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Magnetic Stimulation for Fracture Consolidation – Clinical Study

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***Abstract*— This paper presents a randomized clinical design for evaluating magnetic fields in the consolidation of femoral shaft fractures. The study involved the design and construction of 20 devices (stimulators and placebos) and the development of 3D computer models of stimulated patient´s thighs. A total of 64 patients were included in the study. Follow up time was 8 weeks with 1 hour of stimulation a day. The electrical signals estimated in the computer models were magnetic field, current density and voltage for different frequencies and currents. The results revealed 83% consolidated cases, and 7% with non-union within the stimulation group, and 72% of consolidated cases and 14% with non-union for the control group. The consolidation results of patients who received stimulation were superior in time and number, but were not statistically significant. The values of electrical variables estimated by the computational model were found to be within a range not harmful to the patient (µA/m2, µT, nV).**

I. Introduction

Non-union and delayed fracture consolidation is a frequent complication in the treatment of fractures of long bones like the femur [1]. In our environment the percentage of non-union six months after a femur fracture can be up to 25% [2] representing an important socio-economic impact [3]. Fracture consolidation involves a biological process that promotes a favorable environment for bone formation and mechanical stability that neutralizes the deforming forces, allowing absolute or relative stability for the union of a fractured bone.

Electromagnetic stimulation is a noninvasive method which can promote fracture healing [4]. This type of stimulation has been used since 1841 [5]. In 1957, Fukada and Yasuda showed a close relationship between electrical stimulation and bone callus formation. Recent studies suggest that electromagnetic stimulation impacts several different cellular pathways, including synthesis of growth factors, regulation of collagen and proteoglycan production, cytokine production and calcium stimulation; as well as stabilizing the fracture site [6].

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Several randomized studies have attempted to evaluate the effect of electromagnetic stimulation on fracture healing with mixed clinical results [7,8]. The true impact of these treatments is difficult to assess due to methodological limitations and heterogeneity between the studies [9]. A recent survey of orthopedic surgeons [8] dedicated to handling trauma and fractures, reported that about 50% of orthopedists used and recommended stimulators for bone growth, in order to reduce fracture healing time.

The institutes involved in this research, are working on developing computer models and evaluating electromagnetic signals on biological tissues [10]. In this study, which was approved by the ethics committees of each the institutes involved, and funded by Colciencias, we performed a randomized trial of cases and controls in order to evaluate electromagnetic field stimulation in the consolidation of femoral shaft fractures treated with a locked intramedullar nail. The study was complemented by the development of stimulation devices and the creation of 3D computer models for estimating patient variability induced prior to application. A significant outcome was the design and implementation of stimulation devices, in which the technical features were evaluated every two months during the treatment. Customized 3D computer models were generated of the thighs of patients who were stimulated, with which the induced electrical variables of current density and voltage were estimated (with values below those potentially harmful to the body). The clinical study revealed 83% consolidated cases and 7% with non-union within the stimulated group, and 72% consolidated cases and 14% with non-union within the control group. The consolidation results in patients who received stimulation were improved in time and number but were not statistically significant.

II. Methodology

A. Application Device

For the clinical study 20 devices were built equal in their external display, thus fulfilling the requirements for a double-blind study. 10 of these were stimulators and 10 were placebos. The type of stimulation used was magnetic stimulation for inducing voltage and current signals in the tissues without physical contact. The devices were composed of a programmable power supply to feed a Helmholtz coil, and allowed the digital selection of the magnetic field magnitude to be applied, its frequency, wavelength, and time of stimulation. The data were stored in an internal memory. The study used three different coil radii (10, 12.5 and 15 cm) placed on the patient according to the thigh diameter. The devices were identified, registered and marked to monitor their use. Technical verification tests were conducted every two months. The functionality and form of the device corresponded to the sixth version of the prototype. Prior to application in patients, a 3D computer model of the stimulation coils was constructed using the ANSYS® software tool for estimating the electrical and magnetic signals which were generated. The computer-generated data were compared with the measured values.

B. 3D electromagnetic Model

A 3D model of the thigh, for electromagnetic analysis, was created for patients who received stimulation (33 in total) (Fig. 1 A and B). The 3D geometry was built from two radiographic images taken after the fracture was stabilized.

Fig. 1. 3D computer models for three cases and types of fracture

The components considered in the model were: nail, cortical bone, medulla, fracture shape, muscle and skin (Fig. 2). The assigned electrical property was conductivity (quasi-static conditions were considered due to the low frequency) and the data for each tissue were obtained from the work of Gabriel and Gabriel [11].

Fig 2. 3D volumes considered in the thigh. From left to right: skin, muscle, cortical bone, medulla, fracture, nail

The stimulation source in the model was a Helmholtz coil, whose magnetic field area coincided with the fracture zone (Fig. 3) where the stimulation was focused. The model was created for low-frequency sinusoidal signals (5-105 Hz) and magnetic fields of 0.5 – 2mT (modified via programming). The electromagnetic analysis was performed using the ANSYS® program.

C. Clinical methodology: Controlled Clinical Trial

Sixty four of the eighty three patients who signed informed consent, and were therefore included in the study, met the inclusion criteria (older than 18 and younger than 60, presenting a closed fracture of the femoral shaft caused by a low-velocity firearm, treated with a closed or open locked intramedullary nail and treated within the first ten days of trauma occurrence). The institutes involved followed up patients for 16 months. Patients entered the study six weeks post fracture, were randomly divided into two groups (group A consisting of stimulated patients and control group B) of thirty-two patients each and stimulation was commenced.

Fig. 3. Location of the stimulation source in the 3D model

Patients were accompanied to their place of residence by trained personnel who taught the patient and a relative the correct use of the device. The coils were placed on the thigh in order to generate a magnetic field parallel to the axis of the bone, making sure the uniform magnetic field area coincided with the fracture zone (Fig. 3). Stimulation was performed every day for an hour over a period of eight weeks. Daily phone calls were made to remind the patient and weekly visits were made by study personnel to capture the stored stimulation data and evaluate adherence to the treatment.

Every six weeks the patient attended a specialist consultation which assessed pain, walking with or without external support, length of limbs, muscular atrophy, knee mobility, deformity and the presence of infection. Equally, cigarette smoking, liquor intake, adherence to the treatment or occurrence of an adverse event was assessed. Follow-up X-rays were taken every six weeks up to 24 weeks and the state of fracture consolidation was evaluated according to the Winquist classification.

At week 24 the state of the fracture was radiologically and clinically established in terms of fully consolidated, unconsolidated, partially consolidated. In 77% of the cases the fracture was stabilized in closed form and in 23% reduction of the fracture was open for internal fixation. In 67% of the cases nails of diameter 12 mm or higher were used. All nails were locked and a proximal and distal block was performed.

III. Results

A. Application Device

The stimulation device is composed of amplification circuits and output protection, programmer, source and input protection, frequency control and generation, and Helmholtz coils as magnetic field sources of radii 10, 12.5 and 15 cm.

The values of measured and simulated magnetic fields were compared. The errors were less to 4%.

B. 3D electromagnetic Model

Figure 4 illustrates the distribution of the magnetic field over 3D skin volume. Figure 5 shows the induced current density vs. frequency (at 2 mT) in the volumes concerned.

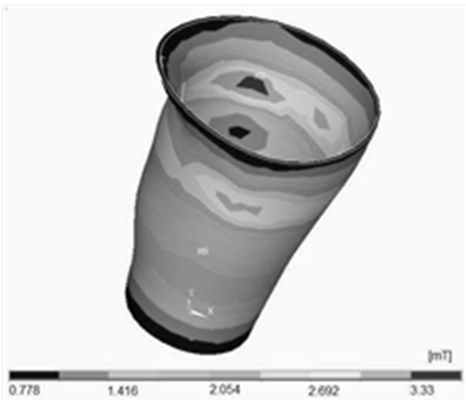

Fig. 4. A: Magnetic field on the skin for a 2mT, 5Hz stimulation

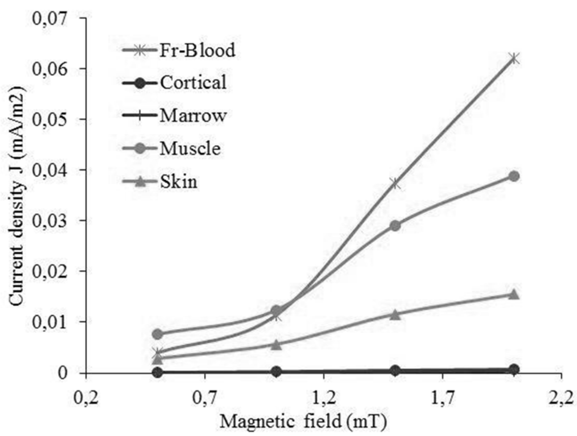

Fig. 5. Induced current density vs. Magnetic field (2 mT) for the considered volumes

Figures 6 Illustrates the current density vs. frequency (at 2 mT) in the fracture area and for the different fracture materials.

The transition from 5Hz to 100 Hz showed a 400 to 500 fold increase in current density. The highest values were found in the nail, muscle and fracture (blood). Material change in the fracture (blood to HC) decreased current density up to 15 times at 5 Hz and up to 19 times at 100 Hz. The highest current density was observed in the fracture (with blood) at 100 Hz and the lowest for the cortical at 5Hz. The highest values were for the nail, muscle and fracture (blood). The current density induced by the material change in the fracture was significant for the fracture but not for the other volumes.

C. Clinical methodology: Controlled Clinical Trial

The average patient age was 30.2 and 81% were male. Fractures were caused 70% of the time by traffic accidents, 16% by gunshot wounds, 11% caused by a fall and 3% due to sports accidents. Overall, 36% had associated injuries (limbs, skull, abdomen or chest). All of these successfully overcame their other injuries without them becoming a risk factor for treatment evaluation. The degree of fractures found in the study was 14% Grade 0, 34% Grade I, 20% Grade II, 17% Grade III and 14% Grade IV. Of the femur fractures 15% were located in the upper third, 44% in the middle third and 41% in the distal femur. None of these patients developed infection at the surgical site of the fractured femur, nor in the area where the nail was inserted in the trochanteric region or at the proximal and distal block sites. Moreover, there was no secondary adverse effect due to the magnetic stimulation device. 13% of the patients did not attend the last two consults, and therefore the state of consolidation could not be established.

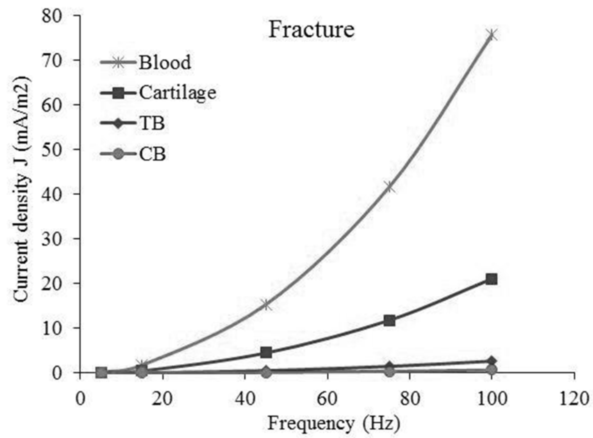

Fig. 6. Current density vs. Frequency (2mT) in the fracture zone for the different fracture materials

Groups A and B were similar in age, gender, cause of fracture, time of fracture fixation and diameter of nails used ($p > 0.05$). Group B included a higher number of patients with gunshot wounds and fewer patients with closed fracture reduction. 3% of the patients with gunshot wounds in group B did not consolidate and 3% did not complete the treatment.

Twelve weeks into the study (ten and eight of the fracture), 42% of the patients in group A and 31% in group B achieved complete consolidation $p = 0.55$. In week eighteen of the study (twenty-four of the fracture) 83% of the patients in group A and 72% in group B exhibited complete consolidation, $p = 0.57$. 14% of the patients from each group displayed partial fracture consolidation twenty-four weeks into the study; in the subsequent follow up the fractures fully consolidated without surgery.

At week twenty-four fracture nonunion was assessed showing that 7% of patients in group A and 14% in Group B fell within this category. Figure 7 shows the failure time measured according to Kaplan-Meier.

In both groups 17% presented shortening of the fractured limb between 1.0 and 2.0 centimeters and 19% presented rotational deformity greater than or equal to 15 degrees (most external rotation). After treatment, 93% of patients demonstrated knee flexion greater than 90 degrees. After twenty-four weeks, patients with fully consolidated fractures could walk without any outside help. Additionally, there was a lower incidence of nonunion (50%) in patients who were stimulated at the fracture site.

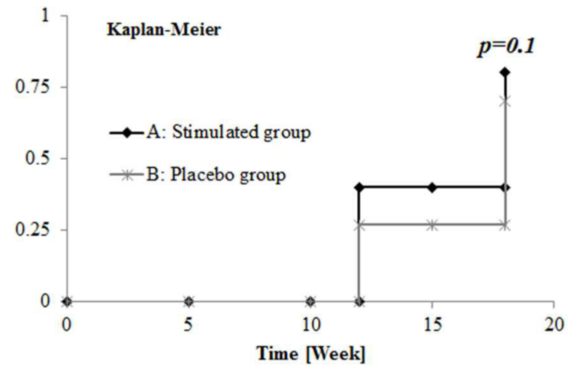

Fig. 7. Fault Time, according to a group in agreement with Kaplan-Meier.

Patients in group A, who had unsuccessful fracture consolidation were correlated with cigarette smoking and alcohol intake. In patients in group B with no fracture consolidation there was no direct correlation with the poor quality of fracture reduction, represented in very little contact between the bone fragments after open reduction.

In both study groups 41% had a fracture in the distal third and 7% of these did not consolidate. It is an accepted fact that there is less irrigation in the femur distal third and the larger bone diameter prevents greater stability with a locked intramedullary nail. It is suspected that this factor may have contributed to cases of fracture nonunion during the study.

IV. Discussion

In the scientific community there is a growing interest in finding elements that stimulate bone growth and promote fracture consolidation. Many patient related factors influence fracture consolidation and are completely independent from adjuvants; such as the patient´s characteristics (age, smoking, alcohol intake, etc), morbidities (diabetes, hypothyroidism, medications such as steroids, anti-inflammatories, etc.) type of fracture (high or low energy trauma, open or closed fracture, infection, etc), and quality of fracture reduction (contact between fragments without angles, adequate fixation stability, etc..), amongst others. On the other hand, case-control studies have limitations (17) regarding the group features. All these factors complicate the analysis of fracture consolidation results in terms of evaluating an adjuvant system such as magnetic field stimulation at the fracture site.

However, despite some differences between the two groups of patients, those who received stimulation exhibited faster and greater consolidation, and a lower incidence of nonunion was found in patients stimulated at the fracture site. These results are satisfactory but not statistically significant. In our patient groups we found that 41% of the fractures were located in the distal third and 14% of these did not consolidate. This was attributed to reduced irrigation in the distal third of the femur and a greater bone diameter, preventing greater stability by fixation with a locked intramedullary nail, a factor that could have contributed in the non-union cases in the study.

V. Conclusions

From this study it was possible to design and construct magnetic stimulation instruments and a 3D computer model customized to the patient in order to assess the induced electrical signals and thus a priori detect potentially dangerous values. From the experience and results obtained in the study, electromagnetic field stimulation can be recommended as a safe procedure that appears to assist in fracture healing, although more evidence and greater number of patients are needed. The consolidation results of patients who received stimulation are better, in time and number but are not statistically significant.

Acknowledgment

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