THE CLASSIC

Bone-Graft Surgery

Fred Houdlette Albee

Fred Houdlette Albee (1876–1945) was a poor farm boy from Maine who worked his way through Bowdoin College and Harvard Medical School with the aid of scholarships. The greatest influence in his life was his grandfather, Charles G. Houdlette, who was a cabinetmaker and an expert in the grafting of fruit trees. After interning at the Massachusetts General Hospital, Albee went to New York City, where he worked with Henry Ling Taylor and Virgil P. Gibney at the Hospital for the Ruptured and Crippled. He remained in New York City for the rest of his life.

Albee became a major proponent for the use of bone grafts. His spinal fusion technique for the treatment of tuberculosis and scoliosis was adopted by many surgeons. He also developed methods in which bone grafts were used to fuse tuberculous joints and to treat ununited fractures and other orthopaedic problems. His techniques were based on the use of an electric saw of his design, with which he was able to make precise cuts. By carefully inlaying his bone grafts and dowels, Albee achieved a new level of graft fixation. He did much to change the image of the orthopaedist from that of a strap-and-buckle doctor to that of a bone carpenter.

Albee, however, was more than just a bone carpenter. He studied bone grafting in his laboratory at Cornell University Medical School, where he was supported and guided by James Ewing. Albee published many articles describing the results of his investigations and of the treatment of his patients. He was ahead of his time regarding his ideas concerning preservation of bone grafts.

During World War I, Albee became chief of surgery and director of United States General Hospital No. 3 in Colonia, New Jersey, a suburb of New York City. His concern went beyond reconstructing limbs of the wounded soldiers returning from Europe; he also considered the future of these greatly disabled veterans. As such, Albee pioneered rehabilitation and training programs for veterans.

Because of his work, Albee became a leading figure in American orthopaedics. He was also well known abroad and traveled widely to lecture and visit famous clinics in Europe and South America.

Leonard F. Peltier, MD, PhD

The most favorable tissues for grafting purposes are the simpler connective tissues, such as bone, fat, fascia, etc., which are endowed with the capacity of extracting nutrition from the soil into which they are planted and at the same time are able to regenerate so that the portion of the graft which disintegrates is replaced. Muscles and nerves are most unfavorable.

Bone has been successfully transplanted since 1809, when Merrem obtained successful healing of bone plates in the skulls of ani-

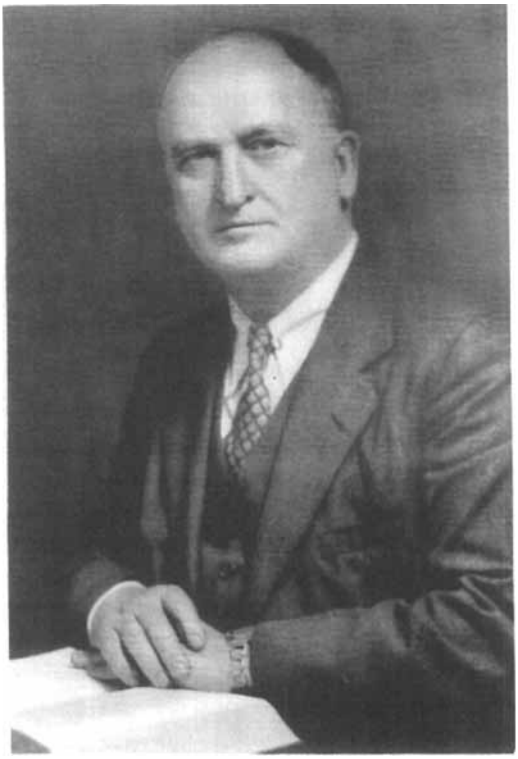

Fig 1. Fred Houdlette Albee (1876–1945). Reprinted with permission from J Bone Joint Surg 27:345–346, 1945.

mals after trephining. Subsequently, Walther, in applying this technique to the human subject, secured partial healing of the graft, in spite of the co-incident suppuration. In 1858, Ollier, after extensive investigations in the use of the bone graft in both animals and man, concluded that fresh bony tissue, covered with periosteum, remains viable. Autogenous grafts, or those derived from the same individual into which they are engrafted, are by far the most trustworthy. The fluids, albumins, and tissues of every individual vary in degree from those of every other, and while this incompatibility may be slight, it is sufficient cause for using, whenever feasible, the individual's own tissue for the repair of his defects.

With primary union and in the absence of infection, autogenous bone grafts, properly contacted, are always successful, and even infection does not necessarily indicate failure. "The vegetative capacity of the bone cell is as great as that of the epithelial cell, and if one grants not only the viability of the transplanted epithelium but also its power of extensive proliferation, then, judging by analogy, the bone cell ought to show, as it has bone in this instance, equal capability of living and growing when transplanted. In proportion to the size of the graft, the smaller the graft the greater the proliferation."—Macewen.

The knowledge of the exact histological role which the bone graft plays is, fortunately, immaterial to its clinical usefulness, whether it serves as an osteoconductive scaffold or as an active osteogenetic force. The extensive experiments and histological studies of Ollier, Macewen, Frangenheim, Cotton and Loder, McWilliams, Mayer, Phemister, and the author have proved the viability and osteogenesis of the grafts when inserted by the proper technique.

"The more quickly and surely this takes place, the more promptly is nourishment assured. Should the cells of the wound be injured because of antiseptic applications, or should they be abnormal because of the presence of scars or hæmatomata, or the seat of previous disease, as tuberculosis, necessary nutrition will be delayed. Very important contributing factors to failure are errors in operative technique, causing infection with a very slight transudate, which is instrumental in destroying the first intimate contact, thus preventing nutrition, partially or absolutely, and predisposing to partial or total necrosis due to suppuration. By means of strict asepsis, this element of failure can be eradicated. Most important, however, is a second factor, which prevents the early intimate adhesion of the wound edge, namely, imperfect hæmostasis. The presence of the slightest amount of blood is dangerous, as it interferes with the nutrition. That this factor has been heretofore disregarded is apparent from the literature. It is the general belief that a smooth, uninfected wound is a sign of perfect technique. This is not true in connection with transplantation. In this instance, perfect technique is recognized by a complete gumming and coaptation of the wound edges. For this reason, every experimenter in recording the results of his transplantations should convince himself that the transplant is really grafted as it should be, in order that his operation be perfect."—Lexer.

Homoplastic grafts are those which are derived from another individual of the same species, and when composed of the lower order of tissues, such as bone or fascia, they may be employed successfully, though not with the same certainty as autogenous grafts; when they consist of the more highly specialized tissues, they result in failures. Homoplastic grafts are often difficult to obtain, and there always exists the danger of transmitting disease from the donor to the host, even when the greatest care has been exercised. Fibrous encapsulation occurs more frequently in homoplasty than in autoplasty. This, as Lexer has pointed out, is probably due to the irritation of a foreign proteid, which varies most with difference in race, next with distant relatives, near relatives, and least with the individuals of one family. This variation prevents proper nourishment of many tissues and, as a result, substitution in the regenerative process occurs very slowly while degeneration takes place rapidly.

Heteroplastic grafts are those which are obtained from an individual of another species. Living grafts from different species may die when implanted into man or the higher animals. The graft in these cases acts as a foreign body, and if there is even mild infection it is liable to ulcerate out. In the event of no infection, it either becomes encapsulated or disappears, and is slowly substituted by the proliferation and migration of the tissues in which it is embedded. This process may require months in the case of the bone graft, and thus it follows that the graft may be a success clinically, though histologically it undergoes partial or even complete absorption, or, in other words, it acts as an osteoconductive scaffold.

The principal difficulty with heteroplastic grafts is that the albumins of different individuals are not alike. Successful experiments are reported as under way in Lexer's clinic, with the object of changing the blood by preliminary treatment. Kuttner has been partially successful in grafting tissue from the ape to man. The cellular mass necroses, as it may in homoplasty. Clinical success in the repair of large denuded bony cavities can be secured only by the use of living autogenous bone covered with periosteum.

Just what happens to the autogenous bone graft from a microscopical standpoint, is still a matter of discussion. Whether the boue [*sic*] graft lives as such, or whether the cells wander into it from the bone with which it is connected, is still *sub judica.* In the author's experience both with human beings and with animals, perfect union of the autogenous aseptic bone graft with the bone into which it was placed has been secured in 100 per cent of cases, and, after all is said, this is the important consideration.

The subject of the bone graft is being widely discussed, and the men who are studying this problem may be divided into two schools: those who claim that a certain portion of the cells in the graft live and that the graft is a distinct and separate osteogenetic force; and those who claim that the cells of the graft do not *per se* have any osteogenetic power and that the graft merely serves an osteoconductive purpose. There are at present, however, very few who continue to uphold the latter view, especially since Barth, its originator, has been convinced that his former position was wrong and that the cells of a portion of an autogenous periosteum-covered bone graft live and play an important osteogenetic rôle.

One should not be too dogmatic concerning the exact role that every graft must play. Individual conditions or individual environment determine the exact role of each particular graft. There may be a considerable blood-clot, or tissue shreds, which interfere with the nourishment of the graft, preventing an immediate and perfect union; or there may be a slight or severe infection, or other disturbances to deal with, and these conditions determine the exact histology in each individual case or, in other words, how many of the graft cells have received sufficiently early nutrition and remain viable, and how much of the graft dies and serves in an osteoconductive rôle. It fortunately does not matter, from a surgical standpoint, what happens histologically, so far as the exact rôle of the graft is concerned. It is known that an autogenous bone graft always "takes" and becomes permanent, if it is put in under aseptic conditions; and, if it has function to perform, it stays there and adapts itself in structure, size, contour, and in strength to the new environment.

Boiled bone has been used by Kausch and others for years as a substitute for the bone graft. From a recent discussion of this matter, one would gather that this material had never been used before. Boiled bone is far inferior to an autogenous bone graft, and Kausch, in 1910, from an extensive experience prepared a table illustrating the scale of value of different material for bone substitution and made the following statement: Boiled bone and bone from the cadaver are not adapted for implantation in a bed free from periosteum, and foreign substances are still less suitable for this purpose.

KAUSCH'S TABLE OF VALUE OF DIFFERENT MATERIALS FOR BONE TRANSPLANTATION

1. Pedunculated soft parts with periosteum-covered bone flap.
2. Free transplanted periosteum-covered autoplastic bone.
3. Free transplanted periosteum-covered homoplastic bone.
4. Fresh boiled bone.
5. Fresh preserved bone.
6. Cadaver or fetal bone, obtained under sterile conditions.
7. The same bone, boiled.
8. Ivory.
9. Foreign bodies, such as metal.
10. Fresh animal bone, living or boiled.

Autogenous live bone is the only material which can be implanted with safety in a bed free of periosteum.

After extensive experimental investigations and a large amount of human work, the author is convinced that the best transplant is a live piece of autogenous bone including all its elements, namely, periosteum, compact bone, endosteum, and marrow substance; that the periosteum which is separated from attached muscles should be incised in numerous places to provoke a greater stimulation and also a freer blood supply; it lets out osteogenetic cells and lets in nourishment, that the bone is best taken from the same individual or, if this is impracticable, from another individual of the nearest kin, preferably a brother or sister; that the bone should never be obtained from an animal, because its viability or replacement is uncertain or, at best, delayed, and according to Axhausen its periosteum does not proliferate.

In the case of the bone transplant, nature is confronted with the following problems: (1) the rapid establishment of cellular nutrition and blood supply, which is brought about by the extension of blood-vessels, and by the cellular assimilation of the serum in which the graft is immersed; (2) the union of the graft to the contacted bones or fragments of bones by osteogenesis on the part of the graft or recipient bone, or both; (3) through Wolff's law, which is the adaptation in form and increased strength of the graft to its mechanical requirements. If nature is to succeed in accomplishing this, it is quite essential that both the graft and the recipient bone should be favorable to cellular life and proliferation.

The surgeon can do much in aiding nature by strict asepsis, by minimizing the trauma to all the tissues involved, by avoiding cellular death through either bruising or comminuting with hand tools, or by frictional heat from motor-driven instruments; by the avoidance of traumatism, thus guarding against necrosis of portions of the graft and lessening the danger of wound infection; by the proper protection and preservation of the graft bed and the graft itself from drying and possible infection; by so arranging his skin incision that it will not come directly over a superficially placed transplant, as this lessens the danger of skin necrosis and infection; by excising, if possible, extensive scars from the field of operation, as their poor blood supply is likely to interfere with the establishment of nutrition to the graft; by closely fitting and contacting bone surfaces which should, whenever possible, include the accurate coaptation of periosteum of graft to periosteum of recipient bone, of cortex to cortex, of endosteum to endosteum, and of marrow to marrow; by properly suturing muscle origins and insertions to the suitable mechanical locations on grafts which replace skeletal bones or portions of them (this is important if muscle control is to be reëstablished); by securing sufficient hæmostasis in the graft bed by means of repeated applications of hot saline solutions, and by careful tying of blood-vessels. (A hæmatoma not only favors the development of infection, but also interferes with the early nutrition of the transplant by the permeating serum; a small amount of blood-clot, however, may be desirable); by including in the graft the periosteum, endosteum, and marrow, which not only contain active osteogenetic elements but, on account of their loose structure, are more favorable than compact bone to a rapid reëstablishment of the blood supply with the recipient tissues of the graft bed, from whence nourishment rapidly reaches the compact part of the graft through the numerous blood-vessels passing from these enveloping membranes into the compact bone. In other words, a bone graft consisting of all its elements approaches more closely a complete physiological unit—especially in reference to nutritional distribution—which is obviously an advantage.

The bone contact should be of generous extent and always with healthy vascular osteogenetic bone—the more unfavorable the bone, the greater should be the area of contact.

A thorough understanding of the *modus operandi* and theory of Wolff's law is imperative. The influence of this law upon the success of bone-grafting procedures of all kinds cannot be too strongly emphasized. It not only influences the graft to proliferate and strengthen to an almost unlimited degree, if the new mechanical environment of the graft requires it, but the action of this law also causes the bone from which the graft was removed to be restored to its original strength. This same influence also causes internal reconstruction of not only the trabeculæ, as the mechanical forces demand, but also of the general histological character of the bone, *i.e.*, cortical bone ultimately becomes spongy bone if implanted in or contacted with bone of that character, and *vice versa.*

The recognition and full appreciation of these important conclusions of Wolff constitute the foundation of the treatment of deformities and the application of grafts of all kinds. It is obvious that it is always advisable to allow the graft to functionate as early as possible by bearing mechanical stress within the limits of safety. This is highly favorable to osteogenesis, establishment of blood supply, and bony union. This functionating period should be preceded by the most efficient fixation of the parts grafted for an interval of not less than 8 weeks.

Human autogenous grafts have been repeatedly so placed that, at their middle portion, they extend through tubercular foci, and in no instance has primary union or taking care of the graft failed. Likewise, grafts have been so placed as to span attenuated pyogenic infected areas, and here the grafts have been equally successful.

The author has found that experimental grafts taken from long bones, such as the tibia or ulna, showed evidence of greater osteogenesis than those taken from vertebral spinous processes. Bone from which the periosteum had been removed proved as satisfactory as bone grafts on which the periosteum had not been removed.

It is deemed advisable, as stated elsewhere, to always include the periosteum and marrow substance, when possible, on the graft.

The bone graft acts always as a stimulus to osteogenesis to the bone into which it is engrafted or to which it is contacted. This is a constant and important factor, and may be depended upon toward securing results. If the graft is placed in a location where there is no mechanical function for it to perform its cells retain their vitality, but nearly always there will be few or no proliferative changes in the transplant. On the other hand, if it is transplanted into a defect where there is a demand for it to perform a mechanical function, proliferative changes are usually marked, and it rapidly becomes united and similar in structure to the part into which it is grafted. This is the law of functional irritation as laid down by Roux. The more perfect the technique of transplantation, the greater will be the effect of this law of irritation.

The bone graft, when well contacted, becomes immediately adherent to the recipient bone by newly formed tissue, which changes to solid bone within 4 weeks. In the author's opinion, this, together with the graft's bacteria-resisting property, strongly favors, when feasible, the employment of the bone graft in place of any metal internal splints, especially when it is appreciated that metal has an effect opposite to that of a graft in that it inhibits callus formation, produces bone absorption, and favors infection.

PRESERVATION OF THE BONE GRAFT

Various methods have been suggested for the preservation of bone-graft material, but in the experience of the author the following have proved most convenient and reliable.

The temporary immersion in normal salt solution is most satisfactory, and even this is usually not necessary, since, when possible, the graft bed should always be prepared prior to the removal of the graft, and the graft is immediately implanted in the prepared bed. This sequence of the operation is important, because (1) it assures an interval of time for the more perfect haemostasis in the graft bed; (2) it enables the surgeon by means of calipers, bone wax model and flexible sterile pattern rod or flexible probe to obtain the exact size and contour of the graft required, thus avoiding unnecessary traumatization from holding forceps in reshaping a graft after its removal. Even in grafts where drill holes are necessary, it is far preferable to drill the graft before loosening it from the bone from which it is obtained. A graft should always be used as soon after its removal as possible, but if it is necessary for any amount of time to elapse before it can be used, normal saline is not satisfactory as a preserving medium because of its evaporation and the consequent toxic effect. In the experiments of the author, sterile vaseline has proved a most satisfactory medium in which to keep the graft. It is not only perfectly non-toxic, but it is an efficient preventive of drying. The graft should either be immersed in a jar of vaseline or wrapped in gauze smeared with the same and placed in cold storage at a temperature of 4° to 5°C. Freezing is not desirable, as the resultant contraction and expansion damage the cellular content of the graft. Human grafts removed from the living as well as from a cadaver have been successfully kept by the author for 48 hours on different occasions. Emphasis should again, however, be laid upon the importance of using autogenous bone grafts whenever possible, as they are the most reliable; and as they are always used immediately, no preserving medium is necessary.

The surgical status of the value of the bone graft has now become so thoroughly established that the surgeon should be ready and equipped to make the best use of it in every individual case requiring osteoplasty. An unabridged enumeration of the indications for the employment of the bone graft would be most difficult, and the following tabulation serves only as a suggestion of its broad field of usefulness.

GENERAL INDICATIONS

1. To immobilize and stimulate osteogenesis in certain tuberculous joints.
2. To repair traumatic bone injuries.
3. To replace bone destroyed by infection.
4. To supply bone congenitally absent.
5. To strengthen or replace bone weakened or destroyed by benign or malignant growths.
6. To correct congenital or acquired deformities of the face.
7. To establish joints congenitally absent and restore those destroyed by disease.
8. To fix in place certain dislocated joints (acquired or congenital).
9. To close bone foramina in neuralgias.
10. To correct congenital or acquired deformities of extremities or trunk.

More specific indications for bone grafting are:

1. To immobilize, support, and stimulate repair in spinal vertebrae whose bodies are infected with tuberculous or other chronic infections where mechanical treatment is indicated. It is also applicable in cases of persistent non-union following fracture of the spine, presenting pain, disability, and increasing deformity, and should be inserted as for Pott's disease. Further indications are for certain fresh fractures of the spine: spondylitis traumatica (Kümmell's disease) and neuropathic spine (Charcot) where, on account of a rarefying osteitis, crushing of the vertebral bodies and increasing deformity is likely to produce cord compression.
2. In the support and immobilization of cases of tuberculosis of the sacro-iliac joint, in certain desperate cases of tuberculosis of the tarsus, and in the form of inlays to hasten or insure bony union in erasure or excision operations for adult tuberculosis of the knee or hip.
3. In certain cases of paralytic scoliosis to support the weakened spine and prevent lateral deviation, due to superincumbent weight and unbalanced muscle pull.
4. To immobilize and support or replace bones of the tarsus destroyed, or partly destroyed, by tuberculosis.
5. To correct deformity or restore balance in congenital clubfoot and acquired deformity from local disease or paralysis.
6. As a substitute for all metal plates, screws, nails, spikes, and wires, as used in the internal fixation of fractures and other conditions. The graft, in the form of inlays and various sizes of nails or pegs, is employed by the author in all types of fractures, such as fresh and ununited fracture of the long bones and of the neck of the femur.
7. To produce a permanent closure of nerve foramina after nerve resection for neuralgia (Kanavel).
8. As a prevention of luxating or slipping patellae by raising the low femoral condyle by inserting a graft in the form of a wedge.
9. To aid, in the form of numerous small grafts, rapid bone union where joint resection has been done or where a large graft has been used.
10. To strengthen and prevent lordosis or other deformity of the spine, in cases of spina bifida, where a large amount of bone is congenitally absent.
11. To replace the head and neck of the femur, when previously destroyed by disease, the head and neck of the astragalus being used as a graft (Roberts).
12. In congenital and paralytic dislocations of the hip where the acetabulum is shallow and the femoral head will not remain in place. The upper half of the meagre rim of the acetabulum is separated with a chisel and forced out and down, forming a pronounced rim. The cuneiform cavity thus produced is filled with wedge grafts.
13. To produce an ankylosis of the ankle joint in severe paralytic cases, or tuber-

culosis in the adult, by placing a bone-graft peg through the os calcis and astragalus into the lower end of the tibia (Lexer).

14. To replace bone removed for osteomyelitis, tuberculosis, and spina ventosa.
15. For deformities of the nose, by contacting graft with nasal bones. If the skin incision is made in the tip of the nose, the scar is not noticeable.
16. To replace or repair defects of the lower jaw; to fill in sunken spaces in the face, in the forehead following operation, in bony defects due to tuberculous osteitis of the facial bones, in recession of the superior maxilla due to harelip. To replace a mastoid process removed by operation.
17. In intraarticular fracture-dislocations, the head of the humerus or femur, etc., should be replaced, at an open operation, as a graft.
18. To repair cavities in the cranial bones by transferring from the immediate neighborhood one or two segments of the external table covered with periosteum. The cortex of the tibia or a portion of the scapula may likewise be used; the latter source is preferable, as both surfaces of the graft are covered with periosteum.

SUMMARY

The bone graft is a trustworthy surgical agent, as proved by the author's uniform success in its use in over 400 surgical cases; also by a careful study of its results, microscopically, macroscopically, and by the X-ray, when used experimentally in the presence of both primary union and sepsis. The field of usefulness of the cortical graft is distinctly enhanced because of its resistance to tubercular and attenuated pyogenic infection. Its field is also enlarged by the employment of motor-driven instruments, circular saws of different sizes, the adjustable twin saws, and the lathe or dowel instrument with different adjustments for making, as conditions demand, various sizes of bone-graft inlays, nails, or spikes. By the use of this motor outfit and its products, in conjunction with kangaroo-tendon, the author has been able during the past two years to avoid entirely the use of metal in the form of screws, nails, Lane's plates, wire, etc., for internal bone-fixation purposes. This has been made possible, largely, by utilizing the best of well-known mechanical devices hitherto rarely, if at all, used in surgery—such as bone inlays, wedges, dowels, tongue and groove joints, mortised and dove-tailed joints.

CONTRAINDICATIONS

The only contraindications to the surgical use of the bone graft are a markedly septic field of operation and excessive scar tissue as an environment. Syphilis should be cured before operation, although one case of syphilitic osteitis of the spine has been unintentionally operated. The graft healed in immediately and controlled entirely the spinal symptoms.