CHAPTER 38
DELAYED UNION, NONUNION, AND MALUNION

DAVID M. NUNAMAKER, FREDERIC W. RHINELANDER, AND R. BRUCE HEPPENSTALL

Inadequate response to the fracture injury sometimes occurs, resulting in delayed union or nonunion. Most fractures, if left completely alone, would probably heal but with such malunion that function might be lost. The role of the clinician is to promote functional fracture healing. This chapter is designed to discuss the problems that sometimes occurwith fracture treatment, the reasons for these problems, and some methods to overcome them.

Since the time of Hippocrates it has been advocated that immobilization of fractures to some degree or another is advantageous to their eventual union. The type and extent of immobility vary with the form of treatment and may play an important part in the overall result. It has been estimated that of the nearly 2 million fractures that occur yearly in humans, nearly 5% become nonunions.(23) In the dog, no such statistics are available. Clinical practice, however, shows that delayed union and nonunion are not uncommon problems.(39)

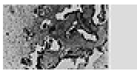
DELAYED UNION

In normal fractures, a certain amount of time is required before bone healing can be expected to occur. This normal time may vary according to age, species, breed, bone involved, level of the fracture, and associated soft tissue injury. Delayed union, by definition, is present when an adequate period of time has elapsed since the initial injury without achieving bone union, taking into account the above variables (Fig. 38-1). The fact that a bone is delayed in its union does not mean that it will become a nonunion. Nonunion is one end result of a delayed union, and the differentiation between the two is sometimes difficult to make. Classically the stated reasons for delayed union are problems such as inadequate reduction, inadequate immobilization, distraction, loss of blood supply, and infection.

Inadequate reduction of a fracture, regardless of its cause, may be a prime reason for delayed union or nonunion. It usually leads to instability or poor immobilization. In addition, inadequate reduction may be caused by superimposition of soft tissues through the fracture area, which may delay healing. Soft tissue disruption usually leads to loss of vascular supply at the fracture site. In well-muscled areas, this vascular supply may return quickly. In other areas, such as the distal third of the radius and ulna in the dog, in which little muscle is present, this vascular supply may not return.

Inadequate immobilization may result in biomechanical as well as physiologic problems associated with fracture healing (Fig. 38-2). Perren, in a recent publication, states his hypothesis regarding the problems associated with relative motion at the fracture site.(30) His concern about the tolerance of repair tissue to motion, especially elongation (strain), fits into what we know about the normal course of classic fracture healing. The interfragmentary strain levels in the tissues of the healing fracture show that small gaps require very little motion to disrupt the tissue, whereas larger gaps may allow for larger amounts of motion before tissue disruption occurs. This theory accommodates the two types of fracture healing that occur so commonly in veterinary orthopaedics: cast immobilization with relative motion (classic fracture healing) and plate fixation with stable internal fixation (primary fracture healing). In classic fracture healing, the fracture ends are usually immobilized first with a hematoma, which until it is organized is capable of an infinite amount of elongation. As this hematoma organizes into a fibrin clot, granulation tissue appears in the area. Granulation tissue can elongate approximately 100% before rupture, thereby allowing early relative immobilization of these fracture fragment ends. As the granulation tissue is replaced by cartilage, which has an elongation property of approximately 10% to rupture, it can be seen that the fracture must become relatively more stable. Finally, bone, with its elongation of approximately 2% to rupture, fills in the fracture gap, completing bone union. Thus it can be seen that if there is a relatively large gap of many millimeters, this gap can change its dimension initially up to lOO% without disrupting the early granulation tissue. If, in fact, the bone is held together with a more rigid plate, the gap would be considerably less. Hence, the motion tolerated at the site of the fracture to provide ingrowth of this granulation would be even more restricted. Therefore, with the small gaps allowed by rigid fixation, small amounts of motion have a much more significant (harmful) effect than the same amount of motion with large gaps. Since the physiology of fracture healing follows this course, which is related to the mechanics of the tissue involved, it is important when dealing with a delayed union or nonunion to ascertain which problems are involved to try to institute changes in the treatment. These changes can be very slight, such as in modification of casts or splints or immobilization of the patient, or they can be the extremes of changing the type of fracture treatment entirely. The fact that fracture healing is delayed and may eventually go on to union is often not sufficient reason to allow treatment to continue as was originally instituted. Many times it will be beneficial to the patient to change the form of treatment so that functional healing can occur more rapidly, thereby returning the animal to a functional life, while at the same time negating some of the problems of prolonged treatment.

FIG. 38-1 Mature canine radius and ulna 6 weeks after displaced fracture and application of plaster cast. (A) Final roentgenograms show external callus traversed by a zone of radiolucency, a typical picture of fibrocartilaginous delayed union. (B) Microangiogram of



the radial fracture shown in A reveals the avascular zone corresponding to the zone of radiolucency. This represents a plate of fibrocartilage. (original magnification x 4) (C) Photomicrograph of histologic section from a similar area in another experiment shows the very active vascular Invasion of the fibrocartilage and the replacement by new bone in the external callus (H & E, x 125). (A, B. Yasuda I: Fundamental aspects of fracture treatment. J Kyoto Med Soc 4:395, l953; G. Rhinelander FW, Sarogry RA: Microangiography in bone healing: Undisplaced closed fractures. J Bone Joint Surg 44A:l273, 1962)

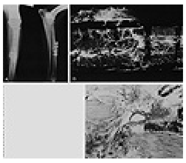


FIG. 38-2 Mature canine radius 6 weeks after osteotomy and fixation with a standard four-hole plate and screws. (A) Standard roentgenogram shows extrusion of the two proximal screws with elevation of the plate. The osteotomy site is radiolucent and is bordered by small mounds of external callus in the cranial-caudal projection. (B) Microangiogram shows loosening and elevation of the plate on the left, with an excellent cortical blood supply, while the vessels in the osteotomy site are a congested mass. The cortex beneath the tight portion of the plate, on the right, contains a few small vessels coming from the medulla. (original magnification x 53 (C) Photomicrographic enlargement at the osteotomy site shows debris and fibrous tissue adjacent to the mass of disorganized blood vessels on the- right. (H & E, x 52.5) (A, Rhinelander FW, Wilson JW: Blood supply to developing mature and healing bone. In Sumner-Smith (ed): Bone in Clinical Orthopaedics, Chap 2. Philadelphia, WB Saunders, 1982; B. C, Rhinelander FW: Circulation in bone. In Boume (ed) The Biochemistry and Physiology of Bone, 2nd ed, vol 2. chap 1. New York, Academic Press, 1972)

NONUNION

As stated above, the differentiation between delayed union and nonunion is sometimes difficult. Nonunion is defined as the cessation of all reparative processes of healing without bony union. Since all of the factors discussed under delayed union usually occur to a more severe degree in nonunion, the differentiation between delayed and nonunion is often based on radiographic criteria and time. In humans, failure to show any progressive change in the radiographic appearance for at least 3 months after the period of time during which normal fracture union would be thought to have occurred, is evidence of nonunion.(23) The changes in radiographic appearance may be slight, and therefore radiographs should be scrutinized monthly to see if, in fact, changes have occurred. Personal experiences with an experimental model of delayed union in the adult beagle radius have shown union occurring in all animals between 37 and 52 weeks. No unions occurred before 37 weeks, although radiographic appearance of nonunion was present as described below. Careful radiographic evaluation did show changes over a 3-month period, however. Thus, it is difficult to imagine at what point fracture healing may cease completely.

The clinical diagnosis of nonunion is usually based on the history and physical findings. The animal may have some pain, which is usually mild. The most common sign is nonuse of the extremity, which may also lead to muscle atrophy, joint stiffness, progressive angulation, and malalignment of the bone. Physical examination reveals motion at the fracture site. Sometimes this motion is difficult to appreciate, since the fracture may be in close proximity to the joint and the motion may be thought to be within the joint. Usually when there is a nonunion close to a joint, the joint motion is limited. Deep palpation over the fracture site may yield an expression of pain in the patient, but this is not a constant finding. Radiographically the diagnosis of nonunion is made by the following findings: a radiolucent line through the fracture site, sealing off of the medullary cavity with sclerosis at the edge of the fractured bone, and bony resorption or regional osteoporosis above and below the fracture site. The bone ends may be somewhat rounded, and a large hypertrophic callus may be present. This "elephant foot" appearance of the callus has been thought of as one of the hallmarks of nonunion. Rarely, an atrophic nonunion is seen without any callus at the fractured bone ends. Sometimes a large gap exists between the ends of the bones while the bones themselves may appear to have little callus formation. This is usually more common when associated with severe soft tissue injury or a loss of vascularity in the area. It may be more common when viewing nonunion after internal fixation and open reduction. When in doubt as to the structural rigidity of the fracture, stress films may be taken to show angular deformities that may occur at the fracture site. Once a diagnosis is complete, treatment must be initiated. Before this is done, however, it is important to do a thorough physical examination of the animal and the injured part to ascertain any associated nerve damage or limitations of joints and soft tissues. It is often possible through surgical treatment to turn a nonunion into a strong union that still leaves the animal with a functionless extremity. The purpose of creating a union is for adequate function. If adequate function is not to be expected, the treatment should not be carried out. Functional requirements may dictate the need for other measures such as amputation.

The incidence of nonunion in the dog is unknown. It is well known, however, that the rates of nonunion seem to be higher in small breed rather than large breed dogs and that certain bones predominate.(39) SumnerSmith and Vaughan in two separate studies showed that approximately 60% of all nonunions in the dog occur in the radius and ulna. Twenty-five percent occur in the tibia, and 15% are in the femur.(33,39) There were no humeral nonunions in this study, but they are not rare in our experience. Nonunion can occur at any level in any bone.

TREATMENT

Treatment of nonunion is directed toward improving the local physiological and mechanical environment to allow fracture healing to proceed. This is done in part by addressing all of the problems that cause delayed union and nonunion as described above. Although many forms of treatment for nonunion have been advocated in the past, we use two methods that can accommodate most if not all nonunions.

TRADITIONAL

The first technique is that of compression plating in which an open surgical reduction is made of the nonunion site. If adequate reduction and alignment of the fracture were achieved initially and some callus is evident at the fracture site, the plate may be applied without disturbing the nonunion site. Compression is applied to the bone ends as the plate is applied. This compression of soft tissues lasts only for a short time, but stability at the fracture site is obtained. No additional bone graft is needed and healing is usually seen within 6 to 12 weeks. When the bone alignment at the time of operation was inadequate, the nonunion site is disturbed and the fibrous connective tissue and cartilage are debrided and the bones realigned before plate application. The use of a cancerous bone graft for these cases helps ensure bone healing. When an atrophic nonunion occurs, most commonly in radial and ulnar fractures of the toy breed dogs, it is important to use cancellous bone grafts to help consolidate a union.

Weight bearing seems to play an important role in bone healing. The fact that bones may grow in tissue culture but fractures do not heal in this environment leads one to suggest partial then full weight bearing when treating fractures and especially nonunions. Many clinicians have seen the gradual osteoporosis and resorption of bone in the ulna and radius of small breed dogs subjected to prolonged cast immobilization and nonweight bearing. This problem, once begun, may be very difficult to reverse, especially in an animal that is quite content to walk only on its other three legs. All attempts at fracture treatment and especially nonunion treatment should have as a goal partial then full weight bearing during the treatment period. This dictum mandates some form of stable internal fixation or functional cast treatment of the fracture

Occasionally, nonunions occur after the use of round intramedullary pins. In such cases the pin maintains reduction, but rotating motion at the level of the fracture site prevents union. Often it may not be necessary to change fixation methods but rather add additional stabilization with a bone graft. The use of an on-edge halfthickness iliac bone graft has been almost universally successful in these cases. No special instrumentation is necessary, and resolution of the fracture usually occurs within 12 weeks. The technique is described in Chapter 39, Bone Grafting.

Often with loose-fitting, round intramedullary pins it is not necessary or desirable to change from an intramedullary device to a periosteal device (plate), since further disruption of the vascular supply to the bone may occur. In these cases the replacement with a tight-fitting intramedullary device plus a bone graft (cancerous or half-thickness on-edge iliac graft) may resolve the problem adequately.

Rectifying the causes of delayed union and nonunion can allow functional fracture healing. Providing stability with weight bearing and the use of bone grafts when necessary will solve most cases of nonunion. Other modes of treatment are becoming more popular in the treatment of nonunions in humans and have been used in animals. Direct electrical stimulation with an electrode placed into the nonunion site as well as noninvasive techniques using electromagnetic fields and capacitive coupling may change the way we treat nonunions in the future. The clinician should be aware of new methods but must try to keep them in perspective, since good results are the objective.

ELECTRICAL STIMULATION

Modern use of electrical energy for the treatment of nonunions had its start in 1953 when Yasuda from Japan demonstrated new-bone formation around a negative electrode (cathode) following application of a small current in the microamperage range, applied continuously for 3 weeks in a rabbit femur.(37) He also described stressgenerated potentials in bone.(22) In the late 1950s Bassett and Becker in the United States reported on similar independent studies with the same result.(2) In the early 1960s Shamos and Lavine, also working in an independent laboratory, reported similar findings.(36) In the early 1960s Friedenberg and Brighton took a different approach to the problem and documented the bioelectrical signals in bone.(16) These were signals from viable, nonstressed bone and represented a different electrical potential that was present in bone. Therefore, two separate types of electrical signals or potentials were described in bone: stress-generated or strain-related potentials and bioelectrical or standing potentials(2,10,16,18,22,36)

If bone is stressed, a negative potential may be measured from the concave side or compression side of the bone and a positive potential from the convex side or tension side of the bone. It is important to realize that these potentials are not dependent on cell viability and are produced whenever the bone is stressed. These potentials are still present even if the bone has been decalcified. Therefore, it has been demonstrated that the potential itself originates from the organic and not the mineral component of bone.(10)

Bioelectrical potentials are measured from viable, nonstressed bone. They are absent in dead bone. In a typical long bone, the diaphyseal region exhibits an electropositive charge, while the growth plate metaphyseal region exhibits an electronegative charge. If a fracture is created in the diaphyseal region, the normal electropositive charge reverts to a negative charge and remains electronegative until the fracture heals, when it again becomes electropositive.(18)

Another important discovery was made in the opposite growth plate metaphyseal area, with a fracture in the diaphysis. Under these conditions, the normal electronegative potential is intensified and remains that way until the fracture has healed. It is known clinically that bone overgrowth has been associated with long-bone fractures in children when the fracture surfaces are properly realigned. It is probable that the increased electronegative charge at the growth plate may account for this finding, since it is absent in adult bone.

At the time of preparation of this chapter, there were three major devices on the market for electrical stimulation of nonunion as approved by the Food and Drug Administration (FDA) for use in humans. The first is the direct-current stimulator supplied by Zimmer (Warsaw, Indiana). It was developed by Brighton, Friedenberg, and Black and the research group at the University of Pennsylvania School of Medicine.(7,8,12,13,24) The second is inductive coupling supplied by Electro-Biology, Inc. (Fairfield, New Jersey). This was developed by Bassett of Columbia University in New York.(3,5,6) The third is direct current stimulation by a completely implantable system supplied by Telectronics Proprietary Ltd. (Milwaukee, Wisconsin). It was developed by Dwyer and Wickham of Australia. (14)

The semi-invasive direct-current stimulator has demonstrated the following results in the laboratory: (1) New bone formation occurs at the negative electrode (cathode). (2) Bone resorption occurs at the positive electrode (anode) if it is implanted in bone. The anode is, therefore, situated externally to the bone on the skin and does not interfere with osseous metabolism. (3) If a constant direct current is applied to bone, a typical dose-response curve is demonstrated. Current levels of less than 5 uA fail to produce new bone. At current levels of 5 uA to 20 uA, progressively increasing amounts of bone are formed. However, if current levels of greater than 20 uA are induced, cellular necrosis results at the cathode. (4) If two electrodes are implanted in tissues, a resistance quickly develops between the electrodes, resulting in a decrease in current. Therefore, a transistorized, controlled power pack must be used if a constant current is to be maintained between the electrodes as the resistance fluctuates. (5) Various metals exhibit different dose response curves at the negative pole. Stainless steel is optimal at 20 uA, platinum is optimal at 5 uA to 20 uA, silver is optimal at 0.1 uA to I. I uA. (6) If the anode is implanted in bone, resorption occurs around the electrode. If, however, the anode is positioned on the skin to complete the circuit, a minimal skin reaction may result. This is decreased or prevented by moving the electrode pad to a different location. The system requires patient cooperation, since the device is transcutaneous, with the electrode implanted at the nonunion site and the power supply and signal generator remaining external.

An electrical signal may also be induced in bone by an electrical field that is applied external to the affected limb. T he electrical field is created by means of inductive coupling. This method involves application of external coils at the level of the fracture site. A current varying with time is applied, which results in a time-varying magnetic field inducing a time-varying electrical field. The basic research behind this method involved applying a pair of Helmholtz coils both medially and laterally to the dog hind limb to stimulate healing of an osteotomy of the fibula between the coils.(4) A time-varying electrical field was initiated in the bone by an alternating current applied to the coils, which resulted in a time-varying magnetic field. Specifics of the circuit involved a pulse duration of 150 us, repeated at 6 Hz to 5 Hz, resulting in a peak of 20 mV/cm of bone. The osteotomized fibula subjected to this treatment for 28 days was mechanically stiffer than the control osteotomized fibula.(5) This method was then applied clinically to patients with nonunion.

The completely invasive direct-current stimulator was originally developed by Dwyer in Australia for the management of spinal fusions. It involves complete surgical implantation of the cathode at the nonunion site, as well as implantation of the power pack and anode in soft tissue in close proximity to the nonunion site. The power pack itself is encapsulated in a pure titanium shell and the cathode is made of titanium, while the anode is made of platinum (Telectronics Proprietary, Ltd.). In the usual management of nonunion, a 20 uA direct current is delivered to a single cathode, which is wrapped in a helical configuration to span the nonunion site. The advantage of this system is that it does not require cooperation on the part of the patient. All the instrumentation is buried under the skin and therefore does not require any type of manipulation by the surgeon or the patient. (I4)

It appears from a review of the literature that all of the three systems described above provide a similar overall success rate of approximately 80% to 87% for the treatment of established nonunions in man. The semi-invasive direct-current system and the inductive coupling coil system both require cooperation on the part of the patient and the treating physician. The completely invasive direct-current stimulator does not require cooperation and has been recommended in humans for patients that may be uncooperative. Infection is a contraindication to the use of the semi-invasive direct-current stimulator and the completely invasive stimulator. However, the inductive coupling coils have been used in the presence of infection and have been reported to give good results to date.(37)

Another application of an electrical field is capacitive coupling. In this type of electrical stimulation, an electrical field is induced in bone by an external capacitor. This requires two charged metal plates that are positioned on either side of the animal's limb and are attached to an appropriate voltage source. A constant capacitive coupled field may then be induced, or a pulsed capacitive coupled field may be used. Early studies to date have demonstrated that both the constant and pulsed capacitive coupled electrical fields have altered fracture repair and epiphyseal plate growth in rabbits. This method is presently being evaluated and may well represent a mode of electrical stimulation in the future.

The exact mechanism of action of electrical stimulation at the cellular level is unknown at the present time. Several theories have been advocated in this regard. It has been demonstrated previously that collagen fibers will realign under the influence of electrical fields. It is possible that the cathode alters the local oxygen microenvironment by consuming oxygen at its tip. If this method is operational, the local environment during bone deposition is one of relative hypoxia. It has been demonstrated that bone forms under conditions of relative hypoxia and that bone follows predominantly an anaerobic pathway for metabolism.9 Activation of the cyclic adenosine monophosphate (cAMP) system has also been suggested as a mechanism of action for electricity. It is probable that the effect of electricity on the cellular environment is multi-factorial, and further studies at a basic level will help to outline the exact mechanisms of action.

MALUNION

Malunion is defined as a healing of the bones in an abnormal position; Malunions can be classified as functional or nonfunctional. Functional malunions are usually those that have small deviations from normal axes that do not incapacitate the patient. Some of these functional malunions may be unacceptable in dogs, especially if the animal is a show specimen. Nonfunctional malunions will be discussed in this section. Malunions can occur with both axial deviations and rotational deformities. Axial deformities such as the valgus or lateral deviation of the forepaw that occurs with a poorly set fracture may cause secondary degenerative joint disease of the carpus because of continued weight bearing in an abnormal position. Very often these axial deviation malunions will develop associated joint problems. Fractures associated with physeal injuries may also lead to deformities that are usually not classified as malunions. These deformities are associated with premature closure of the growth plate. Very often the deformity in these cases is the same as that of malunion, but it occurred after the time of union because of further growth of one or more bones in relationship to other nongrowing bones. Rotational malunions also occur and are usually those of external rotation. These deformities allow a surprising degree of function in most animal species. Conversely, internal rotational deformities may cause more serious problems but are uncommon. Most external rotational deformities are not even appreciated if they are less than 10¡. It must be remembered when dealing with fractures that some animal breeds (chondrodystrophoid) exhibit skeletal abnormalities in their normal state. Therefore, when reducing fractures in these breeds it is important to match the "normal" deformity of the opposite side.

Most external rotational and lateral axis deformities are associated with the improper positioning of the animal during the application of a cast or splint. Placing the injured leg in an uppermost position when the animal is in lateral recumbency will tend to give an external rotational and lateral deviation deformity when the limb is manipulated. This can easily be corrected by placing casts and splints on animals with the injured limb on the down side. Here extension and manipulation of the limb is more likely to give a straight limb without this valgus deformity. External rotation may still occur if special attention is not paid when immobilizing radial and ulnar fractures by this method. Rotational deformities are quite common with femoral fractures and usually relate to the muscles that control each end of the fracture fragment. Fractures of the femur usually allow the proximal fracture fragment to be held in external rotation because of spasms and contractions of the iliopsoas muscle. If, when using internal fixation with an intramedullary pin or external fixation with a cast or splint, this external rotation of the proximal femur is not taken into account, the femur will then heal with the proximal fragment in external rotation and the distal fragment in the neutral position. Following union the animal controls the proximal femur through its proper position, thereby giving an internal rotational deformity to the distal femur, resulting in a knock-kneed stance. This is sometimes a disconcerting problem for the dog and may lead to gait abnormalities or lameness. If, in fact, the femoral fracture is approached with the idea that since the proximal fragment is already in external rotation, the distal fragment should be immobilized in external rotation also, this deformity will not occur. At times loose-fitting intramedullary pins allow this deformity to occur.

Correction of malunions is undertaken when the malunion is a functional liability to the animal. Correction of malunions involves osteotomies of bone, which can have all the serious sequela of bone fractures such as delayed union, nonunion, and infection. No osteotomies should be undertaken lightly, although in most animals adequate treatment of a malunion would give a very good result. The techniques used for treatment of malunions are discussed in Chapter 40, Principles and Techniques of Osteotomy.

Most malalignments should be detected before healing occurs. In these cases adequate treatment is under taken by resolving the axis or rotational deformity that exists, thereby allowing normal union to take place. It is usually better to interrupt the fracture healing at an early stage to correct the deformity than to wait until osteotomy is needed. Proper follow-up of cases after internal fixation or splinting should make the occurrence of malunion very infrequent.

Prev Next Home Contents Glossary

REFERENCES

1. Bassett CAL: Biologic significance of piezoelectricity. Calcif Tissue Res 1:252, 1968
2. Bassett CAL, Becker RO: Generation of electrical potentials by bone in response to mechanical stress. Science 137:1063, 1962
3. Bassett CAL, Pawluk RJ: Noninvasive methods for stimulating osteogenesis. J Biomed Mater Res 9:371, 1975
4. Bassett CAL, Pawluk RJ, Becker RO: Effects of electric currents on bone in vivo. Nature 204:652, 1964
5. Bassett CAL, Pawluk RJ, Pilla AA: Augmentation of bone repair by inductively coupled electromagnetic fields. Science 184:575, 1974
6. Bassett CAL, Pilla AA, Pawluk RJ: A non-operative salvage of surgically-resistant pseudoarthroses and nonunions by pulsing electromagnetic fields: A preliminary report. Clin Orthop 124: 128, 1977
7. Brighton CT: Adler S, Black J et al: Cathodic oxygen consumption and electrically induced osteogenesis. Clin Orthop 107:277, 1975
8. Brighton CT: Treatment of nonunion of the tibia with constant direct current. 1980 Fitts Lecture ASST J Trauma 21: 189, 1981
9. Brighton CT, Adler S. Black J et al: Cathodic oxygen consumption and electrically induced osteogenesis. Clin Orthop 107:277, 1975
10. Brighton CT, Black J. Pollack SR: Electrical Properties of Bone and Cartilage. New York, Grune & Stratton, 1979
Il. Brighton CT, Cronkey JE, Osterman AL: In vitro epiphyseal plate growth in various constant electrical fields. J Bone Joint Surg 58A:971, 1976
12. Brighton CT, Friedenberg ZB, Mitchell EI et al: Treatment of nonunion with constant direct current. Clin Orthop 124:106, 1977
13. Brighton CT, Friedenberg ZB, Zemsky LM et al: Direct-current stimulation of nonunion and congenital pseudoarthrosis: Exploration of its clinical application. J Bone Joint Surg 57A:368, 1975
14. Dwyer AF, Wickham GG: Direct current stimulation in spine fusion. Med J Austr 1:73, 1974
15. Friedenberg ZB, Andrews ET, Smolenski BI et al: Bone reaction to varying amounts of direct current. Surg Gynecol Obstet 131:894, 1970
16. Friedenberg ZB, Brighton CT: Bioelectric potentials in bone. J Bone Joint Surg 48A:915, 1966
17. Friedenberg ZB, Harlow MC, Brighton CT: Healing of nonunion of the medial malleolus by means of direct current: A case report. J Trauma 11: 883, 1971
18. Friedenberg ZB, Harlow MC, Heppenstall RB et al: The cellular origin of bioelectric potentials in bone. Calcif Tissue Res 13:53, 1972
19. Friedenberg ZB, Kohanim M: The effect of direct current on bone. Surg Gynecol Obstet 127:97, 1968
20. Friedenberg ZB, Roberts PG Jr, Didizian NH et al: Stimulation of fracture healing by direct current in the rabbit fibula. J

Bone Joint Surg 53A:1400, 1971
21. Friedenberg ZB, Zemsky LM, Pollis RP et al: The response of non-traumatized bone to direct current. J Bone Joint Surg 56A: 1023, 1974
22. Fukada E, Yasuda 1: Piezoelectric effects in collagen. J J Appl Physiol 3:117, 1964
23. Heppenstall RB: Fracture Treatment and Healing. Philadelphia, WB Saunders, 1980
24. Heppenstall RB: Constant direct current treatment of established nonunion of the tibia. Clin Orthop (in press)
25. Lavine LS, Lustrin I, Shamos MH et al: Electric enhancement of bone healing. Science 175:1118, 1972
26. Lente RW: Cases of un-united fracture treated by electricity. NY State J Med 5:317, 1950
27. Levy DD, Rubin B: Inducing bone growth in vivo by pulse stimulation. Clin Orthop 88:218, 1972
28. Norton LA: In vivo bone growth in a controlled electric field. Ann NY Acad Sci 238:466, 1974
29. Norton LA, Rodan GA, Bourrett LA: Epiphyseal cartilage cAMP changes produced by electrical and mechanical perturbations. Clin Orthop 124:59, 1977
30. Perren SM: Physical and biological aspects of fracture healing with special reference to internal fixation. Clin Orthop Rel Res 138:175, 1979
31. Perren SM et al: Cortical bone healing. Acta Orthop Scand Suppl 125, 1969
32. Rhinelander FW: Circulation in bone. In Bourne (ed): The Biochemistry and Physiology of Bone, vol 2, 2nd ed. chap 1. New York, Academic Press, 1972
33. Rhinelander FW, Baragry RA: Microangiography in bone healing: 1. Undisplaced closed fractures. J Bone Joint Surg 44A:1273, 1962
34. Rhinelander FW, Phillips RS, Steel WM et al: Microangiography in bone healing: 11. Displaced closed fractures. J Bone Joint Surg 50A:643, 1968
35. Rhinelander FW, Wilson JW: Blood supply to developing mature and healing bone. In Sumner-Smith G (ed): Bone in Clinical Orthopaedics, chap 2. Philadelphia, WB Saunders, 1982
36. Shamos MH, Lavine LS, Shamos MI: Piezoelectric effect in bone. Nature 197:81, 1963
37. Spadaro JA: Electrically stimulated bone growth in animals and man: Review of the literature. Clin Orthop 122:325, 1977
38. Sumner-Smith G: Histological study of fracture nonunion in small dogs. J Small Anim Pract 15:571, 1974
39. Vaughan LC: A clinical study of nonunion fractures in the dog. J Small Anim Pract 5: 173, 1964
40. Yasuda 1: Fundamental aspects of fracture treatment. J Kyoto Med Soc 4:395, 1953