Bone Healing

J Orthop Res. 2005 Jun 2; [Epub ahead of print]

Pulsed electromagnetic field treatments enhance the healing of fibular osteotomies.

Midura RJ, Ibiwoye MO, Powell KA, Sakai Y, Doehring T, Grabiner MD, Patterson TE, Zborowski M, Wolfman A.

Department of Biomedical Engineering, The Orthopaedic Research Center, Lerner Research Institute of The Cleveland Clinic Foundation, Cleveland, OH 44195, USA.

This study tested the hypothesis that pulsed electromagnetic field (PEMF) treatments augment and accelerate the healing of bone trauma. It utilized micro-computed tomography imaging of live rats that had received bilateral 0.2mm fibular osteotomies (approximately 0.5% acute bone loss) as a means to assess the in vivo rate dynamics of hard callus formation and overall callus volume. Starting 5days post-surgery, osteotomized right hind limbs were exposed 3h daily to Physio-Stim((R)) PEMF, 7days a week for up to 5weeks of treatment. The contralateral hind limbs served as sham-treated, within-animal internal controls. Although both PEMF- and sham-treatment groups exhibited similar onset of hard callus at approximately 9days after surgery, a 2-fold faster rate of hard callus formation was observed thereafter in PEMF-treated limbs, yielding a 2-fold increase in callus volume by 13-20days after surgery. The quantity of the new woven bone tissue within the osteotomy sites was significantly better in PEMF-treated versus sham-treated fibulae as assessed via hard tissue histology. The apparent modulus of each callus was assessed via a cantilever bend test and indicated a 2-fold increase in callus stiffness in the PEMF-treated over sham-treated fibulae. PEMF-treated fibulae exhibited an apparent modulus at the end of 5-weeks that was approximately 80% that of unoperated fibulae. Overall, these data indicate that Physio-Stim((R)) PEMF treatment improved osteotomy repair. These beneficial effects on bone healing were not observed when a different PEMF waveform, Osteo-Stim((R)), was used. This latter observation demonstrates the specificity in the relationship between waveform characteristics and biological outcomes.

J Orthop Res. 2005 May 20; [Epub ahead of print]

Pulsed electromagnetic fields stimulation affects osteoclast formation by modulation of osteoprotegerin, RANK ligand and macrophage colony-stimulating factor.

Chang K, **Chang WH**, **Huang S**, **Huang S**, **Shih C**.

Department of Biomedical Engineering, Chung-Yuan Christian University, Chung-Li 32023, Taiwan.

Electromagnetic stimulation has been documented to treat recalcitrant problems of musculoskeletal system. Yet, the underlying mechanisms are not completely understood. In this study, we investigated effect of pulsed electromagnetic fields (PEMF) with parameters modified from clinical bone growth stimulator on osteoclast formation, bone resorption, and cytokines associated with osteoclastogenesis. Marrow cells were harvested from both femora and tibiae of 6 week-old mice and cultured in 8-well chamber slides or 16-well calcium phosphate apatite-coated multitest slides. After 1-day incubation, marrow cells were exposed to PEMF at different electric field intensities for 2h/day and continued for 9 days. Osteoprotegerin (OPG), receptor activator of NFkappaB-ligand (RANKL) and macrophage colony-stimulating factor (M-CSF) concentrations of each group were determined after PEMF stimulation. Osteoclast identity was confirmed by both tartrate resistant acid phosphatase (TRAP) stain and bone resorption assay. A statistically significant increase and decrease of osteoclastogenesis and bone resorption areas were found when exposed to PEMF with different intensities. Besides, consistent correlations among OPG, RANKL, M-CSF, osteoclast numbers, and bone resorption after exposure to different intensities of PEMF were observed. These data demonstrated that PEMF with different intensities could regulate osteoclastogenesis, bone resorption, OPG, RANKL, and M-CSF concentrations in marrow culture system.

Int J Artif Organs. 2004 Aug;27(8):681-90.

Current trends in the enhancement of biomaterial osteointegration: biophysical stimulation.

Fini M, **Giavaresi G**, **Setti S**, **Martini L**, **Torricelli P**, **Giardino R**.

Department of Experimental Surgery, Research Institute Codivilla-Putti, Rizzoli Orthopedic Institute, Bologna, Italy.

To enhance bone implant osteointegration, many strategies for improving biomaterial properties have been developed which include optimization of implant material, implant design, surface morphology and osteogenetic coatings. Other methods that have been attempted to enhance endogenous bone healing around biomaterials are different forms of biophysical stimulations such as pulsed electromagnetic fields (PEMFs) and low intensity pulsed ultrasounds (LIPUS), which were initially developed to accelerate fracture healing. To aid in the use of adjuvant biophysical therapies in the management of bone-implant osteointegration, the present authors reviewed experimental and clinical studies published in the literature over the last 20 years on the combined use of biomaterials and PEMFs or LIPUS, and summarized the methodology, and the possible mechanism of action and effectiveness of the different biophysical stimulations for the enhancement of bone healing processes around bone implanted biomaterials.

Int J Low Extrem Wounds. 2002 Sep;1(3):152-60.

Electromagnetic fields for bone healing.

Pickering SA, **Scammell BE**.

Department of Orthopaedic and Accident Surgery, University Hospital, Queen's Medical Centre, Nottingham, UK. simonpickering@tiscali.co.uk

Electrical stimulation has been applied in a number of different ways to influence tissue healing. Most of the early work was carried out by orthopedic surgeons looking for new ways of enhancing fracture healing, particularly those fractures that had developed into nonunions. Electrical energy can be supplied to a fracture by direct application of electrodes or inducing current by use of pulsed electromagnetic field or capacitive coupling. Many of these techniques have not been standardized, so interpretation of the literature can be difficult and misleading. Despite this, there have been a few good laboratory and clinical studies to investigate the effect of electrical stimulation on fracture healing, which are reviewed. These do not permit recommendation or rejection of the technique per se; however, there is some room for optimism. The authors present some of the guidelines for using this treatment modality but suggest that all treatment should be carried out as part of a clinical trial in order to generate reliable data.

J Foot Ankle Surg. 2004 Mar-Apr;43(2):93-6.

The effect of pulsed electromagnetic fields on hindfoot arthrodesis: a prospective study.

Dhawan SK, **Conti SF**, **Towers J**, **Abidi NA**, **Vogt M**.

Department of Orthopaedic Surgery, Interfaith Medical Center, Brooklyn, NY 11213, USA. drdhawan@hotmail.com

The aim of this study was to evaluate the effect of pulsed electromagnetic fields in a consecutive series of 64 patients undergoing hindfoot arthrodesis (144 joints). All patients who underwent elective triple/subtalar arthrodesis were randomized into control and pulsed electromagnetic field study groups. Subjects in the study group had an external pulsed electromagnetic fields device applied over the cast for 12 hours a day. Radiographs were taken pre- and postoperatively until radiographic union occurred. A senior musculoskeletal radiologist, blinded to the treatment scheme, evaluated the radiographic parameters. The average time to radiographic union in the control group was 14.5 weeks in 33 primary subtalar arthrodeses. There were 4 nonunions. The study group consisted of 22 primary subtalar arthrodeses and 5 revisions. The average time to radiographic union was 12.9 weeks (P =.136). The average time to fusion of the talonavicular joint in the control group was 17.6 weeks in 19 primary procedures. In the

pulsed electromagnetic fields group of 20 primary and 3 revision talonavicular arthrodeses, the average time to radiographic fusion was 12.2 weeks (P =.003). For the 21 calcaneocuboid arthrodeses in control group, the average time to radiographic fusion was 17.7 weeks; it was 13.1 weeks (P =.010) for the 19 fusions in the study group. This study suggests that, if all parameters are equal, the adjunctive use of a pulsed electromagnetic field in elective hindfoot arthrodesis may increase the rate and speed of radiographic union of these joints.

Am J Orthop. 2004 Jan;33(1):27-30.

Pseudarthrosis after lumbar spine fusion: nonoperative salvage with pulsed electromagnetic fields.

Simmons JW Jr, **Mooney V**, **Thacker I**.

UTMB, Galveston, Texas, USA.

We studied 100 patients in whom symptomatic pseudarthrosis had been established at more than 9 months after lumbar spine fusion. All patients were treated with a pulsed electromagnetic field device worn consistently 2 hours a day for at least 90 days. Solid fusion was achieved in 67% of patients. Effectiveness was not statistically significantly different for patients with risk factors such as smoking, use of allograft, absence of fixation, or multilevel fusions. Treatment was equally effective for posterolateral fusions (66%) as with interbody fusions (69%). For patients with symptomatic pseudarthrosis after lumbar spine fusion, pulsed electromagnetic field stimulation is an effective nonoperative salvage approach to achieving fusion.

J Am Acad Orthop Surg. 2003 Sep-Oct;11(5):344-54.

Use of physical forces in bone healing.

Nelson FR, **Brighton CT**, **Ryaby J**, **Simon BJ**, **Nielson JH**, **Lorich DG**, **Bolander M**, **Seelig J**.

Henry Ford Hospital, Detroit, MI, USA.

During the past two decades, a number of physical modalities have been approved for the management of nonunions and delayed unions. Implantable direct current stimulation is effective in managing established nonunions of the extremities and as an adjuvant in achieving spinal fusion. Pulsed electromagnetic fields and capacitive coupling induce fields through the soft tissue, resulting in low-magnitude voltage and currents at the fracture site. Pulsed electromagnetic fields may be as effective as surgery in managing extremity nonunions. Capacitive coupling appears to be effective both in extremity nonunions and lumbar fusions. Low-intensity ultrasound has been used to speed normal fracture healing and manage delayed unions. It has recently been approved for the management of nonunions. Despite the different mechanisms for stimulating bone

healing, all signals result in increased intracellular calcium, thereby leading to bone formation.

J Pediatr Orthop. 2003 Jul-Aug;23(4):478-83.

Effects of pulsed electromagnetic field stimulation on distraction osteogenesis in the rabbit tibial leg lengthening model.

Fredericks DC, **Piehl DJ**, **Baker JT**, **Abbott J**, **Nepola JV**.

Bone Healing Research Laboratory, Department of Orthopaedic Surgery, University of Iowa College of Medicine, Iowa City, Iowa 52242, USA. douglas-fredericks@uiowa.edu

The purpose of this study was to determine whether exposure to pulsed electromagnetic field (PEMF) would shorten the healing time of regenerate bone in a rabbit tibial distraction model. Beginning 1 day after surgery, mid-shaft tibial osteotomies, stabilized with external fixators, were distracted 0.25 mm twice daily for 21 days and received either no exposure (sham control) or 1 hour per day exposure to low-amplitude, low-frequency PEMF. Tibiae were tested for torsional strength after 9, 16, and 23 days post-distraction. PEMF-treated tibiae were significantly stronger than shams at all three time points. By 16 days post-distraction, the PEMF group had achieved biomechanical strength essentially equivalent to intact bone. Shams did not achieve normal biomechanical strength even after 23 days post-distraction. In this tibial distraction model, short daily PEMF exposures accelerated consolidation of regenerate bone. Clinical usefulness awaits testing.

Int J Adult Orthodon Orthognath Surg. 1997;12(1):43-53.

Effects of static magnetic and pulsed electromagnetic fields on bone healing.

Darendeliler MA, **Darendeliler A**, **Sinclair PM**.

Discipline of Orthodontics, Faculty of Dentistry, University of Sydney, Australia.

The purpose of the present study was to evaluate the healing pattern of an experimentally induced osteotomy in Hartley guinea pigs in the presence of static magnetic and pulsed electromagnetic fields. The sample consisted of 30 Hartley guinea pigs 2 weeks of age divided into 3 groups: pulsed electromagnetic, static magnetic, and control. An osteotomy was performed in the mandibular postgonial area in all groups under general anesthesia. During the experimental period of 9 days, the animals were kept in experiment cages 8 hours per day, the first two groups being in the presence of pulsed electromagnetic and static magnetic field, respectively. Based on histologic results, both static and pulsed electromagnetic fields seemed to accelerate the rate of bone repair when compared to the

control group. The osteotomy sites in the control animals consisted of connective tissue, while new bone had filled the osteotomy areas in both magnetic field groups.

How can pulsed electromagnetic field therapy assist in the healing of bones and ligaments?

Dr. D. C. Laycock, Ph.D. Med. Eng. Westville Consultants.

Bone is essentially calcium structure which contains trace elements. One particular element recently identified is Alpha Quartz. This is the same type of material used in computers and digital or electronic watches. When this material is compressed, it develops a voltage across its two compressive faces, a phenomenon known as the piezoelectric effect. The old crystal pickups on record players used this effect to generate electrical sound signals. Gas appliances and some cigar lighters also utilize the same effect to generate a spark for ignition.

In bone, areas of stress generate small electric charges which are greater than those of less stressed areas, so that polarized bone-laying cells (osteoblasts) are believed to be attracted to these areas and begin to build up extra bone material to counter the stress.

With bone injuries, bleeding occurs to form a haematoma in which capillaries quickly form, transporting enriched blood to the injury site. Pulsed Magnetic Field therapy of a base frequency of 50Hz, pulsed at above 12Hz, causes vasodilatation and capillary dilatation, so helping to speed up the process of callus formation. Within the bone itself, pulsed electromagnetism causes the induction of small eddy currents in the trace elements, which in turn purify and strengthen the crystal structures. These have the same effect as the stress-induced voltages caused by the alpha quartz and as such, attract bone cells to the area under treatment. This can, therefore, accelerate the bone healing process to allow earlier mobilization and eventual full union. Ligaments and tendons are affected in similar ways to solid bone by pulsed electromagnetic therapy, since they are uncalcified bone structures in themselves.

J Bone Joint Surg Am

The effect of low-frequency electrical fields on osteogenesis.

McLeod K. et.al. Dep. Orthopaedics, School of Medicine, State University of New York,

An in vivo animal model of disuse osteopenia was used to determine the osteogenic potential of specific components of electrical fields. The ability of a complex pulsed electrical field to inhibit loss of bone was compared with the remodeling response generated by extremely low-power, low-frequency (fifteen, seventy-five, and 150-hertz) sinusoidal electrical fields. The left ulnae of thirty adult male turkeys were functionally isolated by creation of distal and proximal epiphyseal osteotomies and then were exposed, for one hour each day, to an electrical field that had been induced exogenously by means of magnetic induction. After a fifty-six-day protocol, the remodeling response was quantified by a comparison of the cross-sectional area of the mid-part of the diaphysis of the functionally isolated ulna with that of the intact contralateral ulna. Disuse resulted in a 13 per cent mean loss of osseous tissue, which was not significantly different than the 10 per cent loss that was caused by disuse treated with inactive coils. Exposure to the pulsed electrical fields prevented this osteopenia and stimulated a 10 per cent mean increase in the bone area. The osteogenic influence of the sinusoidal electrical fields was strongly dependent on the frequency; the 150, seventy-five, and fifteen-hertz sinusoidal fields, respectively, generated a -3 per cent, + 5 per cent, and + 20 per cent mean change in the bone area. These results suggest a tissue sensitivity that is specific to very low-frequency sinusoidal electrical fields and they imply that the induced electrical fields need not have complex waveforms to be osteogenic. Since the frequency and intensity range of the sinusoidal fields producing the greatest osteogenic response are similar to the levels produced intrinsically by normal functional activity, these results support the hypothesis that electricity plays a role in the retention of the normal remodeling balance within mature bone.

Med Biol Eng Comput. 1991 Mar;29(2):113-20.

Comparative study of bone growth by pulsed electromagnetic fields.

Gupta TD, **Jain VK**, **Tandon PN**.

Department of Electrical Engineering, Harcourt Butler Technological Institute, Kanpur, India.

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.

Vestn Khir Im I I Grek. 1989 Feb;142(2):63-6.

[Rehabilitation treatment of patients with uncomplicated fractures of the spine at a hospital rehabilitation center]

[Article in Russian]

Bagaturiia GO, **Chanov VL**, **Kutushev FKh**.

The authors make an analysis of treatment of 188 patients with noncomplicated compressive fractures of the vertebral column in the thoracolumbar part performed at the stationary rehabilitation center. The course of restorative treatment was as long as 31-40 days and included individual and group trainings of exercise therapy, massage, hydrokinesotherapy, thermo-, electro-, photo- and magnetotherapy. Results of the treatment were followed in 81 patients. Excellent and good results were obtained in 43 patients (53%), unsatisfactory--in 7 patients (8.6%). The period of follow-up observation was from 1 month to 1 year.