Analysis of 16 coils over 50 MRI-derived head models in transcranial magnetic stimulation

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Transcranial magnetic stimulation (TMS) is a non-invasive neuromodulation technique investigated for the treatment of various neuropsychiatric disorders such as major depressive disorder and obsessive-compulsive disorder. Coil design and analysis has been a popular topic in TMS studies, primarily as the coil geometry significantly affects the induced electric field (E-field) distribution. In this work, we compare the distribution of the induced E-field of 16 different TMS coils by finite element analysis. The coils are positioned at two head locations; the vertex and the dorsolateral prefrontal cortex (DLPFC). Due to the coil geometry, only 9 of the 16 coils are positioned at the DLPFC. Notably, the authors use 50 heterogeneous head models derived from MRI scans of healthy patients in this analysis. As a result, the sensitivity of the E-field intensity and focality to anatomical variations is investigated. The maximum E-field intensity induced in the Brain (E-Max brain), and the volume in the brain exposed to the E-field with at least half the E-Max (V-Half) were metrics used to assess the intensity and focality of the induced E-field. It was observed that some of the coils induced high E-field intensity and were highly sensitive to anatomical variations. Other coils exhibited high focality and lower sensitivity to anatomical variations at the same time. For the coils positioned at the DLPFC, less variability was observed when compared to the vertex location. This study provides an understanding of the effect of coil geometry and anatomical variation on the induced E-field during TMS.

\textbf{Key Words}—Anatomical Variations, Coil Design, Induced Electric Field, Transcranial Magnetic Stimulation (TMS).

\section{INTRODUCTION}

\textbf{TRANSCRANIAL MAGNETIC STIMULATION} (TMS) is a neuromodulation technique which is capable of stimulating neurons in the brain non-invasively. Transcranial magnetic stimulation provides numerous possibilities for the treatment of a range of neurological disorders such as major depressive disorder (MDD), obsessive-compulsive disorder (OCD), post-traumatic stress disorder (PTSD) \cite{1}–\cite{3}.

TMS devices are relatively universal, which consist of a main unit and a stimulating coil. The stimulating coils have one or more insulated coils of copper wire that are arrayed in various sizes and shapes, that the induced electric field (E-field) in the brain. The focality of the induced E-field in the brain tissue depends on the TMS coil geometry \cite{4}. Therefore, stimulating coil design is always a popular research topic in TMS studies.

Various TMS coils or coil arrays have been proposed to improve the penetration depth \cite{5}–\cite{6} and focality of the induced E-field \cite{7}–\cite{8}. However, there is usually a tradeoff between depth and focality with these coil designs \cite{9}. In this study, 16 different TMS coil configurations are compared by conducting finite element simulations, some of which are commercially available, and the others being novel designs \cite{10}. Notably, the authors have used 50 heterogeneous head models generated from MRI scans of healthy patients to examine the contribution of patients’ anatomical variability to the induced E-field during TMS. One advantage of computational studies is that it provides an understanding of the induced E-field’s distribution during TMS.

The authors also compare the different coils’ performance at two anatomical locations; the vertex and the dorsolateral prefrontal cortex (DLPFC). The positioning of TMS coils at the vertex location is a common control condition in TMS studies \cite{10}.

\section{METHOD}

\subsection{Head Models}

Fifty head models were used in this study developed from MRI scans from the Human Connectome Project \cite{13}. They were converted to three-dimensional images by Lee et al. using the SimNIBS pipeline \cite{14}–\cite{16} which segmented the MRI scans into seven different anatomical regions accounting for the heterogeneity of the head model. The seven different segmented anatomies include the cerebellum, cerebrospinal fluid (CSF), grey matter (GM), skin, skull, ventricles, and white matter (WM). These models are healthy adults within the age range of 22 to 35 years and with an equal number of males and females.

\subsection{TMS Coils}

The commercially available coils amongst the 16 coils include MagVenture MCF-B65 coil \cite{17}, MagVenture MC-B70 coil \cite{17}, MagVenture D-B80 butterfly coil \cite{17}, MagVenture Cool-125 coil \cite{17}, Magstim double cone coil \cite{18}, Magstim figure-8 coil \cite{18}, Magstim 90 mm circular coil \cite{18}, and Magstim double 25 mm coil \cite{18}. The other coils which are not commercially available include Crown 18 coil \cite{19}, Crown 38...
According to the geometry, the coils were divided into three groups, as shown in Fig. 1. Group 1 included coils which had double windings, among which the figure-8 coil is typical. Group 2 contained the coils with single winding, with the most representative coil being the Magstim 90 mm circular coil and MagVenture Cool-125 coil. The Magstim 90 mm circular coil and MagVenture Cool-125 coil have similar designs but with varying diameters and number of turns in their windings. The Crown 18 coil has a slightly different design with a non-planar winding. Halo coils are usually used in combination with a circular coil or figure-8 coil. In this study, we have used it in combination with a Magventure Cool-125 coil. Group 3 contained coils with smaller diameters and more complex geometry. The Magstim double 25 mm coil is designed to stimulate the superficial structures of small animals such as rats [19], however, it is been used for human patients to achieve localized stimulation. The 3D coil arrays in group 3 are coils designed for precise spatial localization [19].

### C. Finite Element Simulations

Finite element modeling of TMS coils and calculation of E-fields were conducted using the Sim4life software, a quasi-static, low frequency solver [21]. The simulations were carried out on different coil configurations positioned over the vertex of one of the head models. The blue coils show the smaller set of windings of the QBC.

![Diagram of coil configurations](#)

**Fig. 1.** Two different views each for the 16 different coil configurations positioned over the vertex of one of the head models.

*The blue coils show the smaller set of windings of the QBC.*
out with 1 mm isotropic voxels, and the total numbers of voxels were of the order of magnitude of six. Voxel discretization can generate artefacts in the simulations, so the selection of the voxel size is fundamental [22]. The influence of voxel resolution on simulation results had been conducted by Rastogi et al. in previous work, using 0.5 mm isotropic voxels to test the stability of simulation results [6]. A peak to peak current of amplitude 5000 A and frequency of 2.5 kHz was applied to the TMS coils. This value is comparable in intensity to the maximum output of a conventional TMS stimulator [23]. The corresponding relative permittivity and electrical conductivity values for the various tissues in the head models were sourced from IT'IS foundation database [24]. 1250 simulations were conducted in this study as there were 50 head models and 16 different coil configurations, with 9 of these coils, positioned over the DLPFC.

III. RESULTS AND DISCUSSION

The maximum E-field intensity induced in the brain (E-Max brain), and the volume of the brain exposed to at least half E-Max (V-Half brain) were metrics used to determine each coil’s induced E-field intensity and focality, and also to evaluate their performance. The existence of sharp contrasts in electrical conductivity values of the different tissues (for example, CSF and GM), and the usage of staircase approximation of curved boundaries might cause unrealistic hotspots in the computed induced E-field [25]. Therefore, to lessen the stair-casing error, the value of E-Max was calculated as the average E-field intensity of the top 100, 1 mm³ voxels in the brain [26].

A. Coils positioned at the vertex

The 16 different coil configurations were positioned over the vertex of the head model. A 10 mm distance accounting for the insulation of the coils was modeled in the FEA simulations.

i. E-Max brain

The distribution of E-field on the gray matter with each coil configuration positioned over the vertex of the head is shown in Fig. 2, from which it is quite evident that the stimulated areas and induced E-field intensities vary with each coil. The spread of the E-Max values across the 50 different head models is represented in histograms in Fig. 3. This figure illustrates the contribution of anatomical variability to the induced E-Max values among the head models and across each coil. Comparing the plots for coils in Group 1, we observe that the double cone coil variability is larger than the figure-8 coil as the spread of the values from the double cone coil is wider. This spread means that the data with the figure-8 coil are more centralized and less sensitive to anatomical variation than the double cone coil. The red dashed line in each subplot represents the average E-Max across the 50 head models. Symmetry is observed with the histograms from the double cone coil, the Crown 38 coil, and the MC-B70 coil, while the MCF-B65 coil exhibits some skewness to the right.

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Fig. 2. Distribution of E-Field in the gray matter for each coil positioned at the vertex of one of the head models.
Fig. 3. E-Max in the Brain of 50 Head Models with each coil positioned at the vertex of one of the head models.

Fig. 4 shows the comparison of the E-Max among the different coil group represented on boxplots. The boxplots show the five-number summary ("minimum", first quartile (Q1), median, third quartile (Q3), and maximum") for easy comparison of the distribution of the E-Max across the 50 head models. The interquartile range provides information about the variability associated with each coil by observing the spread of the boxplot. The interquartile range with the MC-B70 coil is more extensive than the Crown-39 coil, confirming a widespread with the MC-B70 coil.

For coils in Group 2, adding the Cool-125 coil to the Halo coil significantly increased the E-Max with no extra variability introduced. We observe that the induced E-field intensities with the Magstim circular coil and the MagVenture Cool-125 coil are quite close. We also observe that the Crown 18 coil is less sensitive to the anatomical variations than the 90 mm circular coil and Cool-125 coil. For coils in Group 3, it is observed that the average E-Max for the double 25 mm coil is larger and more sensitive to anatomical variability than the other three coils. This observation means that the double 25 mm coil can deliver a higher intensity of induced E-field than the 3D coil arrays. The 3D coil arrays in Group 3 exhibit a lower response to anatomical variability than the double 25 mm coil since they have lower interquartile ranges.

ii. V-Half brain

The V-Half parameter represents the brain’s volume exposed to the induced E-field with intensities of at least half the E-Max. The V-Half is a parameter to measure focality. The boxplots demonstrating the variabilities of V-Half among head models for each coil is presented in Fig. 5.

For coils in Group 1, the Crown-39 coil exhibits a high interquartile range than the other coils. This observation means that the Crown-39 coil is very sensitive to anatomical variations. This finding is quite interesting as the Crown 39 coil’s E-Max value from Fig. 4 shows less sensitivity to anatomical variations. The V-Half values from the MCF-B65 coil and the QBC are relatively resistant to the anatomical variation, which makes prediction with these coils easier.

For Group 2 coils, the interquartile range with Halo coil is more extensive than the Cool-125 coil alone. Unlike the E-Max, an increased stimulated area and sensitivity to anatomical variability is observed with the Halo coil. Unlike the observation with the E-Max value, the circular 90 mm coil’s interquartile range is slightly smaller than the Cool-125 coil. The average E-Max of the double cone coil and the Crown 38 coil from Group 1 in Fig. 4 is close to that of the Cool-125 coil and the 90 mm circular coil in Group 2. However, the V-Half from the two coils from Group 2 is larger than either of the two
coils from Group 1. This result confirms theoretical expectation since coils with single windings will exhibit less focality than coils with double windings.

For coils in Group 3, the variability of the V-Half exhibited by each coil is different from observation with the E-Max value shown in Fig. 4. The stimulated area in the brain by the 3D array varies greatly between head models. This means V-Half with the 3D arrays is also very sensitive to the different anatomical variations. The 3D array #3 exhibits the least focality and the lowest E-max among the coils in group 3. On the contrary, the double 25 mm coil induces an E-field with the highest intensity. It also exhibits a much higher focality (lower V-Half) than the other coils in the group.

**B. Coils positioned at the DLPFC**

i. E-Max brain

Fig. 6 presents the 9 different coil configurations while positioned over the DLPFC of one of the head models. The same coil grouping method as used for the positioning on the vertex is applied here at the DLPFC. The induced E-field distributions in the brain when the coils are positioned at the DLPFC of one of the head models is shown in Fig. 7, and just like the vertex location, it is observed that the coils exhibit unique E-field intensity.

Comparisons were made of E-Max’s distributions in the brain between the coils positioned at the DLPFC and at the vertex. This comparison is shown in Fig. 8 for the different coil groups. There are no noticeable differences for coils in Group 1 whether the coil is positioned at the head’s vertex or DLPFC. For example, at both positions, the double cone coil generates relatively more variabilities among the head models. This observation means that the double cone coil is relatively more sensitive to the head models’ anatomical variations irrespective of the coil’s position. Comparing the magnitude of the E-Max value of the different coils at the vertex and the DLPFC, the only observable difference is that of the figure-8 coil and the D-B80 coil. The E-Max generated by the D-B80 coil is larger than the figure-8 coil when positioned at the vertex but is significantly smaller when positioned at the DLPFC. It is also noticeable that data variabilities with the coils placed at the DLPFC are smaller than at the vertex. When the coils are placed at the DLPFC, the E-Max values are more resistant to the head models’ anatomical variations. For coils in Group 2, the Magstim 90 mm circular coil data is more extensive than the MagVenture Cool-125 coil, irrespective of coil location. There is only one coil in group 3 at the DLPFC; the Magstim double 25 mm coil. Therefore, the E-Max in the brain with double 25 mm coil has been compared between the two locations. The double 25 mm coil delivers E-fields with significantly larger intensities to the brain when positioned at the DLPFC. It is also less sensitive to anatomical variability, which is shown by the shorter interquartile range.
ii. **V-Half brain**

The distributions of V-Half in the brain are compared among the coils when positioned at the DLPFC. Furthermore, the distributions between the two locations of the coils are compared. For Group 1, it is evident from Fig. 9 that the spread of the data from the double cone coil and the D-B80 coil is
relatively more expansive, which is the same observation for E-Max in Fig. 8. These two coils are less resistant to the anatomical variation in terms of both field intensity and focality. For coils in Group 1, Fig. 9 shows that the interquartile ranges when the coils are positioned at the vertex are more extensive at the DLPFC. A similar pattern is observed with the E-Max; that is, both E-Max and V-Half are sensitive to the anatomical variations when the coils are positioned at the vertex. For coils in Group 2, the relationship between the 90 mm circular coil and Cool-125 coil is irrespective of location. However, the data exhibit a narrow spread when the coils are positioned at the DLPFC. For the coil in Group 3, the V-Half values with Magstim double 25 mm coil also have a narrow spread.

Fig. 7. Distribution of E-Field in the gray matter for each coil positioned at the DLPFC of one of the head models.

Fig. 8. Comparison of E-Max in the brain among the coils positioned at the DLPFC and the vertex location.
IV. CONCLUSION

In this study, the authors discuss in detail the performance of 16 different coils based on the induced E-field intensity and focality. The 16 different coils were divided into three groups based on their geometries. E-Max and V-Half comparisons were conducted with the different coils positioned at the vertex and the dorsolateral prefrontal cortex (DLPFC). Due to coil geometry, 9 of the 16 coils were positioned at the DLPFC. The E-Max defines the induced E-field intensity, while the V-Half defines the coils’ focality. Notably, the authors used 50 heterogeneous realistic head models in the analysis to account for the effect of anatomical variations on the induced E-field.

The results have provided information about the induced E-field’s intensity from each coil and the brain’s area exposed to the E-field. The variabilities of E-Max or V-Half associated with each coil due to the different anatomical structures of 50 head models have also been explored. The coils positioned at the DLPFC generate relatively high field strengths from the study than when placed at the vertex. The field strengths and focality are also less sensitive to anatomical variations at the DLPFC.

Coils in Group 1 (double windings) exhibit improved focality compared with coils in Group 2 (single winding). However, this result is not surprising since coils with double windings are designed to achieve more focal stimulation.

This study provides a basis for coil choice for TMS treatment. In the future, more studies will be conducted to estimate the penetration depth and field decay rate from each coil.

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