

ON THE TRANSPLANTATION OF BONE IN THE
TREATMENT OF BONE AND JOINT INJURIES.

by

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It is not Wolff's law which an orthopaedic surgeon should cultivate, but a close acquaintance with the behaviour of osteoblasts.

Sir Arthur Keith

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CHAPTER I

THE HISTORY OF THE STUDY OF THE GROWTH AND REPAIR OF BONE.

The experimental study of the growth and repair of bone began in 1736 at a London dinner table. Early in that year John Belchier, a young surgeon who had just been elected to the Staff of Guy's Hospital, was dining with a friend who was a calico printer. The main dish was a leg of pork, and Belchier was surprised to see that the bone was red instead of white. Upon enquiry he found that his thrifty host fed his pigs on madder which had been used in calico-dyeing. Belchier guessed that this might be the cause of the red staining, established the truth of his surmise by experiments on his own pigs, and reported his findings to the Royal Society in a brief communication which occupies only two pages of its Transactions (12).

That Belchier did not pursue his discovery further was due, in Sir Arthur Keith's opinion (51), to the influence of his master "the great Cheselden" who, Keith says, "knew all there was to be known about bones - particularly so far as concerned those of the human skeleton". In Cheselden's words bones "grew

by continual addition of this ossifying matter"; the periosteum "serves for the muscles to slide easily upon; it is everywhere full of small blood vessels which enter the bones for their nourishment"; fractured bones heal by "the same kind of matter which ossified the bones at first thrown out from the bone ends and formed into a mass of callous matter" (21). These specious phrases were accepted as the whole truth by all who gave any thought to the matter, and Belchier allowed others to solve the mystery with the key which he held unrecognised in his hand.

Duhamel, a remarkable Frenchman, soon extended the knowledge of bone growth. He was not a medical man, he was a land-owner and a lawyer, but he was a member of the Academy of Science and so far as research into the secrets of nature was concerned he was, in Keith's opinion, "a man akin in spirit to Stephen Hales or Benjamin Franklin" (52).

His first paper, published in 1738, did little more than confirm Belchier's findings (24). By 1741 he had begun to experiment on the growth and healing of bone and had shown that only growing bone was stained by madder (25). In 1743 he showed that he could produce concentric rings of red and white in the bones by alternating periods of madder-feeding with periods of ordinary feeding (26). From this he concluded that bone growth was a function of the periosteum. He also noted that bones grow in length at the ends though he did not examine the phenomenon; he noted the epiphyseal lines but he left them

unstudied.

Duhamel's findings may be summarised thus:

- 1) only growing bone is stained by madder-feeding;
- 2) bone grows in thickness by the circumferential deposition of layer upon layer of new bone;
- 3) bone grows in length at the extremities;
- 4) the deepest layer of the periosteum is the "maternal tissue" of bone.

Haller of Berne, a man whose opinions moulded those of the great John Hunter, challenged these views. He said that the periosteum was only the limiting membrane of bone, that its function was nutritional, that bone growth was a function of the blood vessels, and that the callus that repaired fractures was formed "by the broken bone" (37). This is the first appearance of the difference of opinion about the function of the periosteum; there was to be continuous argument on this matter for nearly two hundred years.

John Hunter had no doubt that Haller was right (46), and accepted as additional proof of the theory of the place of blood vessels in the growth of bone the "circulus vasculosus articuli et epiphyseos" which his brother William Hunter described as the actively growing bone ends (47). He also used to show his classes specimens of fractured bones in which "adhesions of detached splinters takes place.....and this takes place not only in these which are attached to the soft parts but

even in those which are entirely loose. Therefore these pieces must retain the living principle".

Hunter's most important observation on bone growth was that as bones grow they are continuously remodelled. He studied in particular the neck of the femur and the angle of the mandible, and he showed that in these sites growth could not be explained only by the deposition of new bone; there must also be concurrent absorption of bone already formed. He concludes, "the remote cause of absorption of whole and living parts implies the existence of two conditions, the first of which is a consciousness in the part to be absorbed of the unfitness or impossibility of remaining under such circumstances, whatever they may be, and therefore they become ready for removal and submit to it with ease. And the second is the consciousness of the absorbents of such a state in the parts. Both of these concurring they have nothing to do but to set to work".

This is a remarkably precise piece of observation and exposition of a physiological principle by one who had never used a microscope or heard of an osteoblast. Its accuracy has been confirmed by many observers among whom are Jansen who, in 1928, applied the term "tubulation" to the process as seen in the long bones (49), and Harris who published a valuable monograph on bone growth in 1933 (39). Hunter's prescient observation anticipates by nearly a hundred and forty years the "Law of Bone Transformation" rather cumbruously enunciated by Wolff, "every

change in the form and function of a bone or of its function alone is followed by certain definite changes in the internal architecture and equally definite alterations in their external form in accordance with mathematical laws" (77), and it rivals in simplicity and directness Murphy's statement of the same principle, "The amount of growth in a bone depends on the need for it" (63).

Thirty-eight years after John Hunter died in London James Syme, the Professor of Clinical Surgery in the University of Edinburgh, published a "Treatise on the Excision of Diseased Joints" (72). His attention having been thus turned to the problems of the growth and repair of bone he published in 1835 the results of experiments on bone regeneration in which he proved to his satisfaction that bone was formed by the periosteum (73). He removed $1\frac{5}{8}$ " from the radius of both right and left legs of a dog; on the right he removed the periosteum also, and on the left he preserved it. Six weeks later when the dog was killed there was a gap in the right radius; the left radius had reformed. Having repeated the experiment and obtained the same result he changed his method. In another dog he raised the periosteum from a segment of the radius and wrapped tinfoil around the bone under the periosteum which he replaced. A layer of bone was formed on the tinfoil. Then he excised the periosteum from a segment of the radius and wrapped the denuded bone in tinfoil. No new bone was formed on the tinfoil. Syme,

therefore, had no doubt that Duhamel was right about the osteo-genetic function of the periosteum.

Shortly after this paper was published a pupil and dresser of Syme's was beginning to work on the subject of bone growth. John Goodsir came to Edinburgh from Anstruther in Fife, became an L.R.C.S. in 1835, and was appointed Curator of the Museum of the Royal College of Surgeons of Edinburgh in 1841. He must have been profoundly influenced by the opinions of Syme who taught him and who was the acknowledged leader of surgical thought at that time in the country if not in the world. But Goodsir's microscope, an instrument which had not been used before in the study of bone, showed him what could not be wholly explained by Syme's theories, for he saw and described osteoblasts. He knew what Hunter had stated about the formation of bones by the blood-vessels, and with his new apparatus and his knowledge of the growth of the simple skeletons of marine animals he was able to explain how they did it. He further showed with his microscope where Syme erred. And he would have saved Ollier from a similar error had he learnt from Goodsir's work, for Goodsir anticipated Macewen in showing that the reason for the deposition of bone by the periosteum as raised by Syme was that he raised bone particles with it (33).

In almost the same year as Goodsir described bone corpuscles and their function in making and unmaking bone Flour-ens in Paris was claiming to have proved Duhamel right and that

the periosteum was the maternal tissue of bone (28). In 1857 he was joined by Louis Ollier of Lyons who came to Paris to work with him and Claude Bernard before going back to the chair of surgery in Lyons in 1859. He went back convinced that Duhamel and Flour-ens had come to the correct conclusions, and by the time that he published his subsequent work in a two volume treatise in 1867 (65) he was an even more firm believer in the osteogenetic function of the periosteum. He saw with the microscope flakes of bone on the deep surface of the raised periosteum, but he regarded them as being "in process of transformation". Though he recognised that transplanted bone could live and grow in suitable surroundings he is remembered chiefly for his over-estimation of the osteogenetic function of the periosteum.

Twelve years after Ollier's treatise was published Macewen in Glasgow showed, by a brilliant piece of experimental surgery, that Ollier's views did not expound the whole truth. In 1878 Macewen removed the entire diaphysis of the humerus of a three year old boy for osteomyelitis which had persisted in spite of several less radical operations. In 1880 the parents brought the boy back to Macewen for amputation of a limb which, though healed, was flail and useless. Macewen re-opened the arm and put into the trough where the shaft of the humerus had been a number of wedges of tibia which he had removed during corrective osteotomies on other patients. This is the first recorded example of the clinical use of homogenous bone-grafting. The

length of the rebuilt humerus was 6", $4\frac{1}{2}$ " of which was made up of grafts. Twenty years later the man had a humerus 11" long, 3" shorter than that of the other arm, and was earning his living by manual work.

The result of this operation and the behaviour of these six wedges could not be explained on Ollier's theory of periosteal osteogenesis, and the question about what happened to transplanted bone became a new subject for controversy. Though it has been intensively studied in the last fifty years, no final agreement has yet been reached.

Barth (1893) held that bone transplants died and were replaced by new bone from the surrounding host bone. His observations were based on experiments with trephine holes in the skull, bone which in some ways does not behave in the same way as the long bones. He assumes without sufficient evidence that new bone formed in relation to a transplant all comes from the surrounding bone and not from the transplant itself. Though his work and his conclusions are not wholly accurate he made two important observations:

- 1) that a graft is slow and indolent in the matter of growth; and
- 2) that final success in grafting depends very largely upon the intimate contact of the graft with the living vascular bone of the bed (9) (10) (11).

In 1907 and 1909 Axhausen published exhaustive

accounts of 146 animal experiments on bone grafting with full details of his histological findings (6) (7). Among his conclusions are:

- 1) that a living graft covered by periosteum shows marked cellular proliferation under the periosteum;
- 2) that a graft containing marrow shows new bone formation from the marrow whenever this is in contact with living vascular tissue;
- 3) that the compact bone of a graft, whatever its source, always shows empty cell spaces in the greater part of its extent; there are, however, areas around the edge of the bone where the cells retain their staining properties;
- 4) that dead compact bone is rebuilt by new bone from the periosteum and the marrow tissue, laid down in channels made by vessels which invade the old dead bone.

Axhausen, therefore, observed and recorded the survival of bone cells in cortical bone transplants (conclusion 3) without recognising the significance of the observation. He was so strongly biased by a pre-conceived idea of the osteogenetic function of the periosteum that he stated in a later paper, which is based mainly on clinical observation, that no tissue could be regarded as periosteum unless its osteogenetic function could be demonstrated (8). In this paper he describes a patient of 23 years in whom a portion of the fibula covered by periosteum was implanted in the femur the upper part of which had been excised.

A marked increase took place in both the thickness and the density of the graft, but this began only after five months. He holds that this delay was due to the time taken by the substitution of the dead compact bone by the periosteal new bone (cf. Mr. B.H. Burns's case, p.19). The influence of Duhamel and Ollier was still predominant.

In 1912 Macewen published his "Observations on Osteogenesis" (58). His brilliantly simple and critical experiments convinced him that the conception of Hunter and Goodsir, after all, was right - that bone grows and repairs itself by the activity of the bone cells, and that if periosteal flaps do not contain bone cells they do not form new bone. He also showed that bone itself could be transplanted and that the transplant produced new bone independently of the periosteum. He removed portions of the radius of two dogs, excised the periosteum, broke the portions of bone into pieces and replaced them, exchanging the radii of the two dogs. A massive piece of new bone formed in each case. In two other dogs he exchanged the right radius of one dog for the corresponding bone of the other. Each radius was stripped of periosteum, but the transplanted bones lived and hypertrophied. Thus Macewen brought our knowledge of the growth and repair of bone and the behaviour of transplanted bone almost to where it stands today.

CHAPTER II

THE DEVELOPMENT OF THE SURGERY OF BONE REPAIR

The work thus far studied has been mainly experimental and its clinical application to bone surgery has been confined almost exclusively to the treatment of severe disease. The hazards of open operations on fractures and joint injuries were such as to make the risk of these procedures more than most surgeons would accept, for before the principles of surgical asepsis had become thoroughly established an open bone injury often resulted in loss of the limb or even the life of the patient. Permanent deformity was a much less heavy price to pay and was accepted as an inevitable consequence of many fractures. It is true that in 1877 Lister had exposed and sutured with wire a fracture of the patella, but this was "a novel and by some then thought an unjustifiable procedure" (57).

Arbuthnot Lane first aroused the surgical conscience of the profession about the appalling results which were accepted in fracture treatment. He pointed out that unless the form of the broken bone was restored the function of the affected

joints was impaired and that when the tibia, for example, was fractured, a man might be reduced to penury as the result of his injury because he was no longer able to work. In 1894 he read a paper to the Clinical Society of London on "A New Method of Treating Simple Oblique Fracture of the Tibia and Fibula more Efficient than Those in Common Use" (54). This method was open reduction and fixation of the broken bone with two oblique screws. In 1914 he described his practice and expounded the principles on which it was founded in a book, "The Operative Treatment of Fractures" (55). In it he states that the ideal method of fracture treatment is the perfect re-approximation and fixation of the parts so that a broken bone may heal by first intention like a surgical incision. Perfect anatomical restoration allows the intricate and precise mechanism of the joints to continue to work as before and without any readjustment with its attendant dangers of arthritic changes. He pointed out that not all fractures were suitable for treatment by this method, notably fractures in the region of the wrist or the elbow. He further emphasised that a surgeon who used the method accepted the heavy responsibility of the risk of infecting the fracture and that he must therefore be sure of his aseptic technique. But he showed that the method, in suitable fractures, was both practicable and effective.

Lane's results were so impressive that the method was widely adopted, and the Committee set up by the British

Medical Association to examine the whole question of fracture treatment referred to it favourably in its Report (1912), (14). The results obtained by many surgeons, however, were not so good as Lane's had been and there was a high rate of infective and other complications. Soon there was a swing of opinion again, led largely by Sir Robert Jones (50) and the Liverpool school, towards the treatment of fractures by manipulation and external fixation by splints and away from open operation and internal splints. Now within the last few years there is growing recognition of the fact that there is a place for both forms of treatment and that the choice of method depends on the site and nature of the fracture. Of late the added help given by chemotherapy in the control of infection has tended to overweight opinion in favour of open operation. This is particularly so in America. I am not yet prepared to believe that the introduction of penicillin has made it good surgery to fix an open fracture with a plate.

It is interesting to speculate on the reason why Lane's methods were abandoned. In my opinion it was largely because he was a man ahead of his time. The late Sir David Wilkie used to speak of Lane as "the master craftsman", and the fact that he could perform with safety operations that others could not copy without disaster is an example of the fact that surgical dexterity is almost as important as a rigid adherence to a no-touch technique. Lane's principle of anatomical re-

duction in the treatment of fractures was temporarily eclipsed by sepsis.

A further reason for some of the complications that accompanied Lane's method was the nature of the metal used to make the plates and screws. It was electrolytic. It was acted upon by the body fluids. Even if there was no infection a chemical change took place around the metal which loosened the screws and produced undesirable reactions in the neighbourhood of the plates. It will be seen how the introduction in 1938 of a non-electrolytic alloy which is inert in the body has modified the methods of bone surgery almost as much as the development of a technique which should eliminate sepsis.

In 1911 Dr. Fred Albee of New York began to make internal splints of live bone instead of metal (2). So that he would not need any metal screws or other metallic internal fixation he devised many ingenious power-driven tools with which he fashioned his grafts to fit with the precision aimed at by an expert carpenter (3). Much of the detail of Albee's work is now outmoded by the introduction of screws and internal splints made of non-electrolytic alloys (see p.22), and he never correctly appreciated a fundamental physiological principle upon which it was based (see p.15), but there can be no doubt of the value of Albee's contribution to the study of bone transplantation and the development of its use in the treatment of injuries and diseases of bones and joints.

The success of Albee's methods and the excellence of his clinical results became widely known and many followed his lead. This increase in its clinical application was followed by a great increase in the experimental study of transplanted bone, and the literature of the last thirty years on the subject is enormous and of varied quality. Some of it is excellent, but some of it can hardly be regarded as accurate observation or sound argument. And just as there had been the earlier Haller-Duhamel controversy on the role of the periosteum so opinion now became divided about the behaviour of transplanted bone..

In the last thirty-four years Albee has produced three books and over forty papers on bone transplantation (for bibliography see "Bone Graft Surgery", New York, 1941), and has had a profound influence on surgical thought in this matter. Since his first paper was published in 1911 he has always maintained with considerable emphasis that a bone transplant lives and grows as a transplanted twig grows in the tree into which it is put. He elaborates the simile in the first chapter of "Bone Graft Surgery" of which the opening sentence is, "The principles of grafting living tissue are exemplified in their simplest form in plant grafting." In plants the wind tends to pull the scion away from the host and the graft has to be protected against this; in bone this force is represented by "the pull of the muscles, both tonic and involuntary, and the exag-

generation of the former by the reflex from pain."

This explains the need for mechanical stability of the graft in its bed so that the Haversian canals of the graft may "rapidly become canalised and increase in size in precisely the same way as we get a collateral circulation established when important blood vessels have been cut or occluded." Power-driven tools are needed so that the graft may be fashioned to fit its bed "with 'glass-stopper' precision." He concludes, "The question of whether a bone-graft lives when properly placed has been answered positively in the affirmative during the past thirty years of the author's personal experience, both in the animal research laboratory and in the clinic at the operating table and the follow-up of over 6000 cases." It is not surprising to find a repetition of this positive assertion in his last paper published in 1944 (4).

On the other hand Leriche and Policard stated with equal emphasis that transplanted bone behaves in an exactly opposite manner (56). "In man a fragment of bone transplanted into another bone always dies." In developing the argument they say, "Bone tissue, having a low vitality, does not survive complete interruption of its circulation." This, of course, is not sound reasoning. Only tissues of "low vitality" can be transplanted and live. No one has ever transplanted brain tissue, liver or kidney, but bone, fascia, cornea and epithelium can be moved as free transplants and live because their rate of

metabolism is low and they can survive till they obtain fresh nourishment from their new bed. Leriche and Policard, however, say, "The question of the death of the transplant should be considered solved. It is 32 years since Barth conclusively showed it. It is truly a waste of time still to seek to verify facts so well demonstrated." And they conclude, "The transplant has served only as a guide and as a furnisher of calcium. It is only the case of a new ossification by the tissues from the host on soil furnished by the graft."

Greig (34) and others (76) followed them in their view that the main function of a bone transplant is to furnish a local supply of calcium. "It is to the need for local excess of calcium that the surgeon panders when he employs a transplantation of bone.....transplanted bone never grows." (Greig).

These opinions are clearly wholly incompatible with those of Albee; where, then, does the truth lie? The literature of the last thirty years contains enough solid experimental evidence to show that it lies midway between these two conflicting views. The work of D.B. Phemister (69) published in 1914, of Hey Groves (35) published in an essay which won him the Jacksonian Prize of the Royal College of Surgeons in 1917, of W.C. Campbell (16) in 1919, of W.G. Stuck and R.K. Ghormley (71) published in 1934 and of R.K. Ghormley (31) shows beyond reasonable doubt what happens when the whole thickness of cortical bone is transplanted into another bone.

Some of the cells of the transplant, those which are near the periosteal or the endosteal surface or in the more accessible Haversian systems, live and grow and form new bone. The bone cells deep in the dense cortical bone die, and this bone is replaced by new bone which grows either from the surviving cells of the transplant or from the cells of the recipient area. Imbert (48) wrote in 1930, "This process is carried on in all parts but not simultaneously, and hence a transplant examined at any moment shows dead bone with empty lacunae and areas of living bone where the lacunae contain nucleated cells". This is also described by Watson-Jones (75) and is now generally or at least widely acknowledged as correct.

Thus a cortical bone graft, though Albee's views about its complete survival have to be modified, has two definite functions in bone repair:

- 1) because of its stability it acts as an internal splint; and
- 2) by the provision of fresh live bone cells it promotes osteogenesis.

It has long been recognised that while the graft is being revascularised the transplanted bone is more fragile. Gallie (29) refers to this phenomenon; Platt (70) writes of "this critical period.....between the eighth and twelfth week following the insertion of the graft." A case treated by Mr. B.H. Burns of London, and to which he has kindly allowed me

to refer, demonstrates clearly how this increased fragility is associated with revascularisation of the graft and how growth in the graft is dependent on the blood supply to the graft.

In September 1938 a young lady with a haemangioma of the tibia came under the care of Mr. Burns (Fig. 1a). He



Fig. 1a.

excised the affected bone and bridged the resultant gap with a segment of the shaft of the fibula which he excised subperiosteally from the other leg. Eight months after the operation the graft was firmly incorporated in the tibial fragments, but the only new bone formation to be seen in or around the graft was at the extreme upper end at its junction with the tibia

(Fig. 1b). Then the graft fractured just at the edge of the area of new bone, i.e., where the graft was weakened by hyperaemic decalcification (Fig. 1c). In four months the fracture had healed with a considerable mass of ensheathing callus (Fig. 1d). Six months later this ensheathing callus had the



Fig. 1b.

Fig. 1c.

Fig. 1d.

appearance of a hypertrophy of the transplanted fibula; the graft then broke again just at the lower limit of the thickened area (Fig. 1e). This fracture healed with a surrounding mass of new bone (Fig. 1f) and two months later the fibular transplant broke (Fig. 1g) and healed again in two months exactly as before (Fig. 1h). Burns then reinforced the remaining lower part of



Fig. 1e.

Fig. 1f.

Fig. 1g.

Fig. 1h.

the fibular transplant with a cortical onlay graft from the other tibia and the limb is now sound.

That this fibular transplant lived during the three and a half years covered by the series of x-ray photographs is shown by the fact that it maintains throughout, the same radiological density as the fibula of the limb into which it was put. But fibular cortex is hard and compact, and there is a large amount of cortical bone in the shaft of a fibula in proportion to the cancellous bone of its medullary cavity. Thus the main length of the transplant could obtain only enough blood to keep it alive; it could not grow. It is possible that the

transplant would have grown better had it been split lengthwise and implanted in two pieces.

New bone was formed where the fibula was embedded into the tibia, for the transplant fused with its bony bed, and a small cuff of new bone formed around its upper end (Fig. 1b), though this last may have been produced by the host. On each occasion the transplant broke just at the edge of the area of new bone formation, i.e. where it was weakened by hyperaemic decalcification. This fracture allowed an increased blood supply to reach the bone cells in that area of the transplant, which had so far only just remained alive, and they were able to grow and produce a local hypertrophy. The sequence of events was repeated twice in an exactly similar manner. The lady not only provided a critical experiment in bone repair, but she repeated it often enough to show that the succession of changes was not accidental.

VITALLIUM.

Before the main thread of the argument about bone transplantation and its use in bone repair is followed further a digression is needed to examine a technical advance which has widened the scope of the method and simplified the technique. It has been seen how one of the factors which defeated Lane's advance was the intolerance of the body to the metals used for internal fixation. Many means were tried to overcome that

difficulty. Campbell (17) used pegs fashioned of autogenous bone at the time of the operation or of homogenous bone obtained from fresh autopsy material. Orell (66), (67) described the preparation of pegs from "os purum" which was either human or beef bone with all its organic matter removed. The fat was extracted by warm potassium hydroxide and the protein by salt solution. Cowhorn was used in a similar manner (20). Clearly, however, all of these materials have disadvantages which a suitable metal would not have, and the search for this metal continued.

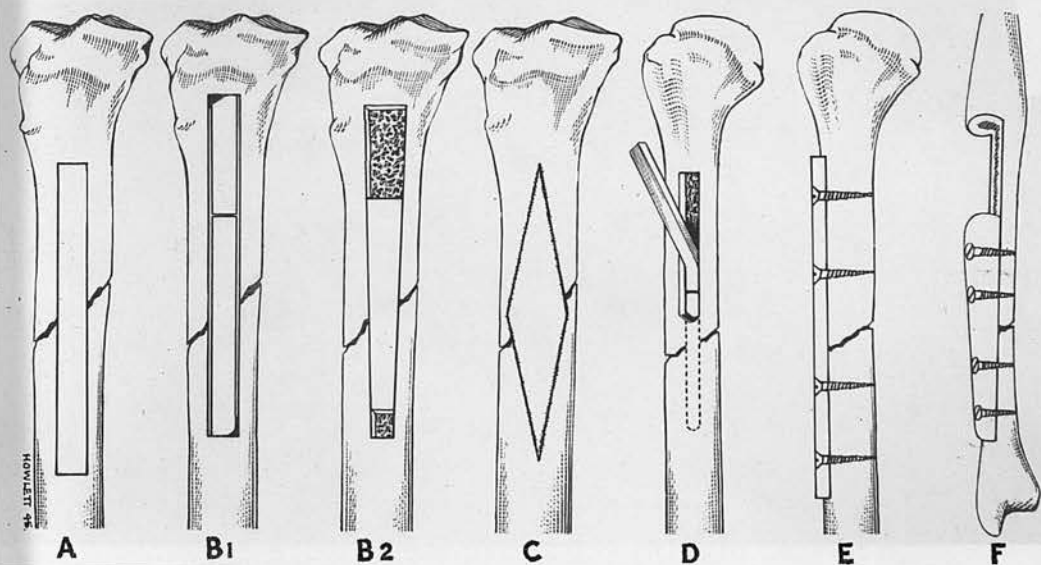
Orsos (68) first noted in 1925 that action currents were induced by metals fixed in bone, and then in 1938 C.S. Venable, W.G. Stuck and A. Beach (74) solved the problem. They described the electrolytic action of metals on bone and other tissues, and they showed that it was possible to make an alloy which did not have this electrolytic action. It must not contain iron, for iron is very subject to the effect of "physiologic body salts". Most of the screws and plates used in the past had contained a large amount of iron. They showed that "the alloy of least reaction is one called vitallium which contains no iron and consists of cobalt, chromium and tungsten." They found no tissue reaction or bone change at the site of any vitallium screw in the course of a large series of experiments, a finding which has since had ample clinical confirmation. This discovery profoundly influenced the operative treatment

of fractures and joint injuries in general and the methods of using cortical bone transplants in particular.

CHAPTER III

THE TRANSPLANTATION OF CORTICAL BONE

Eight methods of cortical bone transplantation have been commonly employed in the treatment of delayed union or non-union of fractures. In six of these an attempt is made to use the transplant as an internal splint (Fig. 2):



- 1) inlay graft (Albee);
- 2) sliding inlay graft (Albee and Kelly);
- 3) diamond inlay graft (Gallie);
- 4) intramedullary peg graft (Hoglund);
- 5) massive onlay graft (Henderson and Campbell);
- 6) massive sliding onlay graft (Gill).

Fig. 2.

In two methods the cortical bone is not intended to act as a splint but is solely a means to promote osteogenesis (Figs. 3 and 4):

- 7) osteoperiosteal graft (Delangiere);
- 8) multiple chip grafts (Henry).

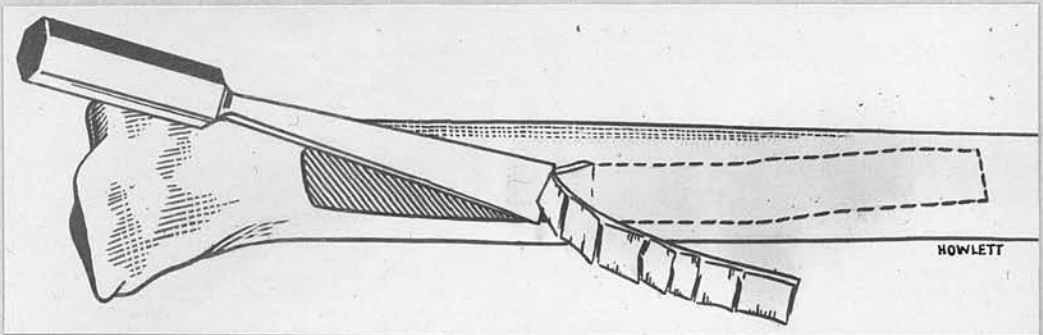


Fig. 3. Osteoperiosteal graft. A strip of periosteum with slivers of the superficial cortex still attached is cut with an osteotome.

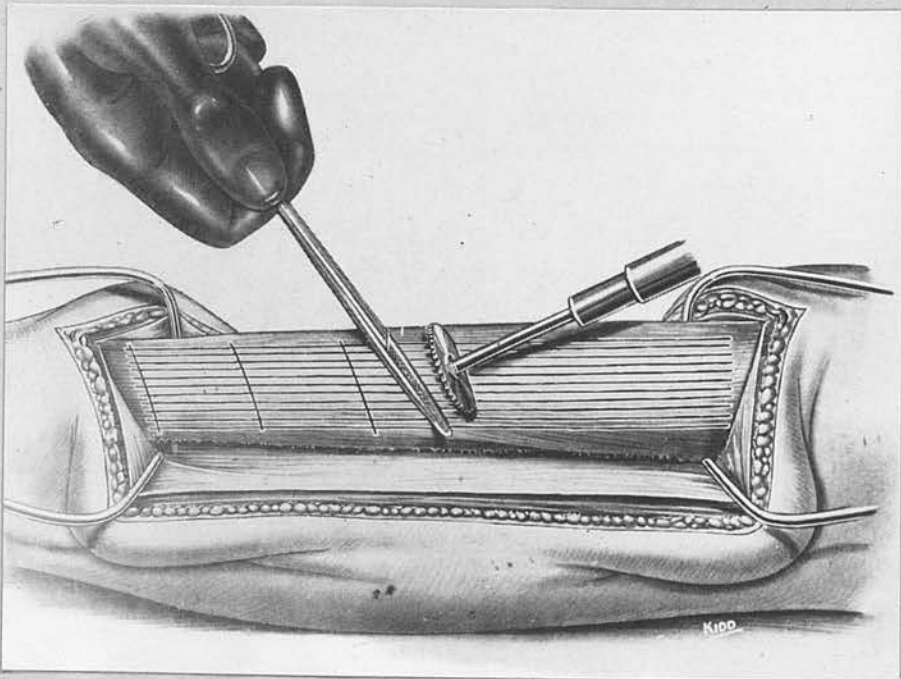
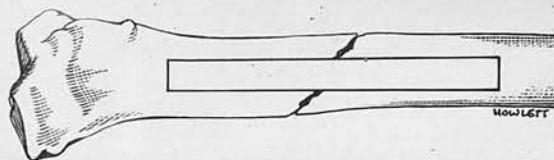


Fig. 4. Method of cutting multiple chip grafts from tibia. (From Architectural Principles in Arthrodesis by H. A. Brittain.)

1. Inlay graft. (Fig. 2, A). Albee introduced

this method of the treatment of fractures in which union was delayed and all his life

A



he was its chief exponent (3). A bed is cut across the fracture site with a power driven twin saw. The interval between the saw blades is then enlarged by the width of two saw cuts and a graft is cut from the intact tibia. This graft is sprung into the previously prepared bed which it should fit so exactly as to be firm without additional fixation by screws, sutures or other means. The method is best suited to the treatment of delayed union of the tibia, though it can also be used in other long bones. It has two main disadvantages:

- 1) if mal-alignment of the fracture has to be corrected the method is not easy;
- 2) the intact tibia is cut (see p.58).

The introduction of internal fixation by vitallium screws has made much of this meticulous carpentry unnecessary. It has also facilitated other methods of cortical grafting which are easier and more effective than inlay grafting. Albee's work on cortical inlay grafting was pioneer work. In its time the method was widely used not only in America but throughout the world, but it is now not so popular and may eventually be almost entirely abandoned.

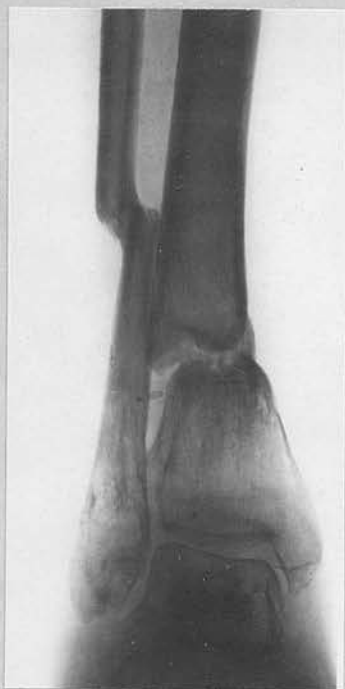


Fig 5a.

Fig. 5a shows a very indolent fracture of the tibia after eleven months immobilisation in plaster. A cortical graft was placed across the fracture as an inlay (Fig. 5b) and

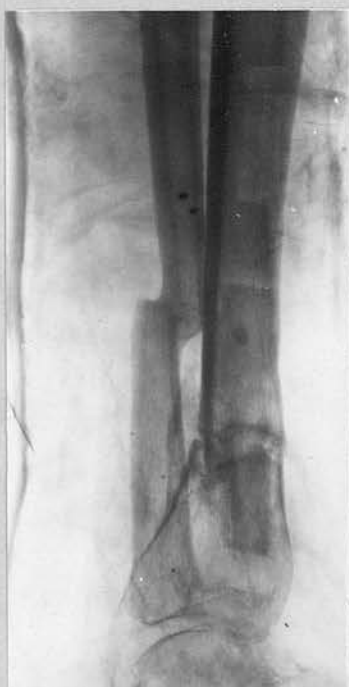
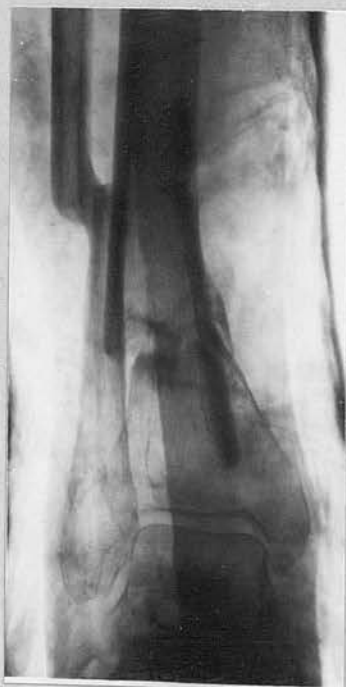


Fig.5b.

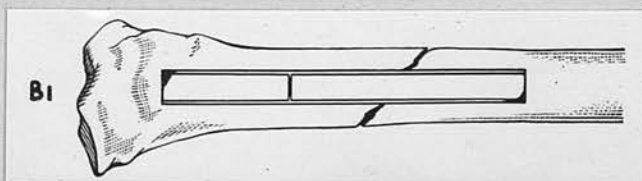


Fig 5c.

satisfactory union resulted in eighteen weeks (Fig. 5c). In this case the inlay graft was cut from the same tibia and the disadvantage of cutting the intact tibia was avoided.

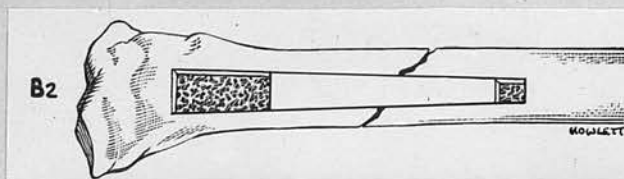
2. Sliding inlay graft. Fig. 2, B1). A bed is

cut across the fracture site so that one third of its length is on one side



of the fracture and two thirds on the other. The larger portion of detached bone is laid across the fracture and the smaller one is used to fill the defect. It is clear that the fit of a sliding graft in its bed can not be tight and accurate as the graft must be less wide than the bed by the width of two saw cuts. Albee (3) recommends that this difficulty be overcome by cutting a "sliver graft" with which to wedge the sliding graft into its

bed. R.E. Kelly (53), Fig. 2, B2), suggests that the bed and the graft be fashioned in the shape of a wedge by making two cuts with a



single saw. The base of the wedge is on the fragment of bone which provides the wedge and its apex is on the other fragment so that when the graft is slid across the fracture its shape makes it impact. Neither of the methods provides the same degree of mechanical stability as the inlay graft, and both are technically more difficult.

One great advantage of the sliding inlay graft over its parent the inlay graft is that the operation is confined to the fractured bone and the intact tibia is not cut. Further, now that vitallium screws are available mechanical stability can be secured without using either of the methods described above. Thus there is still a place for the sliding inlay graft in the treatment of delayed union.



Fig 6a.

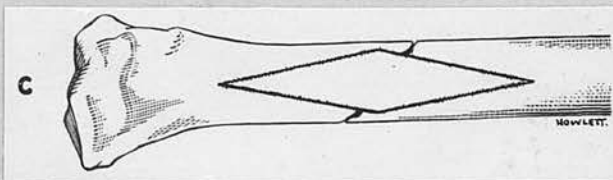
Fig. 6a shows an indolent fracture of the shaft of the tibia at one year. A sliding inlay graft was fixed across the fracture line with vitallium screws and sound union was secured in five months (Fig. 6b overleaf). (Note that the central screw is placed nearer to the fracture line than is desirable).



Fig. 6b.

3. Diamond inlay graft. (Fig. 2, C). Gallie (29)

described this method in 1931. A large diamond-shaped piece of bone, 4" to



5" in length, is cut from the fractured bone so that the wide piece of the diamond is opposite the fracture site. The maximum amount of sclerosed bone or fibrous non-union is thus removed.

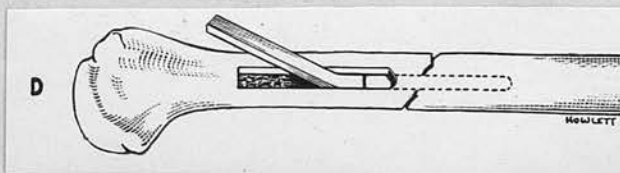
A diamond of cortical bone is cut to pattern from the intact tibia and slotted into the prepared bed. The method has the advantage of removing most bone from the fracture site - where there is most sclerosis. Its disadvantages appear to be:

- 1) the technical difficulties are considerable. It is not easy to cut a diamond graft to fit the bed exactly;
- 2) there is little or no mechanical stability;
- 3) the intact tibia is cut to provide the graft.

I have no personal experience of the method.

4. Intra-medullary peg graft. (Fig. 2, D). This

method was originally described by Hoglund (45) in 1917 and was advocated by



Hey Groves (36) in 1921. A peg is cut from the cortex of the bone adjacent to the fracture and threaded into the medullary canal across the fracture site. The method has several disadvantages. The mechanical stability of the internal fixation is inadequate, rotation strains, in particular, being quite uncontrolled; there is little opportunity to remove the sclerosed bone and open the healthy cortex, and the revascularisation of the fracture site is impaired by the plugging of the medullary cavity. If healthy tibia is used to fashion the peg, as is sometimes advocated, another disadvantage is added. Campbell (19) says, "The use of the intra-medullary peg graft is not only to be

deplored, but condemned." I have not used the method. It was used without success in a patient who subsequently came under my care (Fig. 7). At fourteen weeks from operation there was

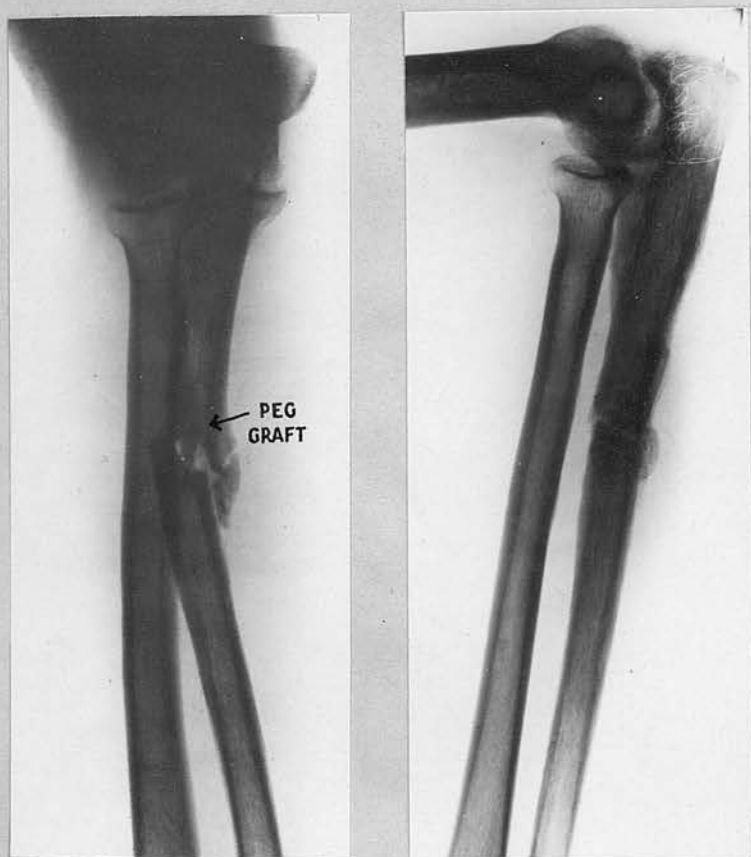
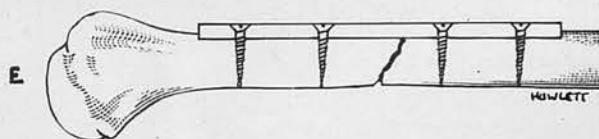


Fig.7.

angular deformity and the fracture was quite mobile. Fracture at this site is noted for its instability and this operation was quite valueless. Union was eventually secured after a massive onlay graft had been applied, but even then the fracture did not unite readily (See p. 64 and Fig. 23).

5. Massive onlay graft. (Fig. 2, E). Hey Groves

(35) originally described this method in 1918; it was later adopted and pop-



ularised by M.S. Henderson (40) and W.C. Campbell (17). The fractured ends of the bone are exposed and all the intervening scar tissue is excised, the displacement is reduced and the alignment is corrected if necessary. A bed is cut on one aspect of the fractured bone so that fresh healthy vascular bone is widely opened and a flat surface is formed to which the tibial graft can be applied. The graft is firmly fixed to that surface with its endosteal side next the host.

When the method was first described fixation was secured by bone pegs, either autogenous or homogenous, a part of the technique that was time-consuming and difficult. Alternatively the graft could be fixed with ligatures of cat-gut or wire, but this was much less secure. In spite of these drawbacks Platt (70) reported favourably on the method in 1938, and emphasised its value in gap fractures. He pointed out that it was easier to perform in these injuries than Albee's inlay method. He speaks of the inlay graft and the onlay graft as "the two standard methods of insertion of a bone graft that are of proved value", and prophesies that, "the onlay technique seems likely to be adopted more frequently in the future." His fore-cast has proved to be accurate. Further evidence of the value of the on-

lay graft was given by Harkins and Phemister (38) who reported on a series of 39 massive onlay grafts with bony union in 38, and W.C. Campbell (18) who secured bony union in 46 out of 50 cases of non-union of the humerus treated by this method.

Now that vitallium screws are available fixation is easily secured, the technical problems are minimal, and the method is one of the easiest and best ways of using a cortical bone transplant. Its chief disadvantage is that the intact tibia is cut; though rare instances occur in which the graft unites with both host fragments but the fracture does not heal.

Its advantages are:

- 1) a large graft gives a very firm and powerful fixation;
- 2) there is contact between the graft and the host bone over a wide area;
- 3) the most osteogenetic part of the graft is fixed to the bed;
- 4) healthy bone in the host is widely opened offering an early and free blood supply to the transplant.

Success with this method is very sure. In my series of 48 cases a further grafting operation was needed in only one, and in this instance failure of the original operation was due, at least in part, to technical imperfections in its performance (see p.60 and Figs. 21a & 21b). Union of the fracture was eventually secured by another method (See p.86 and Figs. 38a & 38b).

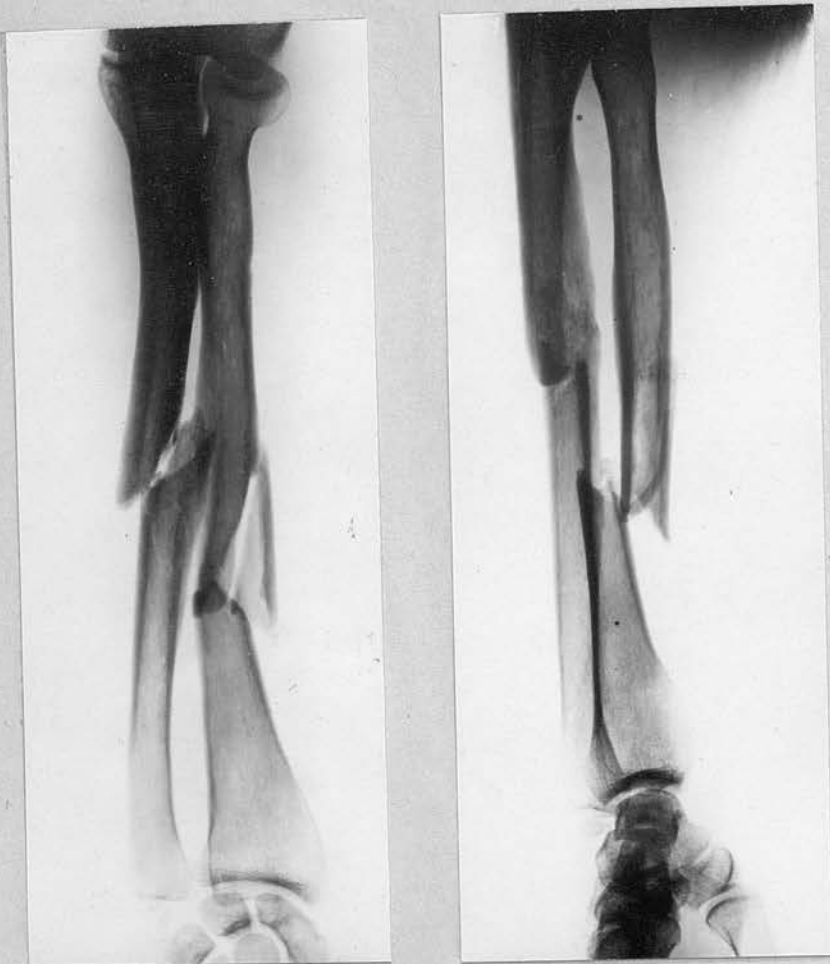


Fig. 8a.

Fig. 8a shows a severe comminuted fracture of both bones of the fore-arm. Union of the radius was secured by a massive onlay graft and, as not infrequently happens, the ulna united without operation after the radius had been fixed (Fig. 8b overleaf).

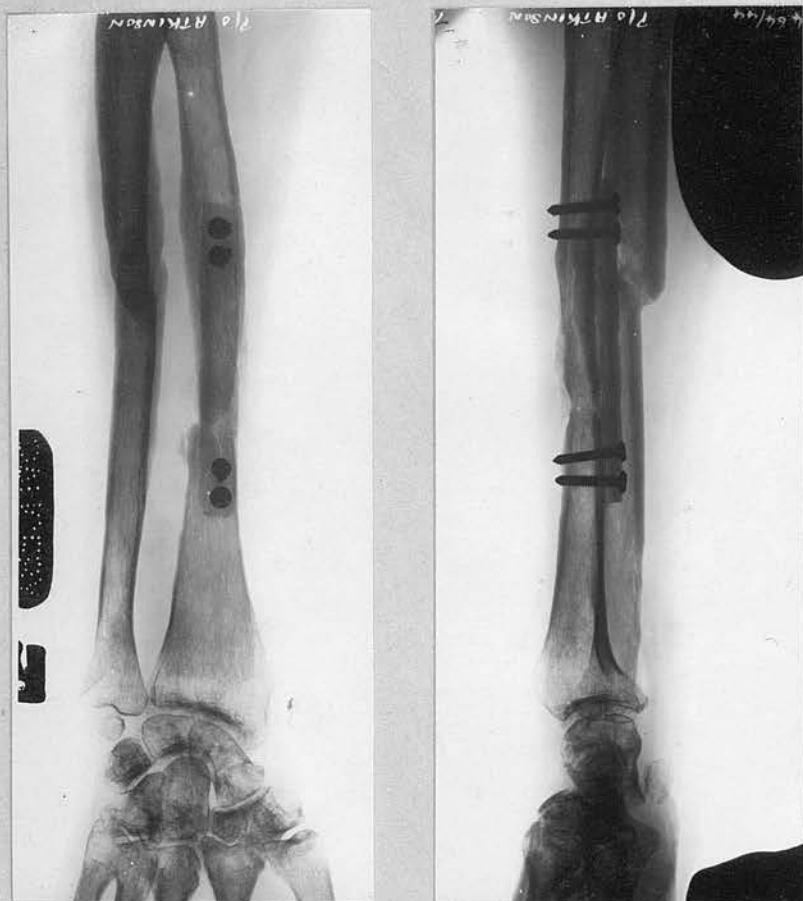


Fig. 8b.

Figs. 9a to 9d show fractures of both bones of the fore-arm repaired in two stages. There was a gap in the ulna. A strip of cancellous bone, taken from the upper end of the tibia when the cortical graft was cut, was used to promote osteogenesis in the ulnar defect. In the antero-posterior views in Figs. 9c and 9d it can be seen fixed to the ulna with two screws at right angles to the stabilising cortical graft. (See pages 39 to 42).

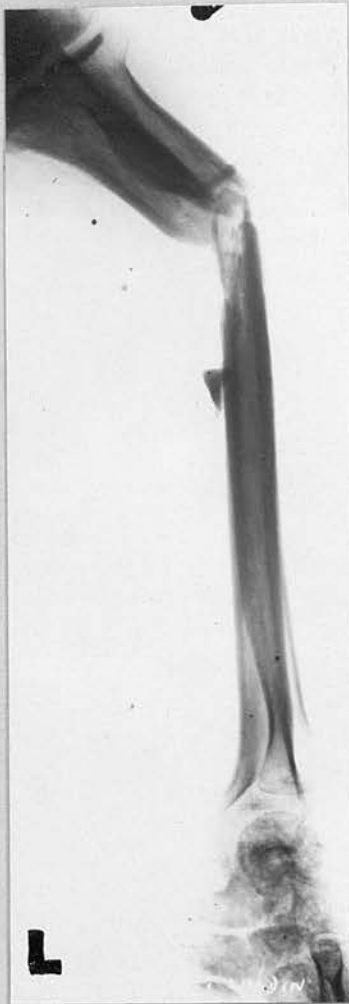
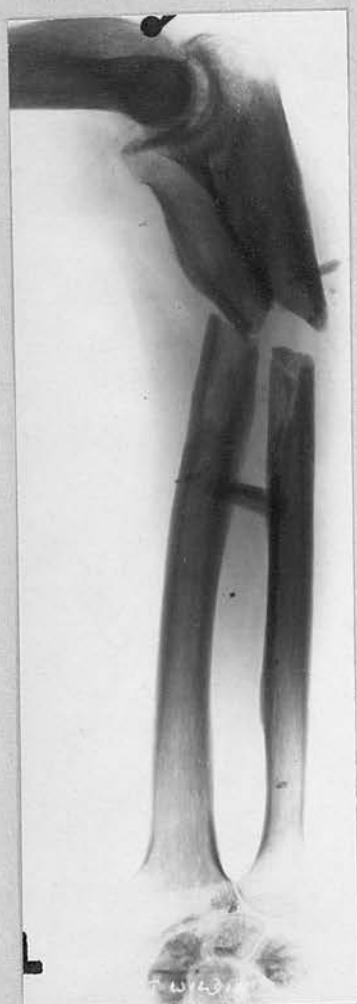


Fig. 9a. Gap fracture of bone bones of fore-arm,
the result of a propellor accident.



Fig. 9b. Radius stabilised with massive onlay graft.

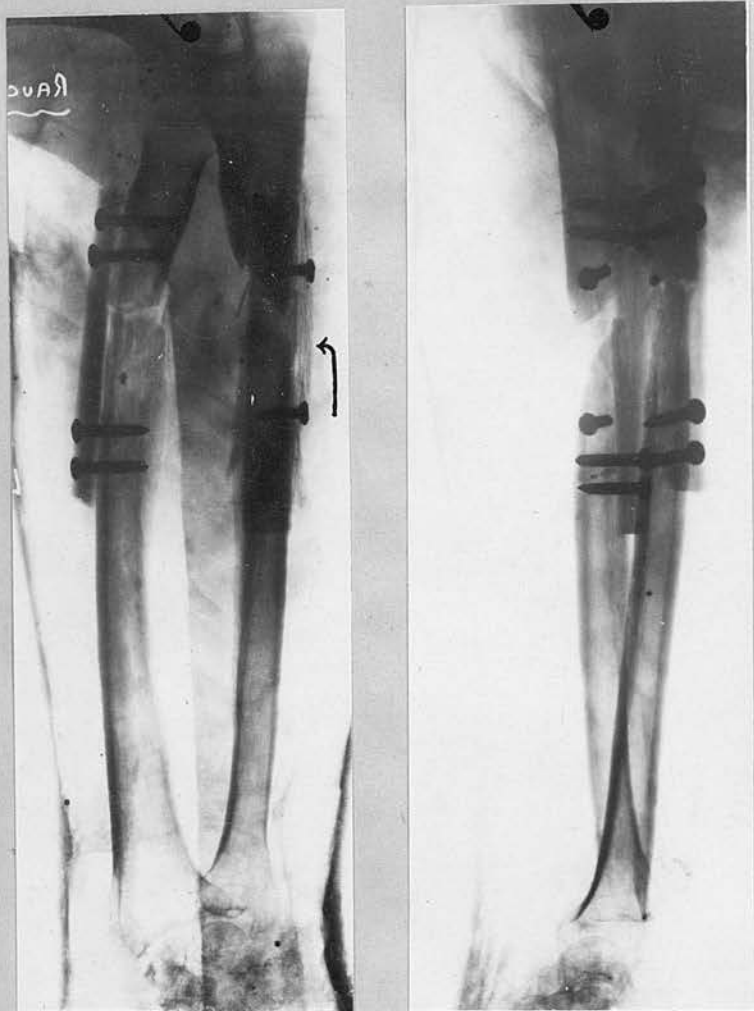


Fig. 9c. Defect in ulna bridged with massive onlay graft and strip of cancellous bone from tibia (seen well in antero-posterior view).



Fig. 9d. Appearance at five months from last operation.

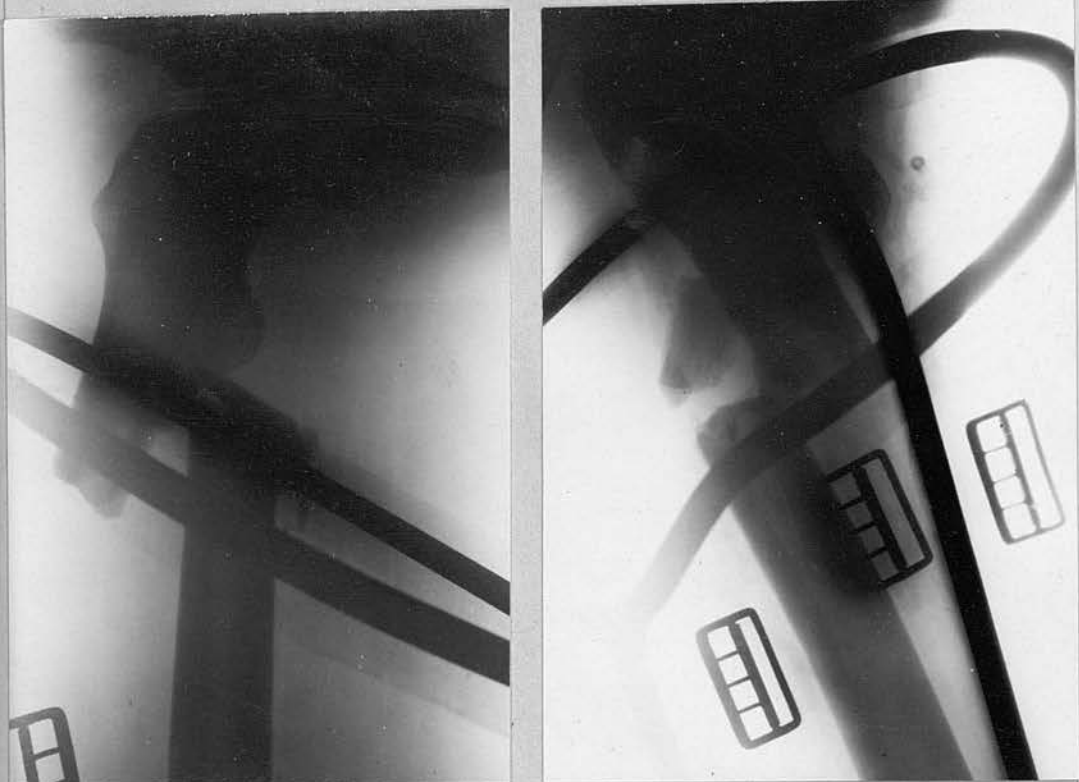


Fig.10a.

It is very difficult to secure and to maintain adequate reduction of a fracture of the upper third of the femur because the proximal fragment is not easily controlled. Had it been possible I should have treated the fracture seen in Fig. 10a by primary open reduction and internal fixation with a vitallium plate. Operation could not be undertaken for three months because of a wound of the thigh. Then fracture, which was mobile and not in apposition (Fig.10a) was reduced and fixed with a massive onlay graft. There was satisfactory union in six months (Fig. 10b overleaf).

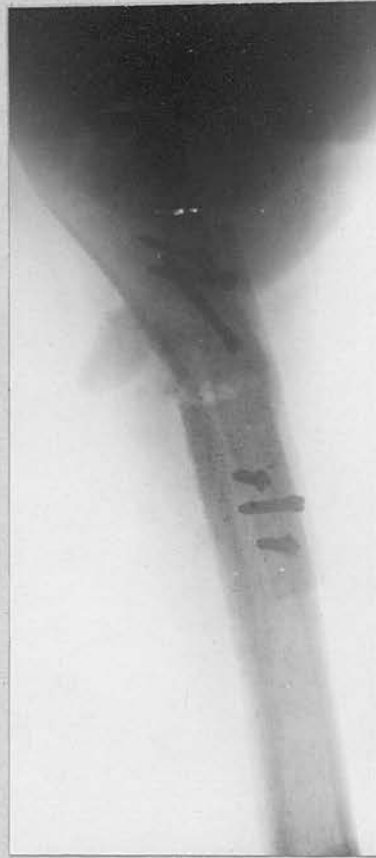
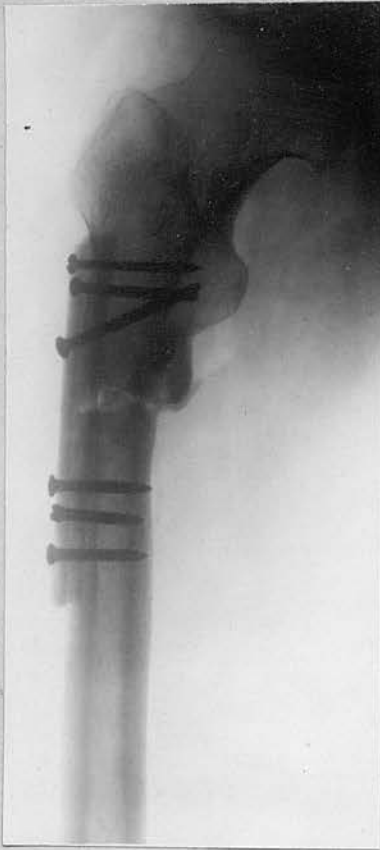


Fig. 10b. Six months after massive onlay graft of femur.



Fig.11a.

Another fracture of the shaft of the femur (Fig. 11a) remained indolent and was quite mobile at one year. It was fixed with a massive cortical onlay graft. At seven months he was walking with a caliper though consolidation of the fracture was even then not complete (Fig. 11b overleaf).

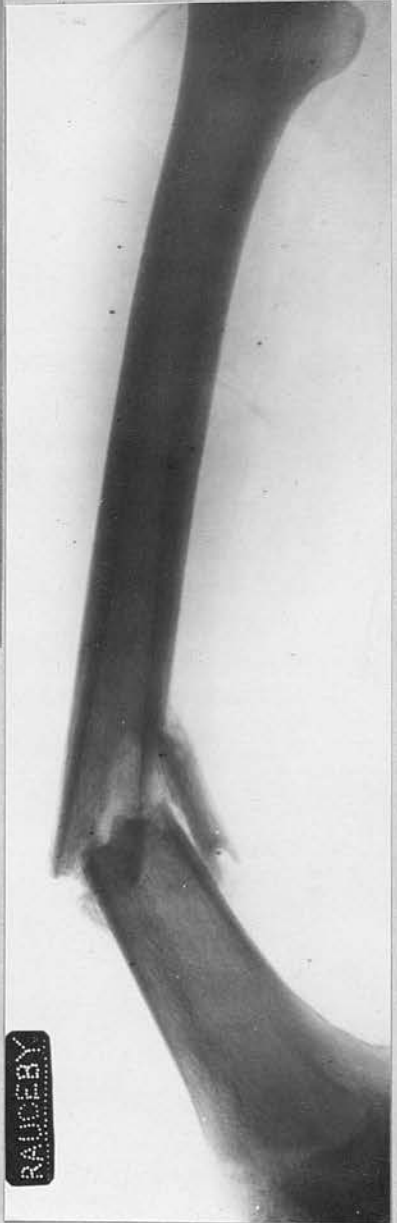


Fig. 11b. Appearance at seven months.



Fig. 12a.

This airman had a fracture of the shaft of the femur which had been allowed to unite with gross displacement (Fig. 12a).



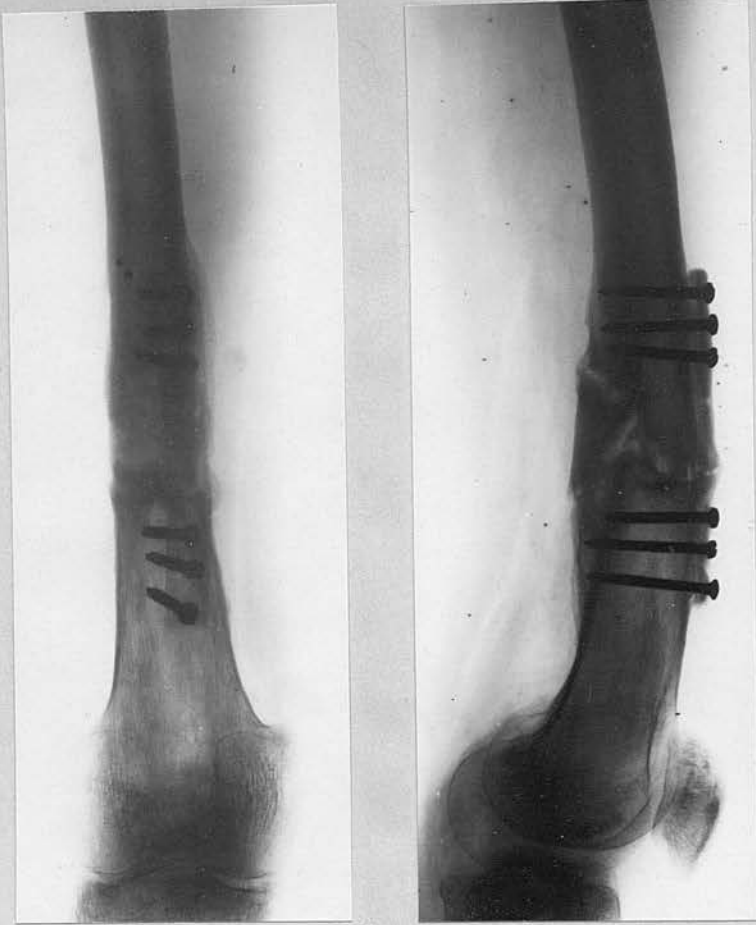


Fig.12b.

The bone was divided at the fracture site, the alignment was corrected, and reduction was maintained by a massive cortical onlay graft. Fig. 12b shows the appearance at six months. The graft had fractured opposite the fracture site, but it had been revascularised and it was throwing out callus of its own (this can be seen in the lateral view). He walked in a caliper for another two months, and the fracture consolidated completely during that period.



Fig.13a.

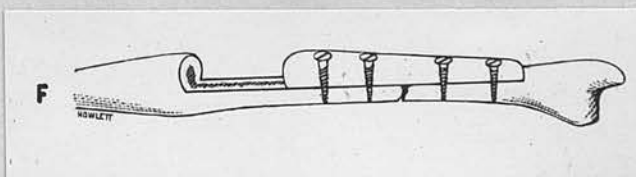
A pilot had a fracture of the shaft of the tibia which did not unite and which ultimately reached the stage of established non-union with gross sclerosis of the bone ends (Fig. 13a). The fracture area was cleared of fibrous tissue and the sclerotic bone was thoroughly opened with drill holes, and a massive onlay graft was applied to the lateral aspect of the tibia (see p.66). The drill holes are well seen in the lateral view (Fig. 13b overleaf).



Fig. 13c. Sound consolidation two years later.

6. Massive sliding onlay graft. (Fig. 2, F).

.This method is comparable with the sliding inlay graft. Though it was



originally described by Gill (32) in 1932 it was little used till after vitallium screws became available. With these for internal fixation, however, it is a very useful method. It has most



Fig. 13c. Sound consolidation two years later.

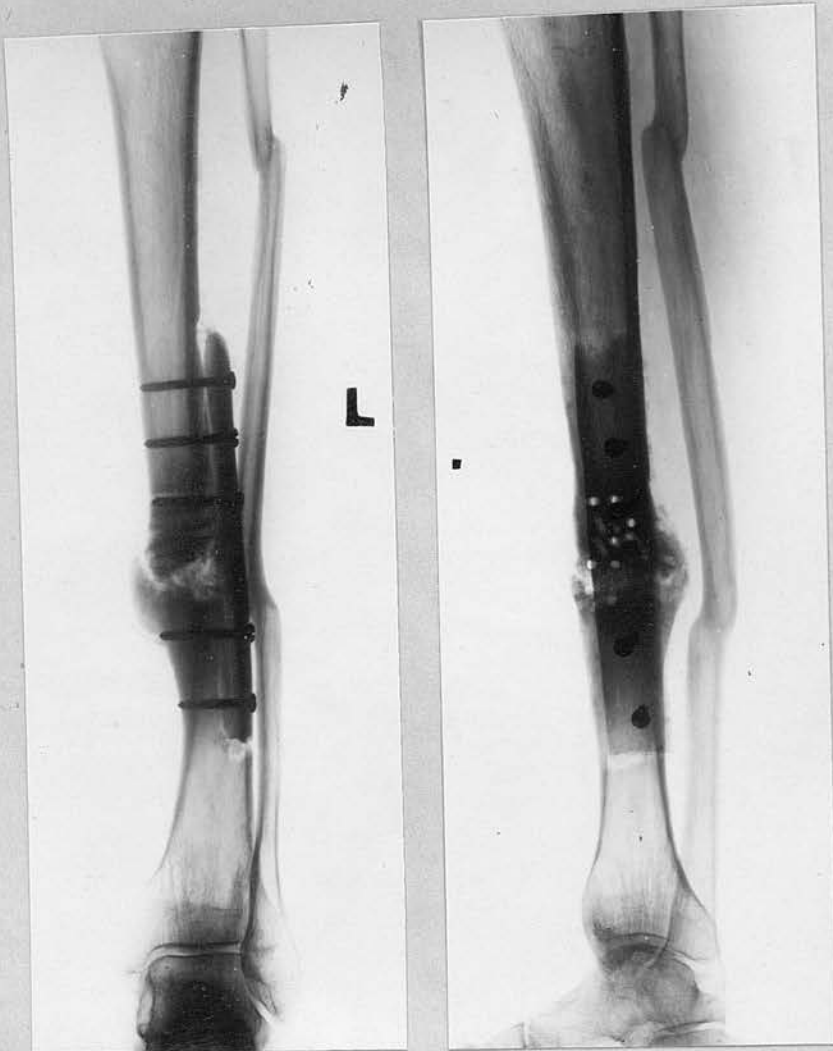
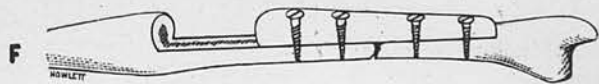


Fig.13b.

6. Massive sliding onlay graft. (Fig. 2, F).

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originally described by Gill (32) in 1932 it was little used till after vitallium screws became available. With these for internal fixation, however, it is a very useful method. It has most

of the advantages of the massive onlay graft and it does not entail cutting an intact tibia. It is particularly suited to the fore-arm bones. It can not be easily used in the femur or the humerus because of the cylindrical shape of these bones, but it can be used in the tibia.



Fig.14a.

Fig. 14a shows a fracture of the shaft of the ulna in which, as is not uncommon at this site, union was delayed. It was treated by a massive sliding onlay graft. The bone consolidated completely (Fig. 14b overleaf).





Fig. 14b. Six months after massive sliding onlay graft of ulna.

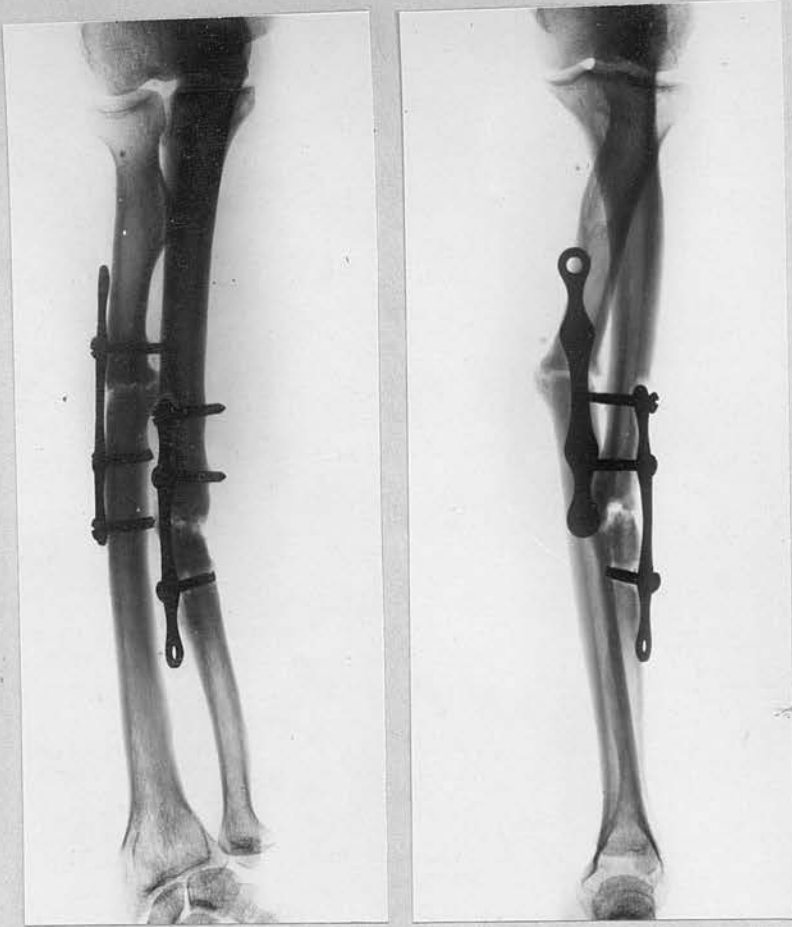


Fig. 15a.

Fig. 15a shows an example of a breach of a fundamental rule of the internal fixation of fractures - inadequate control of one fragment. In both bones only one screw holds the plate on to the proximal fragment, and the fractures have not united. The plates were removed and the radius was fixed by a massive sliding onlay graft correcting the forward bowing (Fig. 15b overleaf).



Fig. 15b. Plates removed and radius re-aligned and held by massive sliding onlay graft.

My experience up to date makes me believe that it is best to use one or other of the two last methods in grafting with cortical bone for non-union or delayed union of fractures. Some points in the operative technique are worth emphasis.

OPERATIVE TECHNIQUE.

A strict no-touch technique, originally advocated by Lane (55) and described by Fairbank (27), is essential in all bone operations and is adhered to throughout.

A tourniquet is used when possible. In the upper limb only a pneumatic tourniquet should be used because of the danger of damage to the nerve trunks in the arm, particularly the radial nerve.

The tourniquet should be removed as soon as the work on the bone is finished and before the wound is closed because the length of time that the limb is kept bloodless is thus reduced to the minimum and the limb has an opportunity to swell before the plaster is applied.

The post-operative plaster must be generously padded and split in its whole length lest post-operative swelling impair the circulation.

DONOR SITE.

The tibia is almost always used to provide the massive onlay graft because it is readily accessible and its cortex is strong. When a small graft is wanted, say 4" x $\frac{1}{2}$ " for grafting the fore-arm bones, it can easily be taken from the middle of the subcutaneous surface of the tibia.

When an exceptionally powerful graft is wanted the whole of the subcutaneous cortex of the tibia may be removed as recommended by Brittain (15) (Fig. 16). This graft consists of the whole of one cortex of the tibia including the crest and is very strong, but I do not consider the method justifiable because it materially

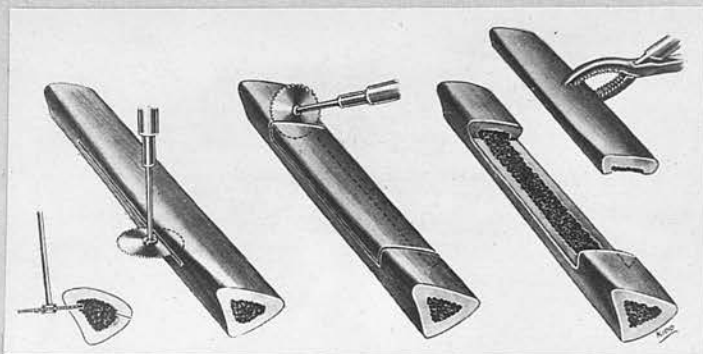


Fig. 16. (From Architectural Principles in Arthrodesis by H. A. Brittain)

weakens the tibia. An Airman had such a graft removed from the tibia shown in Fig. 17a. Three months later he turned sharply on that leg and the tibia fractured (Fig. 17b). In another three months when the fracture had united the tibia was still demonstrably weak (Fig. 17c), i.e. six months after the removal of the graft the tibia was far from complete recovery.



Fig.17a.

Fig.17b.

Fig.17c.

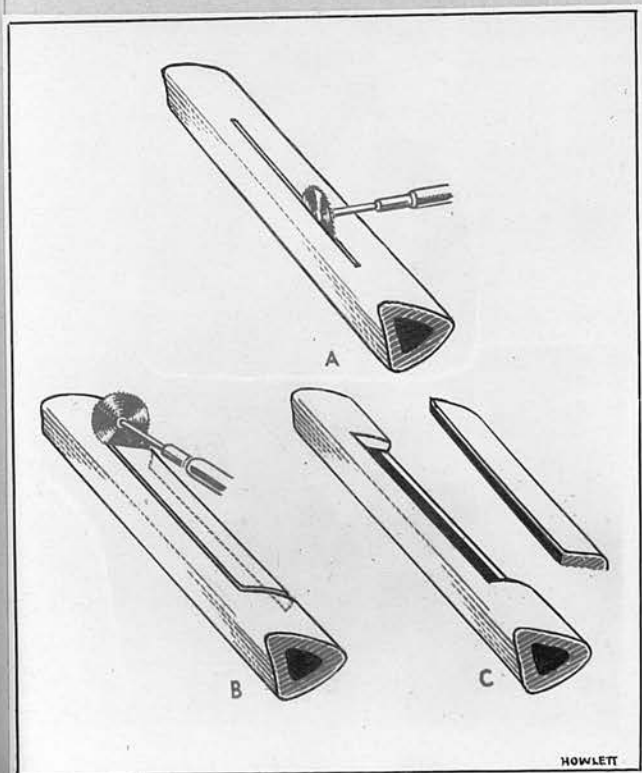


Fig. 18.



Fig. 19.

When a powerful graft from the tibia is needed it is best cut in the manner shown in Fig. 18. This provides ample strength for all purposes, and the crest is left to support the reduced tibial shaft (Fig. 19).

Complications at the Donor Site.

1. Stress fracture. This may follow the removal of any tibial graft. In this patient (Fig. 20a) it developed at



Fig.20a

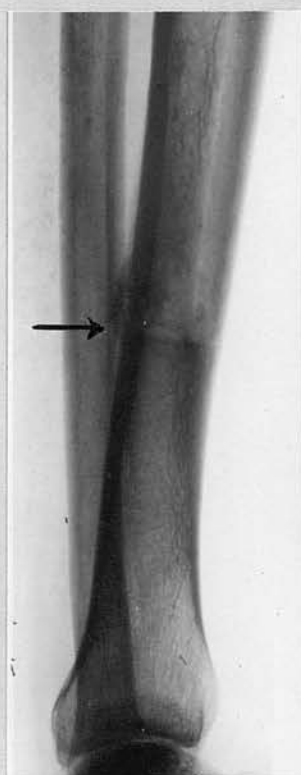


Fig.20b.

eight weeks after the removal of a graft by the method shown in Fig. 18. In Fig. 20a the crack can hardly be seen (it is difficult to see it even in the original x-ray films), but the history was characteristic. He developed a sudden acute pain in the leg while walking; on enquiry he admitted to having had slight pain at that site for twenty-four hours previously. The formation of callus at the site of the pain clinched the diagnosis (Fig. 20b). This is the tibia of the patient whose treatment is described later (Figs. 39a to 39f), and in the end the reconstructed tibia

was taking the body weight four weeks before the donor leg.

As has been stated this complication may follow the removal of any graft from the tibia and the fact that only a small portion of bone is removed is no guarantee that the tibia will not give way. Armstrong (5) reports two instances of stress fracture after the removal of pegs for grafting the scaploid. Stress fracture of the tibia in these circumstances would appear to be due more to damage to the lamellar structure of the bone than to reduction of its absolute strength, and its occurrence indicates that it is never completely safe to cut an intact tibia.

2. Painful donor site. This complication is less often written about and is probably therefore less well known, but it is much more common than stress fracture. The pain may be very troublesome and persistent, and many patients complain of pain in the donor leg long after the grafted area is healed and symptomless.

Therefore although it may be necessary to use a cortical graft from an intact tibia, especially for the femur or the humerus, every consideration should be given to the possibility of other means of obtaining the result before the decision is taken. Osmond Clarke (22) during his R.A.F. experience has seen the end-results of over five hundred bone grafts for the repair of injury in the last four years and says, "The more I see of the results of bone-grafting, the more I become loath to mutilate an intact tibia."

Application of the Graft.

The graft should be well fixed to its bed so that it may soon obtain an adequate blood supply. It should also, for this reason, be in close contact with the bed. The graft should not be subjected to strain by having to maintain an unstable reduction, for it may fracture. Fig. 21a shows a graft

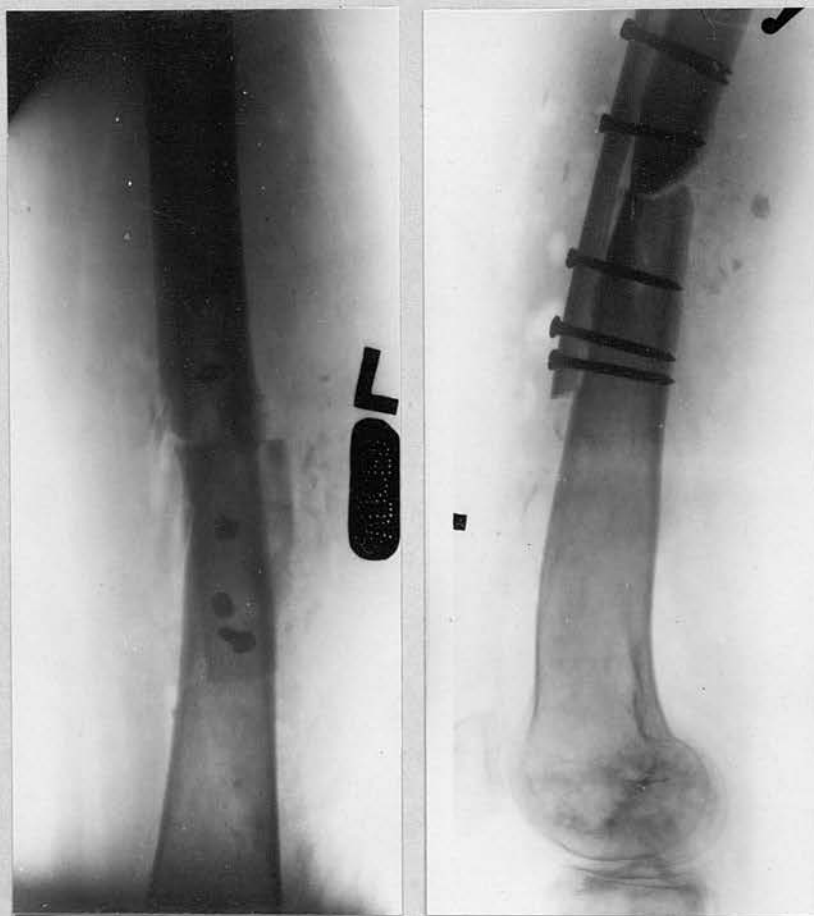


Fig. 21a.

in which the two last conditions were not fulfilled and which fractured in consequence (Fig. 21b overleaf).

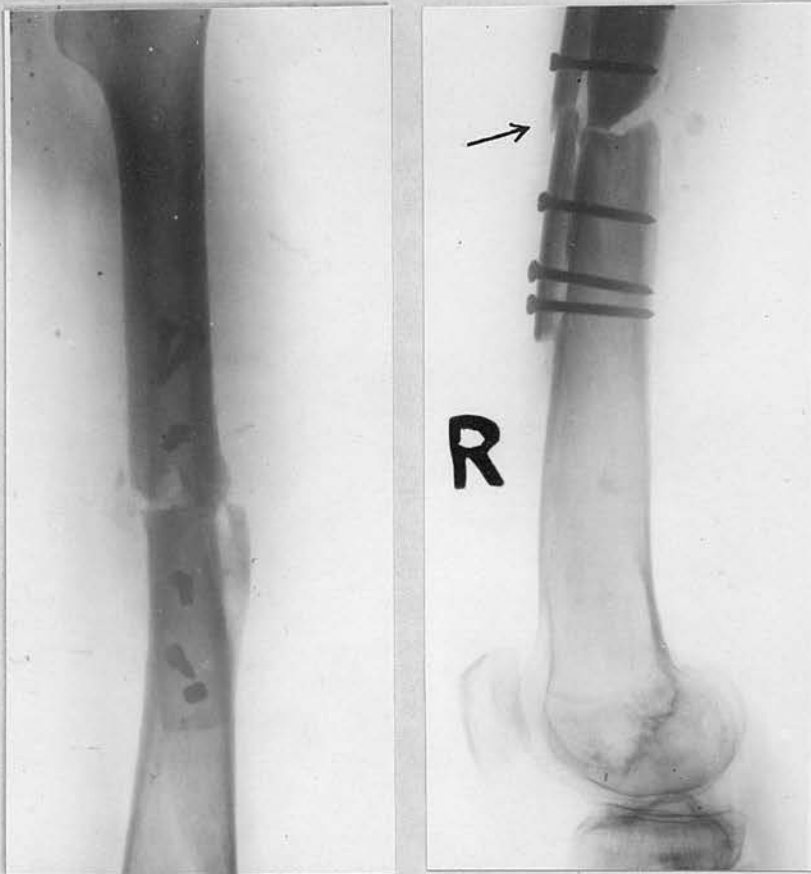


Fig. 21b. Onlay graft fractured in plaster at ten weeks.

If, for any reason, the graft must take strain it is wise to reinforce it with a plate. A prisoner of war returned from Germany with a fractured femur which had been allowed to unite in gross malalignment and with $2\frac{3}{4}$ " of shortening (Fig. 22a). He was unwilling to have the other femur shortened to equalise the limbs, and anyway it was necessary to improve the alignment in order to minimise the risk of osteoarthritis in the knee. The

Fig. 22a.





Fig. 22a.

femur was cut across at the fracture site, lengthened by continuous skeletal traction, and fixed, at a second operation, with a massive onlay graft. There was great difficulty in securing accurate end-to-end apposition and normal realignment without shortening the bone unduly (it will be seen that the alignment was not fully corrected). As the graft was under strain it was reinforced with a plate applied to its cortical surface. At twelve weeks the osteotomy is uniting satisfactorily (Fig. 22b overleaf).

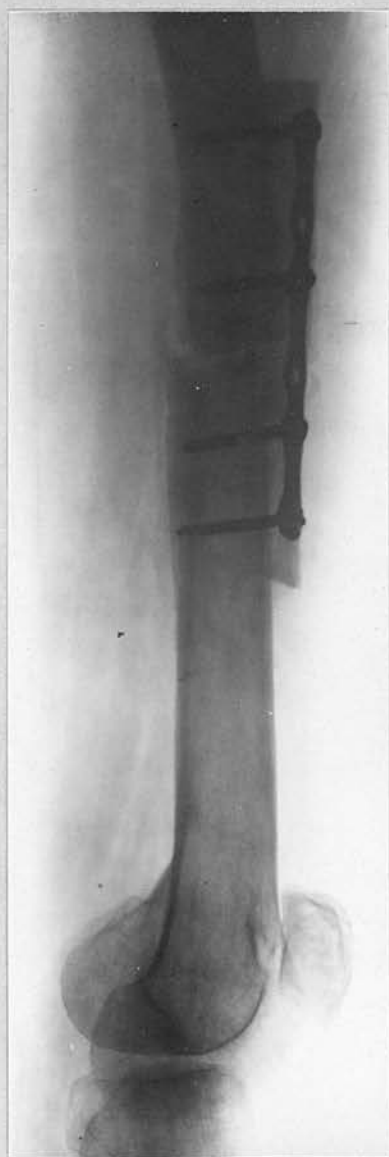
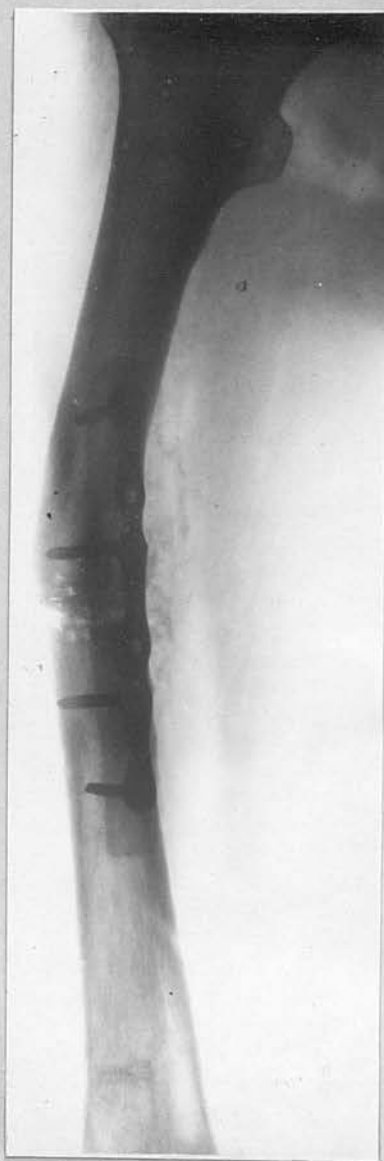


Fig. 22b. Massive onlay graft reinforced with plate holding femur after corrective osteotomy.

Fig 23 shows another massive onlay graft which fractured under stress. This is the same ulna as is shown in Fig. 7. The bone had been deformed for six months before the onlay graft was applied and the soft parts had contracted to the shape of the deformity so that after the bone was re-aligned it was under continuous stress.

This re-fracture united with prolonged immobilisation in plaster, but some deformity had to be accepted. Had this onlay graft been protected with a plate (see Fig. 22b) re-fracture would have been prevented. The line of the re-fracture should be noted. An onlay graft fractures either directly opposite the original fracture (see Fig. 21b), or

this Z-shaped defect develops. It passes through the fracture line, between the graft and its bed, and through the graft at an inner screw-hole. If this possibility is not recognised attention, in a suspicious case, may be concentrated on the graft opposite the original fracture line and an early re-fracture may be missed.

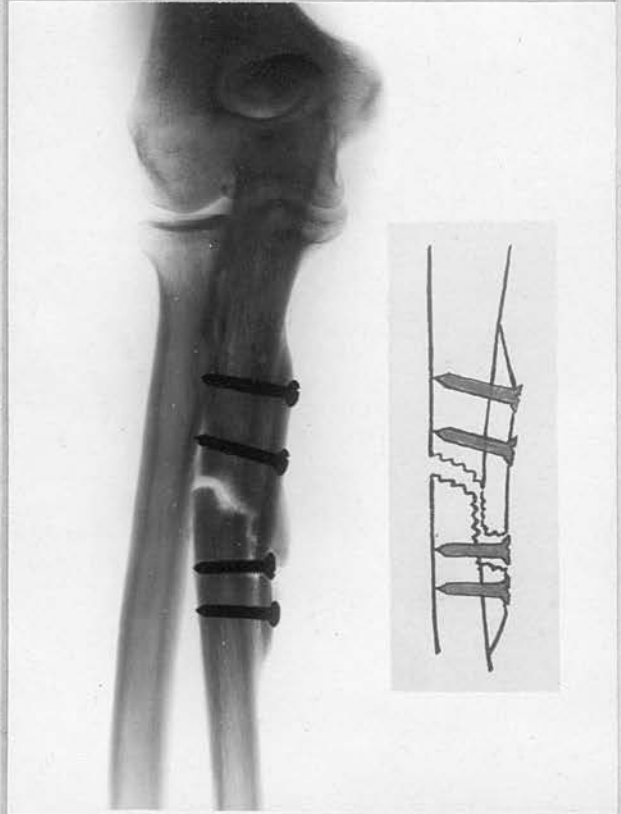


Fig. 23.

Fig. 24 shows another example of this type of re-fracture and illustrates another error in technique in onlay grafting. The screws are placed too near the ends of the graft and have therefore a less secure hold than screws spaced equally along the graft would have had (see Fig. 2, E). Again prolonged immobilisation in plaster was needed before the graft and the fracture consolidated.

The screws holding the graft should be long enough to grip the far cortex of the host bone but should not project beyond it, (see Fig. 15a). I have seen a patient with intractable sciatica due to screws in a fractured femur which projected far beyond the bone into the back of the thigh. He

recovered at once when the screws were removed. The length of the

screw needed is easily measured by an instrument such as that devised by Adams (1)(Fig. 25).

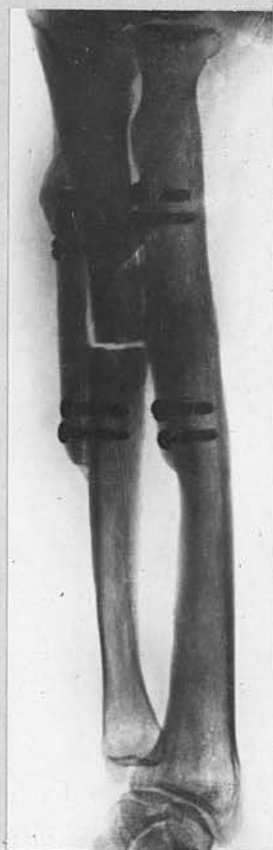


Fig.24.

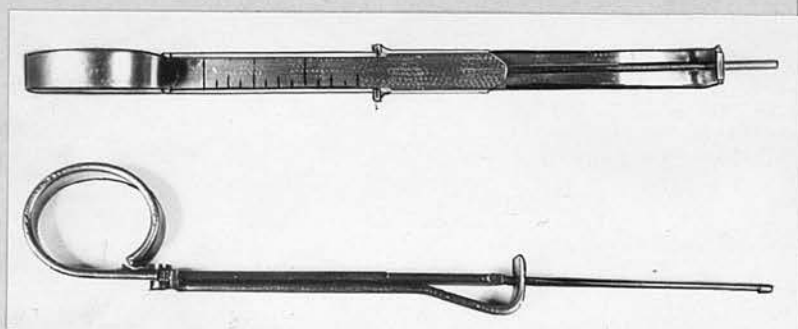


Fig.25.

Surgical Approaches.

The shaft of the tibia and the shaft of the ulna are easily exposed as both of the bones are immediately subcutaneous. Grafts, however, should not be placed on the subcutaneous surface of the tibia, for the blood supply to this region is poor. Not only is the graft not given the best opportunity for growth, but the overlying skin may give way. Though it is not technically so easy it is much better to apply the onlay graft to the outer aspect of the tibia. There it is covered by a mass of muscle which provides an abundant blood supply and which protects the skin over the graft and the screws. (Fig. 13b)

The best approaches to the shafts of the radius, the humerus and the femur are those described by A.K. Henry (41) (42). Each is designed so that the whole length of the bone is exposed without transecting muscle. The muscles are separated by dissection in intermuscular planes. Only two muscles have to be cut (the crureus and the brachialis anterior) and they are divided in the line of their fibres. Familiarity with these approaches is essential.

ARTHRODESIS

Cortical bone grafts are often used to help to promote union in arthrodesis of joints; their functions again are:

- 1) to act as an internal splint; and
- 2) to provide a source of new bone formation.

They may be used either as an inlay as in the technique described by Watson-Jones (75) for arthrodesis of the ankle, or as an onlay (Fig. 27b). A cortical bone graft is used alone in some forms of extra-articular arthrodesis of which Brittain's ischio-femoral arthrodesis is an example (15). Arthrodesis is made more certain, however, by thorough removal of all the articular cartilage from the joint surfaces and this should always be done when possible. Five examples of the use of cortical bone transplants in arthrodesis are described.

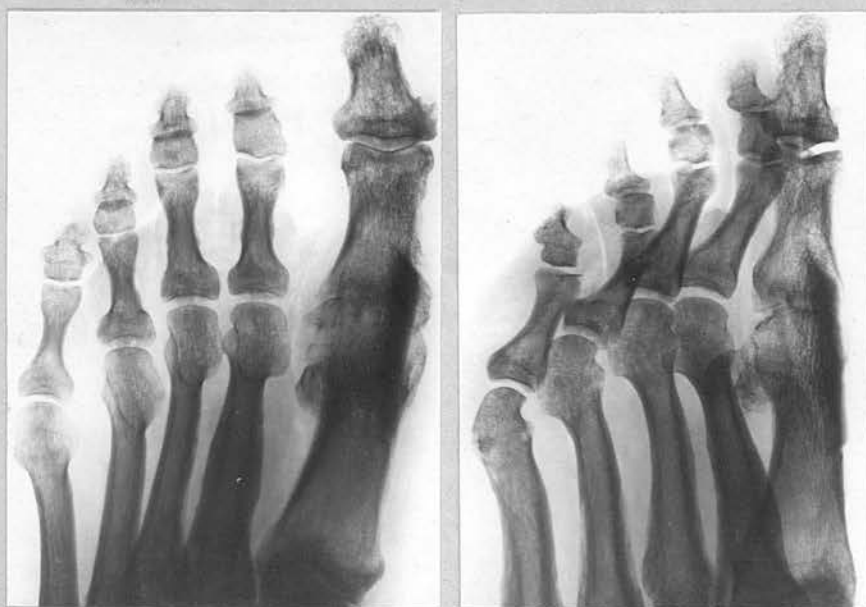


Fig. 26.

Fig. 26 is an example of arthrodesis of a first metatarsophalangeal for severe hallux rigidus. A cortical inlay graft was used and there is sound fusion at four months.

Fig. 27a shows

an ankle joint destroyed by a fracture-dislocation.

In the lateral view the anterior two-thirds of the tibial articular surface can be seen driven up into the cancellous lower end of the tibia. Fusion of the joint was clearly indicated.



Fig. 27a.

The ankle was exposed by an antero-lateral incision and the articular cartilage was removed. The damage to the lower end of the tibia was such that the

foot was very unstable in relation to the tibia, so it was fixed with a massive cortical onlay graft which was cut from the shaft of the same tibia and applied to the outer aspect of the tibia and the talus. (Fig.

27b). The joint was soundly fused in three

months (Fig. 27c overleaf).



Fig. 27b.

Fig. 27c. Ankle joint soundly fused at three months.



Fig. 28 shows a wrist fused for osteoarthritis.



Fig. 28. Six months after operation.

The radio-carpal joint was excised and a cortical graft was in-laid from the radius, across the carpus, and into the base of the third metacarpal.

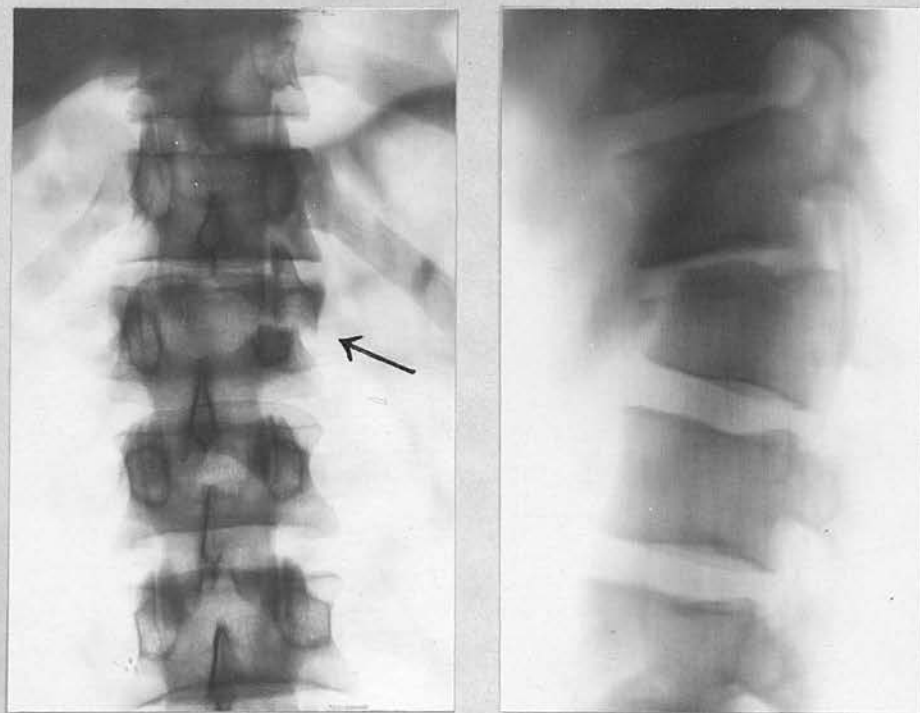


Fig. 29a. Note the fracture of the articular facet of L.1 (indicated by arrow) and the dislocation of D.12 on L.1.

Experience in the late war has shown that fractures of the spine with severe compression of a vertebral body or fracture-dislocations with gross joint damage are better treated by primary fusion of the spine. Such an injury is shown in Fig. 29a. The displacement was reduced by extension of the spine and the injured area was protected by fusing four vertebrae with twin cortical grafts from the tibia. Fig. 29b overleaf shows the appearance at six months from operation.

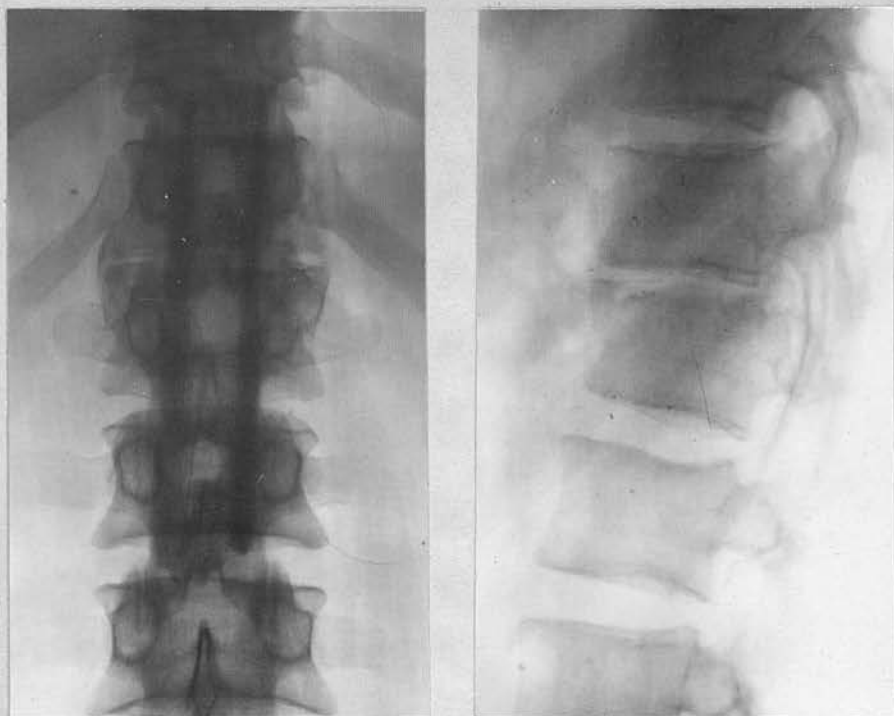


Fig. 29b. Spinal fusion with twin cortical grafts;
six months after operation.

When deformity of the spine due to injury (or to disease) is irreducible straight tibial grafts may be unsuitable. Albee recommends that this difficulty be overcome by the use of shaped grafts cut from the tibia (3). It is, however, not easy to cut these grafts satisfactorily and large portions of the tibial cortex may have to be removed.

If cortical bone is to be used it is better to adopt the method described by Delangiere (23) or Henry (43) (44), (see Figs. 3 and 4). These may with advantage be used in combination, the same tibia providing both sets of grafts. Fig.

30a shows a fracture of the ninth dorsal vertebra with severe wedging which was irreducible when the patient came under my care. The spine was fused from D.7. to D.11 using both osteoperiosteal strips and "match" grafts from the tibia.



Fig.30a.

There was solid fusion in six months (Fig. 30b).

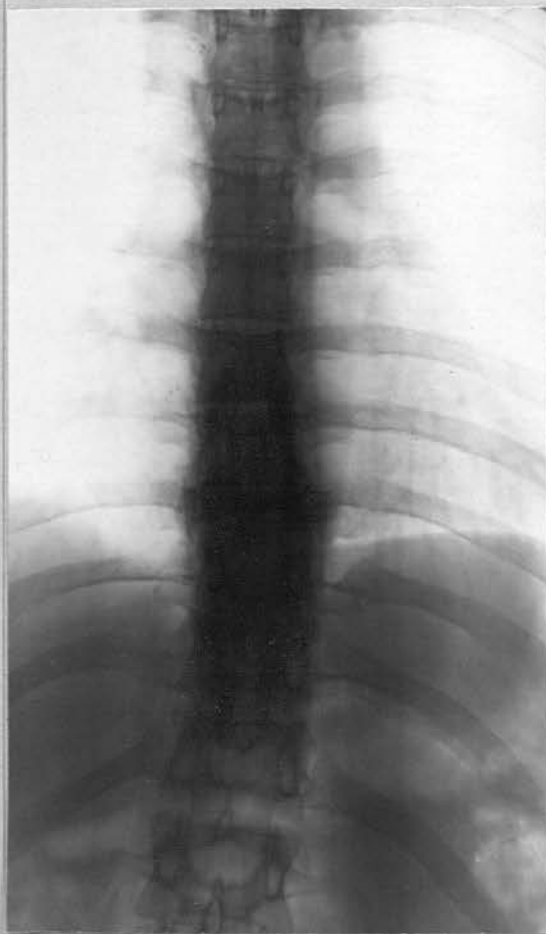


Fig.30b.

CHAPTER IV

THE TRANSPLANTATION OF CANCELLOUS BONE.

It has been stated that the two functions of a cortical bone transplant in bone repair are stability and osteogenesis; when it is properly used it performs the first of these functions well. Let us now examine its value in respect of the second function.

In a cortical transplant new bone grows from the bone cells which survive the transplantation. These are cells in the periosteal surface, in the endosteum and in the more accessible Haversian systems. But cortical bone contains only a small proportion of live bone cells, and when it is transplanted some of these are bound to die before a new blood supply reaches them. In cancellous bone the relative content of bone cells is much higher and the texture of the bone is such that it is much more easily revascularised. Thus if mechanical stability can be maintained while the reconstructed area heals and consolidates it should be possible to make use of the superior osteogenetic properties of cancellous bone.

Clinical and experimental evidence supports this hypothesis. In 1923 Campbell (17) noted that cancellous or

endosteal bone is "the most osteogenetic type of bone graft" and recommended its use "where new bone formation is most necessary as in areas of greatest stress or in bone grafts for non-union". He supplemented his onlay grafts with cancellous bone from the upper end of the tibia which he packed around the fracture site. For lumbo-sacral fusion he used blocks of bone cut from the ilium.

The first experimental comparisons between the osteogenetic properties of bone from various sources were made in 1931 by Gallie of Toronto (29) and Matti of Berne (60) (61) working quite independently. Gallie showed that cancellous bone had osteogenetic properties much greater than those of cortical bone and advocated its use in fractures of the mandible, where stability could be maintained by dental splinting, and in fusion of the spine and the subastragaloid joint. He considered that it was not suitable in fractures of the long bones because it did not provide stability. Matti went further and showed in experiments on dogs that cancellous bone chips could produce union across a gap in a fractured femur if the bone was stabilised by a plate (60).

In 1934 Stuck and Ghormley (71) published abundant evidence obtained from experiments on dogs. They compared the relative osteogenetic properties of bone transplanted from various sites. They showed conclusively that of all the known methods of bone transplantation that which produced the most

rapid and sure new bone formation was the transplantation of cancellous bone chips from the ilium.

This conclusion is exactly in accord with physiological first principles. A transplanted tissue can continue to live only if it can derive in time nourishment from the bed into which it is transplanted. A comparison of their microscopic structures shows that the abundant bone cells in cancellous bone are much more accessible to the transudation of body fluids and the ingrowth of vascular buds than the scanty cells of cortical bone. In this connection there is a close parallel to be observed in the behaviour of transplanted skin. Small pieces of split skin thrive readily as free transplants; transplants of the whole thickness of the skin have to be managed with considerable care or they die. The former can obtain their nourishment from their new bed because they are thin and permeable; the latter have to carry their blood supply with them.

Interest in the use of cancellous bone transplants in the surgery of bone repair was recently reawakened by the experience of the plastic surgeons. They used cancellous bone chips in the reconstruction of the contour of the facial bones because it was easily moulded and they commented on the rapidity with which it consolidated. After only seven to ten days from the operation it was no longer possible to alter the contour of the reconstructed area. Similar examples of rapid union were remarked in fractures of the mandible (59) (62).

I first had personal experience of the rapidity with which this type of transplant consolidates when I assisted one of my colleagues to repair a skull defect 3" by 1" with iliac chips. The edges of the defect were rawed and the chips were laid over the whole area between the dura mater and the scalp. When the skin sutures were removed at ten days the defect was covered by bone which was already quite firm to finger pressure. Only its irregular surface distinguished it to the palpating finger from the surrounding skull.

OPERATIVE TECHNIQUE

Fig. 31 shows that the two accessible regions in the ilium where cancellous bone is most abundant are 1) below the crest just behind the anterior superior iliac spine and 2) the posterior aspect of the ilium in the region of the posterior superior iliac spine. Of the two donor sites the latter provides by far the more abundant supply of cancellous bone. It should be used when a generous amount of bone chips is needed (as in

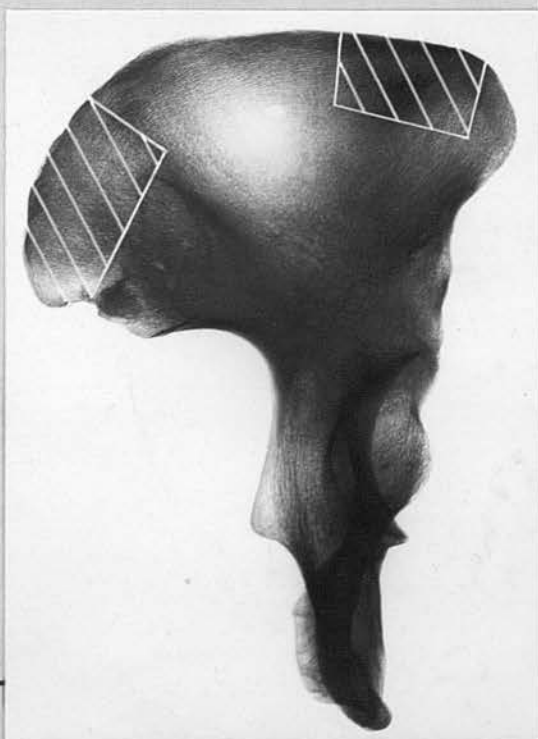


Fig.31.

fusion of the knee or in filling a tibial defect) even if the patient has to be turned during the operation and has therefore to be draped twice.

The cancellous bone of the ilium is exposed by cutting a window in the outer cortex or by turning up the crest as a lid or by combining both procedures, the choice depending on the amount of bone chips needed. The cancellous bone can then be easily cut out with a hand gouge. This method obviates the danger of penetration of the inner cortex. This is of importance in the posterior approach because of the proximity of the sacro-iliac joint, and hernia of the caecum has followed removal of part of the whole thickness of the right iliac crest in front (64). The cancellous bone is cut into cubes of .5 cm. side or smaller.

The recipient area is prepared so that there is an immediate free blood supply to the transplants. If a joint is to be arthrodesed it is important not only to remove all the articular cartilage but also to open the cancellous bone of each bone end. If a bone defect is to be filled the fibrous tissue between the bone ends and the sclerotic bone ends themselves must be cut away, healthy vascular bone above and below opened with saw cuts or by drilling and the fibrous tissue covering the muscle bellies around the bone removed or freely incised. The cancellous bone chips are then packed into the cavity in the bone and around the shaft.

If a rigid internal splint is not used the alignment of the limb is corrected by moulding during the application of the plaster. In this respect iliac bone chips offer an advantage over rigid cortical grafts fixed by screws in that there is a second opportunity for manipulative correction of the alignment when the padded post-operative plaster is changed for an unpadded plaster at 10-14 days. Any necessary correction of alignment should not be deferred longer than this, however, for often by the fourteenth day fusion is already so advanced that strong manipulation on an anaesthetised patient may be needed in order to alter the position.

When a gap has to be bridged, either in the shaft of a long bone or in arthrodesis, it may be advisable to use a cortical transplant as well to act as an internal splint and provide stability and preserve the shape of the bone, but this is not always needed. Alternatively a vitallium plate may be used for fixation but plaster alone is commonly enough.

I have used the method in forty-eight cases of which ten are described.



Fig.
32a.

1. Fusion of knee. This severely comminuted fracture of the tibial plateau was sustained in an aircraft crash (Fig. 32a). It was decided that arthrodesis of the knee offered the only prospect of a painless stable limb. The joint was excised

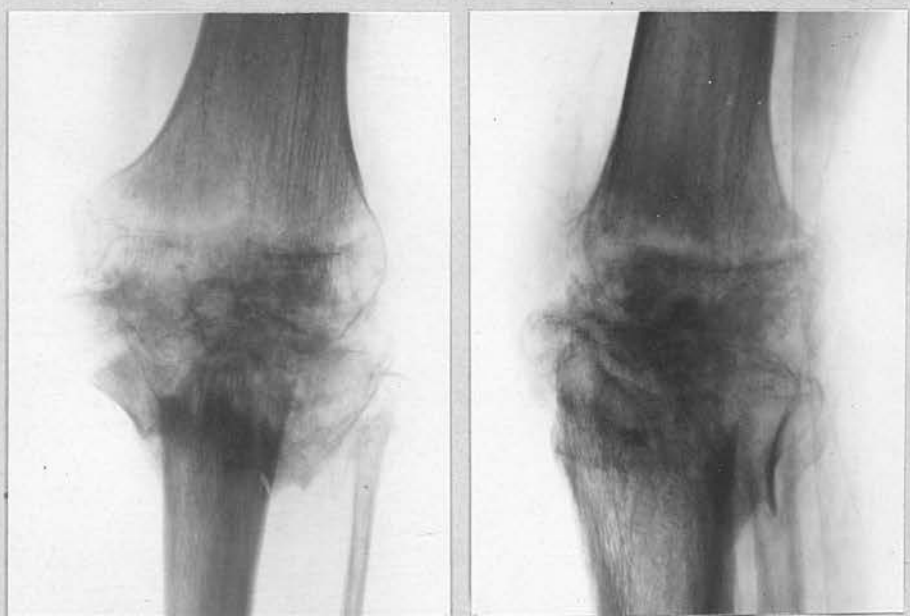


Fig.
32b.

and packed with iliac chips. When the post-operative plaster was changed at 21 days the joint was already firm (Fig. 32b).



Fig.
32c.

He began to walk in a guarding plaster at 10 weeks; Fig. 32c shows the appearance at 20 weeks. All external fixation had been discarded and the fusion was solid.

2. Fusion of wrist. This osteoarthritic wrist (Fig.

33a), result of an old ununited fracture of the carpal scaphoid,



Fig.33a.

was excised and packed with iliac chips. At eight weeks fusion was clinically solid and painless (Fig. 33b overleaf). A short plaster was applied for a further four weeks.



Fig. 33c. Appearance when plaster was finally discarded at twelve weeks.



Fig. 33b. Fusion of wrist at eight weeks.

3. Fusion of ankle. An attempt to remodel an ankle

after a severe fracture-dislocation was not successful and the joint was stiff and painful (Fig. 34a). It was excised through



Fig. 34a.

a short lateral approach, dividing the external malleolus and



Fig. 34b.

turning it down, and packed with iliac chips. Fusion was solid at ten weeks (Fig. 34b).

4. Fusion of subastragaloid joint. Painful osteoarthritis of the subastragaloid joint followed a fracture of the os calcis. Iliac bone chips were packed into a cavity cut in the back of the joint by the posterior approach described by Gallie (30). Fusion was clinically solid at 12 weeks (Fig. 35).



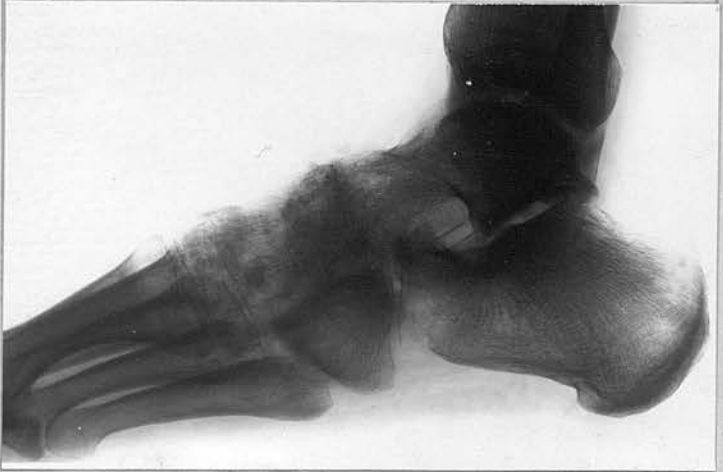
Fig. 35.



Fig.36a.



Fig.36b.



5. Fusion of tarsus. The only effective treatment for the injury shown in Fig. 36a is primary fusion of the affected joints. Fig. 36b shows the appearance 8 weeks after the area had been excised and packed with iliac chips. Fusion was clinically solid and not tender but he wore a protective plaster for another four weeks.

6. Fusion of spine. A pilot sustained a severely comminuted fracture of the body of the first lumbar vertebra. The displacement was reduced in a hyper-extension jacket and primary fusion of D.12 to L.1 was performed eight weeks later. The affected vertebra was identified radiologically on the operating table by a screw driven into its spinous process. (Fig. 37a is

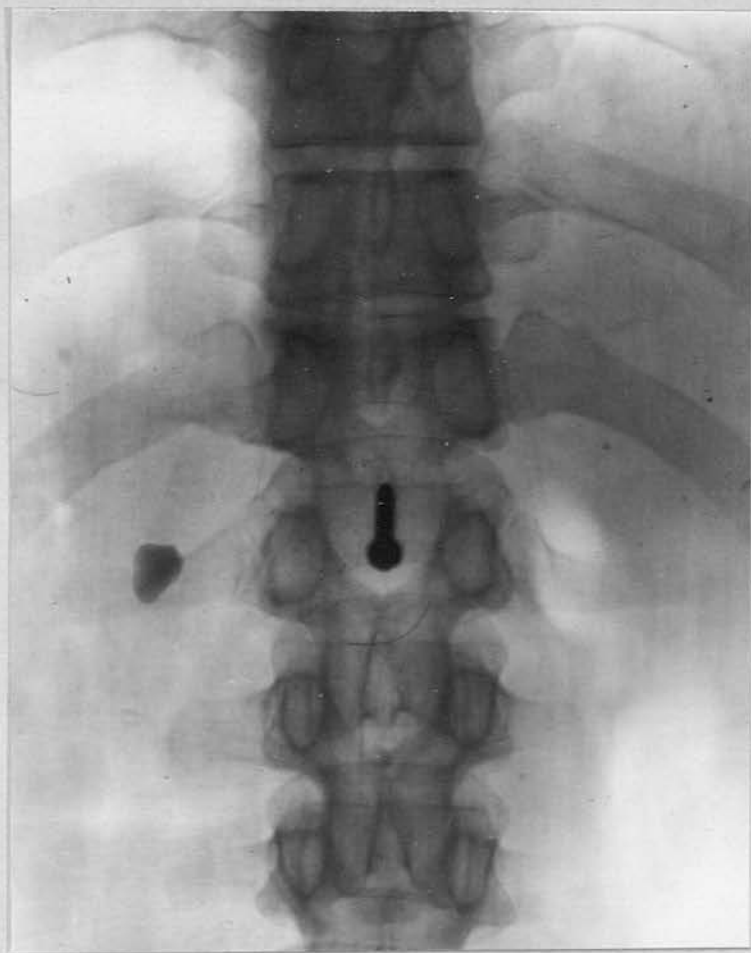


Fig.37a.

an x-ray of another patient in whom D.12 was fractured but it illustrates what is an essential step in all localised spinal fusions). The laminae of the vertebrae were rawed and the spines were rawed and split and the whole area was packed with

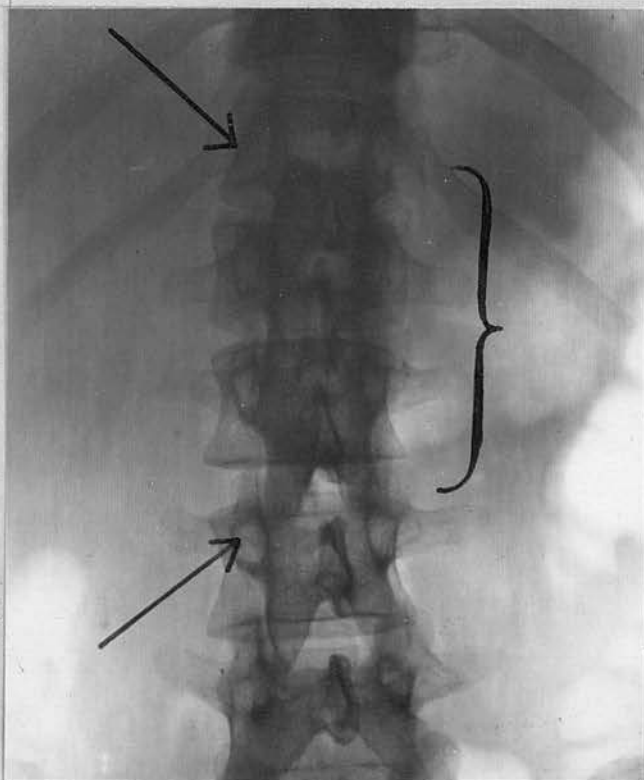
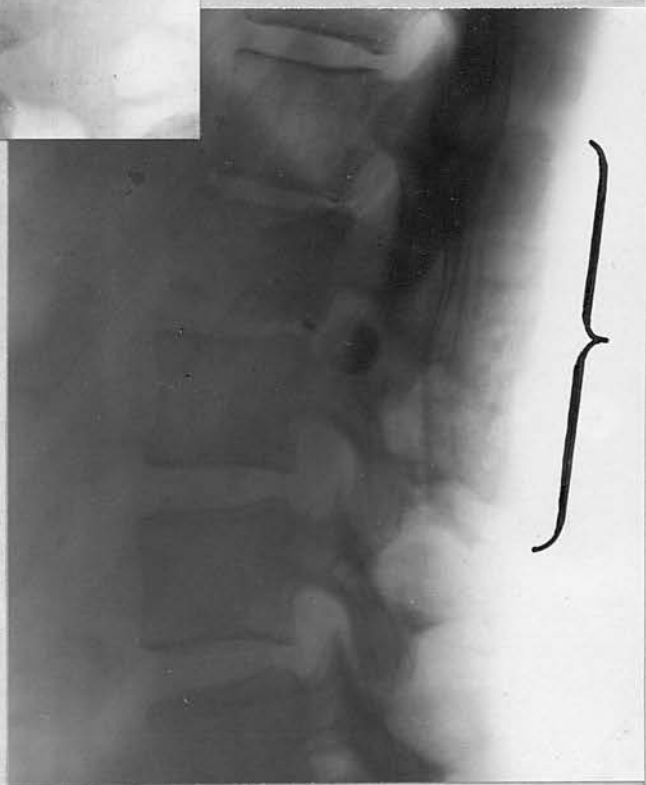


Fig. 37b.



iliac chips. Fig. 37b shows the appearance when the plaster was discarded at 3 months.

7. Non-union of femur. Reference has already been made to an onlay graft of the femur which failed to secure union (see p. 60 and Figs. 21a and 21b). After a further 12 weeks in plaster the refracture was still mobile and the whole area was completely indolent. The fracture was exposed again, the fibrous tissue was cleared from between the bone ends, and the bone was opened with numerous drill holes. A cavity was cut in the outer side of the femur and iliac bone chips were packed into it and around the fracture site (Fig. 38a). In 20 weeks



Fig. 38a.



Fig.38b.

union was clinically sound (Fig. 38b), but a plaster spica was reapplied for another eight weeks to allow the union to consolidate further.



Fig. 39a. (x-rays overleaf).

8. Reconstruction of tibia. A pilot sustained, as one of his injuries, a severely compound and grossly comminuted fracture of the tibia and fibula (Fig. 39a). The wound was



Fig. 39a.

heavily infected and for some time the wisdom of trying to save the limb was in considerable doubt. Ultimately a large part of the shaft of the tibia sequestered and was removed, the infection subsided, and the remaining wound was healed with split skin grafts and pinch grafts. A large tibial defect was left



Fig. 39b

covered by an unstable adherent scar (Fig. 39b). The scar was



Fig. 39c.

replaced by a cross-leg flap and later through that flap (Fig. 39c) the tibia was rebuilt with twin cortical onlay grafts from



Fig. 39d

the other tibia with cancellous bone from the ilium packed into the defect (Fig. 39d), after the method described by Boyd (13).

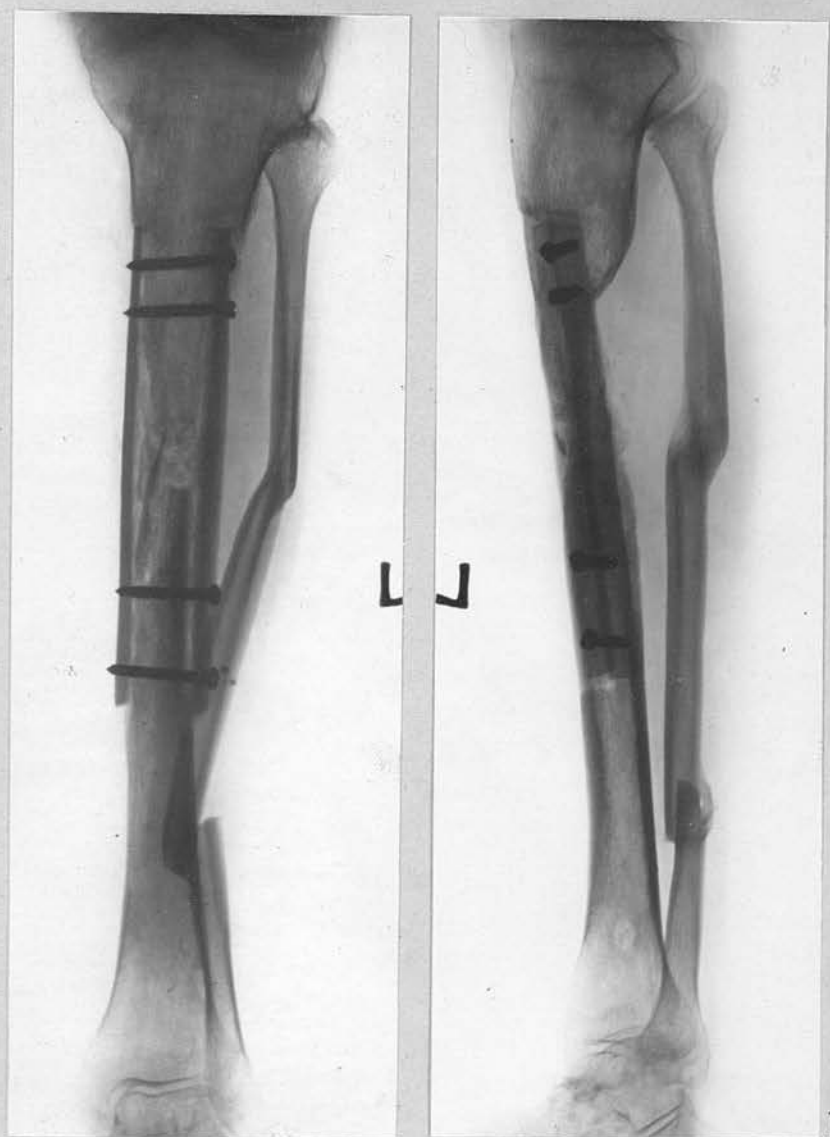


Fig. 39e.

At twelve weeks he was remobilising the limb in bed (Fig. 39e) and three weeks later he began walking with crutches. A stress fracture developed in the donor tibia eight weeks after the operation (see p.58 and Figs. 20a and 20b) and in the end the rebuilt tibia was taking the body weight unsupported four weeks before the donor tibia. Fig. 39f overleaf shows the rebuilt tibia at thirty-six weeks.



Fig. 39f. Re-built tibia at thirty-six weeks.

An instructive comparison is afforded by a similar injury (Fig. 40a overleaf) which was repaired with cortical bone only (in another hospital). Though the tibia ultimately con-



Fig. 40a.

solidated satisfactorily the limb was still in plaster at eight months (Fig. 40b overleaf). At this stage the repair was less well consolidated than that of the previous patient was at twelve weeks (compare Fig. 39e with Fig. 40b).

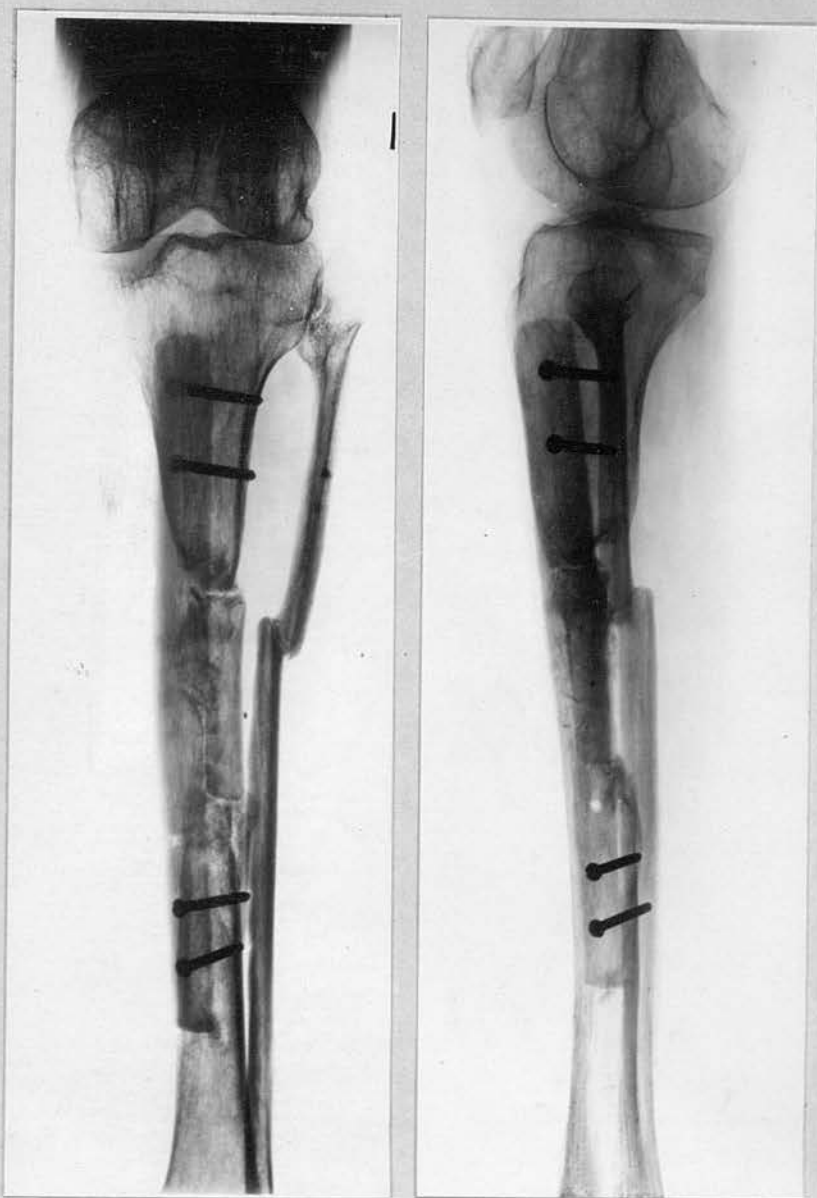


Fig. 40b. Tibia, re-built with cortical bone only;
at eight months from operation.

10. Non-union of radius. A patient aged 31 sustained a severe fracture of both bones of the fore-arm which united with overlap and in poor alignment. The head of the ulna was then excised in an attempt to restore rotation. When I first saw him some six months after this the fractures were soundly

healed and he had quite good fore-arm movement including nearly 90 degrees of rotation. Its range, however, was from full supination to the mid-position and was in consequence of less functional use to him than a range between the mid-position and full pronation would have been.

A rotation osteotomy of the radius was accordingly performed to pronate the lower fragment and the bone was fixed with a vitallium plate. Twenty weeks later the osteotomy was quite unhealed. (Fig. 4la). The bone ends were then excised



Fig. 4la.



Fig. 4lb.

between the two central screws, the shafts were drilled thoroughly above and below, and the cavity was packed with iliac chips.

Fig. 4lb shows the appearance eight weeks later; at sixteen

weeks there was no doubt that the bone was uniting (Fig. 41c). The limb was left out of plaster at this stage and when the plate was removed at twenty-four weeks there was solid union (Fig. 41d).



Fig. 41c.



Fig. 41d.

10. Non-union of tibia. I have recently used this method in the treatment of simple non-union of the tibia without displacement. A fractured tibia remained tender to the touch and painful after walking two years after the plaster had been



Fig.42a.

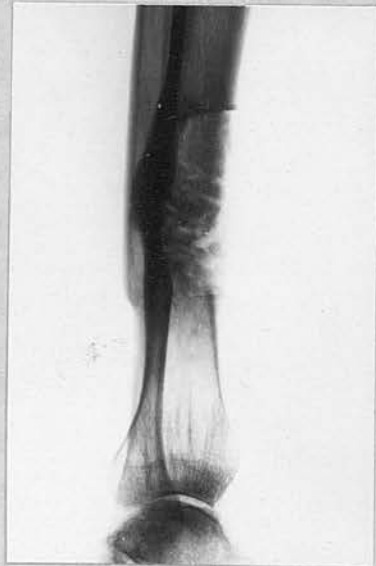


Fig.42b.

discarded from the limb. Fig. 42a shows the appearance nearly three years after injury. The indolent area was excised and the cavity was packed with iliac chips. The x-ray appearances at eight weeks are encouraging; it is still too soon to form a final opinion (Fig. 42b).

SUMMARY AND CONCLUSIONS

The indications for the transplantation of bone in the treatment of bone and joint injuries are:

- 1) delayed union and non-union in the shaft of a long bone;
- 2) correction of mal-union in the shaft of a long bone when osteotomy alone is not enough;
- 3) reconstruction of the shaft of a long bone by bridging a gap;
- 4) closure of gaps in the skull and remodelling of the facial bones;
- 5) arthrodesis of a damaged joint.

Two types of bone transplant are used:

- 1) cortical bone;
- 2) cancellous bone.

The main function of a cortical bone transplant is to provide stable internal fixation thus preserving the form of the part which is being repaired. The advantages and disadvantages of the various types of cortical bone transplant have been discussed. The massive onlay graft or the massive sliding onlay, secured with vitallium screws, are the best methods of internal fixation of bones at present available. When the scheme of treatment of a patient is under consideration a decision to use

the intact tibia as the donor of the transplant should be taken only when all other methods are considered impracticable.

There is great and widening scope for the use of transplants of cancellous bone. They produce more rapid union than cortical bone grafts. The intact tibia is not damaged. The method is of particular value in fusion of the spine and in arthrodesis of joints.

The combination of a cortical bone transplant with cancellous bone chips is a very effective way of securing union in gap fractures.

Cancellous bone chips will promote union in a bone which is immobilised by a vitallium plate. This method will probably be more widely used in future.

An internal splint and screws made of an absorbable plastic material used in conjunction with cancellous bone chips would be an ideal method of treating delayed union or non-union of fractures. We may yet see that ideal realised.

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