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Original Study

Enhancement of Bone Healing by Static Magnetic Field in the Dog: Biomechanical Study

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Abstract-

Objective- Although the promotional effects on bone healing of pulsed electromagnetic fields (PEMF) have been well demonstrated, the effects of static magnetic fields (SMF) remained unclear. In this study, effects of SMFs on clinical and biomechanical aspects of bone healing using a canine unstable osteotomy gap model were investigated.

Design- Prospective descriptive trial.

Animals- Fifteen mongrel dogs, 4 to 5 years old and weighing 15.5 to 21.3 kg.

Procedures- After an osteotomy of the midshaft radius, bone healing was evaluated over an 8-week period in control dogs (n = 5) and experimental dogs exposed to medium (700 gauss) (MSMF) and high

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(1500 gauss) (HSMF) magnetic fields (n = five/each group). Bone healing was assessed clinically and biomechanically.

Results- Dogs exposed to HSMF had more improved lameness scores in contrast to the MSMF and control dogs. Significantly, greater forces *($p<0.05$)* were required to break the osteotomized radii exposed to HSMF as compared with MSMF and control ones.

Conclusions and Clinical Relevance- These results suggested that using the osteotomy gap model. HSMF enhanced the clinical and biomechanical aspects of bone healing in dogs. Dogs at risk for delayed healing of fractures may benefit from treatment with HSMF.

Key Words- Static magnetic field, osteotomy, lameness, biomechanics, dog.

Introduction

Magnetic therapy is nothing new. The effects of magnets on biologic processes have been discussed for over 2000 years. The idea that magnetic therapy could be used to treat disease began in the early 16th century with the Swiss physician, philosopher and alchemist Paracelsus, who used magnets to treat epilepsy, diarrhea and hemorrhage.

The proliferation and/or differentiation of osteoblasts, which are responsible for the growth, remodeling, and repair of bone, is modulated by several extracellular factors, such as cytokines and hormones. Bone formation is also affected by pulsed electromagnetic fields. At present, pulsed electromagnetic fields are extensively applied in clinical treatments involving the non-union of bone fractures, bone grafts, osteotomies, fresh fractures, osteonecrosis, and osteoporosis. As for the effects of pulsed electromagnetic fields on bone, much evidence has suggested that they enhance the activities of osteoblasts, i.e., proliferation and differentiation, the expression of bone morphogenic protein-2 and -4, extracellular matrices, alkaline phosphatase, and net flux and the uptake of calcium.

Since pulsed electromagnetic fields yield both a magnetic field and an electric current, no definite conclusion can be drawn as to which factor is more responsible for bone formation. Furthermore, it cannot necessarily be assumed that a positive result from PEMF will automatically translate to a positive result from a static magnetic field (SMF). Therefore, there needs to be more study in the area of fixed magnets. The purpose of the present study, hence, was to investigate the effects of SMF on bone healing in a canine osteotomy gap model, determined by means of biomechanical and clinical factors.

Materials and Methods

Fifteen sexually intact male mongrel dogs, 4 to 5 years old and weighing 15.5 to 21.3 kg, were studied. Dogs were determined to be healthy on the basis of physical, orthopedic and radiographic examination findings and normal CBC and serum biochemistry results. Dogs were randomly assigned to two experimental [high (HSMF) or medium strength magnetic field (MSMF)] (n = 5/each) or control (n = 5) groups. The experimental protocol was approved by the Veterinary Clinical Sciences Committee at Urmia University.

Custom-made magnetic wraps composed of three square-shaped permanent magnetic plates (L. 1 inch; H. 1/8 inch) (Aerospace complex, Malek-e-Ashtar University, Isfahan, Iran) were used to create the static magnetic fields, in this study. Wraps were made of commercial 15 cm elastic bandage rolls. Each magnetic plate was made of an alloy of strontium ferrite ($SrFe_{12}O_{19}$). The magnetic powers of the plates were 700 and 1500 gauss for MSMF and HSMF groups, respectively. The magnetic force between two facing magnet plates was attractive to each other, one polarity is north (N) and another one is south (S). Inactive plates, without magnetic power, were used in control group.

Dogs were premedicated with atropine (Darou pakhsh, Tehran, Iran) (0.04 mg/kg, intramuscularly [IM]) and acepromazine (Hoogsrraten, Belgium) (0.1 mg/kg, IM). Anesthesia was induced with sodium thiopental (Biochemie GmbH, Vienna, Austria) (10 mg/kg, 2.5% intravenously) and maintained with halothane after intubation. Right radius was selected for creation of midshaft osteotomy in each dog. The limb was clipped and prepared for aseptic surgery.

The limb was draped, and an approach to the craniomedial radius was made. A Kelly hemostat was passed between the radius and ulna to protect the ulna from damage during osteotomy. A Gigli wire was used to create an osteotomy, leaving a 2-mm gap between bone ends. The area was lavaged. Closure was routine.

All dogs received sodium ampicillin (Zakaria Pharmecutical Co., Tabriz, Iran) (25 mg/kg, intravenously, every 6 hours), and gentamicin sulfate (Darou pakhsh, Tehran, Iran) (5 mg/kg, intravenously, every 24 hours) for 5 consecutive post-operative days. Tramadol (KRKA, d. d., Novo mesto, Slovenia) (0.2 mg/kg, IM) was administered every 3 hours after surgery for 24 hours and as needed thereafter to control pain and discomfort.

Two days postoperative, the experimental (HSMF and MSMF) magnetic wraps were placed over the operated regions (right mid-antebrachium) in either 5 dogs of the experimental groups. They were fixed with noncompressive dressings and oriented in a way to assure the North Pole facing the limb. The operated regions in 5 control dogs were covered by inactive magnetic wraps, as well. The operated regions in each experimental group were exposed to static magnetic field continuously throughout the entire experimental period (8 weeks).

Lameness scoring was performed independently by 2 of us (SS, MA) during the entire experimental period, based on Smith *et al.*[4] The lameness was scored for both forelimbs by both examiners as: 0= non weight-bearing, 1= weight-bearing, but lame; 2= no lameness. Lameness score for each time point was the mean of results of the 2 examinations. Total scores and mean values were calculated for each group.

During week 8 of the study, dogs were euthanized by intravenous administration of sodium thiopental solution. Immediately after euthanasia, both radii were removed, cleaned of soft tissue, wrapped in saline-soaked tampon and subjected to mechanical testing. The mechanical properties were measured by a manual custom-made three-point bending machine (Rezazadeh *et al.*, Urmia University, Iran). The Young's modulus of elasticity, ultimate strength, failure load, and maximum bending moment were determined. Data derived from mechanical testing were expressed as the mean (± SD) for each group.

Statistical Methods

The results of lameness scoring were statistically evaluated using Kruskal-Wallis test. Differences in fractional changes in mechanical properties between experimental and control groups were analyzed with an unpaired Student's t test. Differences were considered significant if $p<0.05$ (SigmaStat for Windows, version 2.03, Jandel Corporation, San Rafel, CA).

Results

All dogs were recovered from surgery without complication. All dogs had some degree of incisional swelling, which resolved in a few days. All dogs remained healthy throughout the study. Magnetic wraps were well tolerated and no sores were observed due to limb wrapping.

Results of forelimbs lameness scoring are presented in table 1. Dogs exposed to HSMF had a mean lameness score of 1.27, whereas dogs in control and MSMF groups had a mean score of 0.77 and 0.86, respectively. Mean of lameness score was significantly improved in HSMF dogs as compared with either MSMF or control groups.

Mechanical properties measured for the three groups are shown in table 2. Significant differences in the examined mechanical properties were found between percent of decreased values of HSMF and either MSMF or control dogs. Statistically, the percent of reduction in biomechanical values of HSMF group was significantly less than both other groups, which revealed that radial osteotomy sites were stiffer in the former group.

Table 1: Results of forelimbs lameness scoring (based on Smith *et al.*, 1985)

		Groups		
		Control	*MSMF*	*HSMF*
Days postoperative	1	0	0	0
	3	0	0	0
	5	0	0	0
	7	0	0	1
	14	0	1	1.5
	21	1	1	1.5
	28	1	1	2
	35	1	1	2
	42	1.5	1.5	2
	49	2	2	2
	56	2	2	2
	mean±SD	**0.77±0.82**	**0.86±0.77**	**1.27±0.88***

MSMF: medium strength magnetic field
HSMF: high strength magnetic field
* differ from scores for either control or MSMF groups *($p<0.05$)*

Table 2: Statistical comparison of biomechanical parameters of radii in control and experimental groups

	Young's modulus of elasticity (MPa)			Ultimate strength (MPa)			Failure load (N)			Maximum bending moment (N.m/m^2)		
	intact limb	*operated limb*	*% Decrease*	*intact limb*	*operated limb*	*% Decrease*	*intact limb*	*operated limb*	*% Decrease*	*intact limb*	*operated limb*	*% Decrease*
control	758.2±53.58	464.6±39.27	38.72±9.5	198.24±35.21	70.12±9.36	64.62±9.5	709.4±78.56	250.3±54.62	64.71±9.5	301.17±58.54	107.24±51.91	64.39±7.8
MSMF	783.3±44.41	452.6±29.45	42.22±9.8	195.61±31.34	68.34±8.92	65.07±8.7	685.3±64.32	278.8±48.21	59.32±8.9	298.3±48.72	99.23±43.82	66.74±8.2
HSMF	818.42±54.36	732.68±52.17	10.47±11.7*	208.87±39.65	186.52±40.26	10.7±4.5*	652.7±71.54	582.12±48.67	10.81±9.3*	308.21±69.68	232.22±47.78	21.65±5.9*

MSMF: medium strength magnetic field
HSMF: high strength magnetic field
* differ from values for either control or MSMF dogs *($p<0.05$)*

Discussion

In the present study we showed that in dogs, the static magnetic field associated with application of the 1500 gauss custom-made wraps for 8 weeks, promoted bone healing in osteotomized radii. It is in agreement with the results of Bruce *et al.*, Darendeliler *et al.* and Yan *et al.* in which SMF increased the rate of bone repair and new bone deposition, and prevented decreases in bone mineral density.[5-7]

The ability to withstand loads is the most important feature of a healing bone. Young's modulus of elasticity is a measure of the stiffness of a material, and the higher its value the stiffer the material.[8] The stiffness of a material is related to its composition.[9] In this study, stiffness of bridging tissues in healing stabilized tibial osteotomies increased over the 8-week experimental period in the HSMF dogs as compared with the MSMF and control dogs, which corresponds to the type of tissue in the osteotomy gap. Defects are initially bridged with undifferentiated connective tissue during the first 2 weeks. As healing progresses, stiffness increases as the composition of bridging tissues changes from predominantly undifferentiated connective tissue to cartilage and mineralized cartilage and eventually to bone.[9] The mean of Young's modulus of the osteotomy site in this study was more than 3 times greater in HSMF dogs than in MSMF and control dogs, suggesting that healing of osteotomy sites was more advanced in HSMF dogs. The ultimate strength at failure of a bone is related to bone size and bone geometry.[9] The mean of ultimate strength of the osteotomy site in this study was more than 6 times greater in HSMF dogs than in MSMF and control dogs, reflecting larger callus size and more advanced mineralization of the callus.

The most plausible mechanism for SMF is the enhanced blood flow to the site of surgery, which is pooling oxygen and nutrients thereby speeding the overall healing process.[8] It has been suggested that static magnetic fields have a stimulatory effect on regional blood flow to the extremities and that this enhances healing of musculoskeletal injuries. Kobluk *et al.* reported that a static magnetic field significantly increased blood flow and metabolic activity in the metacarpus of horses. The magnet improves circulation, allowing blood vessels to dilate and bring a greater volume of blood flow to the injured area. This helps to bring in natural healers and to remove the toxic byproducts of inflammation, bradykinens, and prostaglandins.

It has been demonstrated that magnetic field increased the production of collagen in the *in vitro* grown rabbit marrow fibroblasts, defined as determined osteogenic precursors, and of glycosaminoglycans from cultures of chondrocytes and articular cartilage, possibly via an intracellular reduction of cyclic adenosine monophosphate (AMP). The increased formation of matriceal components may explain the accelerated fracture healing rate when subjected to magnetic field.[5] Bassett *et al.* speculated that magnetic field may perturb and/or modify the cellular membranes thereby allowing ionic movement from the extracellular environment into the osteogenic cells thereby promoting osteogenesis.

The use of magnetic fields in fracture healing increases the adherence of calcium ions to the blood clot formed at the site of the break. This allows for the proper formation of the callus that is necessary for fracture to heal properly.

The success of magnet therapy on bone healing is also attributed, in part, to its facilitating the migration of calcium ions and osteoblasts to heal broken bones in less than the usual time.

Significant improvement in the mean of lameness score of the HSMF dogs as compared with the MSMF and control dogs may reflect the pain relief they attained during this 8-week trial. The mechanistic basis of these promising results in pain reduction is not entirely understood. Constant magnetic stimulation may influence small C-fibers and may preferentially desensitize sensory neurons by modifying membrane potentials. The SMF produced fields that block firing of sodium-dependent action potentials of sensory neurons in cell culture. Moreover, it has been shown to block calcium-dependent responses to capsaicin and sodium-dependent action potential firing simultaneously in the same neurons.

The results of this study are encouraging and revealed that strong static magnetic fields may have clinical application in the treatment of fractures in patients at risk of developing delayed or nonunion fractures. Whilst it is still too early to predict the eventual role that static magnetic fields may play in the future treatment of bone defects and fractures, this report certainly suggests that the subject should be taken seriously and that more controlled, clinical investigation is warranted.

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چکیده:

اثر مشوق میدان مغناطیسی ایستا بر التیام استخوان در سگ: مطالعه بیومکانیک

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هدف: بررسی اثرات میدان مغناطیسی ایستا تولید ایران برجنبه های بیومکانیک و بالینی التیام استخوان. با استفاده از مدل نقیصه استخوانی ناپایدار در سگ.

طرح: مطالعه تجربی

حیوانات: ۱۵ قلاده سگ

روش کار: به دنبال استئوتومی میانه دیافیز زند اعلی، روند التیامی استخوان در سه گروه ۵ تایی شاهد، آزمون متوسط شدت (در معرض میدان مغناطیسی ایستا با شدت ۷۰۰ گوس) و آزمون پرشدت (در معرض میدان مغناطیسی ایستا با شدت ۱۵۰۰ گوس) در یک دوره ۸ هفته ای، موردمطالعه قرار داده شد. ارزیابی های بالینی و بیومکانیک در پایان دوره مطالعه انجام گرفت.

نتایج: میزان تنگش در گروه آزمون پرشدت نسبت به گروه های آزمون متوسط شدت و شاهد، بهبودی بیشتری را نشان داد. افزایش معنی دار آماری ($P<0.05$) در اندازه نیروی مورد نیاز برای شکست زند اعلی استئوتومی شده در سگ های گروه آزمون پرشدت نسبت به دو گروه دیگر مشاهده شد.

نتیجه گیری: نتایج این مطالعه نشان داد که میدان مغناطیسی ایستای پر شدت قادر به ارتقا التیام استخوان از جنبه‌های بیومکانیک و بالینی است. بنابراین استفاده بالینی از میدان مغناطیسی ایستای پرشدت در شکستگی های دیر جوش استخوانی سگ پیشنهاد می گردد.

کلید واژه ها: میدان مغناطیسی ایستا، استئوتومی، تنگش، بیومکانیک، سگ.