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Non-invasive System of Deep and Focused Transcranial Magnetic Stimulation

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Abstract- the Transcranial Magnetic Stimulation (TMS) is a non-invasive stimulation process which induces an electric field in the brain, to excite or inhibit groups of neurons. However, the current technology reaches only the motor cortex, about 1.5 cm deep, thus greatly restricting the areas of stimulation. This paper proposes a new geometry of TMS coil to reach further internal brain structures, such as the basal ganglia, with improved focality.

I. Introduction

Transcranial Magnetic Stimulation (TMS) is a non-invasive technique of neuronal stimulation, based on Faraday's law. In TMS, a time-varying magnetic flux density induces an electric field in the brain, which generates eddy currents thereof, due to the finite electrical conductivity of the neural tissues. The electric field is commonly used to test the motor cortex, as well as a research tool for investigating brain functions and physiology, such as for the treatment of depression, among other psychiatric conditions [1].

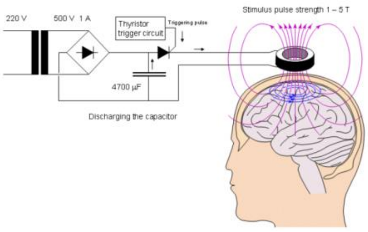

Fig. 1. Picture representing a TMS system.

The first successful application of TMS is due to Barker and collaborators, in England, in 1985 [2]. TMS makes use of coils, whose impulsive current induces electric currents (eddy currents) in the brain tissue, to stimulate groups of neurons. While the primary current pulses are quite intense, the induced eddy currents are of very short duration and have physiological intensities [3]. In the brain, these currents interact with neurons, promoting depolarization (excitation) or hyperpolarization (inhibition) of the cell membranes. However, with the current technology, the induced stimulus reaches only the motor cortex located, on average, about 1.5 cm below the scalp. Besides that, a major problem with conventional TMS coils is related to the difficulties to stimulate sub-cortical deep regions, due to the fact that the induced field rapidly decays and loses focality with depth.
In order to overcome these limitations we propose, in this paper, a study of new geometries of coils, aimed at inducing focused stimulation and reach deeper brain structures, such as the basal ganglia.

II. Physical Principles

In TMS, stimulation occurs by the conduction of intense current impulses, *I (t)*, through a coil located about 1 cm above the patient's head, as shown in Fig. 1. The magnetic electric field induced by the magnetic current pulse, typically used in TMS, has a spectrum of frequencies ranging from DC to about 10 kHz [4,5]. For these frequencies, and for most of biological tissues, we can adopt a quasi-static approximation for Maxwell's equations, resulting in [6]

$$\boldsymbol{E} = \boldsymbol{E_p} + \boldsymbol{E_s} = \frac{-\partial \boldsymbol{A}}{\partial \boldsymbol{t}} - \nabla \boldsymbol{V}, \tag{1}$$

where the primary electric field, $\mathbf{E_p}$, is due to the current in the coil, while the secondary field, $\mathbf{E_s}$, is produced by the accumulation of electric charges at the interface between two tissues of different conductivities [6]. On the other hand, the magnetic induction vector is given by $\mathbf{B} = \nabla \times \mathbf{A} = \mu_0\mu_r\mathbf{H}$. Replacing **H** and **E** in the laws of Ampère-Maxwell and Faraday, respectively, we obtain the following system of simultaneous equations for the potentials **A** and **V** [6].

$$\text{curl}[\mu_0^{-1}\mu_r^{-1}\text{curl}(\mathbf{A})]+(\sigma+j\omega\varepsilon)\text{grad}(V)+(j\omega\sigma-\omega^2\varepsilon)\mathbf{A}=\mathbf{J}^e \quad (2)$$

$$-\text{div}[(\sigma+j\omega\varepsilon)\text{grad}(V)+(j\omega\sigma-\omega^2\varepsilon)\mathbf{A}-\mathbf{J}^e]=0 \quad (3)$$

In order to solve this TMS systems simulation it was used the 3D finite element analysis software to conduct the modeling. All the simulations were made at the COMSOL Multiphysics v.4.3.a and was based on the solution of the Biot-Savart Law:

$$\vec{B}(\vec{r},t) = I(t)\frac{\mu_0}{4\pi}\oint_{coil}\frac{(\vec{r}-\vec{r_0})}{|\vec{r}-\vec{r_0}|^3} \times \partial\vec{l} \quad (4)$$

III. TMS System proposed

TMS Systems are widely used for many medical purposes. The classical architecture (Fig.2) is based on a discharge of a capacitor on the coil, creating the necessary magnetic field. This architecture does not take on account the focus, the depth and neither the wave form of the current discharged. Recent studies [3] shows that a rectangular waveform is the most appropriate for medical purposes and other studies [8,9,10] proves that with different geometries of coils it's possible to improve both focus and depth of the stimulation. Based on that, we propose one coil geometry and the stimulation circuit.

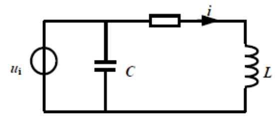

Fig.2. Classical architecture

A. Coil Geometry

By the Biot-Savart's Law (Eq.4) it's possible to see that the geometry of the coil influences directly on the generated magnetic field Many recent studies proposes geometries or arrays of coils aiming to improve either focus or depth of the stimulation. With that in sight, the following geometry called "trapezoidal" is proposed and represented on Fig. 3.

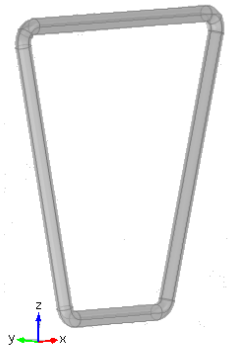

Fig.3. Trapezoidal Coil

This geometry improves the focus and depth of the stimulation as seen on the graphs below (figures 4 to 6). based on the geometry called "cuboid" [7], this geometry, as well as the "cuboid", achieves a deeper stimulation but as it has one of its sides smaller than the others, the focus improves. Although, it´s possible to make an arrangement of more coils [8,9,10] to achieve even better results as will be shown ahead.
This model, when compared to the "8-figure coil" (used at commercial TMS systems), shows an improvement at the focus and depth on the stimulation region. This is caused only by the geometry difference. 8-figure coils have some focus improvement when compared to circular coils [10], but it doesn't reaches regions 9 or 10cm below the scalp keeping the focus, as the trapezoidal does.

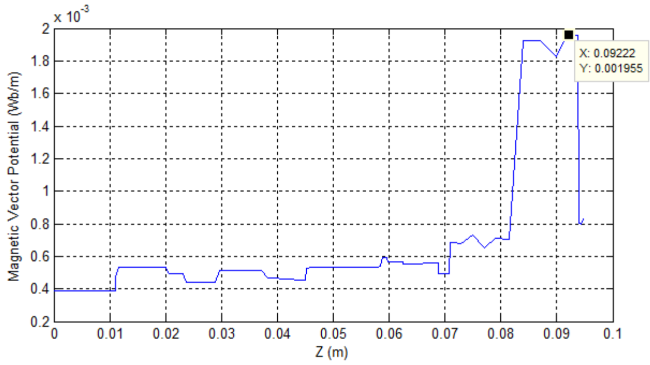

Fig. 4. Magnetic Vector Potential for the trapezoidal coil

As it's seen on figure 4, the magnetic vector potential shows a quick increase around the desired stimulation area (around 9 or 10cm below the scalp). The electric field is proportional to the magnetic vector potential, as can be seen on figure 5. It has a defined focus and a good increasing of the magnitude of the electric field and the values are suitable to the human head.

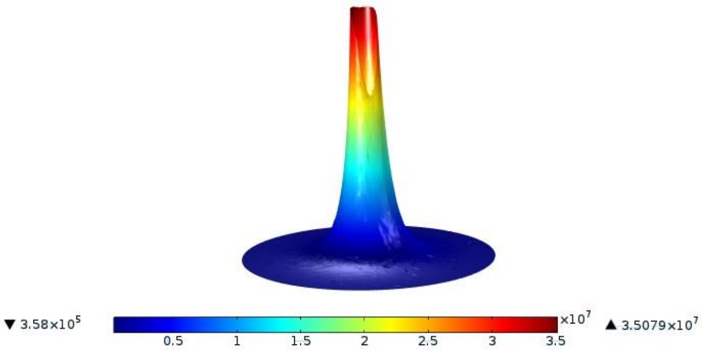

Fig. 5. Electric field norm increases along the Z axis.

Simulations were made using the parameters at the table I in order to observe the contributions of the coil to the electromagnetic fields. The coil was supposed 1cm over the spherical model of the head with 4 layers. A better result would be approached using an anatomical model of the head but so far the model we're developing is not ready yet due to some technical problems.

Table 1. Simulation Parameters

Parameter	Value	Unit
Voltage	1.65	kV
Current	2.00	kA
Layer 1 (Scalp)	1.0523e-3	S/m
Layer 2 (cranio)	1.0871e3	S/m
Layer 3 (CSF)	2.0000	S/m
Layer 4 (Grey matter)	1.0696e-1	S/m
Effective Pulse Width	100	µs

B. Stimulation Circuit

The stimulation circuit should generate an electrical discharge on the coil in a rectangular waveform (or the closest to it as possible) for better medical results [3]. So, the switching (done by the SCR at the classical architecture) should promote a response with the same waveform. With the SCR such proposal is not achieved. So, we did simulations using an IGBT module instead of the SCR, as seen on figure 6 (a).

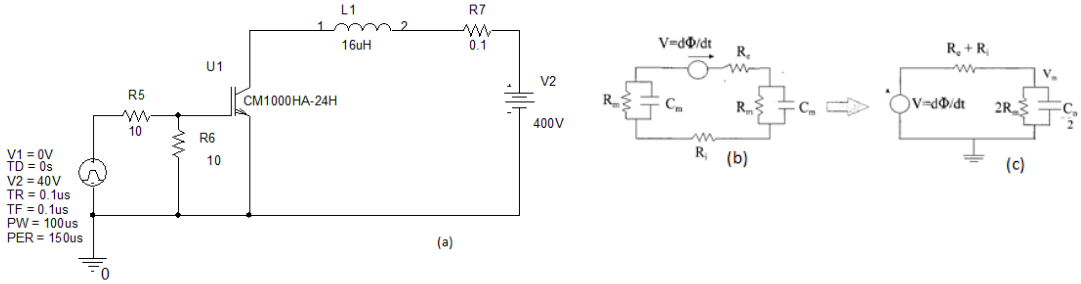

Fig. 6. (a) Stimulation Circuit (b) Electrical representation of a two-patch sub block of the membrane wall. (c) Equivalent electrical circuit. [11]

The biological circuit [Fig.6.(b) and (c)] is an abstraction of the biological tissue demonstrating how a changing magnetic flux induces a voltage within a nerve fiber [11]. The ideal value for the pulse duration should be comprehended between 50 and 150µs [3], and for a better biological interaction, the pulse duration 100µs it's ideal.

Simulating the circuit using PSPICE® software, it's possible to see the waveform similar to the expected one (Fig.7.). The circuit, on the other hand, is not ready yet. Some improvements should be done for security reasons and to ensure more fidelity to the needs of the biological circuit of the human head although this version already takes on account some parameters as the inductance of the coil, the maximum value for both voltage and current and the pulse duration.

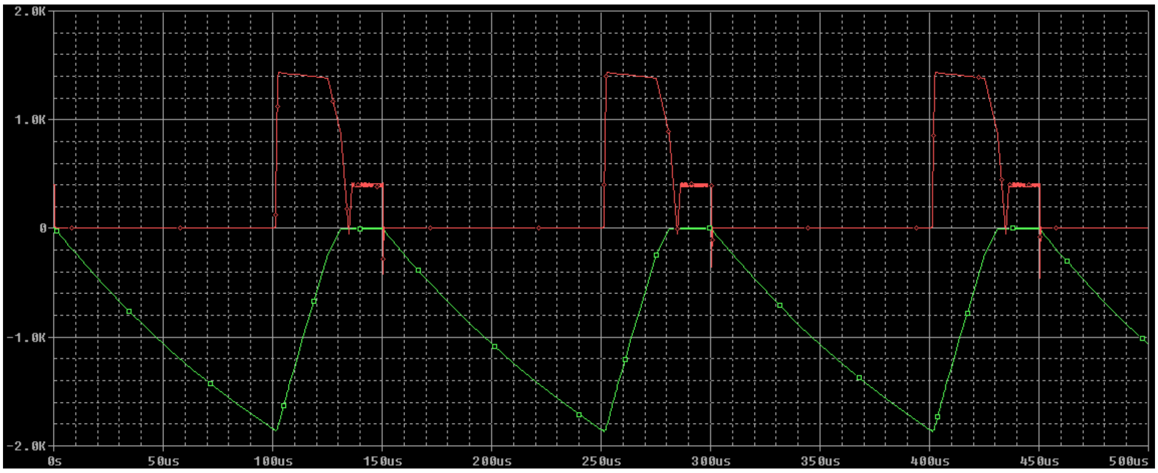

Fig. 7. Waveform of voltage and current at the inductor: Green line – current; Red line – Voltage.

IV. Results

The array of two or more coils is used on TM systems because it improves the focus and the depth of the stimulation [4]. With that information, it was simulated on array with three trapezoidal coils, as it's shown on figure 8. Such disposal should allow improving the focus 9 cm below the scalp.

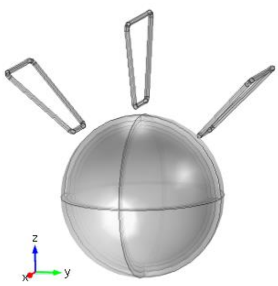

Fig. 8. Coil array

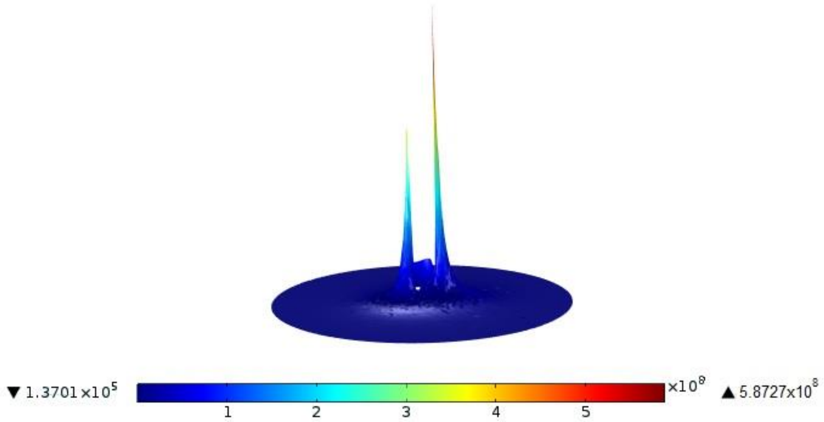

Fig. 9. Electric field norm

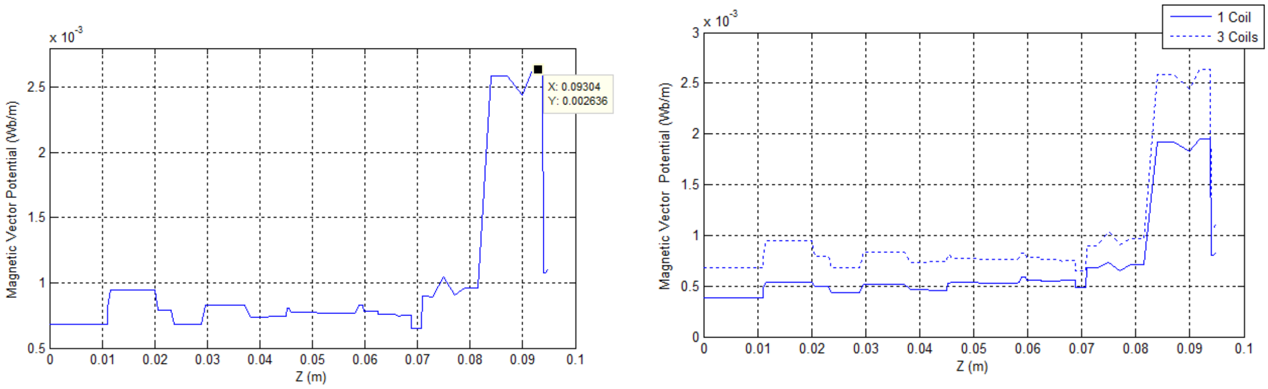

Fig. 10. (a) Magnetic Vector Potential for the array of 3 coils - (b) Comparison between the array of the 3 coils and just one coil.

The graphs on figures 9 and 10 shows that the array with three coils has a more defined focus as well as the magnitude. From these results, another simulations are being made with more coils in order to make the focus and the magnitude loss as small as possible.

V. Conclusions

It's possible to conclude in this paper that the trapezoidal coil geometry it's responsible for the improvement of the focus and depth of the stimulation when compared to the commercial coils, such as the "8-figure" coil. It's also true to conclude that the array of the coils should improve even more the focus, according to the number of the coils used. With that on hands, an anatomical model of the human head would tell more precisely the real improve of this kind of geometry and to make the inductor for lab experiments.

The circuit, on the other hand, is at a very early stage, once it can only be tested with an actual trapezoidal coil but once it's done, the parameters should be adjusted for the necessary magnitude of the magnetic field and consequently the electric field.

Those improvements can be used to treat many diseases on more deep regions of the brain such as the amygdala, basal ganglia and so on, regions that nowadays are not reached with commercial TMS systems.

It's important to note that the focus isn't 3D, which means that there are stimulation all along the "z axis" (depth) and not only in a specific point. That's another challenge on TMS.

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