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Comparison of the Effect of Coil Configuration and the Variability of Anatomical Structure on Transcranial Magnetic Stimulation

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Abstract

Transcranial Magnetic Stimulation (TMS) is a non-invasive therapeutic and restorative mode of treating neurological disorders which has been approved by the United States Food and Drug Administration (FDA). It has proven to be an effective way of treating disorders as it is a less risky technology compared to conventional brain surgery. Various researchers have proposed coil designs for TMS aimed at achieving high focality and increased penetration depth of the induced electric field in the brain. In the present research, the authors compare the Figure of Eight (FOE) coil, Quadruple Butterfly Coil (QBC) and Triple Halo Coil (THC) on different head models to confirm the different effect of coil configuration on the induced electric field. Finite element simulations were conducted with Sim4life software to determine the maximum electric field intensity, E-Max (V/m) and the stimulated volume of the brain, V-Half (mm3). The coils were positioned at the dorsolateral prefrontal cortex (DLPFC) location of the head and results were compared of the gray matter and white matter with the entire anatomic structure of the brain to confirm the effect of coil configuration and the variability of the anatomical structure.

Keywords

Quadruple Butterfly Coil (QBC), Transcranial Magnetic Stimulation (TMS), Triple Halo Coil (THC), variability of the anatomical structure

Disciplines

Bioelectrical and Neuroengineering

Comments

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Comparison of the Effect of Coil Configuration and the Variability of Anatomical Structure on Transcranial Magnetic Stimulation

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Transcranial Magnetic Stimulation (TMS) is a non-invasive therapeutic and restorative mode of treating neurological disorders which has been approved by the United States Food and Drug Administration (FDA). It has proven to be an effective way of treating disorders as it is a less risky technology compared to conventional brain surgery. Various researchers have proposed coil designs for TMS aimed at achieving high focality and increased penetration depth of the induced electric field in the brain. In the present research, the authors compare the Figure of Eight (FOE) coil, Quadruple Butterfly Coil (QBC) and Triple Halo Coil (THC) on different head models to confirm the different effect of coil configuration on the induced electric field. Finite element simulations were conducted with Sim4life software to determine the maximum electric field intensity, E-Max (V/m) and the stimulated volume of the brain, V-Half (mm^3). The coils were positioned at the dorsolateral prefrontal cortex (DLPFC) location of the head and results were compared of the gray matter and white matter with the entire anatomic structure of the brain to confirm the effect of coil configuration and the variability of the anatomical structure.

***Index Terms*— Quadruple Butterfly Coil (QBC), Transcranial Magnetic Stimulation (TMS), Triple Halo Coil (THC), variability of the anatomical structure.**

I. Introduction

Transcranial Magnetic Stimulation (TMS) is a non-invasive therapeutic and restorative mode of treating neurological disorders which has been approved by the U.S. Food and Drug Administration [1]. TMS has been reported as successful in treating major depressive disorders (MDD), obsessive compulsive disorders (OCD) and currently being considered in the treatment of Parkinson's disease (PD) and post-traumatic stress disorders (PTSD) [1], [2]. Unlike the deep brain stimulation, it has proven to be an effective way of treating brain disorders since it is a less risky technology when compared with conventional brain surgery. Additionally, in comparison with drug treatment therapies, TMS causes little or no serious side effects as compared to these common therapies [3].

TMS involves the use of a transient magnetic field produced from coils positioned close to the skull to induce an electric field within the brain [4], [5]. This induction is based on the principle of electromagnetic induction with the induced electric field causing polarization or depolarization [6] of the brain tissues depending on the mode of treatment. In addition to TMS being used in treatment of psychiatric diseases and neuropsychiatric diseases, it is also used in the field of neuroscience as a tool to investigate brain functions and also map activities in the brain [7], [8].

With researchers and clinicians continually trying to understand the distribution of the induced electric field within the brain tissues, coil design has been one major research area in recent times. Various coil designs [9] have been proposed and designed for TMS. While some are commercially available and already in use for administering treatment, the designs are aimed mostly at achieving high focality and increased penetration depth of the induced electric field on the brain as coil geometry and configuration affect the distribution of induced electric field within the brain and hence, determining the precision (focality) and penetration depth of the induced electric field. By focality, we mean how much of the targeted region of the brain the coil can activate without affecting the non-targeted regions and by penetration depth, we mean how deep within the brain the stimulation is able to reach [11], [12].

The effect of the variation of the anatomical structures in the brain tissue has also been pointed out by various researchers as an important factor in analyzing the induced electric field to determine the efficacy of the TMS [7].

In this research, the authors compare the performance of the Figure of Eight (FOE) coil, Quadruple Butterfly Coil (QBC) and Triple Halo Coil (THC) on head models to confirm the effect of coil configuration on the induced electric field. The FOE coil is a commercially available coil and is used as the reference for comparison as it has been used in much TMS literature [10]. The QBC and THC are novel designs aimed at inducing the brain tissues with high focality and increased penetration [11], [12]. The FOE coil consists of two sets of circular coils of outer dimension of 95 mm and with nine windings on each coil. The two sets of coils are positioned close to each other with both coils making an angle of 90 degrees to the left and right of the vertical axis. The THC aims for the deep regions of the brain such as hippocampus, thalamus which cannot be stimulated by standard coils and because of the deep penetration that the THC delivers, it has potential applications in the treatment of Parkinson's Disease and PTSD [13]. The THC configuration consists of three

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large elliptical coils with an eccentricity of 0.74 and with each coil having four windings [13]. The inner coil is positioned at an angle of 0 degrees, the middle coil at an angle of 30 degrees and the outer coil at an angle of negative 30 degrees to the axial plane [13]. The QBC consists of two sets of coils: two large coils and two small coils. The large coils are the same size as the FOE coil and the small coils have a 60 % reduction in size as compared with the FOE coil. The two sets of coils have the same number of windings (18 for each set) and are inclined at an angle of 45 angle to the vertical axis [12].

To confirm the effect of coil configuration and the variability of the anatomical structure, the FOE coil and QBC were positioned at the left dorsolateral prefrontal cortex (DLPFC) location of the head model and results were compared of the gray matter and white matter with the entire anatomic structure of the brain. The left DLPFC has been a widely used location for stimulation by clinicians and is approved by the US FDA for the treatment of depression since it is responsible for neural functioning and connectivity that controls sensing and emotions [14], [15].

II. Method

The head models employed in the simulation analysis were obtained from MRI images sourced from the Human Connectome Model Library [16] and developed by using the SimNIBS pipeline [17]. The 50 head models are those of healthy subjects with age ranging from 25-35 years. The effect of the variability of the anatomical structure of the various head models is considered with seven different anatomic layers to determine their contribution to the simulation results. These anatomical structures include cerebellum (cb), cerebrospinal fluid (csf), gray matter (gm), skin (sn), skull (sk) ventricles (vc) and white matter (wm). The values of the electrical properties of the different anatomies of the models were obtained from the Information Technologies in Society (IT'IS) foundation database [18] and are reported in Table 1.

Table 1: Electrical Properties of the Seven different Anatomical Regions at a frequency of 2.5 kHz.

Tissue Name	Electrical Conductivity (S/m)	Relative Permittivity
Cerebellum (cb)	0.124	78400
Cerebrospinal fluid (csf)	2	109
Gray matter (gm)	0.104	78100
Skin (sn)	0.0002	1140
Skull (sk)	0.0203	1440
Ventricles (vc)	2	102
White matter (wm)	0.0645	34300

The coils were modeled, and simulations were run using a quasi-static, low frequency electromagnetics field solver, Sim4Life software [19] to simulate the TMS pulses and to determine the magnetic field and induced electric field in each head model. Fig. 1a shows the FOE coil, QBC and THC positioned on the head model. The electromagnetic coils are pulsed with an operational frequency of 2.5 kHz and supplied with a current of amplitude 5000A. The FOE coil and QBC are positioned at a distance of 5 mm from the origin (at coordinate 0,0,0) of the head models to account for the insulation of the electromagnetic coils. The THC, because of its configuration, is positioned with the vertical center at a distance of 110 mm from the origin of the head model.

Simulations were performed with each coil and the different head models with the Sim4Life software to determine the magnetic field and induced electric field on each head model. This made a total of 150 simulations. The results from Sim4Life software were exported to MATLAB [20] for data post processing and interpretation. The maximum electric field intensity (E-Max) and the stimulated volume of the brain (V-Half) are extracted. The maximum electric field intensity is the maximum value of the electric field induced within the brain. The stimulated volume is the volume of the brain that is exposed to the electric field at least half of the E-Max [11].

An additional 100 simulations were run with the FOE coil and QBC to confirm the effect of coil configuration and the variability of the anatomical structure. In this second analysis, the coils were positioned at the left dorsolateral prefrontal cortex (DLPFC) location of the head model as shown in Fig. 1b and results are compared of the gray matter and white matter with the entire anatomic structure of the brain. Results obtained from the Sim4Life software were exported to MATLAB for analysis and interpretation.

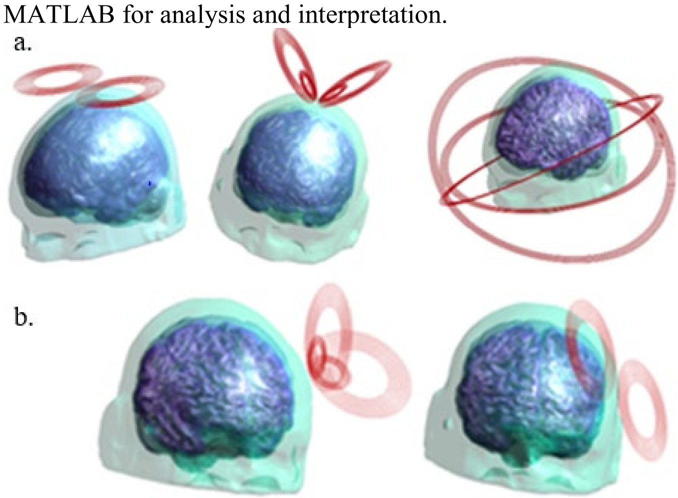

Fig. 1. Positioning of the (a) FOE coil (left), QBC (middle) and THC (right) on the head model. (b) QBC (left) and FOE coil (right) on the DLPFC location of the head model.

III. Results and Discussion

With the maximum electric field (E-Max) and the stimulated volume (V-Half) extracted from the simulations for each coil, comparison is made. As seen in Fig. 2, the distribution of the induced electric field in the gray matter within one of the head models is represented with the FOE coil at the left, the QBC in the middle and the THC at the right. The surface plot of Fig. 2 has been normalized with the maximum value of the E-Field induced by the FOE coil, since it is the standard for comparison. As seen from Fig. 2, the THC induces a higher electric field in the gray matter of the head model than both the QBC and the FOE coil. The FOE coil however induces a higher electric field than the QBC within the head model.

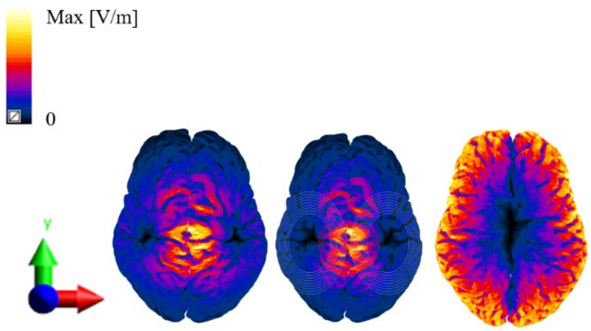

Fig. 2. Induced electric field in the gray matter with the FOE coil (left), QBC (middle) and THC (right) on the head model. The surface plots have been normalized with the maximum value of the induced electric field that the FOE coil induces in the brain.

Slice view along the coronal (XZ) plane and the transverse (XY) plane helps to better understand the distribution of the electric field of the three coils. Fig. 3 shows slice views along the coronal plane for one of the head models for the induced electric field from the stimulation by the three coils. We see that for the FOE coil and QBC, the intensity of the electric field is high from the vertex of the model and then starts to decay with depth. This is also clearly illustrated in the graph in Fig. 4 as we see the FOE coil exhibiting an induced electric field of about 250 V/m at the origin (z = 0 mm) and the QBC exhibiting an induced electric field value of above 250 V/m. However, the FOE coil exhibits a higher induced electric field as depth increases. Along the coronal plane, the THC exhibits a very low induced electric field along the z-axis and this is because of the coil geometry.

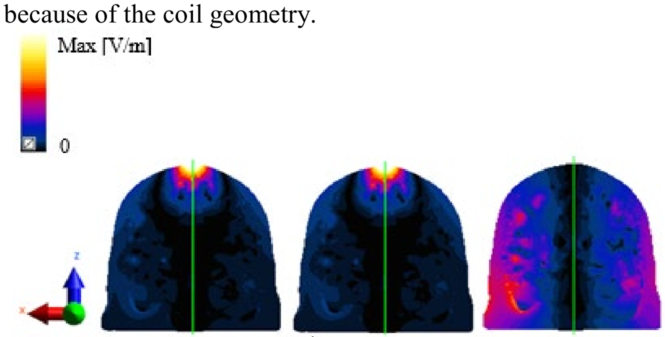

Fig. 3. Slice view along the z-axis of the Coronal Plane showing the induced electric field in the gray matter with the FOE coil (left), QBC (middle) and THC (right) on the head model. The surface plots have been normalized with the maximum value of the induced electric field that the FOE coil induces in the brain.

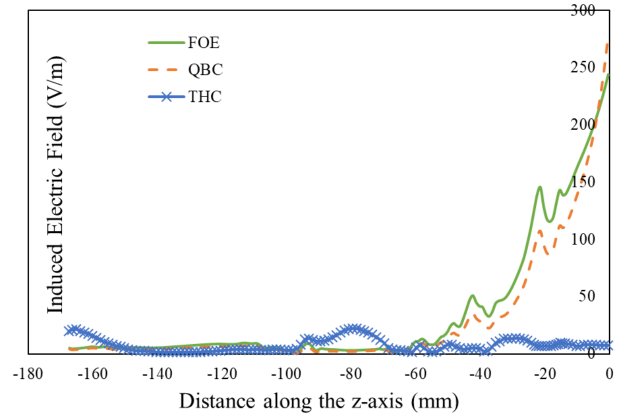

Fig. 4. Comparison of induced electric field along the z-axis on the coronal plane of the three coils.

Fig. 5 shows slice view along the transverse plane for one of the head models for the induced electric field from the stimulation by the three coils. Along the x-axis of the transverse plane in Fig. 6, we see that the FOE coil and QBC exhibit low intensity of the electric field as compared with the THC. The THC exhibits a very high induced electric field along the x-axis and this is because of the coil geometry, hence making it suitable for deeper penetration.

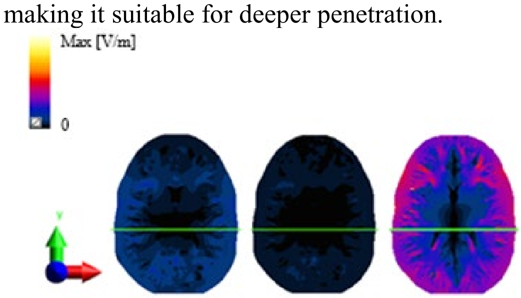

Fig. 5. Slice view along the x-axis of the Transverse Plane showing the induced electric field in the gray matter with the FOE coil (left), QBC (middle) and THC (right) on the head model. The surface plots have been normalized with the maximum value of the induced electric field that the FOE coil induces in the brain.

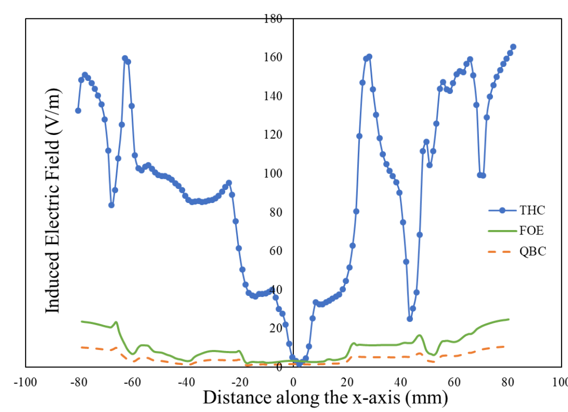

Fig. 6. Comparison of induced electric field along the x-axis on the transverse plane of the three coils.

Fig. 7 presents the distribution of the maximum electric field of the 50 head models to give a better representation of this comparison. This helps to understand the distribution of the electric field while considering the 50 head models. The box-plot displays the characteristics distribution of the E-Max values across the 50 head models on the basis of middle quartile (median), minimum, maximum, first quartile and third quartile. With the box plot, we are able to also observe the outliers in the extracted values of the E-Max. For the THC, the average value of the E-Max across the 50 head models is calculated as 457 V/m with a standard deviation value of 97 V/m. The FOE coil has an average value of 200 V/m for the E-Max across the 50 head models with a standard deviation value of 51V/m. For the QBC, average E-Max across the 50 head models is calculated as 144 V/m with a standard deviation value of 41 V/m.

Fig. 7 shows that the THC induces the largest electric field in comparison with the two other coils as the upper quartile of the THC shows a higher value than the others. Additionally, the FOE coil induces higher electric field than the QBC as its upper quartile has a higher value than the QBC. The interquartile range which is represented by the rectangle at the center helps to define the variability with each coil. Interpreting the result in Fig. 7, the interquartile range of the THC is much larger than both the QBC and the FOE coil, which means that the THC coil exhibits more variability than the two other coils. The QBC has a smaller interquartile range and hence exhibits a lesser variability than the other two coils.

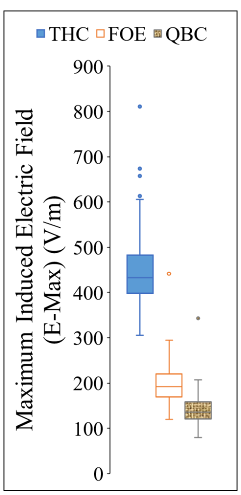

Fig. 7. Comparison of the maximum induced electric field, E-Max (V/m) on the head model between the FOE coil, QBC and THC.

The V-Half is also considered in the comparison of these three coils. The THC has a larger area (Fig. 2) that is stimulated by the electric field and also a larger stimulated volume. This is further confirmed in the box plot of Fig. 8. In Fig. 8a, the THC has a higher value of V-Half as compared with the other three coils. To compare the FOE coil and QBC, a second box plot (Fig. 8b) was created so that the values are visible. We observe that the FOE coil has a higher V-Half than the QBC.

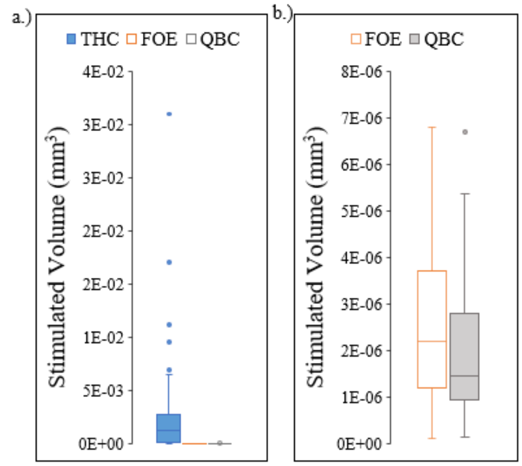

Fig. 8. Comparison of the stimulated volume, V-Half (mm^3) on the head model between the (a) FOE coil, QBC and THC (b) FOE coil and QBC. Fig. 8b has been represented to give a better understanding of the comparison of the V-Half between the FOE coil and the QBC.

With these having been interpreted, we can say that the QBC which has a lower stimulated volume exhibits a higher focality than the other coils. Focality is the ability of the coil to induce electric field at a targeted region of the brain during the administration of TMS without stimulating unwanted area. The THC delivers a higher induced electric field to the brain which would be beneficial for disorders that require a high electric field delivery during TMS administration. However, the THC stimulates a larger volume of the brain and hence delivers a less focal stimulation.

The second analysis which involved the positioning of the QBC and the FOE coil on the (DLPFC) location of the head model yielded the following result as shown in Fig. 9. This shows the distribution of the induced electric field in the gray matter within one of the head models with the FOE coil at the left and the QBC at the right. Although not so much of a difference, the QBC shows a smaller distribution of the induced electric current when compared with the FOE coil.

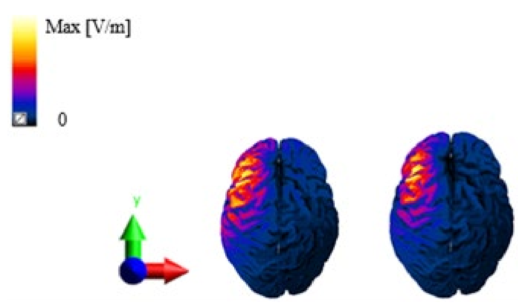

Fig. 9. Induced electric Field in the gray matter by the FOE coil (left) and QBC (right) at the left DLPFC location of the head model. The surface plots have been normalized with the maximum value of the induced electric field that the FOE coil induces in the brain.

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Fig. 10 shows a box-plot representation of the E-Max (Fig. 10a) and V-Half (Fig. 10b) of the FOE coil and the QBC. For the FOE coil, the average value of the E-Max across the 50 head models is calculated as 227 V/m with a standard deviation value of 33 V/m. The QBC has an average value of 168 V/m for the E-Max across the 50 head models with a standard deviation value of 23 V/m. The interquartile range of the FOE coil is much larger than that of the QBC for both the E-Max and the stimulated volume. This means that the FOE coil exhibits more variability than the QBC, and also confirms that the QBC is a more focal coil as it exhibits a lower stimulated volume.

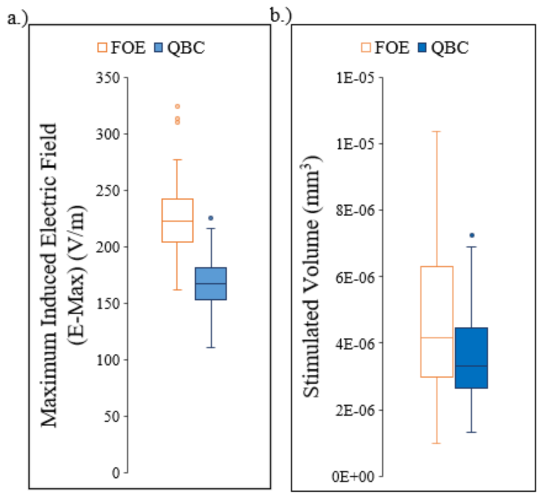

Fig. 1. Comparison at the DLPFC location of the a.) maximum induced electric field, E-Max (V/m) and b.) the stimulated volume, V-Half (mm^3) between the FOE coil and QBC.

IV. Conclusion

Three electromagnetic coils; FOE coil, QBC and THC, have been compared using 50 different head models. The THC was placed on the head model while the FOE coil and the QBC were placed on the head model and also on the left DLPFC of the head model. Simulations were run with the Sim4Life software and we conclude that the THC is preferred for deep penetration for TMS while the QBC and FOE coils are preferred when focality is important in administering TMS. The QBC, however, delivers a higher focality than the FOE coil and this is observed on the head model and also the left DLPFC location.

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