

ELECTROMAGNETIC FIELDS AND MAGNETS

Investigational Treatment for Musculoskeletal Disorders

David H. Trock, MD

In technology, men know that all the wishes and prayers in the world will not change the nature of a grain of sand.

AYN RAND, *The Voice of Reason, Ayn Rand: Essays in Objectivist Thought*

Our generation has seen unprecedented advances in electromagnetic wave technology such as the microwave oven, the cellular telephone, and the magnetic resonance imager, each a creative exploitation of an invisible electromagnetic signal that was initially met with rigid skepticism. The modern bone growth stimulators that employ pulsed electromagnetic fields (PEMFs) have been available for 20 years, although they are just becoming a standard of care for delayed union fracture. A foundation of in vitro and clinical studies has demonstrated that electric and magnetic energy may favorably affect disorders of dense connective tissue. These signals have become a fertile area of research in orthopedics and rheumatology.

From the Yale University School of Medicine, New Haven; and the Section of Rheumatology Danbury Hospital, Danbury, Connecticut

RHEUMATIC DISEASE CLINICS OF NORTH AMERICA

BACKGROUND

The first concept of electricity was known when a static charge resulted from rubbing fur on amber; hence, the Greek name for amber, *elektron*, was adapted.

Accidentally, in 1820, Oersted noticed the relationship between magnetism and electricity when his compass needle was deflected by the current of a nearby wire. Also in 1820, Ampere developed the electromagnet and postulated that tiny electric currents circulate within the molecules of magnetic material. In 1832, Michael Faraday confirmed that electric charges could be transferred by electromagnetism, later called electromagnetic induction. Approximately 150 years later, Faraday currents would become relevant in the microenvironment of dense connective tissue, the basis of modern bone growth stimulators and other new electromagnetic devices that affect biological tissue.

In 1865, James Clerk Maxwell prophetically stated that when magnetic lines of force move sidewise, their movement results in an electric field at right angles to the magnetic lines, that is, if a magnet were pushed through a coil of wire, it could start an electric current going through the wire. The theory of Maxwell states that an electric field is always accompanied by a magnetic field and, conversely, a variable (i.e., pulsed) magnetic field is always accompanied by an electric field.

To explain the effect of electromagnetism on growth and repair of bone and cartilage, three physical concepts, including Wolff's Law, the piezoelectric effect, and the concept of streaming potentials, must first be discussed.

Wolff's Law of reorganization states that the balance between bone formation and resorption is largely controlled by mechanical strain. When a long bone is compressed, bone formation occurs at the periosteal surface of the compressed side, whereas bone resorption occurs on the side of tension. It is no coincidence that a negative charge occurs on the compressed side, where bone formation occurs (Fig. 1). Indeed, the external application of such a current also results in bone growth. Wolff's Law has been explained by the electric transduction of mechanical deformation, which promotes bone differentiation.³⁹ In dense connective tissue, the electric potential immediately generated by mechanical stress is the piezoelectric effect, first described in 1957 by Fukada and Yasuda,¹⁶ which states that if you deform a crystalline structure (such as bone), electrons migrate to the compressed side, creating a negative potential that quickly disappears if the compression is maintained. . As compression is released, however, an equal and opposite positive pulse appears as the electrons rebound back into place. Hydroxyapatite and collagen are piezoelectric by nature, and their deformation creates an electric potential.

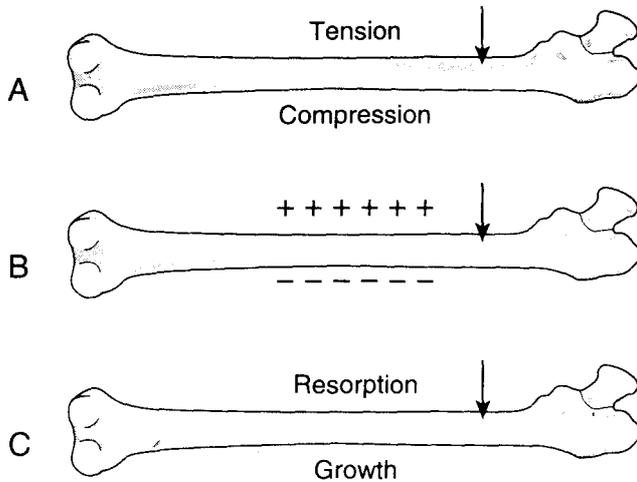


Figure 1. *A*, A compressive force on a femur. *B*, The piezoelectric effect occurs after compression. *C*, Wolff's Law is the transduction of mechanical stress into bone growth and remodeling, guided by electricity.

Wolff's Law and the merits of weight-bearing exercise to preserve bone density apply to cartilage too. In vitro, the beneficial effects of weight-bearing exercise with cyclic loading rates of a few hertz (cycles per second) on proteoglycan synthesis have been confirmed in both organ cultures^{36,40} and animal models.³⁵

In addition to the crystalline-generated electric potential of bone, a "streaming potential" develops in other dense connective tissues, particularly cartilage when the movement of mobile ions within the fluid stream past the fixed negative charges in the sulfated proteoglycan matrix in response to compression or mechanical deformation (Fig. 2). With each compressive cycle, an electric current is generated by the streaming potential, which may be an important signal to the chondrocyte.

A report on the "streaming potentials in cartilage" that are generated by the application of pressure was published in 1969.³⁰ For the mathematic equations associated with streaming potentials, the

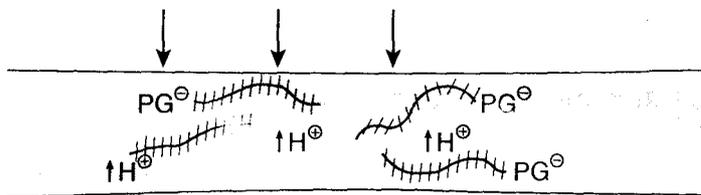


Figure 2. Streaming potentials. Dynamic compression of cartilage causes the positive charges in the fluid phase to "stream" past the negatively charged, sulfated proteoglycan (PG) matrix. This results in a voltage which is a stimulus to the chondrocyte.

reader is referred to a report by Frank and Grodzinsky.¹⁴

It is also well accepted in physical law that exogenous electric fields can induce current through ionic solutions affecting cell behavior. Recall that an external PEMF of varying frequency induces an electric current to which cells respond. The chondrocyte appears to respond most optimally to low frequencies of less than 15 Hz, with increased glycosaminoglycan production evidenced in several studies. In fact, stimulation of chondrogenesis is one way in which the PEMF affects the early stages of bone repair, and this may have important implications for the treatment of osteoarthritis.

CURRENTS OF INJURY: THE FRACTURE MODEL

Drs Robert Becker and C. Andrew Bassett deserve much credit for the early work in this area. Inspired by his work in orthopedics, Becker theorized that a "negative current of injury" accompanies a bone fracture, which triggers a cascade of events leading to repair.

Normal fracture healing is dependent on a negative current of injury, whereas nonunion fracture occurs in an electrically silent void. Nonunion fracture is a complication that affects roughly 3% of all long bone fractures and is a source of great morbidity and discomfort. Physicians at the University of Pennsylvania reported the first successful use of electric treatment for a human nonunion fracture in 1971, using a 10mA direct current stainless steel electrode directly placed in the bone marrow of the fracture void.' The technique was successful, but its invasiveness was apparent. The direct placement of electrodes may cause electrolysis (in which the water molecule is broken apart into toxic hydrogen gas and oxygen radicals) and local heat production.'

To circumvent this problem, Bassett and his colleagues used a noninvasive PEMF to create small Faraday currents across the fracture void. He reported a child with a nonunion fracture of the tibia, who failed several operations over a 10-year interval, facing amputation of the limb. As a last resort, a pair of energized wire coils were placed opposite the defect; within 4 months, healing occurred. This finding inspired much research leading to the development of the bone growth stimulators that were approved by the US Food and Drug Administration in 1979. Several application systems of varying energy and frequency have since been developed.

In the treatment of ununited fractures, PEMF stimulation has become an effective alternative to surgery. It is noninvasive, cost-effective, and free of complications. Success rates of up to 80% compare well with

those of open surgical repair.^{21,42} The long-term follow up of fracture nonunions treated with PEMF stimulation is superior to that of placebo, and the technique is now well accepted.¹⁷ Moreover, the indications for use of PEMFs are changing. In the past, a nonunion fracture required 9 months before PEMF stimulation was indicated, but there are newer guidelines that allow earlier use of bone growth stimulator devices. It is anticipated that PEMF stimulation may be indicated for ordinary fractures in the near future, shortening the time that a patient is required to wear a typical cast.

CARTILAGE EFFECTS

The challenge of repairing the surface of hyaline cartilage is well known, but in a recent experiment using 37 New Zealand white rabbits in which osteochondral defects were imposed on the distal femoral condyle, there was superior quality of repair when the rabbits were exposed to a pulsing direct current compared with controls,²⁸ confirming earlier studies.⁵ Certain electromagnetic fields have been shown to stimulate chondrocytes to proliferate or increase synthesis of proteoglycans.^{3,5} Aaron and Ciombor have made important contributions in this area. An in vitro study of PEMF stimulation at 15 Hz on articular cartilage explants resulted in a threefold increase of sulfate incorporation over that of controls and a far greater increase than expected when PEMF stimulation was added to selected growth factors,¹ including epidermal growth factor and fibroblast growth factor. This suggested a synergy among the known methods of cartilage stimulation, with implications for future treatment of osteoarthritis. In hyaline cartilage, stimulation with certain PEMFs may elevate glycosaminoglycan content and suppress degradation of existing glycosaminoglycan.²⁹

An important study by Grande et al²² confirmed that low-energy alternating and direct current magnetic fields stimulate the metabolism of articular cartilage (measured by radiolabelled sulfate incorporation) coincidental to calcium ion uptake by the cells. This study mathematically satisfied Liboff's ion cyclotron resonance theory²⁶ that ion transport requires the application of a static and alternating magnetic field adjusted to the following equation:

$$fA = 1/2 \text{ Pi } \times B_s \times q/m$$

where fA is the frequency of the alternating field, B_s is the magnitude of the static field, and q/m is the charge-to-mass ratio of the ion to be stimulated. For the calcium ion, using a static magnetic field of 20.9 uT, the optimal frequency for ion transport would be 16 Hz, which is the

frequency used in commercially available PEMF bone growth stimulators. At this frequency, calcium ion transport occurred and cartilage growth was stimulated. This study and others suggest that the mechanism of action of PEMF stimulation may involve cell membrane receptors or ion transport across channels and that there may be windows of optimal frequency affecting different target tissues (Table 1).

Extremely low frequencies (i.e., <60 Hz) are nonionizing and do not create heat, but they affect cell behavior via increased transcription¹⁹ and enhanced DNA synthesis.²⁷ It is unlikely that the mechanism of action is solely a result of transmembrane potentials, because the potentials generated by extremely low-frequency electromagnetic fields are much lower than the cell membrane potentials. Recall that the interior of the cell is negative with respect to the exterior. The lipid plasma membrane that creates an electric gradient of 10^5 V / cm across the cell membrane (the energy required for penetration) is an effective electric barrier against cell stimulation by weak electromagnetic fields. It is postulated that PEMF stimulation probably acts on cell surface receptors and secondary messengers to affect cell function.¹³

Certain cells within dense connective tissue respond to electromagnetic fields by increasing their transcription within minutes, with a peak stimulation occurring around 20 minutes.²⁰ Goodman¹⁸ suggested that a synergy exists between the electric and magnetic fields, where the electric field component is responsible for the negative surface charge (current of injury) and the magnetic field produces a separate and different effect. Adey⁴ hypothesized that electromagnetic fields change the receptor activity, stimulating a second messenger. Possibilities include calcium channels or cyclic adenosine monophosphate signalling. Electromagnetic fields may affect the way cells communicate with each other in ways that we do not yet understand. Some pulsed magnetic fields upregulate

Table 1. FREQUENCIES OF THE ELECTROMAGNETIC SPECTRUM

Frequency (Hz)	Signal
0	Static magnets
6-12	PEMF device ^{37, 45}
16-70	PEMF device ⁶
100	Electric device ⁵³
10^6	AM radio
10^7	Short wave diathermy
10^8	Television and FM radio
10^{10}	Microwave
10^{13}	Infrared
10^{14-15}	Visible light
10^{16}	Ultraviolet
10^{18}	X-ray
10^{21}	Gamma ray

gene expression with increased messenger RNA levels demonstrated,¹⁹ followed by feedback inhibition, whereas genes not normally expressed are unaffected by exposure to extremely low-frequency pulsed magnetic fields, underscoring their safety.

CLINICAL APPLICATIONS: ARTHRITIS AND PAIN

Electromagnetic fields can be delivered to biological systems by the direct placement of an electrode or noninvasively by two means:

- Capacitive coupling in which opposing electrodes are placed within a conducting medium, that is, in contact with the skin surface overlying a target tissue (e.g., bone, joint, wound).
- Inductive coupling in which a time-varying PEMF induces an electric current in the target tissue. This technique does not require direct contact with the skin or biological system.

In 1965, Melzack and Wall²⁰ published their gate control theory of pain, which asserts that the slow and poorly myelinated C-fibers carry pain information through a "gate" on the substantia gelatinosa of the spinal cord and that this information can be "blocked" or overwhelmed by additional electric information of proper synchronization. After the gate theory, Shealy⁴³ reported success with the first dorsal column stimulator. Thereafter, transcutaneous electric nerve stimulation was developed in the early 1970s to exploit the gate control theory, and it has become a useful physical therapy tool for acute and subacute pain, although Deyo et al¹¹ found it to be comparable to placebo in the treatment of chronic low back pain. Therapeutic ultrasound has been evaluated for osteoarthritis of the knee, and the clinical benefits were comparable to those of placebo.¹²

At higher frequencies, short-wave diathermy functions at a frequency of 27.12 MHz and is indicated for the treatment of pain in sports injuries. Initial experiments with this signal were performed by Tesla 100 years ago, and many devices were developed after success was reported in the treatment of sports injuries sustained during the 1968 Olympic Games in Mexico). A recent investigation compared diathermy at 27 MHz with PEMF stimulation at 17 Hz in the treatment of experimental Achilles tendinitis in the rat.²⁵ The lower frequency PEMF signal resulted in a greater reduction of inflammation with a better return of the tendon to histologic normality. In another study using cultured cartilage cells to explore the benefits of PEMF stimulation on glycosaminoglycan synthesis, Sakai et al⁴¹ confirmed that intermittent exposure to PEMF stimulation was superior to continuous exposure. This finding mirrors many of the intermittent

application systems of PEMF stimulation that are available for clinical use.

In a randomized trial, Zizic et al⁵³ studied a pulsed electric device used to treat 78 patients with chronic knee osteoarthritis. The stimulus was generated by a portable battery-operated device that delivered a 100-Hz low-amplitude signal to the knee joint via skin surface electrodes when worn for 6 to 10 hours daily during a 4-week period. The active treatment was superior to placebo in reducing symptoms. A subsequent study by Zizic et al⁵² found the device to be cost-effective as well by relieving pain, thus forestalling the need for total knee replacement surgery.

The application of PEMF stimulation for osteoarthritis is a relatively new area, which has been supported by several trials.^{45, 46} Eighty-six patients with osteoarthritis of the knee were exposed to 9 hours of PEMF stimulation over a 1-month period using a noncontact device that delivered three signals in stepwise fashion, ranging from a 5-Hz to 12Hz frequency at 10 G to 25 G of magnetic energy. The treated patients with knee osteoarthritis averaged between 29% and 36% improvement in each of the variables tested, including pain and function. Similar findings using the same PEMF device were reported in 1998 by Perrot et al.³⁷

PERMANENT STATIC MAGNETS

Around 1000 BC in Asia Minor, the shepherd Magnes was drawn to the earth by the tacks in his sandals.³² On that day, he unearthed a magnetic oxide of iron, FeSO₄ or "lodestone." During the 1740s, "artificial lodestones" became popular when scientists learned that ordinary pieces of iron could be magnetized. Their use in medicine was embraced by Franz Anton Mesmer during the 1770s, who initially used magnets to achieve "miracle cures" of many different ailments, many of which were self-limiting or psychosomatic.

In 1938, Hansen²³ reported, ". . . in experiments on myself, I found that pain of various origins subsided when a magnetic pole was applied firmly to the skin over the site of the pain." Although her later experiments used electromagnets, Hansen's original findings involved static magnets. Little attention was paid to this report until recently.

A magnetic field is the region surrounding a magnet or an electric current (Table 2). Recall that electric current through a wire creates a magnetic field and that a pulsed magnetic field induces an electric current. On the other hand, a static magnet does not induce an electric field when juxtaposed to a stationary conducting medium. So, how would static magnets induce electricity if applied to an arthritic joint or

Table 2. STRENGTH OF MAGNETIC FIELDS

Signal	uT Frequency
Human body	10-6
Residential exposure	0.5
Earth's field	50.0
PEMF device ⁴⁵	2000.0
Bone growth stimulator	5000.0
Magnetic resonance imaging scan	1,500,000.0

tender point? The answer may involve the movement of ions in that microenvironment by way of blood flow. This can be explained by the Hall effect. In 1879, Edwin Hall of Johns Hopkins University discovered that if a strip of fold leaf carrying an electric current were placed perpendicularly in a magnetic field, the edges of the strip acquired different electric potentials, suggesting a feeble new source of current.¹⁰ A Hall voltage may explain the clinical usefulness of static magnets for certain painful conditions, albeit with a smaller potential than the Faraday currents induced by PEMFs.

Constant magnetic stimulation may influence small C-fibers and may preferentially desensitize sensory neurons by modifying membrane potentials.^{24,34} A recent pilot study supported the use of magnetic foot pads for painful diabetic peripheral neuropathy.⁴⁹

A reduction of experimental synovitis was observed in response to a static magnetic field. Ten rats whose hind joints were injected with zymosan developed synovitis over 3 weeks, with an average inflammatory score of 6.8 in the control group compared with a score of 3.4 in rats continuously exposed to a 3800-G magnet ($P < 0.002$). Larger studies are needed for validation of this finding.⁴⁸

In one study of 50 patients with chronic pain caused by the postpolio syndrome, the placement of static magnets over trigger points resulted in temporary relief of pain compared with placebo.⁴⁷ Using the McGill pain questionnaire, improvement occurred in 76% of those exposed to a 300- to 500-G magnet compared with 19% who received the inactive device ($P < 0.001$). Although relatively easy to perform, similar studies for more common painful conditions such as osteoarthritis are conspicuously lacking. Static magnets are enjoying popularity, although more research is needed.

SAFETY ISSUES

The evidence that certain electric and magnetic fields augment DNA synthesis was met with concern about cancer risk. At a time when medical PEMF devices were rarely used, much of the

attention involved electric blankets, video display terminals, home microwave ovens, and high-voltage power lines. In 1979, Wertheimer and Leeper⁵⁰ reported that childhood death from cancer in Denver, Colorado, were more likely if children lived near high-current wiring. Other studies have correlated continuous exposure to magnetic fields over 0.4 T with leukemia, mindful that residents living near high-tension lines also mirror exposure to industrial pollution and other carcinogens.³³

In 1995, the world's largest group of physicists, the American Physical Society, took a stance by stating that they could find no evidence that electromagnetic fields from power lines caused cancer.⁸ Although the debate about power lines continues, most investigators believe that the relative low energy of magnets and brief exposure to medical PEMF devices are safe; this conclusion is supported by the safety data of the bone growth stimulators over the past 20 years. Regardless, PEMF treatment in patients with known cancer, those who are pregnant, or those with permanent pacemakers is avoided.

CONCLUSIONS

Static magnets are probably safe, but their efficacy for painful conditions such as arthritis remains dubious because of limited research. Although there is a foundation of hope based on personal testimonials and a few small studies, much of the enthusiasm has been propelled by uncontrolled observations. Larger independent studies should validate the benefits of magnets before recommending them to patients.

Likewise, PEMFs appear promising in vitro; based on a few small clinical studies, this technology should be considered as an investigational tool that may become a useful adjunctive treatment for bone and joint disorders. PEMF stimulation is already a proven remedy for delayed fractures, with potential clinical application for osteoarthritis, osteonecrosis of bone,^{2,44} osteoporosis, and wound healing. Larger independent studies are in progress.

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Address reprint requests to

David Trock, MD
Danbury Hospital
24 Hospital Avenue
Danbury CT 06810