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Improved Cortical Stimulation Efficiency Using 3D Rotating Fields in Transcranial Magnetic Stimulation

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Abstract— **This investigation proposes using 3D rotating fields for coupling the coil with neurons as an alternative to conventional Transcranial Magnetic Stimulation (TMS) techniques. This method requires calculating the field components necessary to rotate the vector field in a two-dimensional plane at a given point of interest. Our results indicate that this approach activates neurons in that plane efficiently. In addition, the study demonstrates that selective activation of neurons is possible by restricting the rotation of the vector field plane to a three-dimensional sphere using an external circuit that adjusts the amplitude and phase difference between the field components. Computer simulations of human head models with orthogonal coils were used to verify the suggested approach.**

I. Introduction

Transcranial Magnetic Stimulation (TMS) has gained importance for the non-invasive stimulation of neurons in treating several neurological disorders. For example, in recent years, the FDA has approved TMS for the treatment of obsessive-compulsive disorder (OCD), major depression (MDD), post-traumatic stress disorder (PTSD), and addiction [1]. The TMS coil activates neurons by generating magnetic pulses of high strength, which induce an electric field inside the brain. Coupling between the TMS coil and neurons at the stimulation location determines the excitability of the cortex.

Various high-power TMS coil designs, such as Figure-8, H-coil, Multicoil array, and Double-cone coil, have been suggested to enhance cortical activity [2]. In [3], the notion of a lossless electromagnet is utilized to create fields with a lower power need. While these coils stress on enhancing focality and depth of penetration to achieve high stimulation efficiency, the random orientation of neurons limits coupling since cortical excitation is only efficient when the produced electric field is aligned parallel to the axon path. Rotating field transcranial magnetic stimulation (rfTMS) was launched in [4,5] and has proven to be a considerable increase in motor-evoked potentials (MEP) employing orthogonal coils with the phase-shifted current. As the field rotates in a two-dimensional plane, it activates all the neurons in random directions in that plane. Rotating the field in a three-dimensional coordinate system makes it possible to activate all neurons.

This research begins by identifying the field components needed to rotate along the 3D coordinate axis in order to activate the arbitrary orientation of neurons in a plane. Later, a technique of selective stimulation utilizing an external circuit to rotate the resultant vector plane is provided. Finally, using the Finite-Element Method simulation of a coil with a human head, the field rotation in the horizontal and vertical planes are displayed.

II. Method

Consider an infinitesimal point P in the region of interest. The field components H_X, H_Y, and H_Z are specified along the vector coordinate system in three dimensions. The sinusoidal field components are given as shown in (1-3), form the magnitude of the normalized, resulting vector,

$$H_X = A_x \sin(\omega t + \varphi_x) \qquad (1)$$

$$H_Y = A_y \sin(\omega t + \varphi_y) \qquad (2)$$

$$H_Z = A_z \sin(\omega t + \varphi_z) \qquad (3)$$

The field components are generated using three orthogonal coils, as shown in Fig. 1. The resultant vector at P, generated by these field components, rotates in a plane. This planar rotation of the resultant field depolarizes the neuron in that plane.

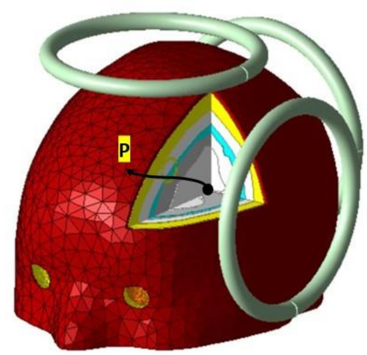

Figure 1. Orthogonal coils were placed on the head model to generate magnetic fields in (1-3) at P

However, the random orientation of neurons inside the brain makes it vital to rotate the resultant vector plane. Consequently, the phase difference and amplitude between fields along the 3D coordinate system is shifted using an external circuit. The required amplitude and phase difference for each component stimulating the plane at 0˚, 45˚ and 90˚ are presented in Table I. This allows the generated 2D vector plane to rotate along point P in response to a specified input. The field components along the vectors at point P are sinusoidal with a phase difference of 90°.

TABLE I. MAGNITUDE AND PHASE OF FIELD COMPONENTS

θ	0°	45°	90°
$A_x\angle\varphi_x$	0	$1\angle 0°$	$1\angle 90°$
$A_y\angle\varphi_y$	$1\angle 0°$	$1\angle 90°$	$1\angle 0°$
$A_z\angle\varphi_z$	$1\angle 90°$	$1\angle 0°$	0

III. RESULTS

As illustrated in Fig. 2, the resultant field vector plane is plotted at 2 kHz frequency using MATLAB. An external circuit that employs switching to adjust the amplitude and phase of the field components helps to rotate the vector plane along θ.

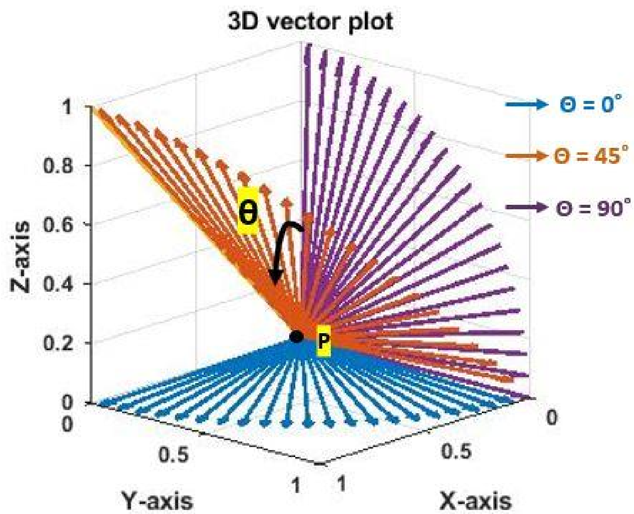

Figure 2. Rotation of 2D resultant vector plane using the external circuit for θ = 0°, θ = 45°, θ = 90° using the value in Table I.

The resultant vector field due to the field components are generated and plotted using three orthogonal coils around the head, as modeled in Fig. 1 in ANSYS HFSS.

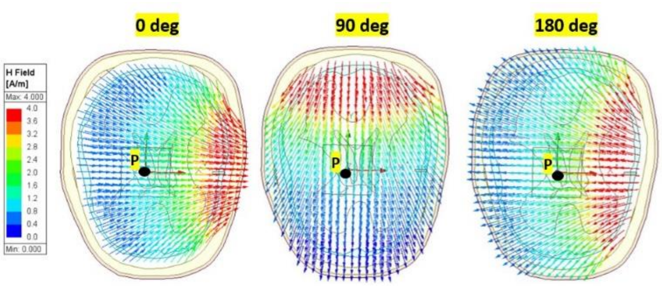

Figure 3. H-field rotation in XY- plane by stimulating at ($1\angle 0°$, $1\angle 90°$, 0)

The dielectric properties of the multi-layered human head model are taken from ITIS [6]. The spatial orientation of the resultant vector field is determined for a point P located inside the brain, as shown in Fig. 3. Exciting coils achieve the XY rotation of the magnetic field in Fig. 3 along X and Y with a 90° phase shift.

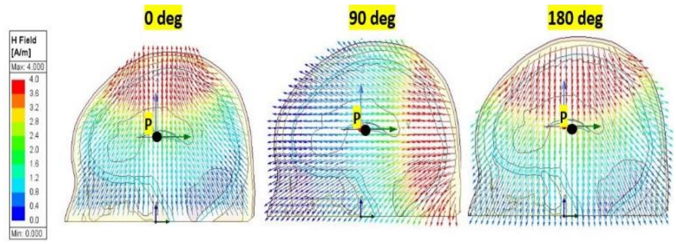

Figure 4. H-field rotation in YZ-Plane by stimulating at (0, $1\angle 0°$, $1\angle 90°$)

To rotate the resultant magnetic vector along YZ-plane, the current through the orthogonal coils along Y, Z axis are phase shifted by 90°. At point P in Fig. 4, the rotating vector field can depolarize all the neurons in the vertical plane.

IV. CONCLUSION

This research provides a way to increase the effectiveness of TMS devices by rotating the magnetic field in three dimensions. The necessary axis components for field rotation are computed and shown using MATLAB. This 3D rotating field eliminates the requirement for exact coil alignment during TMS therapy. A simple technique to rotate the resultant vector plane by adjusting the amplitude and phase difference between the components is modeled and simulated in HFSS. This methodology confines the stimulation to a desired plane. These findings indicate that an orientation-independent stimulation device with better coupling is feasible.

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