

METHOD AND DEVICE FOR TREATING OSTEOARTHRITIS, CARTILAGE DISEASE, DEFECTS AND INJURIES IN THE HUMAN KNEE

Cross-Reference to Related Applications

[0001] The present patent application claims priority to U.S. Patent Application Serial No. 10/457,167 filed June 9, 2003 which is a continuation-in-part patent application of U.S. Patent Application Serial No. 10/257,126, which is the U.S. national phase patent application of PCT/US01/05991, filed February 23, 2001, which, in turn, claims the benefit of the filing date of U.S. Provisional Patent Application Serial No. 60/184,491, filed February 23, 2000.

Field of the Invention

[0002] The present invention is directed to the method of determining the voltage and current output required for the application of specific and selective electric and electromagnetic signals to diseased articular cartilage in the treatment of osteoarthritis, cartilage defects due to trauma or sports injuries, or as an adjunct with other therapies (e.g., cell transplantation, tissue-engineered scaffolds, growth factors, etc.) for treating cartilage defects in the human knee joint and a device for delivering such signals to a patient's knee.

Background of the Invention

[0003] The bioelectrical interactions and activity believed to be present in a variety of biological tissues and cells are one of the least understood of the physiological processes. However, there has recently been much research into these interactions and activity regarding the growth and repair of certain tissues and cells. In particular, there has been much research into stimulation by electric and electromagnetic fields and its effect on the growth and repair of bone and cartilage. Researchers believe that such research might be useful in the development of new treatments for a variety of medical problems.

[0004] Osteoarthritis, also known as degenerative joint disease, is characterized by degeneration of articular cartilage as well as proliferation and remodeling of subchondral bone. The usual symptoms are stiffness, limitation of motion, and pain. Osteoarthritis is the most common form of arthritis, and prevalence rates increase markedly with age. It has been shown that elderly patients with self-reported osteoarthritis visit doctors twice as

frequently as their unaffected peers. Such patients also experience more days of restricted activity and bed confinement compared to others in their age group. In one study, the majority of symptomatic patients became significantly disabled during an 8-year follow-up period. Massardo et al., *Ann Rheum Dis* 48: 893-7 (1989).

[0005] Nonsteroidal anti-inflammatory drugs (NSAIDs) remain the primary treatment modality for osteoarthritis. It is unknown whether the efficacy of NSAIDs is dependent upon their analgesic or anti-inflammatory properties or the slowing of degenerative processes in the cartilage. There is also a concern that NSAIDs may be deleterious to patients. For example, NSAIDs have well known toxic effects in the stomach, gastrointestinal tract, liver and kidney. However, aspirin inhibits proteoglycan synthesis and normal cartilaginous repair processes in animals. One study in humans suggested that indomethacin might accelerate breakdown of hip cartilage. All adverse effects appear more commonly in the elderly—the very population the most susceptible to osteoarthritis.

[0006] In the disease commonly known as osteoporosis, bone demineralizes and becomes abnormally rarefied. Bone comprises an organic component of cells and matrix as well as an inorganic or mineral component. The cells and matrix comprise a framework of collagenous fibers that is impregnated with the mineral component of calcium phosphate (85%) and calcium carbonate (10%) that imparts rigidity to bone. While osteoporosis is generally thought as afflicting the elderly, certain types of osteoporosis may affect persons of all ages whose bones are not subject to functional stress. In such cases, patients may experience a significant loss of cortical and cancellous bone during prolonged periods of immobilization. Elderly patients are known to experience bone loss due to disuse when immobilized after fracture of a bone, which may ultimately lead to a secondary fracture in an already osteoporotic skeleton. Diminished bone density may lead to vertebrae collapse, fractures of hips, lower arms, wrists, ankles as well as incapacitating pains. Alternative nonsurgical therapies for such diseases are needed.

[0007] Pulsed electromagnetic fields (PEMF) and capacitive coupling (CC) have been used widely to treat nonhealing fractures and related problems in bone healing since approval by the Food and Drug Administration in 1979. The original basis for the trial of this form of therapy was the observation that physical stress on bone causes the appearance of tiny electric currents that, along with mechanical strain, were thought to be the mechanisms underlying transduction of the physical stresses into a signal that

promotes bone formation. Along with direct electric field stimulation that was successful in the treatment of nonunion, noninvasive technologies using PEMF and capacitive coupling (where the electrodes are placed on the skin in the treatment zone) were also found to be effective. Pulsed electromagnetic fields generate small, induced currents (Faraday currents) in the highly conductive extracellular fluid, while capacitive coupling directly causes currents in the tissues; both PEMFs and CC thereby mimic endogenous electrical currents.

[0008] The endogenous electrical currents, originally thought to be due to phenomena occurring at the surface of crystals in the bone, have been shown to be due primarily to movement of fluid containing electrolytes in channels of the bone containing organic constituents with fixed negative charges, generating what are called "streaming potentials." Studies of electrical phenomena in cartilage have demonstrated a mechanical-electrical transduction mechanism that resembles those described in bone, appearing when cartilage is mechanically compressed, causing movement of fluid and electrolytes over the surface of fixed negative charges in the proteoglycans and collagen in the cartilage matrix. These streaming potentials apparently serve a purpose in cartilage similar to that in bone, and, along with mechanical strain, lead to signal transduction that is capable of stimulating chondrocyte synthesis of matrix components.

[0009] The main application of direct current, capacitive coupling, and PEMFs has been in orthopedics in healing of nonunion bone fractures (Brighton et al., *J. Bone Joint Surg.*, 63: 2-13, 1981; Brighton and Pollack, *J. Bone Joint Surg.*, 67: 577-585, 1985; Bassett et al., *Crit. Rev. Biomed. Eng.*, 17: 451-529, 1989; Bassett et al., *JAMA* 247: 623-628, 1982. Clinical responses have been reported in avascular necrosis of hips in adults and Legg-Perthes's disease in children. Bassett et al., *Clin. Orthop.* 246: 172-176, 1989; Aaron et al., *Clin. Orthop.* 249: 209-218, 1989; Harrison et al., *J. Pediatr. Orthop.* 4: 579-584, 1984. It has also been shown that PEMFs (Mooney, *Spine*, 15: 708-712, 1990) and capacitive coupling (Goodwin, Brighton et al., *Spine*, 24: 1349-1356, 1999) can significantly increase the success rate of lumbar fusions. There are also reports of augmentation of peripheral nerve regeneration and function and promotion of angiogenesis. Bassett, *Bioessays* 6: 36-42, 1987. Patients with persistent rotator cuff tendonitis refractory to steroid injection and other conventional measures, showed significant benefit compared with placebo treated patients. Binder et al., *Lancet* 695-698, 1984. Finally, Brighton et al. have shown in rats the ability of an appropriate capacitive

coupling electric field to both prevent and reverse vertebral osteoporosis in the lumbar spine (Brighton et al., *J. Orthop. Res.* 6: 676-684, 1988; Brighton et al., *J. Bone Joint Surg.*, 71: 228-236, 1989).

[0010] More recently, research in this area has focused on the effects stimulation has on tissues and cells. For example, it has been conjectured that direct currents do not penetrate cellular membranes and that control is achieved via extracellular matrix differentiation (Grodzinsky, *Crit. Rev. Biomed. Eng.* 9:133, 1983). In contrast to direct currents, it has been reported that PEMFs can penetrate cell membranes and either stimulate them or directly affect intracellular organelles. An examination of the effect of PEMFs on extracellular matrices and *in vivo* endochondral ossification found increased synthesis of cartilage molecules and maturation of bone trabeculae (Aaron et al., *J. Bone Miner. Res.* 4: 227-233, 1989). More recently, Lorch, Brighton et al. reported (*Clin. Orthop. Related Res.* 350: 246-256, 1998) that signal transduction of a capacitively coupled electric signal is via voltage gated calcium channels, leading to an increase in cytosolic calcium with a subsequent increase in activated (cytoskeletal) calmodulin.

[0011] Much research has been directed at studying tissue culture in order to understand the mechanisms of response. In one study, it was found that electric fields increased [³H]-thymidine incorporation into the DNA of chondrocytes, supporting the notion that Na⁺ and Ca²⁺ fluxes generated by electrical stimulation trigger DNA synthesis (Rodan et al., *Science* 199: 690-692, 1978). Studies have found changes in the second messenger, cAMP, and cytoskeletal rearrangements due to electrical perturbations (Ryaby et al., *Trans. BRAGS* 6: 1986; Jones et al., *Trans. BRAGS* 6: 51, 1986; Brighton and Townsend, *J. Orthop. Res.* 6: 552-558, 1988). Other studies have found effects on glycosaminoglycan, sulfation, hyaluronic acid, lysozyme activity and polypeptide sequences (Norton et al., *J. Orthop. Res.* 6: 685-689, 1988; Goodman et al., *Proc. Natn. Acad. Sci. USA* 85: 3928-3932 1988).

[0012] It was reported in 1996 by the present inventor that a cyclic biaxial 0.17% mechanical strain produces a significant increase in TGF-β₁ mRNA in cultured MC3T3-E1 bone cells (Brighton et al., *Biochem. Biophys. Res. Commun.* 229: 449-453, 1996). Several significant studies followed in 1997. In one study it was reported that the same cyclic biaxial 0.17% mechanical strain produced a significant increase in PDGF-A mRNA in similar bone cells (Brighton et al., *Biochem. Biophys. Res. Commun.* 43: 339-346, 1997). It was also reported that a 60 kHz capacitively coupled electric field of 20 mV/cm

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produced a significant increase in TGF- β_1 in similar bone cells (Brighton et al., *Biochem. Biophys. Res. Commun.* 237: 225-229, 1997). However, the effect such a field would have on other genes has not been reported in the literature.

5 In the above-referenced parent patent application, entitled "Regulation of Genes Via Application of Specific and Selective Electrical and Electromagnetic Signals", methods were disclosed for determining the specific and selective electrical and electromagnetic signals for use in creating specific and selective fields for regulating target genes of
10 diseased or injured tissues. The present invention builds upon the technique described therein by describing the method of determining the voltage and current output required and the corresponding apparatus for delivering specific and selective electrical and electromagnetic signals to the human knee joints in patients afflicted with osteoarthritis and other cartilage defects, diseases and injuries.

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Summary of the Invention

The present invention provides a device for treating diseased tissue in a human knee joint through the application of a specific and selective electric or electromagnetic field to the
20 diseased or injured tissue in the human knee joint, comprising:

- a. one of (a) at least two electrodes, in the case of capacitive coupling, adapted for application in the proximity of a patient's knee joint; and (b) a solenoid or at least one coil, in the case of inductive coupling, adapted for application in the proximity of a patient's knee joint; and
- 25 b. a signal generator having a select control that selects, based on the size of the patient's knee joint, electric signals for application to the electrodes, the solenoid or at least one coil so as to produce an electric field range of approximately 8mV/cm to 360mV/cm and a current density range of approximately 8 μ A/cm² to 300 μ A/cm² within the synovium and articular cartilage of the patient's knee joint.

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The present invention also provides a device for treating osteoarthritis, cartilage defects due to trauma or sports injury, or used as an adjunct with other therapies for treating cartilage defects in a human knee joint through the application of a specific and selective electric or electromagnetic field to the afflicted tissue in the human knee joint, comprising:

- 35 a. one of (a) at least two electrodes and (b) a solenoid or at least one coil adapted for application in the proximity of a patient's knee joint; and
- b. a signal generator having a select control that selects, based on the size of the patient's knee joint, electric signals for application to the electrodes, the solenoid or at

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least one coil so as to produce an electric field range of approximately 8mV/cm to 360mV/cm and a current density range of approximately $8\mu\text{A}/\text{cm}^2$ to $300\mu\text{A}/\text{cm}^2$ within the synovium and articular cartilage of the patient's knee joint.

- 5 Preferably the signal generator provides one of a plurality of output electric signals with a voltage selected by a user in accordance with a size of the human knee joint.

Preferably one of the plurality of output electrical signals of the signal generator for a 60kHz frequency has a voltage of approximately $4.6 V_{p-p} \pm 10\%$ for a small size knee joint.

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Preferably one of the plurality of output electrical signals of the signal generator for a 60kHz has a voltage of approximately $5.0 V_{p-p} \pm 10\%$ for an average size knee joint.

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Preferably one of the plurality of output electrical signals of the signal generator for a 60kHz has a voltage of approximately $5.6 V_{p-p} \pm 10\%$ for a large size knee joint.

Preferably one of the plurality of output electrical signals of the signal generator for a 60kHz has a voltage of approximately $7.6 V_{p-p} \pm 10\%$ for an extra large size knee joint.

- 20 The invention also provides a method of treating osteoarthritis, cartilage defects due to trauma or sports injury, or used as an adjunct with other therapies for treating cartilage defects in a human knee joint through the application of a specific and selective electric or electromagnetic field to the afflicted tissue in the human knee joint, comprising the steps of:

- 25 a. converting electric potential into an electric signal that when applied to one of (a) at least two electrodes and (b) a solenoid or at least one coil adapted for application in the proximity of a patient's knee joint produces an electric field range of not less than approximately 8mV/cm to 360mV/cm and a current density range of approximately $8\mu\text{A}/\text{cm}^2$ to $300\mu\text{A}/\text{cm}^2$ within the synovium and articular cartilage of the patient's knee joint; and

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b. applying the electrical signal to either (a) the at least two electrodes or (b) the solenoid or at least one coil so as to produce the electric field within the synovium and articular cartilage of the patient's knee joint.

- 35 Preferably the method comprises the additional step of selecting one of a plurality of output electric signals with a voltage in accordance with a diameter of the human knee joint.

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Preferably the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $4.6 V_{p-p} \pm 10\%$ for a small size knee joint.

- 5 Preferably the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $5.0 V_{p-p} \pm 10\%$ for an average size knee joint.

Preferably the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $5.6 V_{p-p} \pm 10\%$ for a large size knee joint.

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Preferably the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $7.6 V_{p-p} \pm 10\%$ for an extra large size knee joint.

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Brief Description of the Drawings

Preferred embodiments of the invention will be described in conjunction with the accompanying drawings, of which:

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Figure 1 illustrates a human knee joint with applied electrodes used for the treatment of osteoarthritis, cartilage defects, or as in accordance with the invention.

Figure 2 illustrates a front view of an analytical model of the human knee joint of Figure 1 for use in calculating voltage and current requirements for the treatment of osteoarthritis in accordance with the invention.

- [0024] **Figure 3** illustrates a cross-sectional view of an analytical model of the human knee joint of **Figure 1** for use in calculating voltage and current requirements for the treatment of osteoarthritis in accordance with the invention.
- [0025] **Figure 4** illustrates electric field histograms plotting the percentage of the total tissue volume as a function of the electric field amplitude for each of the tissues.
- [0026] **Figure 5** illustrates current density histograms plotting the percentage of the total tissue volume as a function of the current density amplitude for each of the tissues.
- [0027] **Figure 6** illustrates the electric field histograms plotting the percentage of the total tissue volume as a function of the electric field amplitude for three values of gap width of the cartilage/synovial fluid compartment.
- [0028] **Figure 7** illustrates electric field histograms showing that as the knee size increased from the size of a rabbit knee to the size of a human knee, the electric field in the cartilage/synovial fluid compartment decreased.
- [0029] **Figure 8** illustrates electric field histograms for the analytic model of the human knee with and without subcutaneous fat.
- [0030] **Figure 9** illustrates current density histograms for the analytic model of the human knee with and without subcutaneous fat.
- [0031] **Figure 10** illustrates electric field histograms for four longitudinal positions of the electrodes relative to the cartilage zone in the analytic model of the human knee.
- [0032] **Figure 11** illustrates current density histograms for four longitudinal positions of the electrodes relative to the cartilage zone in the analytic model of the human knee.
- [0033] **Figure 12** illustrates electric field histograms for anatomic models of the rabbit fibular osteotomy and human tibial non-union for effective driving signals.
- [0034] **Figure 13** illustrates current density histograms for anatomic models of the rabbit fibular osteotomy and human tibial non-union for effective driving signals.
- [0035] **Figure 14** illustrates a human knee joint with applied coils used for the treatment of osteoarthritis, cartilage defects due to trauma or sports injury, or used as an adjunct with other therapies (cell transplantation, tissue-engineered scaffolds, growth factors, etc.) in treating cartilage defects using inductive coupling.
- [0036] **Figure 15** illustrates a coil of N total turns of wire of radius a and length l used in determining the dimensions and number of turns of wire required to make a coil

for producing the desired electric field in the articular cartilage when using inductive coupling.

[0037] Figure 16 illustrates the cross-section through a coil in relation to the knee joint zone along the axis at which the magnetic flux is calculated.

Detailed Description of Preferred Embodiments of the Invention

[0038] The invention will be described in detail below with reference to Figures 1–16. Those skilled in the art will appreciate that the description given herein with respect to those figures is for exemplary purposes only and is not intended in any way to limit the scope of the invention. All questions regarding the scope of the invention may be resolved by referring to the appended claims.

Definitions:

[0039] As used herein, the phrase “signal” is used to refer to a variety of signals including mechanical signals, ultrasound signals, electromagnetic signals and electric signals output by a device.

[0040] As used herein, the term “field” refers to an electrical field within targeted tissue, whether it is a combined field or a pulsed electromagnetic field or generated by direct current, capacitive coupling or inductive coupling.

Description of Illustrated Embodiments:

[0041] Previous studies by the present inventors have shown that a capacitively coupled field significantly increased the proliferation of bone cells grown in culture (Brighton, Pollack, et al., *J. Orthop. Res.* 3: 331–340, 1985) and significantly increased the rate of healing in a rat fractured fibula model (Brighton, Pollack, et al., *Clin. Orthop. Related Res.* 285: 255–262, 1992). Also, the field distributions in the vertebral bodies of rats during capacitively coupled electrical stimulation have been determined (Carter, Vresilovic, Pollack, and Brighton, *IEEE Trans. Biomed. Eng.* 36(-3): 333–334, 1989). In order to determine the required output voltage and current required to produce an equivalent electric field and current density in a human knee as found in bone cell and rabbit fibula studies, the analytical model depicted in Figures 2 and 3 was developed in accordance with the invention for representing the typical human knee joint illustrated in Figure 1.

[0042] As shown in Figure 1, the typical human knee joint includes a compartment filled with synovial fluid that is bounded by the articular cartilage on the

ends of the femur and tibia, respectively, and fibrous capsules. In accordance with the invention, osteoarthritis in the knee joint is treated by the application of specific and selective electric fields via flexible electrodes attached relative to the knee joint substantially as shown in **Figure 1**. A signal generator provides the appropriate signals to the electrodes for generating the specific and selective electric fields. The specific and selective electric field needed to treat osteoarthritis in the knee joint is calculated in accordance with the invention using the analytical model of the knee joint depicted in **Figures 2 and 3**.

[0043] In the analytical model of **Figures 2 and 3**, the following elements are identified as indicated: electrodes 1, skin 2, muscle 3, bone 4, and cartilage and synovial fluid compartment 5. In arriving at the analytical model, the following assumptions were made regarding the sizes of the elements: the femoral width = 76.5 mm; the tibial width = 101.5 mm; and the interelectrode distance = 108 mm. The specific account of the electrical properties of ligaments was not included—rather, space other than cartilage and bone was considered to have the same electrical properties as muscle and marrow. Also, the conductivities of the tissues included in the study were measured as follows:

Material	Complex Conductivity (S/m) at 60 kHz
Muscle	
Parallel to fibers	7.0×10^{-1}
Perpendicular to fibers	2.0×10^{-1}
Marrow	2.0×10^{-1}
Bone Cortex	1.0×10^{-2}
Cartilage	8.9×10^{-2}
Subcutaneous Fat	2.0×10^{-1}
	Admittance/Area (S/cm ²) at 60 kHz
Electrode-Dermal Interface	3.0×10^{-3}

As will be explained below, the cartilage and synovial fluid compartment 5 was computed for three sizes: 0.3 cm, 2.3 cm, and 4.3 cm, and the applied electrode potential (potential between the two electrodes) was taken as 1.0 V.

[0044] The approximate results for the analytic model of the human knee for an applied voltage of 1.0 V peak-to-peak at 60 kHz are given below for various parameters as a function of the electric field and the current density.

[0045] As shown in **Figure 4**, the electric field in the cartilage/synovial compartment 5 is not uniform in value over the entire volume of the compartment. This is also true for all compartments and reflects the complex geometry even for the analytical model. Also, as shown in **Figure 5**, the current density in the cartilage/synovial fluid compartment 5 is not uniform over the volume of the compartment. This is also true for all other compartments and reflects the complex geometry even in the analytical model.

[0046] As shown in **Figure 6**, as the cartilage/synovial fluid compartment 5 increased in thickness, the electric field in the cartilage/synovial fluid compartment 5 increased and became more uniform.

[0047] As shown in **Figure 7**, as the knee size increased from the size of a rabbit knee to the size of a human knee, the electric field in the cartilage/synovial fluid compartment 5 decreased. In general, increasing or decreasing the knee diameter was found to change the entire field distribution by the reciprocal of the distance between the two electrodes. In other words, the larger the knee diameter, the smaller the electric field for a fixed applied voltage.

[0048] The amount of subcutaneous fat has also been found to have little effect on field and current density. Subcutaneous fat has a lower conductivity than muscle and, therefore, the electric field (**Figure 8**) and current density (**Figure 9**) are slightly decreased, but this is not substantive in most cases of the knee.

[0049] Finally, it has been discovered that the effect of improper alignment of the electrodes 1 placed on the knee relative to the cartilage/synovial compartment 5 is not critical. Four cases were considered: 1) mid-gap (middle of the cartilage/synovial compartment 5); 2) half diameter below the gap; 3) diameter below the gap; and 4) 2 diameters below the gap. The results for the electric field are shown in **Figure 10** and for the current density are shown in **Figure 11**. Thus, alignment of the electrodes is not a critical factor in this model.

[0050] Previous work by the present inventors on stimulation of fracture healing with capacitive coupling led to the following understanding of field and current levels as a progression was made sequentially from bone cell studies to animal studies to human studies:

Cell (<i>in vitro</i>) Results:	Maximum effect at 20 mV/cm electric field Current density of 200 $\mu\text{A}/\text{cm}^2$.
Animal (rabbit) Results: Successful healing of Fracture Callus	Voltage output of 0.25 V_{p-p} for the device with electrodes on the rabbit knee. Approximate range of peak of the electric field of 8–200 mV/cm in the fracture callus. Approximate range of peak electrical current density 8–195 $\mu\text{A}/\text{cm}^2$ in the fracture callus.
Human (nonunion) Results: Successful healing Nonunion fracture	Voltage output of 5 V_{p-p} for the device with the electrodes on the skin. Approximate range of peak electric field of 8–360 mV/cm. Electric current density of 8–300 $\mu\text{A}/\text{cm}^2$

[0051] This is shown in Figures 12 and 13 in which the anatomical models of both the rabbit fibula fracture model and the human nonunion model are compared. It is seen that the same successful electrical stimulation conditions are achieved at the tissue level by scaling the device voltage applied externally for treatment in accordance with the relative tissue volumes between the animal model and the human model.

[0052] As a result of these prior comparisons, the present inventors have determined the following therapeutic effective ranges of field (E) and current density in the callus (see Figure 12: callus) and for *in vitro* studies of the bone cells (Brighton, Pollack, et al., *Clin. Orthop. Related Res.*, 285: 255- 262, 1992) are desirable:

(J)	Animal/Human Callus	Bone Cells
E	8 mV/cm to 180 mV/cm	20 mV/cm
J	8 $\mu\text{A}/\text{cm}^2$ to 180 $\mu\text{A}/\text{cm}^2$	200 $\mu\text{A}/\text{cm}^2$

These animal/human ranges of electrical field amplitude and current density take an important factor into account. It is that their extreme limits must encompass the results obtained from bone cell studies where geometric factors permitted more exact field determinations. In this way regions of the human/animal tissue cycle through the therapeutic effective range of the electric field and current density as the sinusoidal applied voltage cycles through the sine wave.

[0053] Since *in vitro* cartilage cell results also occurred at an effective field of 20 mV/cm, and since the measured circumference of the human knee joint is approximately the same as the measured diameter of the mid-calf region of the leg in a given patient, then

the same scale factor of 5, used in the human tibia fracture model (**Figure 12**), applies to the human knee joint analytical model of **Figure 2** where the callus is replaced by the synovial membrane and articular cartilage.

[0054] Thus, if the circumference of a given human knee = 15.7 inches, then the diameter = 5 inches. This was found to be the most common mean knee circumference measured in patients with osteoarthritis. An output voltage of 5 V_{p-p} should produce the above E field and current density in the average size knee joint cartilage/synovial compartment. A smaller knee joint diameter, say 4.6 inches as an example, would require less voltage output (4.6 V_{p-p}), and a very large knee joint diameter, say 7.6 inches, would require more voltage output (7.6 V_{p-p}). Thus, a voltage output of 4.6 V_{p-p} to 7.6 V_{p-p} would cover the full range of knee sizes measured to date to produce the desired therapeutic E field and current density in the cartilage/synovial fluid compartment of the knees as described above. Variations of $\pm 10\%$ in the applied voltage are tolerated because of the distribution of values E and J resulting from anatomical complexity.

[0055] Thus, in accordance with the invention, the approximate size (and hence approximate diameter) of the patient's knee is determined, and a signal is generated and applied to the electrodes that will generate the desired electric field in the range of 8 mV/cm to 360 mV/cm and a current density range of 8 $\mu A/cm^2$ to 300 $\mu A/cm^2$ for treatment of osteoarthritis in the knee, for example. Preferably, the signal generator includes a select control (**Figure 1**) that allows the operator to select the proper output based on the size of the patient's knee.

[0056] Also in accordance with the invention, the appropriate electric field can be delivered to diseased or traumatized articular cartilage using an inductive coupling device of the type shown in **Figure 14**. To calculate the electric field generated by the coil in **Figure 14**, we imagine an elastic bandage containing a coil of N turns that is slipped over the knee and centered thereon. A battery-powered supply of current is attached to the coil leads such that a time varying current flows through the coil. This current produces a magnetic flux which in turn produces a time-varying electric field. It is understood that the current amplitude, frequency, duty cycle and wave form(s) can be controlled from the power supply so as to produce a therapeutic value for the E field. We now calculate the combinations that will accomplish this.

[0057] Schematic diagrams showing a coil of N total turns of wire and a cross-section through this coil are shown in **Figures 15** and **16**, respectively. The angles θ_1 and

θ_2 are those between the point on the X-axis at which the magnetic flux is calculated and the ends of the coil in the +Z and -Z directions. For arbitrary sizes, the flux is given by the equation:

$$(1) \quad B = \frac{1}{2} \mu_0 \frac{N}{l} I (\sin \theta_2 - \sin \theta_1)$$

$$\text{where } \sin \theta_1 = \frac{l_1}{\sqrt{l_1^2 + a^2}}$$

$$\sin \theta_2 = \frac{l_2}{\sqrt{l_2^2 + a^2}}$$

and I is the current in the coil, l is the length of the coil and μ_0 is the magnetic permeability of air (and tissue). In the central region of the coil, the field of a solenoid is quite uniform so we can select the values of l_1 and l_2 so that they are equal. Since $\sin \theta_1$ is a negative number because l_1 is negative along the Z axis, $\sin \theta_2 - \sin \theta_1 = 2 \sin \theta_2$ if $l_1 = l_2$.

[0058] Therefore, Equation (1) becomes:

$$(2) \quad B = \mu_0 \frac{N}{l} I \left(\frac{l}{(l^2 + 4a^2)^{\frac{1}{2}}} \right)$$

The current, I is a sinusoidal varying current and it can be written as:

$$(3) \quad I = I_0 - e^{i\omega t}$$

where I_0 is the amplitude of the sinusoidal current, ω is 2π times the frequency (which we will set to 60 kHz, and i is the imaginary number $\sqrt{-1}$. This notation is equivalent to the following:

$$(4) \quad I = I_0 \sin \omega t$$

Therefore, Equation (2) becomes:

$$(5) \quad B = \mu_0 \frac{N}{l} I_0 \left(\frac{l}{(l^2 + 4a^2)^{\frac{1}{2}}} \right) \sin \omega t$$

[0059] From Maxwell's Equations we obtain an expression for the amplitudes of the electric field associated with the time-varying magnetic flux. It should be noted that the magnetic flux is parallel to the long axis of the leg and is therefore perpendicular to the planes of the cartilage in the knee. The electric field, however, is in the planes of the cartilage, is circular in direction, and will vary in amplitude with radius such that at the

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geometric center of the knee, the electric field amplitude will be zero and it will increase in amplitude in a linear dependence on radius.

[0060] The theory says that

$$(6) \quad |E| = -\frac{dB}{dt} \cdot \frac{r}{2}$$

where $|E|$ is the electric field amplitude, dB/dt is the time derivative of Equation (5), and r is the distance from the geometric center of the knee joint to an arbitrary radius, r . Placing Equation (5) into equation (6) and performing differentiation gives

$$(7) \quad |E| = \mu_0 \frac{N}{l} I_0 \omega \cos \omega t \left(\frac{l}{(l^2 + 4a^2)^{\frac{1}{2}}} \right) \cdot \frac{r}{2}$$

where the $\cos \omega$ indicates that the electric field is 90° out of phase with the magnetic flux.

[0061] If we insert the values of all the parameters in Equation (7), namely

$$a = 6.35 \times 10^{-2} \text{ meters}$$

$$l = 6.35 \times 10^{-2} \text{ meters}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ T meters/A}$$

$$N = 3 \times 10^3 \text{ turns}$$

$$I_0 = 100 \text{ mA}$$

$$r = 6.35 \times 10^{-2} \text{ meters}$$

$$\omega = 2\pi \times 60 \times 10^3 \frac{1}{\text{sec}}$$

we obtain

$$|E|_{\text{Max}} = 315 \text{ mV/cm}$$

where $|E|_{\text{Max}}$ is the amplitude at the maximum radius of the knee, namely 6.35×10^{-2} meters.

[0062] Therefore, for any given cycle of the magnetic field, the center of the knee has zero electric field, while at the extreme radius, the field cycles from 0 to 315 mV/cm. For 90% of the area of the cartilage synovial region to achieve an electric field strength of 20 mV/cm, the maximum field at the periphery of the knee joint must be 65 mV/cm. This means that the number of turns (N) in the transducer can be reduced from 3000 to $(65/315) \times 3000 = 620$.

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[0063] Although implementations of the invention have been described in detail above, those skilled in the art will readily appreciate that many additional modifications are possible without materially departing from the novel teachings and advantages of the invention. Any such modifications are intended to be included within the scope of the invention as defined in the following claims.

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What is claimed is:

1. A device for treating diseased tissue in a human knee joint through the
5 application of a specific and selective electric or electromagnetic field to the diseased or injured tissue in the human knee joint, comprising:
 - a. one of (a) at least two electrodes, in the case of capacitive coupling, adapted for application in the proximity of a patient's knee joint; and (b) a solenoid or at least one coil, in the case of inductive coupling, adapted for application in the
10 proximity of a patient's knee joint; and
 - b. a signal generator having a select control that selects, based on the size of the patient's knee joint, electric signals for application to the electrodes, the solenoid or at least one coil so as to produce an electric field range of approximately 8mV/cm to 360mV/cm and a current density range of approximately $8\mu\text{A}/\text{cm}^2$ to $300\mu\text{A}/\text{cm}^2$ within
15 the synovium and articular cartilage of the patient's knee joint.
2. A device for treating osteoarthritis, cartilage defects due to trauma or sports injury, or used as an adjunct with other therapies for treating cartilage defects in a human knee joint through the application of a specific and selective electric or
20 electromagnetic field to the afflicted tissue in the human knee joint, comprising:
 - a. one of (a) at least two electrodes and (b) a solenoid or at least one coil adapted for application in the proximity of a patient's knee joint; and
 - b. a signal generator having a select control that selects, based on the size of the patient's knee joint, electric signals for application to the electrodes, the solenoid
25 or at least one coil so as to produce an electric field range of approximately 8mV/cm to 360mV/cm and a current density range of approximately $8\mu\text{A}/\text{cm}^2$ to $300\mu\text{A}/\text{cm}^2$ within the synovium and articular cartilage of the patient's knee joint.
3. A device as in claim 2, wherein the signal generator provides one of a plurality
30 of output electric signals with a voltage selected by a user in accordance with a size of the human knee joint.
4. A device as in claim 3, wherein one of the plurality of output electrical signals of the signal generator for a 60kHz frequency has a voltage of approximately $4.6 V_{p-p} \pm$
35 10% for a small size knee joint.

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5. A device as in claim 3, wherein one of the plurality of output electrical signals of the signal generator for a 60kHz has a voltage of approximately $5.0 V_{p-p} \pm 10\%$ for an average size knee joint.
- 5 6. A device as in claim 3, wherein one of the plurality of output electrical signals of the signal generator for a 60kHz has a voltage of approximately $5.6 V_{p-p} \pm 10\%$ for a large size knee joint.
7. A device as in claim 3, wherein one of the plurality of output electrical signals
10 of the signal generator for a 60kHz has a voltage of approximately $7.6 V_{p-p} \pm 10\%$ for an extra large size knee joint.
8. A method of treating osteoarthritis, cartilage defects due to trauma or sports injury, or used as an adjunct with other therapies for treating cartilage defects in a
15 human knee joint through the application of a specific and selective electric or electromagnetic field to the afflicted tissue in the human knee joint, comprising the steps of:
- a. converting electric potential into an electric signal that when applied to one of (a) at least two electrodes and (b) a solenoid or at least one coil adapted for
20 application in the proximity of a patient's knee joint produces an electric field range of not less than approximately 8mV/cm to 360mV/cm and a current density range of approximately $8\mu A/cm^2$ to $300\mu A/cm^2$ within the synovium and articular cartilage of the patient's knee joint; and
- b. applying the electrical signal to either (a) the at least two electrodes or
25 (b) the solenoid or at least one coil so as to produce the electric field within the synovium and articular cartilage of the patient's knee joint.
9. A method as in claim 8, comprising the additional step of selecting one of a plurality of output electric signals with a voltage in accordance with a diameter of the
30 human knee joint.
10. A method as in claim 9, wherein the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $4.6 V_{p-p} \pm 10\%$ for a small size knee joint.
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11. A method as in claim 9, wherein the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $5.0 V_{p-p} \pm 10\%$ for an average size knee joint.

12. A method as in claim 9, wherein the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $5.6V_{p-p} \pm 10\%$ for a large size knee joint.

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13. A method as in claim 9, wherein the selecting step comprises the step of selecting an electrical signal of a 60kHz frequency having a voltage of approximately $7.6 V_{p-p} \pm 10\%$ for an extra large size knee joint.

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