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USE OF ELECTRICAL AND MAGNETIC STIMULATION
IN ORTHOPEDICS AND TRAUMATOLOGY

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Introduction.

The scientific origins of the electrical and magnetic stimulation of osteogenesis are acknowledged to lie in the by now classic studies performed first by Fukada and Yasuda (1), then by Bassett and Becker (2).

The electrical and magnetic stimulation of osteogenesis belongs in the area of research of bioengineering and biophysics. It is employed in many countries in the orthopedic field to promote and reactivate the formation of bone tissue. The method was approved for clinical use some twenty years ago by the U.S. Food and Drug Administration.

The aforementioned studies performed in the 1950s and 1960s (1,2) highlighted the relation between bone tissue and electric potentials.

Bone generates two types of electric signal: one in response to mechanical deformation **(I)**, the other in the absence of deformation **(II)**.

I. the signal induced by structural deformation following the application of a load is present in bone, not necessarily vital, and can be ascribed to a dual origin: a) to the *direct piezoelectric effect,* and b) to the *electrokinetic phenomenon of the flow potential*.

a) The signal measured on the bone surface deformed by a load can be attributed to the piezoelectric properties of the collagen matrix only when the bone is dehydrated (3). The signal is generated by the asymmetric redistribution of the molecular charges resulting from mechanical deformation (3,4).

b) In physiological conditions, i.e. in hydrated bone, the electrical signal induced by mechanical deformation can be imputed to the electrokinetic phenomenon occurring in a porous material like bone, when the fluid permeating it flows as a result of the action of the mechanical deformation itself. Its mechanism of formation depends on the selective adsorption of ions on the molecular surface and, hence, on the formation of ions of opposite sign outside the molecular surface. The endosteal ion flow occurs in two spaces: haversian and endocanalicular (4-7).

Independently of the mechanism, piezoelectric or electrokinetic, by which it is generated, the electrical signal induced by the mechanical deformation, containing the information of site, direction and amplitude necessary to modulate the bone remodelling, has been considered to be the transducer of a physical force in a cell response. It is, indeed, intelligible from the cells, as is proved by the cellular effects that can be activated by exogenous electrical signals similar to the endogenous ones (8). The aforesaid electrical signal has thus been taken to be the mechanism that determines the continuous adaptation of the mechanical competence of bone to variations in load, according to the well-known law of Wolf.

Nevertheless, it should be taken into account that the ion flow induced by mechanical deformation in the endocanalicular space could be, in itself, the transducer of the mechanical signal, since it would bring about a deformation of the osteocytes tangential to the direction of the flow (9). In whatever way it operates, this system would not necessarily rule out the role of the endogenous electrical signal, but might combine with it in local control of the remodelling of the load.

II. In the absence of mechanical stress, the vital bone generates an electrical signal detectable *in vivo* as surface *stationary bioelectric potential* and *ex vivo* as *stationary electric (ionic) current*.

a) In intact bone, the stationary bioelectric potential measured *in vivo* on its surface displays a characteristic distribution with an electrically negative area in the metaphyseal site (10-13) and cartilage accretion (11). The distribution of the bioelectric potential is modified by placing a cathode in the marrow cavity and the resulting changes are associated with the formation of new bone on the endosteal surface (12), but the cell type by which it is generated has not been defined. The fracture immediately alters the typical distribution of the bioelectric potentials, inducing an electrically negative area at the site of the lesion (14,10). It is thought that the lesion generates an electrical signal because it disturbs the different ion distribution between endocanalicular fluid and systemic extracellular fluid. The electrical signal at the site of the lesion has been ascribed to the endostal cell stratum (14) which is probably responsible for the compartmentalization of the endosteal fluid (5). One cannot, however, disregard the electrical contribution from the concomitant muscular lesions (15) and cutaneous lesions (14) caused by the fracture or by the necessary exposure of the bone surface.

b) The electric (ionic) current is detectable *ex vivo* on bones freed from muscle insertions and immersed in a physiological solution with an ionic composition analogous to plasma. The ionic current is induced by a transcortical lesion and enters in the site of the lesion. It is generated and sustained by ion transport cell systems that require expenditure of metabolic energy (16,17). It is thought that the fracture exposes the endocanalicular ionic fluid to the external plasma environment, and thus the cellular system deputed to maintaining the bone-plasma ion gradients is activated, in spite of the damage that would otherwise tend to annul them (16,18). The anatomical definition of the cellular system generating the signal and the biomolecular characterisation of the ion transport systems at the origin of the electrical signal itself have yet to be made.

Despite the different experimental conditions of detection, both the electrical signals induced by mechanical deformation and those generated by vital bone in its absence have been interpreted as local control factors of bone remodelling/modelling and reparative osteogenesis. Ever since the first detection of these signals it has therefore been held that inducing them in bone by means of external generators could be of clinical importance particularly in situations where repair processes have remained incomplete (8,10,16,19-22).

In the research sector involved in the histophysiology of bone tissue, the above observations regarding the relation between bone tissue and electric potentials have aroused great interest in the possibility of active intervention, with exogneous electrical and magnetic fields, on the cell-metabolic activity of bone, especially on the osteoblasts.

A number of experimental studies have shown how and to what extent, in various animal models, it is possible to apply or induce electrical currents with the aim of promoting osteogenesis. In humans, electrical and magnetic stimulation has been studied with the goal of enhancing the spontaneous repair capacity of bone tissue, i.e. to reactivate it in pathological conditions such as delayed consolidation and pseudoarthritis.

Research performed up to now has enabled evaluation of: A) the different effectiveness of methods of applying the electrical and magnetic signals to the bone tissue; B) modalities, times and doses needed to obtain a positive influence on osteogenesis. (23-27).

To every electric field in conductive media, as are biological tissues, there corresponds a current density and vice versa. Moreover, a magnetic field variable in time induces an electric field. Lastly every ion, subjected to an electric or magnetic field, undergoes a Lorentz force. The electric component of this force is given by the product of the ionic charge multiplied by the intensity of the electric field, while the magnetic component is proportional to the product of the ionic charge multiplied by the velocity of the ion and the intensity of the magnetic field.

On the basis of these premisses, three methods of electrical and magnetic stimulation of osteogenesis have currently been developed:

a) electric currents of continuous type directly applied to the bone tissue by means of implanted electrodes **(faradic systems)**;

b) alternating electric currents externally induced by pulsed electromagnetic fields (PEMF) in the bone tissue **(inductive systems)**;

c) alternating electric currents externally induced by pure electric fields **(capacitive systems)**.

While the faradic systems require surgical intervention, though minimal, to position the electrodes that release the current in the site of the fracture, the inductive and capacitive systems are entirely non-invasive. In particular, the inductive systems do not necessitate physical contact between application device and tissue.

Analysis of the methods

There are various mechanisms of action by which osteogenesis is enhanced through application of electric current with the three methods described above.

Directly applied continuous electric current: faradic systems.

The direct action of continuous electric current manifests both with purely electrical phenomena, which affect the dynamic of the ions at the site of the fracture, and with chemical-type phenomena, which lead to a reduction in the local tension of oxygen and a small increase in pH. Furthermore, the positioning of the electrode, by means of a small surgical intervention, determines a mechanical stimulus that may, however, interfere with the osteogenetic processes. With the faradic systems the electrical tensions applied to the bone tissue are of various entities, but in any case greater than those applied with inductive or capacitive systems (3,26).

The therapeutic effectiveness of the continuous electric current depends on its intensity. Values of electric current ranging from 2 to 20μA/cm^2 are considered optimal for stimulation of osteogenesis. From the point of view of application, the current is utilized 24 hours per day; the negative pole must be positioned very precisely in the site of the fracture where stimulation of the osteogenetic response is desired; the positive pole is placed in contact with the soft tissues, far from the site.

Values of applied current below 2μA/cm2 are ineffective, while currents of over 50μA may cause necrosis of the tissue. For this reason the aparatus employed in clinical practice is limited in tension (typically below 2.3 V).

Alternating electric current induced by electromagnetic fields: inductive systems.

As regards PEMFs (inductive), the biological activity may occur both by means of the magnetic component varying in time and by means of the electrical component, i.e. the induced electric field. These are signals with a complex wave form, whose predominant spectral content ranges between a few tenths to a few ten thousandths of Herz (20). Various mathematical models have been developed to explain the biological effects of the inductive systems: cyclotronic resonance, ligand-receptor interaction, and stochastic resonance. The first two have certainly received most attention and are in any case compatible with experimental evidence (28,29). By now there is broad consensus on the fact that the main sites of action of PEMFs are at the level of cell membrane, and the most favoured candidates are the calcium receptors and canals. Experiments *in vitro* have shown that exposure to PEMFs favours the proliferation both of elements of the immune system and of human osteoblasts, and is able to favour neoangiogenesis in cultures of endothelial cells (30-35). *In vivo*, authors have observed an increase in the formation of bone tissue (36) and a shorter time of consolidation of experimental fractures and/or bone lesions (37-39). Studies of newly formed bone tissue performed with tetracycline marking have demonstrated that, *in vivo* following exposure to PEMFs, the ability of the osteoblastic activity to lay down bone tissue, i.e. to form trabeculae, is doubled (40).

Also in the case of the inductive systems, threshold values for the magnetic field intensity, the values of frequency of the field and the waveform of the magnetic field have been described. Times of administration are also of determining significance.

Some signals have been shown to be ineffective in promoting osteogenesis; inhibiting effects on osteogenesis have also been described (27,37,41).

All authors agree in constating the direct link between the specificity of the electromagnetic signals and the effects observed in bone tissue.

For both clinical and experimental applications, use has been made of signals with frequency of repetition ranging between 2 and 100 Hz, with spectral content up to 100 kHz with intensity between 0.1 and 30 gauss of magnetic induction (10 gauss = 1mT) and with induced electric field between 0.01 and 10 mV/cm. More limited findings have been reported with magnetic fields of greater intensity, up to 200 gauss, and much lower intensity, of the order of mgauss. In the latter case, the modalities of administration of PEMFs are extremely sophisticated, since the influence of the terrestrial magnetic field must also be taken into account.

The form of signal most frequently employed is that with impulses or impulse burst. The duration of treatment initially proposed was 12-14 hours per day; recent findings, however, suggest that stimulation of 6 hours may produce good results; with success rates of over 80%.

Among the inductive systems the employment of high frequencies has also been proposed, but the data available in literature are scanty, nor have any controlled studies been forthcoming, so that more detailed investigation will be needed for a more complete evaluation (42,43).

Alternating electric current induced by electrical fields: capacitive system.

With this non-invasive method the biological effects are linked with the sole presence of the time varying electric field. The literature on these systems (44) is certainly not as abundant as for the inductive systems. The site of interaction of the electric field lies at the level of the cell membrane. The electric field produced by the capacitive systems is able to increase osteoblastic activity, both *in vitro* and *in vivo*. In experimental fractures produced on rabbit fibula, a significant shortening of consolidation time has been observed (24).

The intensity of the signal, its frequency, and the duration of the stimulation represent the dosage needed to obtain a response at bone tissue level. The electric tension applied ranges between 1 and 10 V at frequencies from 20 to 200 kHz. The electric field within the tissue ranges from 1-100 mV/cm. Optimal values lie, however, between 50 and 100 kHz. The density of the electric current produced in the tissue varies between 0.5 and 50 microA/cm2 (24).

The employment of electrical and magnetic stimulation, in its various forms, has often been likened to a pharamacological treatment. And, indeed, in the various experimental models dose-response curves have been observed, thus linking modalities and times of administration to effectiveness.

Electrical and magnetic stimulation is maintained until consolidation occurs; common experience suggests, however, that if at 90 days from start of treatment the X-ray images show no trend towards healing of the fracture, it is advisable to halt the treatment and consider alternative solutions.

Using the different methods of stimulation, every year tens of thousands of patients currently undergo treatment throughout the world (45).

Among the practical methods of application of electrical and magnetic stimulation there is adequate scientific documentation in support of those put forward by Brighton (59), using implanted electrodes, by Bassett (41) and Fontanesi (50), using pulsed electromagnetic fields, and by Brighton (44), using pure capacitive systems. All other methods must be considered experimental and carefully evaluated by the orthopedist both in their clinical use and in the analysis of the results. Table I reports a list of the studies with double blind or control group taken from the literature.

Demonstration of effectiveness in humans

Over the last twenty years in which electrical and magnetic stimulation of osteogenesis has been in clinical use, a great number of clinical studies has been performed: using the appropriate double-blind or control group protocols, these have shown the ability of the aforesaid stimulation to promote osteogenetic activity in humans and hence to favour bone consolidation. These research protocols were necessitated in order to discriminate effectively between the effects of electrical and magnetic stimulation and other possible associated orthopedic manoeuvres, and to quantify the efficacy of the treatments in human subjects (46,47).

Rationale for employment of electrical and magnetic stimulation in clinical practice

In the orthopedic-traumatologic practice, osteogenetic activity aimed at consolidation of a fracture continually comes up against problems of mechanical and biological kind (21).

The good outcome of the repair process in bone tissue is especially complex owing to the structural characteristics of the tissue itself, the loads and forces in question, and the times necessary for healing.

Among the factors that may jeopardize a repair process at bone tissue level, primary consideration is usually accorded to the mechanical aspects, on which orthopedic research has successfully been focused for upwards of 50 years. More recently it has been observed that failed consolidation can be ascribed to an insufficient osteogenetic response at the level of the fracture site, rather than to inadequate immobilization.

Assessment of the mechanical and biological factors that have hindered bone consolidation is the particular responsibility of the orthopedic surgeon, who, on the basis of knowledge and experience, can apply the solution best able to heal the patient. Just as stimulation of a fracture with evident problems of mobility or diastasis between the stumps is contraindicated, so it appears unuseful to operate on a patient with a satisfactory mechanical stability of the lesion when the problem can be attributed to an impaired osteogenetic response (48-51).

Frost has assessed that only 40-50% of failed consolidations can be ascribed to problems of a strictly mechanical kind (21). In all other failed consolidations, therapy focused on the biological response may suggest itself. A variety of options are available to the orthopedic surgeon to reactivate the repair process: intervention on the stumps, bone grafts (52), electrical and magnetic stimulation.

These observations represent the rationale for indication of treatment by electrical and magnetic stimulation: bearing in mind these principles, the rate of sucess — that is, of consolidations — obtained with electrical and magnetic stimulation exceeds 90 per cent.

Indications

The table II reports the modalities of application indicated and their efficacy recorded in literature for the various orthopedic traumatologic pathologies.

Electrical and magnetic stimulation in congenital pseudoarthritis.

Congenital pseudoarthritis is an especially complex lesion, the treatment of which is aimed not only at bone consolidation but also at preventing refracture of the consolidated site and at protecting the failure of the synthesis devices utilized to maintain alignment. Congenital pseudoarthritis has been treated with inductive and with faradic systems. The repair rate with inductive systems reaches 80%. In particular, a control study on a group of congenital pseudoarthritis of tibia has shown that employment of stimulation in support of surgical intervention with endomedullar synthesis is able to limit dysmetry of limbs and protect the patient at risk of refracture (53-58).

Electrical and magnetic stimulation of acquired pseudoarthrosis and delayed unions.

The three different methods have been demonstrated to be capable of obtaining healing in a high percentage of patients with failed union.

The faradic systems have been used to treat patients having delayed union and pseudoarthrosis. The most important study, involving 467 patients, reports an overall success rate of 66%. Other more limited series have recorded success rates ranging from 70% to 90% (59-63).

Regarding the inductive systems, which certainly represent the most frequently used mode of administration of electrical and magnetic stimulation, the most important series on 1000 patients recorded a success rate of 77%. Other series, also involving ample numbers of patients, have achieved success rates of over 90% (23,48,50,51,64-84).

Good results, with percentages slightly lower than 70%, have also been obtained with the capacitive systems (44,49,85).

Electrical and magnetic stimulation with inductive and capacitive systems is particularly indicated in cases of infected lesions. The infection of the bone tissue or the surrounding soft tissues does not affect the outcome of the treatment (41,49,51,86). Employment of electrical and magnetic stimulation is able to promote healing in short times of large lesions of the soft tissues associated with very serious traumas (74,88,89).

All authors concur on the need to employ electrical and magnetic stimulation in combination with correct orthopedic treatment, and in particular it has been observed that the possible diastasis of the fracture stumps must not exceed half the diameter of the skeletal segment site of the failed union.

Electrical and magnetic stimulation in recent fractures.

Electrical and magnetic stimulation has been shown to be able to accelerate consolidation of recent fractures, whether fractures of the leg treated with plaster and/or external splinting, or of especially complex fractures with serious damage to the soft tissues and ample exposure of the bone tissue. In all cases, stimulation succeeded in shortening the average time of healing. None of the authors suggests a generalised use of the therapy in all fractures; however, in those cases where the site, type of exposure, morphology of the fracture or conditions of the patient foreshadow difficulties in the repair process, electrical and magnetic stimulation is rightly indicated (39,69,73,89-94).

Electrical and magnetic stimulation in presence of bone grafts.

Electrical and magnetic stimulation is aimed at favouring early and rapid activation of the repair process, which must lead to of bone grafts healing and hence to bone consolidation. Employment of electrical and magnetic stimulation is particularly indicated when bone grafts have been used to make up for abundant loss of substance. Lastly, the combination of the aforesaid stimulation with bone grafts has achieved very favourable results in cases of vertebral arthrodesis (48,49,95-104).

Electrical and magnetic stimulation in avascular necrosis of the femoral head .

In stages I, II and, with reservation, III of the Ficat classification electrical and magnetic stimulation with inductive systems has proved effective in arresting the progress of the lesion, thus limiting recourse to surgical intervention or replacement with prosthesis. An ample comparative study between various orthopedic treatments (core decompression and stimulation with inductive technique), confronted with the indication not to load, has shown that stimulation achieves the best results in the long term (105-110). The inductive systems have been demonstrated to be useful in treating avascular necrosis in association with bone grafts (111).

On the other hand, the employment of capacitive or faradic systems seems unable to affect the natural course of necrosis, thus they are not indicated in this connection (112,113).

The indication for employing bone stimulation with electromagnetic fields is especially important when one considers that, thanks to the introduction of nuclear magnetic resonance and scintigraphic techniques, it is now possible to reach a very early diagnosis. In the initial stages of the disease, the use of PEMFs can justly be considered the treatment of choice for avascular necrosis of the head of the femur.

Electrical and magnetic stimulation in presence of metals.

Electrical and magnetic stimulation in presence of steel or alloys is not in itself contraindicated; the therapeutic effect of the inductive systems is not hindered by the presence of the implanted metals. Nevertheless, the presence of metal may, at least partly, screen the electric field and thus interfere with its spatial configuration. According to the literature, this fact does not appear to affect importantly the osteogenetic response at the site of the lesion. In any case, there are no indications of interference such as to lead to phenomena of electrolysis of metals with production of toxic substances (39,45,49,114).

Contraindications and side effects.

In Europe, unlike in the USA, the employment of stimulation is not regulated. Hence it comes about that, at times, patients are treated with signals that are not supported by any studies regarding either their biological safety or their therapeutic efficacy. The risk for the patient is that of undergoing treatment that may be unuseful or may even worsen the pathological situation. Following clinical employment of uncontrolled signals, complications have been documented, including inhibition of osteogenesis, bone reabsorption and hence increase of diastases between the fracture stumps. This provides confirmation of experimental observations on the ability of certain signals to inhibit osteogenetic activity (27,41,115).

Literature contains no evidence of negative side effects in patients undergoing treatment with the methods and dosages described above whose therapeutic effectiveness had been proved.

Some patients mention a disagreeable burning sensation combined with pain while undergoing treatment. However, the symptoms always resolved spontaneously on interrupting the treatment. This effect has been attributed to intolerance and hypersensitivity to the electric or magnetic field.

Even though it does not constitute a real contraindication, it should be noted how electrical stimulation with faradic systems is to be preferred to the other methods in subjects in which there is not sufficient guarantee of correct use of electrical or electromagnetic field generators (patients with mental disorders, Alzheimer’s disease, alcohol or substance abuse).

Future applications for use of electrical and magnetic stimulation

A variety of uses of electrical and magnetic stimulation are currently the focus of detailed study and represent an important challenge for this area of orthopedics and medicine.

Electrical and magnetic stimulation in presence of prostheses.

For the orthopedic surgeon, the possibility to stimulate osteogenetic activity in presence of a primitive prosthetic implant — and most important in revision arthroplasty — represents an important therapeutic possibility. Data in this connection are available in literature, but eventual use must be confined to specific cases, since indication for this therapy cannot yet be considered definitely proven. Some studies indicate that electrical and magnetic stimulation in the short term may resolve pain in subjects with mobilized, painful prostheses (116-119).

Electrical and magnetic stimulation in osteoporosis.

This represents an important field of investigation, considering the number of patients suffering from this pathology. Possible indications, however, rule out the faradic systems. In various animal models, the inductive and capacitive systems have been shown to be effective in preventing osteoporosis from castration and immobility; further research is necessary to assess the applicability of these results to humans (120-123). To date, clinical studies are extremely limited (124,125).

Electrical and magnetic stimulation in joint cartilage.

Use of electrical and magnetic stimulation is currently being evaluated in order to prevent or limit the degeneration of joint cartilage. The literature contains a number of positive reports on its effectiveness: the first clinical results, in double blind, indicate that the initial stages of arthritic degeneration in the knee may be significantly improved by treatment with inductive systems. Further confirmation on a broader sample will be needed before electrical and magnetic stimulation can be employed on a wider scale (126-129).

Conclusions

Electrical and magnetic stimulation represents an important and reliable device specifically in the hands of the orthopedic surgeon: it is able to restore and augment osteogenetic activity in bone repair tissue, and is indicated in all situations where there is clear evidence of impaired osteogenetic response.

Needing to be carried out under direct medical control, it constitutes a specific therapy in the armoury of the orthopedic surgeon, who is able to discriminate among mechanical and biological problems; its use is not indicated in inadequate mechanical conditions.

It must be performed only with equipment of proven efficacy and biological safety, following the methods and dosages described in the literature.

The use of electrical and magnetic stimulation with inductive systems should be considered the treatment of choice in the initial stages of avascular necrosis of the femoral head.

Electrical and magnetic stimulation is an important segment of biotechnology and biophysics as applied to human pathology. It requires care and precision in use if it is to ensure the success expected of it by physicians and patients.

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Table I

Clinical studies regarding demonstration of the osteogenetic effect of electrical and magnetic stimulation

Author	**Method**	**Pathology**	**Protocol**
Fontanesi 1986 (39)	Inductive	Recent Tibia Fractures	Control
Borsalino 1988 (91)	Inductive	Femur Osteotomies	Double-blind
Marchetti 1988 (74)	Inductive	Cutaneous Lesions	Open
Aaron 1989 (105)	Inductive	Avascular Necrosis	Control
Lee 1989 (99)	Inductive	Vertebral Arthrodesis	Double-blind
Traina 1989	Inductive	Pseudoarthritis	Control
Sharrard 1990 (82)	Inductive	Tibia Delayed Union	Double-blind
Mooney 1990 (102)	Inductive	Vertebral Arthrodesis	Double-blind
Parnell 1991 (78)	Inductive	Pseudoarthritis	Double-blind
Mammi 1993 (93)	Inductive	Tibia Osteotomies	Double-blind
Capanna 1994	Inductive	Osteotomies + Bone Grafts	Double-blind
Hinsenkamp 1984 (92)	Inductive	Recent Fracture with External Fixators	Control
Betti 1997 (90)	Inductive	Recent Femur Fractures	Double-blind
Scott 1994 (85)	Capacitive	Tibia Pseudoarthritis	Double-blind
Brighton 1995 (49)	Capacitive	Pseudoarthritis	Control
Kane 1988 (98)	Faradic	Vertebral Arthrodesis	Control
Rogozinski 1996 (103)	Faradic	Vertebral Arthrodesis	Control

Table II

Indications for use of the different modalities of application of electrical and magnetic stimulation for the various pathologies of orthopedic traumatologic concern

Pathology	**Modality of application of therapy**		
	Faradic	Inductive	Capacitive
Congenital Pseudoarthrosis	yes	yes	no
Pseudoarthosis	yes	yes	yes
Delayed Union	yes	yes	yes
Fracture at risk	no	yes	no
Recent Fracture	no	yes	no
Bone Grafts	yes	yes	yes
Vertebral Arthrodesis	yes	yes	no
Avascular Necrosis	no	yes	no
Limb Lenghtening	no	no	no