Electrical Stimulation And Fracture Healing

Satter S.A., Islam M.S., Rabbani K.S., and Talukder M.S. (1999) Pulsed electromagnetic fields for the treatment of bone fractures. *Bangladesh Med. Res. Counc. Bull.* 25, 6-10.

Abstract: The effectiveness of electrical stimulation and Pulsed Electro Magnetic Field (PEMF) stimulation for enhancement of bone healing has been reported by many workers. The mechanism of osteogenesis is not clear, therefore, studies look for empirical evidence. The present study involved a clinical trial using low amplitude PEMF on 19 patients with non-union or delayed union of the long bones. The pulse system used was similar in shape to Bassett's single pulse system where the electric voltage pulse was 0.3 mSec wide repeating every 12 mSec making a frequency of about 80 Hz. The peak magnetic fields were of the order of 0.01 to 0.1 m Tesla, hundred to thousand times smaller than that of Bassett. Among the 13 who completed this treatment schedule the history of non-union was an average of 41.3 weeks. Within an average treatment period of 14 weeks, 11 of the 13 patients had successful bone healing. The two unsuccessful cases had bone gaps greater than 1 cm following removal of dead bone after infection. However, use of such a low field negates Bassett's claim for a narrow window for shape and amplitude of wave form, and justifies further experimental study and an attempt to understand the underlying mechanism

Abeed R.I., Naseer M., and Abel E.W. (1998) Capacitively coupled electrical stimulation treatment: results from patients with failed long bone fracture unions. *J. Orthop. Trauma* 12, 510-513.

Abstract: OBJECTIVE: To determine the extent to which capacitively coupled electrical stimulation (CCEST) at a long bone fracture site can promote healing of nonunited fractures. DESIGN: Sixteen patients with nonunited fractures of nine to seventy-six months were treated with CCEST. Thirteen patients had previously undergone one or more surgical procedures, and the other three had been given plaster casts. A sixty- three-kilohertz, six-volt peak-to-peak sine wave signal was applied across two forty-millimeter-diameter stainless steel plates placed on the skin at opposite sides of the fracture site. The device was used for up to thirty weeks until either healing occurred or it was removed after this period and considered to have failed. RESULTS: Eleven of the nonunions achieved union at an average of fifteen weeks of stimulation. The only significant factor determining the success of healing was the distance between the plates; a distance of eighty millimeters or less resulted in healing in all cases. Healing was not affected significantly by any of the following factors: whether or not the nonunion had been treated surgically prior to stimulation, whether or not it had been infected, whether or not the patient bore weight after treatment, or by the presence or absence of metal at the fracture site from previous surgery. CONCLUSIONS: These findings confirm those of previous studies that CCEST promotes bone healing of fracture nonunions. The dependence of healing on the interplate distance suggests that maintaining sufficient current across the plates is necessary to allow healing, which for larger bones may be achieved by increasing the area of the plates, the applied voltage, or the excitation frequency of the stimulation signal

Zamora-Navas P., Borras V.A., Antelo L.R., Saras A., Jr., and Pena Reina M.C. (1995) Electrical stimulation of bone nonunion with the presence of a gap. *Acta Orthop. Belg.* 61, 169-176.

Abstract: A total of 22 established nonunions was treated with a capacitively-coupled electrical signal. A gap of 0.5 cm or more between the fragments was present in all of these nonunions. After an average of 26 weeks of treatment with capacitive coupling, radiographic assessment showed solid bone union in 72.7% of the cases. The results were better when the fracture site was metaphyseal. When the site was diaphyseal, bone healing was mainly achieved by bone trabeculae invading the gap. When the site was metaphyseal, healing occurred by the formation of a peripheral callus. The results were not affected by the presence of infection. In 8 of the cases osteomyelitis occurred, but all healed

MacGinitie L.A., Wu D.D., and Cochran G.V. (1993) Streaming potentials in healing, remodeling, and intact cortical bone. *J. Bone Miner. Res.* 8, 1323-1335.
Abstract: Electrical fields have been implicated in accelerated bone healing and as a transduction mechanism for mechanically driven bone remodeling. Applied mechanical or electrical stimulation of bone remodeling suggests that this depends on the magnitude, frequency, and duration of the stimulus. The magnitude of endogenous electrical fields, manifest by streaming potentials (SPs) across canine cortical bone, were measured as a function of bending frequency in vivo and then in vitro at healing drill holes and at remodeling (ipsilateral) and normal, intact (contralateral) control sites in canine tibia. SP magnitudes normalized to periosteal strain were smaller for drill holes at 2 and 4 weeks postsurgery relative to either remodeling ($P < 0.05$ at 10 Hz) or normal intact ($P < 0.001$ at 10 Hz) controls both in vivo and in vitro. SPs of 12 week drill holes were similar to SPs of remodeling controls and tended to be smaller than SPs of normal intact controls. Mean SP normalized to bone impedance was approximately the same for all sites, suggesting that the smaller SPs during healing and remodeling relate to smaller bone impedance and/or larger porosity. SP as a function of bending frequency for normal sites was similar to that observed previously. SP versus frequency for drill holes and remodeling controls was more variable, probably because of variations in bone microstructure, and displayed a higher frequency content. The observed differences in SP magnitude and frequency response to loading associated with stages of healing indicate that endogenous electrical fields do indeed respond to the structural changes in healing and remodeling and are therefore capable of providing structural feedback information for the repair and remodeling process

Sisken B.F., Walker J., and Orgel M. (1993) Prospects on clinical applications of electrical stimulation for nerve regeneration. *J. Cell Biochem.* 51, 404-409.
Abstract: Regenerative capability is limited in higher vertebrates but present in organ systems such as skin, liver, bone, and to some extent, the nervous system. Peripheral nerves in particular have a relatively high potential for regeneration following injury. However, delay in regrowth or growth, blockage, or misdirection at the injury site, and growth to inappropriate end organs may compromise successful regeneration, leading to poor clinical results. Recent studies indicate that low-intensity electrical stimulation is equivalent to various growth factors, offering avenues to improve these outcomes. We present a review of studies using electric and electromagnetic fields that provide evidence for the enhancement of regeneration following nerve injury. Electric and electromagnetic fields (EMFs) have been used to heal fracture non-unions. This technology emerged as a consequence of basic studies [Yasuda, 1953; Fukada and Yasuda, 1957] demonstrating the piezoelectric properties of (dry) bone. The principle for using electrical stimulation for bone healing originated from the work of Bassett and Becker [1962], who described

asymmetric voltage waveforms from mechanically deformed live bone. These changes were presumed to occur in bone during normal physical activity as a result of mechanical forces, and it was postulated that these forces were linked to modifications in bone structure. Endogenous currents present in normal tissue and those that occur after injury were proposed to modify bone structure [Bassett, 1989]. These investigators proposed that tissue integrity and function could be restored by applying electrical and/or mechanical energy to the area of injury. They successfully applied electrical currents to nonhealing fractures (using surgically implanted electrodes or pulsed currents using surface electrodes) to aid endogenous currents in the healing process.(ABSTRACT TRUNCATED AT 250 WORDS)

Albert S.F. and Wong E. (1991) Electrical stimulation of bone repair. *Clin. Podiatr. Med. Surg.* 8, 923-935.
Abstract: Interest in methods of accelerating bone healing persists. Electrical stimulation has demonstrated consistently high success rates in recalcitrant, complicated nonunions. The promise of successful noninvasive alternatives for treating nonunions continues to be realized. Given the rapidity of advances in this field, it appears likely that acceleration of fracture repair by electrical stimulation will become more widespread in the future

Barden R.M. and Sinkora G.L. (1991) Bone stimulators for fusions and fractures. *Nurs. Clin. North Am.* 26, 89-103.
Abstract: Even though a complete understanding of electrical responses of bone has not been fully obtained, useful data toward this end have been gathered. The development of devices that use what is known about the bone's electrophysiologic properties has impacted patient care. Many health care professionals remain skeptical about the effects of electrical stimulation in bone healing. Therefore, further research is needed to help the practitioner formulate a more educated opinion on this form of therapy

Gupta T.D., Jain V.K., and Tandon P.N. (1991) Comparative study of bone growth by pulsed electromagnetic fields. *Med. Biol. Eng Comput.* 29, 113-120.
Abstract: Pulsed electromagnetic fields have been widely used for treatment of non-united fractures and congenital pseudarthrosis. Several electrical stimulation systems such as air-cored and iron-cored coils and solenoids have been used the world over and claimed to be effective. Electrical parameters such as pulse shape, magnitude and frequency differ widely, and the exact bone-healing mechanism is still not clearly understood. The study attempts to analytically investigate the effectiveness of various parameters and suggests an optimal stimulation waveform. Mathematical analysis of electric fields inside the bone together with Fourier analysis of induced voltage waveforms produced by commonly used electrical stimulation wave-forms has been performed. A hypothesis based on assigning different weightings to different frequencies for osteogenic response has been proposed. Using this hypothesis astonishingly similar effective values of electric fields have been found in different systems. It is shown that effective electric field rather than peak electric field is the main parameter responsible for osteogenesis. The results are in agreement with experimental findings made on human beings by different investigators

Uhl R.L. (1989) The use of electricity in bone healing. *Orthop. Rev.* 18, 1045-1050.
Abstract: The history of electrical bone healing and the vast amount of laboratory and

clinical data that support its efficacy are reviewed. The paper presents guidelines for the proper use of electrical stimulation and a description of the various systems available. The use of electrical stimulation to treat scaphoid fractures is covered in detail. Contraindications to the use of electrical stimulation are also addressed

Sanders-Shamis M., Bramlage L.R., Weisbrode S.E., and Gabel A.A. (1989) A preliminary investigation of the effect of selected electromagnetic field devices on healing of cannon bone osteotomies in horses. *Equine Vet. J.* 21, 201-205.
Abstract: The effect of electrical stimulation by means of selected electromagnetic field devices on healing of cannon bone osteotomies in horses was examined. The defects were created as 3 cm x 1 mm longitudinal osteotomies through the dorsal cortices of the mid- metacarpi/metatarsi of adult horses. This type of defect would asses bone healing in a situation similar to an acute, stable fracture of the cortex. Three electromagnetic devices of different design were tested in three different groups of horses. Healing was evaluated radiographically and histologically. Results showed that osteotomies treated with the electromagnetic devices healed similarly to untreated controls. Our conclusion is that the electromagnetic devices studied did not have a local effect on the repair process of an acute, stable, osseous defect

Ferrier J., Ross S.M., Kanehisa J., and Aubin J.E. (1986) Osteoclasts and osteoblasts migrate in opposite directions in response to a constant electrical field. *J. Cell Physiol* 129, 283-288.
Abstract: We have investigated in vitro the effects of the electrical field produced by constant current on freshly isolated rabbit osteoclasts and on well characterized clonal rat osteoblastlike cells. At field strengths of 0.1 and 1 V/mm, the osteoclasts migrated rapidly toward the positive electrode, whereas the osteoblastlike cells migrated in the opposite direction, toward the negative electrode. Thus, different cell types from the same tissue can respond differently to the same electrical signal. These results have important implications for hypotheses concerning the cellular mechanism of galvanotaxis, and may also clarify the cellular basis of the clinical application of electrical stimulation of bone healing

Schubert T., Kleditzsch J., and Wolf E. (1986) [Results of fluorescence microscopy studies of bone healing by direct stimulation with bipolar impulse currents and with the interference current procedure in the animal experiment]. *Z. Orthop. Ihre Grenzgeb.* 124, 6-12.
Abstract: 42 cross-breed rabbit bastards of either sex were osteotomized on the left proximal third of the tibia. A teflonisolated stable plating was made by means of the polychromatically KF-AO-instrumentarium. The animals were fluorescentlabelled in weekly intervals. Tetraverinex, alizarin complexon, fluorexon, xylenol orange and calceine were used as colours. The animals were stimulated in the bipolar squaretopped pulse current procedure (1 Hz and 10 Hz, resp., +/- 25 and +/- 50 microA, resp., intensity, permanent stimulation) or in the interference current procedure (oscillation frequency 100 Hz, intensity 1 mA, 4 hours daily). An osteotomized group served as a control. The undecalcified bone sections were quantitatively measured in the area of the periosteal and endoosteal accummulation seams as well as in the area of the Haversians canals and compared by means of multiple variance analyses. A delay in the Haversian remodelling within the first 2 weeks was found in the animals only osteotomized. This delay could not be detected in all electrically stimulated groups. The electrical stimulation leads to a shortening of the fracture healing period by skipping the physiologically occurring delay of the

Haversian remodelling in fractures and osteotomies. Further on there was derived a growth function of the osteones as a regression function r (t) = a + beta X e gamma t. For the rabbit the concrete formula expression r (t) = 50.9 X e-0.094 X t + 17.4 for the animals not treated and r (t) = 42.9 X e-0.067 X t + 8.5 for the electrical stimulated animals has been found.(ABSTRACT TRUNCATED AT 250 WORDS)

Kondo J. (1985) [Experimental histopathological studies of electrical callus formation and mechanism of bone healing by direct micro-electrical current]. *Nippon Seikeigeka Gakkai Zasshi* 59, 803-817.
Abstract: In order to get better understanding of the effects of electrical stimulation on bone healing processes, the author compared the healing processes of the femur in dogs between two groups: a stimulation group and a control group (non-stimulation group) which were experimentally prepared. These bone specimens were periodically extirpated and used for pathological examinations and X-ray micro-analysis. In the stimulation group, strong proliferation of osteoblasts and new trabecular formation in the bone marrow were observed at the 3rd day, and transition from fibrous to bony callus were noted at the 9th day; after the 3rd week bone remodeling was sparsely seen and bone healing period was shortened. In electromicroscopic observation, calcification of bone matrix and bone remodeling also seemed to be facilitated in this group. However, no marked differences in histological process of bone healing were observed between the stimulation group and the control group

Collier M.A., Kallfelz F.A., Rendano V.T., Krook L.P., and Schryver H.F. (1985) Capacitively coupled electrical stimulation of bone healing in the horse: in vivo study with a Salter type IV osteotomy model with stainless steel surface electrodes. *Am. J. Vet. Res.* 46, 622-631.
Abstract: The use of capacitively coupled low-voltage signals for stimulation of osteogenesis has been reported in a variety of animal models. Electrically induced osteogenesis was investigated with a capacitively coupled electric field on a radius (distal-lateral orientation) osteotomy model, in conjunction with internal fixation and postoperative loading. Twelve adult horses of either sex were allotted to 2 groups of 6; 1 group was given electrical stimulation and the other served as controls. A low-voltage high-frequency capacitively coupled electrical signal was locally and continuously applied to the electrically stimulated group for 60 days through external, bare stainless steel surface electrodes which were placed on the skin in circuit with a small, portable power source. Harness compatibility and stimulator and battery durability were excellent. However, stainless steel electrodes required a rigid maintenance schedule to maintain consistent current levels. Synovial fluid evaluation demonstrated intra- articular inflammation (decreased viscosity, hyaluronic acid, and increased protein concentration) 1 week postoperatively that generally improved during subsequent weeks and no distinction between groups was observed at 60 days. Radiographically, there was no difference in the appearance of the healing process of control and that of stimulated horses during the 60 days. Angiography showed bridging blood vessels in both groups. Uptake of a bone seeking radiopharmaceutical peaked at 3 weeks in both groups and was 1.92 +/- 0.6 cps/pixel/mCi and 1.26 +/- 0.40 csp/pixel/mCi for control and stimulated horses, respectively. At any given observation period, uptake in the lesion area was greater in the control group. Ultimate strengths of trabecular bone in 60-day control radii and stimulated radii were 12.64 +/- 3.013 and 9.60 +/- 3.95 MN/m2, and the flexural moduli of elasticity were 698.0 +/- 423 and 402.0 +/- 523 MN/m2, respectively.

Porosity index was similar for all specimens. Gross, histologic, and microradiographic evaluations indicated that controls healed more efficiently than stimulated horses. A capacitively coupled applied voltage of 2.2 V RMS (mean) producing a current of 17.32 mA (mean) did not stimulate sufficient bone production in a metaphyseal osteotomy model to affect the mechanical properties of the bone or accelerate the healing process

Cochran G.V., Johnson M.W., Kadaba M.P., Vosburgh F., Ferguson-Pell M.W., and Palmieri V.R. (1985) Piezoelectric internal fixation devices: a new approach to electrical augmentation of osteogenesis. *J. Orthop. Res.* 3, 508-513.
Abstract: Prototype testing has been accomplished on a piezoelectric, internal fixation plate. This device combines a piezoelectric material with an internal fixation device as an integrated structure that provides mechanical stability, together with self-generated electrical stimulation, for treating fractures and nonunion. In bench and animal tests we have demonstrated that cyclical loading can cause a device of this type to generate electrical charge while attached to bone. After rectification, direct currents within the range known to stimulate osteogenesis can be produced by weight-bearing loads. Furthermore, electrical output of the implants can be increased by externally applied ultrasonic energy. These twin developments add significantly to the potential armamentarium of devices to enhance bone healing

Ahl T., Andersson G., Herberts P., and Kalen R. (1984) Electrical treatment of non-united fractures. *Acta Orthop. Scand.* 55, 585-588.
Abstract: The semi-invasive technique for electrical stimulation of bone healing developed by Brighton et al. (1977) was used in 23 patients with nonunited fractures of the tibia (14 cases), humerus (4 cases), scaphoid, femur and fibula as well as one failed arthrodesis of the ankle. The fractures were clinically not healed and not operated on within a minimum of 6 months. The mean period from fracture to treatment was 18 months. Electrical stimulation led to solid bone healing in 10 cases. Two deep infections occurred during the treatment. Of 13 cases that did not unite, a great range of motion in the nonunion area was an obvious cause of failure in seven cases. The results in this series cannot compete with those of bone graft surgery for nonunions

Paterson D. (1984) Treatment of nonunion with a constant direct current: a totally implantable system. *Orthop. Clin. North Am.* 15, 47-59.
Abstract: There is now sufficient basic research and clinical experience to establish that electrical stimulation produces osteogenesis. Furthermore, electrical stimulation significantly helps union where impaired bone healing exists. The implanted bone growth stimulator is one effective method of electrical stimulation. It can be used in a wide variety of problems: delayed union and nonunion of bones with or without chronic infection and in failed posterior spinal fusion. Successful treatment of congenital pseudarthrosis of the tibia has been encouraging. The implanted bone growth stimulator technique requires a simple operation with strict adherence to detail. There is minimal postoperative discomfort and a short hospital stay. The average time to union is 16 weeks. The Osteostim can be used in the presence of chronic infection and internal fixation. Above all, the technique does not require any cooperation from the patient. The implanted bone growth stimulator should be accepted as a method of treatment for delayed and nonunion of bones, as it is at least as effective as other more conventional methods of surgical treatment for this

situation. It has been proved that electrical stimulation produces osteogenesis. Orthopedic surgeons should no longer be skeptical about this

Hanaoka T. (1983) [The effects of pulsed micro-electrical currents on internal remodeling in long tubular bone and bone healing]. *Nippon Seikeigeka Gakkai Zasshi* 57, 151-166.
Abstract: The effects of pulsed micro-electrical currents on internal remodeling in the cortex of long tubular bone were evaluated by the following three experiments. 1. Electrodes were inserted in both femora of 14 adult mongrel dogs, 15 mm apart, and pulsed micro-electrical current was applied in the right femoral cortex for 4 weeks, but not in the left femur, which was left as a control. Dogs were divided into 4 groups; in each of these groups current with 1Hz-10 microA, 0.1 Hz-10 microA, 50 Hz-10 microA and 1Hz-20 microA was applied. The effects were evaluated by histometric parameters, i.e. number of resorption cavities (Ar), osteons with osteoid seam (osAf), mineralization rate of osteoid seam (Mo), and perimeter of osteoid seam (Sf). Number of Ar and osAf increased. Bone formation rate (Vf) which is the product of osAf, Mo and Sf increased, especially in the group in which current with 1Hz-10 microA was applied. The main reason for increase of Vf was considered due to that the activation frequency in internal remodeling increased by electrical stimulation. 2. A metal plate was placed on the right humerus, not on the left humerus, both femora of 5 dogs, and electrical current of 1Hz-10 microA was applied in the right femur for either 12 or 16 weeks. Decrease of internal remodeling tended to take place in the mid-portion of the plated area of femur, whereas Vf increased by pulsed micro-electrical currents. Decrease of internal remodeling thus caused by placing a plate and screws increased by pulsed micro- electrical current. 3. Number of osteons in the newly formed bone in the osteotomized gap and in the cortex adjacent to the gap of femora of 7 dogs, which were plated for either 4 or 6 weeks, was measured in longitudinal sections labelled by tetracycline. The number of osteons increased more in the right femur in which current of 1Hz-10 microA was applied than in the left femur. Based on the results above described, it was concluded that bone healing was enhanced by pulsed micro- electrical currents

Paterson D.C., Hillier T.M., Carter R.F., Ludbrook J., Maxwell G.M., and Savage J.P. (1977) Experiemtnal delayed union of the dog tibia and its use in assessing the effect of an electrical bone growth stimulator. *Clin. Orthop.* 340-350.
Abstract: A technique has been described for the consistent production of delayed bone healing of the tibia in an animal model. A controlled double blind trial, where independent observors did not know the coding of the stimulators and did not collaborate with each other, has evaluated the use of a direct current bone growth stimulator in such an animal model. The conclusion of the experiment is that this commercially available direct current stimulator does produce a significant acceleration of bone healing at 4 weeks in the experimental model used. There is no evidence of inflammatory or neoplastic changes. The eventual clinical role of electrical bone stimulation remains uncertain and many questions remain unanswered, but are promising enough to encourage a controlled clinical trial in situations of disturbed bone healing. Electrical stimulation is apparently safe and appears to significantly augment bone formation. A controlled clinical trial is now being carried out in major medical centers in Australia

Paterson D.C., Carter R.F., Maxwell G.M., Hillier T.M., Ludbrook J., and Savage J.P. (1977) Electrical bone-growth stimulation in an experimental model of delayed union.

Lancet 1, 1278-1281.
Abstract: An experimental model has been devised for the consistent production of delayed bone healing of the tibia in adult dogs. A double-blind trial, with bias eliminated, was used to evaluate the use of a commercially available direct-current bone-growth stimulator with this model. The stimulator produced a statistically significant acceleration of bone healing at four weeks in the experimental model. Osteogenesis was normal, and no dysplastic, inflammatory, or neoplastic changes were found. This research has shown that electrical stimulation of bone is safe and augments bone formation. The bone-growth stimulator unit remains on trial, but in future it may alter the management of many difficult orthopaedic problems

McElhannon F.M., Jr. (1975) Congenital pseudarthrosis of the tibia. *South. Med. J.* 68, 824-827.
Abstract: Congenital pseudarthrosis of the tibia is a rare and difficult problem. The cause is unknown, the treatment is nonstandardized, and the results are generally poor. One or two good attempts at union should be made, followed by amputation if union is not obtained or if deformity is worse than that produced by a prosthesis. Electrical stimulation of bone healing is not yet technically advanced enough for use in stimulating fractures to heal in humans, but it has been proven to promote healing in animals and holds considerable promise for the future

Van Cochran G. (1974) Acceleration of bone healing by electrical stimulation. *Bull. Prosthet. Res.* 291-294.