirect Methods of Fixing the Bones.

In my experiments these have only been represented by the double transfixion apparatus. By the use of this I have obtained better results than with any method of direct operative attack upon the area of fracture. That is to say, in every case there was rapid union, perfect function, and absence of sepsis (apart from cases where plates were also inserted), and further, the method is as readily applicable to comminuted and open, as to simple and closed, fractures.

I think my experiments bear this out so amply that I need spend no more words in enforcing it, beyond pointing out that the method is much easier of application than any other. In fact, it only constitutes a minor surgical proceeding, which can be carried out in a few minutes with a very simple technique and the minimum of risk of sepsis.

The question of real moment about this method is, how far the experimental conditions are representative of those occurring in actual fractures. In the experiment, the transfixing rods are applied before the bone is divided, and thus anatomical accuracy ensured. This is the crux of the whole matter. Any method which lays hold of the two bone ends in such a way as to restore good anatomical position and maintain it until union has occurred, without interfering with the function of the joints and muscles, may be regarded as fulfilling the conditions of these experiments, and may be expected to give equally good results. In some cases, simple extension by weights, springs, or screws, applied by apparatus which acts only through the unbroken skin, will do this. In others, some sort of transfixion of the bone ends will be necessary, in order both to overcome the muscle tension, and to maintain this without immobilizing the limb. But in many cases, any of these methods will fail in attaining the experimental conditions, either because they do not accurately reduce the fractured ends, or because they fail to retain the broken bone firmly, or because in doing these things they require the long immobilization of the muscles and joints.

III.—The Treatment of Comminuted Fractures.

The success of the indirect fixation of the fracture is nowhere seen to greater advantage than in the comminuted cases. In the experiments I have related, the bones were not merely divided into several parts, but they were crushed so as to be reduced to many small pieces. In any given case where there are only a few large fragments, these may of course be united severally to one another and to the main parts of the bone. But the cardinal principle of mechanically efficient fixation will be in danger of violation in direct proportion to the complexity of the fracture. On the other hand, by securing the main fragments in correct position and fixing them to one another, and by leaving the small fragments as little disturbed as possible, the best possible result may be obtained. This principle can be carried out either by the transfixion rods with outside connecting-bars, or else by long plates applied on each side of the bone, bridging the comminuted portion, and connected to one another by bolts which pierce the whole thickness of the shaft.

To ensure rapid and strong union, every fragment is to be left in position, quite regardless of whether it has a periosteal attachment or not. But in cases where the strength of the bone is not of such importance as the mobility of a neighbouring joint, it is wise to remove some of the loose fragments of bone in order to avoid callus excess. If any part of the bone is removed, then broken up and put back in place, these ill-fitting bone chips are apt to take on osteogenetic function very slowly (*see Figs*. 325 and 326 *b* and *c*) and therefore even the temporary removal of pieces of bone and a return of these in a disorderly manner is to be deprecated. The reason for this will be alluded to in a later section.

IV.—The Treatment of Open Fractures.

In the strict sense of the word all my cases were open fractures; but in the ordinary clinical sense none of them were such, except those where the wound broke open subsequent to the operation. Open fractures in the usual sense of the term must all be regarded as septic; but practically they are divisible into those where the infection is so trivial that no serious delay is occasioned by the wound, which quickly closes and then allows operative treatment to be carried out, and those where the infection is of a serious character, dominating the case.

My experiments have no practical bearing on the latter group; but as regards the former, which are much the most numerous, they give some useful suggestions. In such cases, clearly some indirect method of fixation should always be adopted without delay. In many this will be all that is necessary, and in others it will suffice to minimize displacement until the wound has healed and direct operative attack can be undertaken. What I have written in the last sections about the indirect method of bone fixation, applies with great force to these cases of open fracture, and there is this fact in addition: with the transfixion or other similar apparatus, the wound can be dressed without disturbing the fracture, and owing to the whole of the surface of the limb being left uncovered, any extension of septic mischief can be detected and dealt with as it arises.

ON THE REGENERATION OF BONE AND THE THEORIES OF CALLUS FORMATION.

It would require a large treatise to discuss adequately all that has been done and written on this subject, and I propose to content myself with a very brief statement of some of the main matters of dispute, pointing out the bearing that the facts of my experiments have upon them. For the reasons both of brevity and simplicity, I have referred but little to microscopical appearance, for although parts of the bones from all the important specimens have been decalcified, embedded in paraffin, and cut in serial sections, the description of these would take me far beyond the scope and purpose of this article.

The Parts played by Periosteum, Medulla, and Dense Bone in the Process of Regeneration and Repair.—The teaching on this subject, of which Ollier has been the most distinguished author, and which has dominated the conceptions of surgeons, pathologists, and students, has been that the periosteum is the all-important factor in bone growth. It has been proved by Ollier and many others that the separated periosteum can and does reproduce bone under certain conditions, particularly in young subjects and when the periosteum is left partly attached to its original bed. There is a negative side to this evidence which has been rather overlooked, the practical importance of which, however, is very great; that is to say, many, in fact the majority of experiments of transplanting periosteum have had no result. These have been assumed to be due to some technical error or experimental accident, and the positive results have been held to outweigh the negative. The fact that periosteum can, and does, reproduce bone sometimes, being taken as proved, many experiments have been cited in which all new bone formation connected with the periosteum has been regarded as derived from the latter. For example, the well-known silver ring experiment, in which a metal band laid round a bone under the periosteum is covered over in time by new bone between the metal and the periosteum. The fallacy of this deduction lies in the fact that in this, and in all similar experiments, it is obvious that the new bone may be derived from the old bone, and merely grow thence under the periosteal envelope. Macewen's experiments have, on the other hand, proved that the living bone is the main origin both of regeneration and repair, and that these can take place in the absence of the periosteum. He entirely denies the osteogenic faculty of the periosteum, and points out that whereas bone growth is only occasional and exceptional from periosteum completely separated from the underlying bone, on the other hand, bone growth from living bone deprived of its periosteum is regular and constant. It is evident, as I have said, that in the examination of fractured bones, apart from special devices to separate the periosteum from the bone, it is impossible to be certain whether a given mass of external callus is derived from the periosteum which is on one side, or the bone which is on the other (see for example the specimens in *Fig.* 308), and it is rather astonishing that so many observers have attributed the origin of external callus to the overlying periosteum, without considering that it may equally well have grown out from the underlying bone. But even with such simple specimens of external callus, the appearances support much rather the osseous than the periosteal origin of callus. *Fig.* 327 gives a good illustration of this; and the specimens shown in *Figs.* 289, 291, and 302 *a* go a step further, for in all these it is seen, even with the naked eye, that the callus is formed both of bone and cartilage. The process of repair consists in the cartilage being converted into bone,

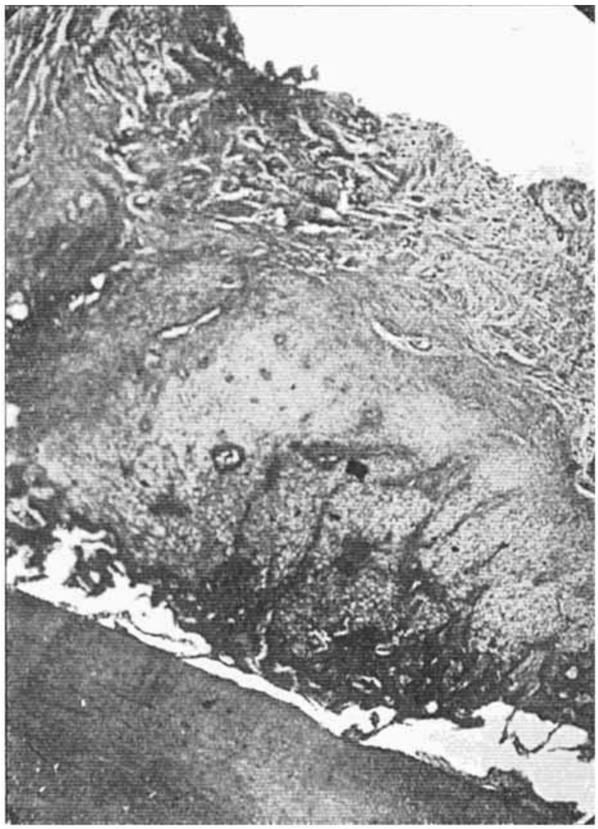


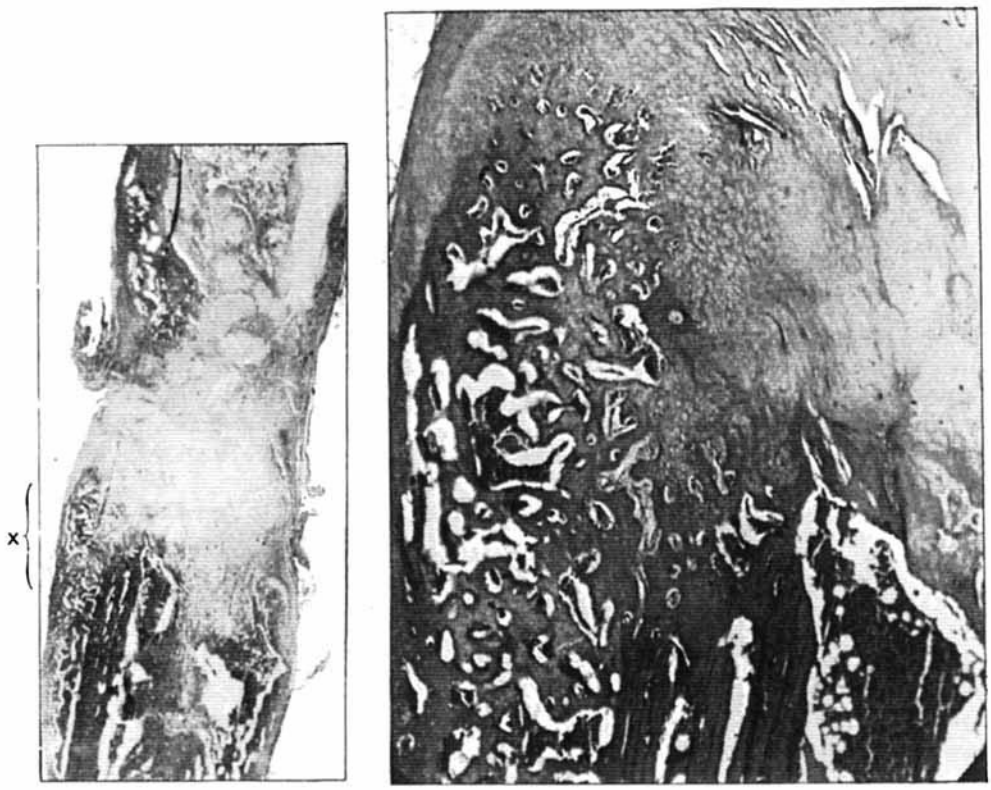
FIG. 327.—CAT'S TIBIA (NO. 5), THE WHOLE SPECIMEN BEING SHOWN IN FIG. 300 *a*, 17 DAYS AFTER OPERATION.

Longitudinal section of the dense bone, with the overlying external callus, as seen under a ½-in. objective.

B, Dense bone of the shaft. S, Space between the callus and the dense bone artificially produced in the cutting of the section. O,C., Deep layer of ossified callus. C.C., Outer layer of cartilaginous callus. P, Periosteum fused with overlying connective tissue.

There can be no doubt that this thick layer of external callus is growing in direct continuity with the bone, and the ossification proceeding from the bone. The way in which the callus breaks from the bone in the process of cutting the section, although purely accidental, is nevertheless very instructive, because it marks the line of most ready cleavage, between two layers of tissue of different density. When necrosis occurs, it is in this line of cleavage that the inflammatory products accumulate and separate the outer involucrum from the inner sequestrum. But nevertheless, the involucrum has grown from the bone.

and this process of ossification can be seen to proceed from the surface of the bone outwards towards the periosteum, and not in the reverse direction. When the periosteum has been excluded by the use of encircling metal plates, the formation of callus by the bone itself is demonstrated to take place without fail. In *Fig.* 298 *a* the bone is seen after ten days, rough and pitted by granulation tissue, which is the first stage of callus; in *Fig.* 298 *b* the external callus is well advanced. In *Fig.* 299, after fifty-two days, the bones are seen to be united by a thin layer of external callus, the amount of which has been limited by the steel plate, and a thin transverse disc of cartilage at the line of fracture. The interior of the bone is occupied by a large mass of internal callus; this can only



A *B*

FIG. 328.—NO. 70, THE SAME SPECIMEN AS SHOWN IN FIG. 314 *b*. AFTER 42 DAYS. LONGITUDINAL SECTION.

A.—Magnification by ½-in. objective. X is the portion of bone shown in *B*. At the upper and lower parts are seen the ends of the bone, and between them the new callus. This is cartilaginous in the centre, but from the bones osseous tissue is growing into it.

B.—Magnification by ¼-in. objective. The direct structural continuity between the bone and the ossified callus is seen.

have originated from the marrow cavity and from the dense bone, which has almost disappeared in giving rise to this new tissue. *Figs.* 317 *a* and *b* show the same thing in comminuted fractures.

In the next place, we have a series of cases where a piece of bone has been removed from the shaft, leaving the periosteum in its place. Some of these were comminuted fractures, and in others a piece of bone was cleanly cut out. In the former there was a uniform filling up of the gap by callus of a very immature character. In the latter there was no callus formation except at the ends of the cut bone. In all these cases the space left is bounded both by the sleeve of periosteum and by the cut or broken bone ends, and therefore either of these structures may take part in filling it. *Figs.* 314 and 315 show the crushed bones. In all four specimens the gap is filled with callus; in *Figs.* 314 *a*, 314 *b*, and 315 *a*, there is more, or more advanced, callus next to the bones than in the centre—evidence that these bones have produced the callus. In *Fig.* 314 *a* the central point is merely fibrous, whereas at either end it is ossified. In *Fig.* 314 *b* the central part is cartilage, whilst the part in contact with the bones is bony. This is seen in greater detail in the sections shown in *Fig.* 328, *A* and *B*.

Figs. 319 *a* and *b* and 320 (specimens 80 and 79), show the result of cutting out a part of the bone and leaving the periosteum. There is a complete absence of any callus in the greater part of the gap left. *Fig.* 319 *a* (80) shows a cap of callus upon the cut bone end, sharply limited, and looking as if it was unlikely to have spread much further if the animal had been left alive. The only difference between these cases and those of the comminuted fractures was, that in one case the bone was clean-cut and in the other crushed. The periosteum was similarly treated in both. The crushed bones, having a larger broken surface, exude more callus, and the cut bones less, and in none of these particular specimens is there any evidence of the periosteum taking any important part in the regeneration of bone. In two cases, not only was a part of the bone removed, but the cut bone ends were covered by rubber tissue in order to exclude them from a share in the formation of any tissue that filled the gap. In one (No. 84) there was nothing in the gap; but in the other (No. 85), shown in *Figs.* 319 *c* and 321, there was quite good callus formation. Such a specimen as this, taken by itself, might be put forward as a convincing demonstration that the periosteum, and periosteum only, is the source and origin of callus; but taken in conjunction with all the other evidence in this paper, it is merely an example of the fact, incontestably proved by Ollier and others, that under certain conditions the periosteum can and does reproduce bone. It in no way shakes the evidence that, under usual conditions, new bone and bone repair originate by proliferation from bone tissue, in which process the periosteum plays quite a secondary part.

Between the fibrous periosteum and the bone there lies a layer of cells which are nothing more or less than a layer of osteoblasts. If, in separating the periosteum from the bone, this layer of osteoblasts be taken with it, as will usually be the case in young bones or after inflammatory changes have occurred (*see Fig.* 327) when the layer is thick, then the separate periosteum has osteogenetic power in virtue of the bone layer which adheres to it. But the removal of this osteoblast layer with the periosteum is more or less accidental, and hence the great uncertainty of reproducing bone by a transplantation of periosteum. On the other hand, the bone itself is full of osteoblasts, and when any portion of it is removed without interfering with its vitality, it will always be capable of reproducing new bone. If the term periosteum were applied, as it ought to be, simply to the fibro-elastic tissue layer, then it may be held that this is nothing more than a limiting membrane without any osteogenetic power.

But if by periosteum is meant the fibrous layer with the bone-cells adhering to its deep surface, then it has osteogenetic power just in proportion as it takes with it this part of the living bone. The observation has often been made, but its significance in this connection rather overlooked, that whatever doubt and uncertainty there may be as to whether the periosteum can and does reproduce bone, there is no doubt whatever that the bone can and does always reproduce periosteum when a part of the membrane has been removed from its surface. If then the bone is certainly the mother of the periosteum, it is very unlikely that the periosteum is also the mother of the bone.

The Amount, Position, and Constitution of Callus.—Callus, as the chief material of bone repair, is laid down in an amount which differs according to certain well-defined conditions. In the case of the soft tissues, the healing of a wound is said to be by first intention when the severed tissues seem to grow directly together with the minimum of cementing new tissue, or by granulation where there is a large gap to be filled and the original tissues are eventually united by a large mass of scar tissue. So it is with broken bones. When the fractured surfaces are placed in accurate apposition and firmly held in that position, as seen in *Figs.* 295 *a* and *c*, 307 *a* and *e*, 311 *b*, 312 *a b* and *c*, there is the very minimum of reparative callus, and a direct continuity of the bones is re-established. This is shown in microscopical section in *Fig* 329. A consideration of my experiments makes it difficult to believe that any such result could be obtained in complete fractures, when the bone ends are not accurately apposed, or when they are allowed free movement. On the other hand, there is a great callus excess produced by mal-position and mobility (*Figs.* 285, 287, 289, 290, 291, 302 *a*), or by a degree of mobility without mal-position (*Figs.* 307 *b*, 308 *a* and *b*), or by any condition of tissue irritation (*Figs.* 305 *a* and *b*, 308 *a* and *b*), or by great fragmentation of the bone (*Figs.* 307 *c*, 313 *b* and *c*). These facts are so generally conceded that it is not necessary to do more than illustrate them by the examples given.

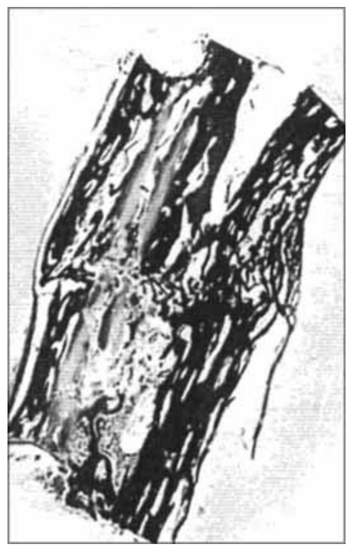


FIG. 329.—Longitudinal section of the site of fracture in No. 53; $\frac{1}{3}$-in objective. The same specimen as that shown in Fig. 295 *c*, after 42 days. The section passes through the side of the bone, the marrow cavity not being fully shown. Note the great thickening of the dense bone and its great canalization. The fracture is seen to be merely a linear irregularity, and there is practically no callus.

The opposite extreme, the failure of callus formation, with consequently delayed union, is seen in *Figs.* 295 *d*, 302 *b*, and specimen 52 (not illustrated), and I have discussed the explanation of this phenomenon in connection with the factors relating to operative treatment above. I would merely repeat here that this seems to be due to an interference with the blood-supply of the bone ends by a simultaneous interference with the periosteum and medulla. Such specimens as that in *Fig.* 302 *b*, and others in the same series, are susceptible of a further explanation. An oblique fracture is surrounded by several turns of wire. This is not enough to hold the bones rigid, and there must therefore be a tendency to the mechanical destruction by the chafing wire of external callus exuding from the bones.

The formation of a false joint, illustrated by *Figs.* 292, 293, 301 *a*, and 301 *b*, in my experiments has always been associated with great displacement of the fragments and unrestrained mobility. In the specimens figured in 292 and 293 there is little or no callus, but in *Figs.* 301 *a* and *b* are seen cases where the pseudarthrosis co-exists with callus excess.

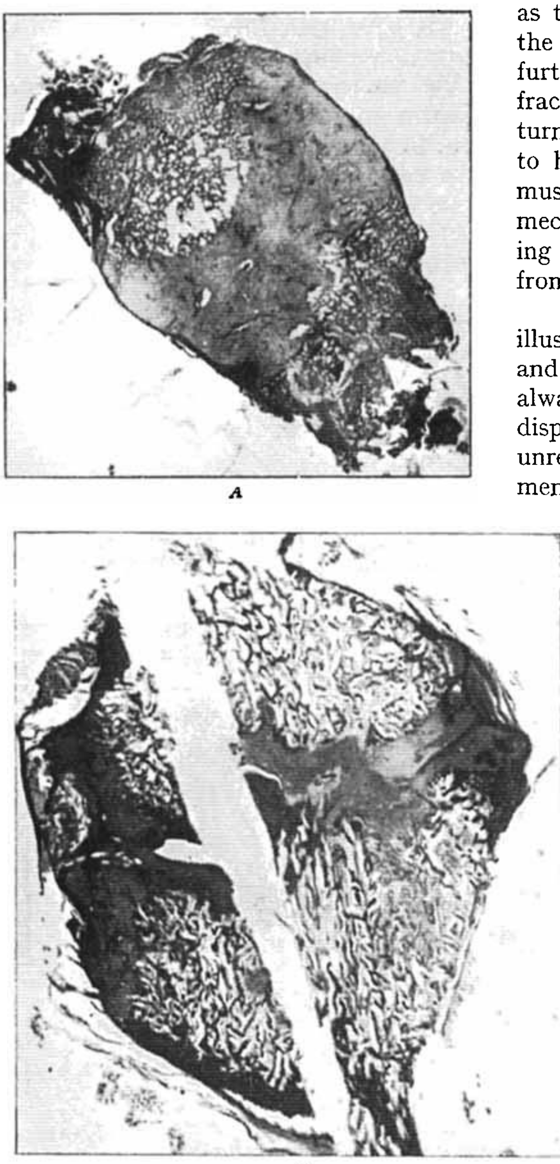


FIG. 330.—SECTIONS SHOWING THE RELATION OF CARTILAGINOUS AND BONY CALLUS. $\frac{1}{2}$-IN. OBJECTIVE.

A.—No. 48, the specimen shown in Fig. 294 *b*, after 34 days. The section is longitudinal, and passes tangential to the dense bone, through the external callus. The cartilage zone is opposite the line of fracture.

B.—No. 44, the specimen (shown in Fig. 307 *b*, after 42 days. Two longitudinal sections through the external callus, showing the cartilage remaining at the line of fracture (right-hand section) and beneath the periosteum (left-hand section).

The occurrence of cartilage in callus is a matter which has given rise to much discussion. That it is a constant feature of the repair of animal fractures has always been recognized. It is present in relatively large amounts when the callus mass itself is great, i.e., when displacement and mobility co-exist. This is well illustrated in *Fig.* 302 *a*. It persists longer and in greater amount at the line of fracture and under the periosteum than elsewhere, and this is well shown in *Figs.* 289, 291, 295 *b*, 298 *b* 302 *a*, and 307 *b*, and in microscopical sections in *Fig.* 330. It is usually absent, or present only in microscopical amount, when union is complete and when union has taken place in good position with fixation, and this is illustrated by *Figs.* 295 *a*, 295 *c*, 311 *b*, 312 *b*, and 312 *c*. All my specimens seem to show that there is a direct conversion of osteoblasts into cartilage cells, and of cartilage cells into osteoblasts. The generally accepted statement that cartilage is not a constituent of human callus is probably incorrect, and due to the fact that the specimens on which the statement is founded were of an age when the cartilage has disappeared. Many observers who have studied early cases of human fracture have found that cartilage is abundantly present. Amongst these are Duhamel, Maas, Flourens, Hofmokel, Dupuytren, and Orth (quoted by Zondek). Ziegler gives details of a human complicated fracture above the ankle, eight weeks old, in which there was abundant cartilage, and he states that he has found it in over fifty human fractures; and as recently as December 6, 1913, Morley, in the *British Medical Journal*, has described and figured luxuriant cartilage growth as resulting from a periosteal injury in a human femur.

On the Behaviour of Isolated Bone Fragments.—This subject, trending as it does on the large field of the transplantation of bone, is so difficult, and my experiments are so few, that I wish to speak with some reservation, realizing the dangers of drawing far-reaching conclusions from insufficient data.

I have three groups of experiments which bear upon this point.

The first deals with comminuted fracture, and is illustrated in *Fig.* 313 and the microphotos, *Figs.* 331 *A* and *B*. In these, and particularly in *Figs.* 313 *b* and *c* and *Fig.* 331, it is seen that every isolated piece of bone acts as a centre of active bone proliferation, and forms a firm mass of ossified callus. Seeing what rapid callus formation occurred around these fragments in comminuted fractures, I thought it would be easy to demonstrate that bone-grafting would take place much more readily from bone chips than from large fragments of transplanted bone. But, unless the remaining groups of experiments are for some reason fallacious and exceptional, this is proved to be incorrect.

The second set of experiments dealing with isolated bone chips is illustrated in *Figs.* 325 *b* and *c*, 326 *b* and *c*, representing two cases. In both these a part of the tibia was removed, crushed into as small fragments as possible, and then these pieces were returned to the trough of periosteum, the bone being put up in the transfixion apparatus; but at the end of fourteen and seventy days, it is seen that the majority of these bone chips still remain isolated and inactive. When the specimens were cut with a fine fret-saw, many of the chips fell out, instead of remaining firmly embedded in callus, as in the case of the comminuted fractures. It is not worth discussing these at length, for they may be exceptional cases, but I would venture to put forward a possible explanation. In the case of the comminuted fractures, the bone fragments were left fitting together with but little space between; hence their blood-supply is not completely isolated, and new blood-vessels readily grow across from one fragment to another. When the piece of bone is removed and broken up, and the bits are put back in a disorderly fashion, there are relatively large spaces between the bones, filled up with blood-clot. This clot has first to be vascularized before the bone chips can get a sufficient blood-supply to provide for new growth.

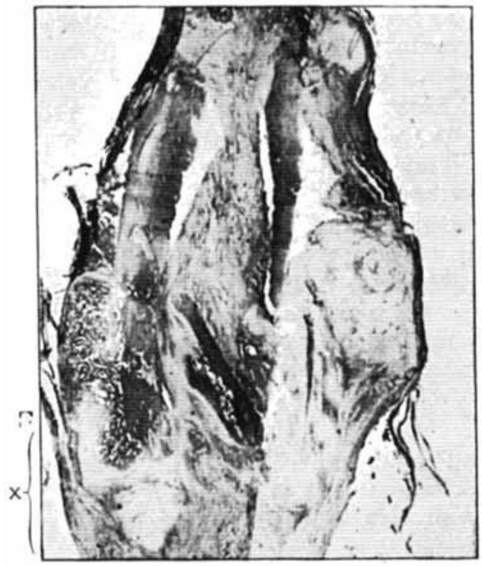
The third group of experiments is illustrated in *Figs.* 325 *a* and 326 *a*. In this case a long splinter of bone was taken from the opposite tibia, and its ends were placed tightly in the medullary cavities of the bones above and below a gap made by taking out a piece of the bone. There is good vital union between the bone ends and the graft, and the graft itself is the centre of new callus formation.

These experiments appear to prove, therefore, that isolated bone fragments can and do act as centres of new bone growth, but that for this to take place most effectively, the fragment must be placed in close apposition to neighbouring living vascular bone.

SUMMARY OF CONCLUSIONS.

1. That the most rapid and perfect method of fracture repair follows "indirect fixation," namely, fixation which does not directly interfere with the area of fracture.

2. That for such perfect results to be obtained by "indirect fixation," it is necessary for the method to ensure (*a*) perfect anatomical restoration, (*b*) fixation for the period required by union, and (*c*) perfect freedom of all the soft parts and joints, so that the limb can be used directly pain has ceased.



A

B

FIG. 331.—LONGITUDINAL SECTIONS FROM NO. 72, THE SPECIMEN OF COMMINUTED FRACTURE SHOWN IN FIG. 313 *b*, AFTER 28 DAYS.

A. Magnification by ½-in. objective. The fragments of the original bone are seen to be the centre of new bone growth.
B. Magnification by ¼-in. objective of the portion of *A* marked X. In the upper part of the section is seen a bone fragment in active growth, and lower down is a large area of cartilaginous callus.

3. That in all complete fractures there exists a very strong force which tends to displace the fragments until the muscles are thrown out of action and a position of stability free from tension is acquired. This involves great deformity, consisting of shortening, overlapping, and angulation.

4. The operative treatment of fractures should aim at completely counteracting this displacing force. It should not only accurately replace the fragments, but do so in a manner of such mechanical efficiency that displacement cannot occur.

5. The mere presence of an aseptic indifferent foreign body in the tissues has no ill effect upon healing tissues, unless there is an interposition of its substance between structures which ought to unite.

6. That the frictional grip between a bone and a screw will rapidly give way if subjected to much tension, owing to the absorption of the bone.

7. That the union of bones by plates and short screws is mechanically inefficient, because the screws are quickly pulled out of the bones.

8. Sepsis is often the result, and not the cause, of inefficient mechanical fixation.

9. Mechanical efficiency in the direct operative treatment of fractures can be attained in two ways: (*a*) By the use of long plates and pins or bolts which transfix and hold the bone by some broad flange or nut; and (*b*) Strong, solid intramedullary pegs.

10. Perfect anatomical union and normal function usually result from either of the above methods. Normal, sound, and rapid repair is perfectly consistent with absolute rigidity.

11. Delay in union is a possible, though exceptional, result of perfect operative fixation of a fracture. It is due probably to interference with the blood-supply of the bone ends, and will cause no disadvantage if the mechanical fixation be so efficient as to hold the bones in good position for an indefinite time.

12. The fixation of transverse or slightly oblique fractures by encircling wire is unsatisfactory, because it is mechanically inefficient, and allows from the outset a mobility which delays union by interfering with the zone of repair.

13. All forms of absorbable pegs that I have tried are unsatisfactory, because they either break or bend before good union has occurred.

14. Metallic magnesium, when used as a peg, acts as a powerful stimulus to callus formation.

15. The natural position assumed by bones which are not fixed, results in deformity, callus excess, or the formation of a false joint.

16. In the treatment of severely comminuted fractures, and in certain cases of open fracture, the best method of treatment is by a fixation of the main fragments, leaving the small pieces in position when strength of union is the chief object, and removing some of them when callus excess is likely to interfere with the mobility of a joint.

17. In the repair of bone defects: (*a*) Natural repair occurs rapidly when only part of the thickness of the bone is destroyed; (*b*) Fragments of bone used as a graft (from the same animal) form new bone very slowly if they are only loosely inserted in the gap; (*c*) Large pieces of bone used as a graft unite quickly, and form the centre of new bone growth, if they are tightly fixed to the raw surfaces of vascular bone.

18. The periosteum is the product, and not the mother, of bone. All the osteogenetic properties of the periosteum, whether in the repair of fractures or in grafting, are due to the more or less accidental presence of the outer layer of bone-cells adherent to its deep surface.

19. Living bone is the chief source and origin of callus, which grows mainly from its outer or periosteal surface, and to a less extent from its deep or medullary surface and its cut ends.

20. Cartilage is a constant stage in the transformation of bone-granulation tissue into bone. It is present chiefly (*a*) in early stages of repair, and (*b*) when there is much displacement and mobility; and it remains longest under the periosteum and at the line of fracture.

[The experimental part of this investigation was carried out in the research department of the Medical School of University College Hospital, London, and the pathological part in the laboratory of the General Hospital, Bristol. My most cordial thanks are due to Dr. Bolton and Dr. Scott Williamson as the respective directors of these two laboratories for their kindness and assistance, and also to the Scientific Grants Committee of the British Medical Association, who have defrayed a large part of the expenses of the work.]

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