Influence of Brain Conductivity on Magnetoencephalographic Simulations in Realistic Head Models

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Abstract— **The influence of brain tissue conductivity on magnetoencephalography (MEG) has been largely unknown. We compared the normal component of the magnetic field calculated at 61 detectors and the localization accuracy of 9 different realistic head finite element method (FEM) models containing various gray and white matter conductivities to the results obtained using a FEM realistic head model containing published baseline conductivity values. In the models containing altered conductivity values, the gray and white matter were varied, one at a time, between 10% and 200% of their baseline values and then varied simultaneously. Although changes in conductivity values for gray and for white matter individually altered the calculated magnetic fields and source localization accuracy only slightly, altering both gray and white matter conductivities simultaneously caused significant discrepancies in calculated results compared to the model with the baseline conductivity values. This study suggests that accurate gray and white matter conductivities may be important for MEG source localization in human brain.**

Keywords—**MEG, Conductivities, Source Localization**

I. INTRODUCTION

MEG models that use homogeneous spheres need not account for volume currents nor the conductivity of the tissue through which currents flow in their simulations of magnetic fields emanating from current electric dipole neuronal activity or in source localization calculations. With more realistic, inhomogeneous, nonspherical head models, however, volume currents become of critical importance in determining magnetic fields [1], and tissue conductivity values must be considered in calculations of volume currents. In the literature, gray and white matter conductivity values have been reported to be between 0.33 S/m - 1.0 S/m and 0.31 S/m - 0.48 S/m, respectively [2-6]. To determine how much influence brain conductivity has on MEG forward calculations and inverse source localization, we compared the normal component of the magnetic field at the MEG detectors and the inverse solution accuracy of several realistic finite element method (FEM) head models, each model containing a different set of conductivity values for the brain tissues, with results obtained using data generated from dipoles placed in a realistic head model with a baseline set of reported brain conductivity values.

II. METHODOLOGY

The finite element realistic head model was created from 256 volume magnetic resonance image (MRI) slices and consisted of 72,745 nodes, 406,493 tetrahedral elements, and 61 magnetic field detectors placed over the head [1]. The model consisted of five conductivity values: scalp (σ=1.0 S/m), skull (σ=0.05 S/m), cerebrospinal fluid (CSF) (σ=4.62 S/m), gray matter (σ=1.0 S/m), and white matter (σ=0.43 S/m) [2]; these conductivity values were considered the baseline conductivities. The conductivity values of the scalp, skull, and CSF remained the same in each model. The gray and white matter were varied, one at a time, to 10%, 25%, 50% 75%, 110%, 125%, 150%, 175%, and 200% of the baseline value. The normal component magnetic field calculated at the detector using the model with the varied conductivity value was compared to the results obtained using the data generated using the baseline model.

The finite element method was used to approximate the

TABLE I
Forward MEG Error; Gray Matter Conductivity Varied

Dipole Position	Percentage of Baseline Conductivity Used in Model								
	10%	*25%*	*50%*	*75%*	*110%*	*125%*	*150%*	*175%*	*200%*
Left Occipital	29.6%	14.0%	3.53%	0.561%	$5.51x10^{-2}$%	0.290%	0.903%	1.64%	2.41%
Right Occipital	0.736%	0.322%	0.150%	$4.8x10^{-2}$%	$1.1x10^{-2}$%	$8.1x10^{-2}$%	0.416%	1.20%	2.74%
Right Frontal	1.34%	0.661%	0.207%	$3.95x10^{-2}$%	$4.67x10^{-3}$%	$2.61x10^{-2}$%	$8.81x10^{-2}$%	0.170%	0.263%
Right Internal Capsule	1.04%	0.500%	0.161	$3.36x10^{-2}$%	$4.64x10^{-3}$%	$2.79x10^{-2}$%	0.107%	0.239%	0.428%
Right Cingulate Gyrus	0.634%	0.456%	0.181%	$411x10^{-2}$%	$5.92x10^{-3}$%	$357x10^{-2}$%	0.134%	0.286%	0.482%
Left Hippocampus	14.4%	10.2%	3.00%	0.497%	$4.92x10^{-2}$%	0.258%	0.795%	1.42%	2.06%
Right Temporal	2.58%	0.546%	0.2.81%	$9.61x10^{-2}$%	$1.82x10^{-2}$%	0.116%	0.463%	1.01%	1.71%
Right Globus Pallidus	3.49%	1.40%	0.6.28%	0.188%	$3.87x10^{-2}$%	0.264%	1.20%	2.96%	5.65%

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TABLE II

Forward MEG Error; White Matter Conductivity Varied

Dipole Position	Percentage of Baseline Conductivity Used in Model								
	10%	*25%*	*50%*	*75%*	*110%*	*125%*	*150%*	*175%*	*200%*
Left Occipital	7.13%	3.40%	1.08%	0.218%	$2.75x10^{-2}$%	0.158%	0.549%	1.09%	1.71%
Right Occipital	13.6%	5.46%	0.939%	0.123%	$1.04x10^{-2}$%	$5.27x10^{-2}$%	0.155%	0.270%	0.383%
Right Frontal	3.35%	1.84%	0.629%	0.130%	$1.70x10^{-2}$%	$9.87x10^{-2}$%	0.355%	0.728%	1.19%
Right Internal Capsule	1.28%	1.06%	0.488%	0.123%	$1.98x10^{-2}$%	0.125%	0.502%	1.14%	2.04%
Right Cingulate Gyrus	1.05%	0.292%	$5.19x10^{-2}$%	$7.33x10^{-3}$%	$7.19x10^{-4}$%	$3.92x10^{-3}$%	$1.34x10^{-2}$%	$2.73x10^{-2}$%	$4.58x10^{-2}$%
Left Hippocampus	23.1%	5.29%	1.06%	0.165%	$1.64x10^{-2}$%	$8.71x10^{-2}$%	0.274%	0.502%	0.744%
Right Temporal	11.6%	6.96%	2.48%	0.506%	$6.23x10^{-2}$%	0.350%	1.18%	2.27%	3.47%
Right Globus Pallidus	2.53%	2.08%	1.19%	0.370%	$7.77x10^{-2}$%	0.541%	2.56%	6.67%	13.3%

magnetic field value at each detector according to the Biot-Savart law for a current dipole with the moment Q:

$$B(r) = (\mu_o/4\pi)[Q \text{ x } (r-r')/(r-r')^3 - \Sigma\sigma_j \int_{Gj} \nabla \varphi \text{ x } (r - r')/|r - r'|^3 \, dv'] \qquad (1)$$

where μ_o is the homogeneous magnetic permeability, φ is the electric potential, r is the point of detection, r' is the coordinate of the dipole, G is the conductive region of the brain , and σ is the conductivity of the region [7].

The BioPSE Problem Solving Environment [8] was used to drive the forward and inverse MEG simulations. Placing a dipole within the realistic head model with the baseline conductivity values and computing a forward solution generated the magnetic field values that were used in the inverse problem for all models. Inverse localizations were performed using the downhill simplex method starting at multiple points including the true dipole positions.

On completion of the studies in which the gray and white matter conductivity values were altered individually, similar models were constructed in which the conductivity values of both the gray and white matter were altered simultaneously for both the forward and inverse simulations.

III. RESULTS

The eight current electric dipoles that were used individually in the forward and inverse MEG calculations were located in the gray matter of the left occipital cortex, the right occipital white matter, the right posterior frontal subcortical white matter, the white matter of the right anterior internal capsule, the gray matter of the anterior right cingulate gyrus, the left hippocampal white matter, the right medial temporal white matter, and the gray matter of the right globus pallidus. Dipole distance from the closest magnetic detector was, respectively, 53.6mm, 53.8mm, 65.6mm, 84.5mm, 84.6mm, 92.5mm, 95.9mm, 97.1mm. Magnetic field values at detectors as predicted by forward MEG calculations for each of the models with either gray or white matter conductivity values varied between 10% and 200% of the baseline conductivities were compared to the solutions obtained from the baseline model with the dipole at the same position (Table I, Table II); the discrepancies between the models' results are reported in Tables I and II as one minus the correlation coefficient expressed as a percent.

For the forward study, changing the gray matter's conductivity by 25% of the baseline value resulted in a

TABLE III

Inverse MEG Error; Gray Matter Conductivity Varied

Dipole Position	Percentage of Baseline Conductivity Used in Model								
	10%	*25%*	*50%*	*75%*	*110%*	*125%*	*150%*	*175%*	*200%*
Left Occipital	6.18mm	2.66mm	1.21mm	1.98mm	0mm	0mm	1.06mm	2.53mm	2.71mm
Right Occipital	4.87mm	6.01mm	0.024mm	0mm	0.60mm	0.82mm	0.83mm	2.51mm	3.04mm
Right Frontal	7.20mm	1.86mm	2.81mm	0mm	0mm	0mm	0mm	0mm	0mm
Right Internal Capsule	5.51mm	3.98mm	2.80mm	0mm	0mm	0mm	0mm	0.56mm	1.00mm
Right Cingulate Gyrus	10.03mm	3.59mm	3.29mm	1.37mm	0.41mm	0mm	1.54mm	5.84mm	6.12mm
Left Hippocampus	14.87mm	15.18mm	2.07mm	4.17mm	0.96mm	0mm	2.11mm	0mm	1.30mm
Right Temporal	10.62mm	0.75mm	0.77mm	0.71mm	0mm	1.81mm	3.58mm	2.53mm	3.92mm
Right Globus Pallidus	3.60mm	1.81mm	2.66mm	5.06mm	0mm	0mm	8.54mm	13.48mm	17.19mm

TABLE IV
Inverse MEG Error; White Matter Conductivity Varied

Dipole Position	Percentage of Baseline Conductivity Used in Model								
	10%	*25%*	*50%*	*75%*	*110%*	*125%*	*150%*	*175%*	*200%*
Left Occipital	4.19mm	186mm	2.71mm	0mm	0mm	0mm	2.89mm	0mm	2.29mm
Right Occipital	4.67mm	0mm	0mm	0mm	0.025mm	0mm	0mm	0mm	0mm
Right Frontal	25.55mm	13.45mm	8.99mm	2.11mm	0mm	2.68mm	6.44mm	7.01mm	7.48mm
Right Internal Capsule	2.35mm	4.04mm	7.69mm	1.66mm	1.10mm	0mm	9.08mm	7.30mm	7.36mm
Right Cingulate Gyrus	12.94mm	1.59mm	2.29mm	0.37mm	0mm	0mm	0.14mm	0.14mm	0mm
Left Hippocampus	16.17mm	11.59mm	7.30mm	1.89mm	0.43mm	0.11mm	3.12mm	1.55mm	3.15mm
Right Temporal	20.73mm	22.43mm	7.14mm	8.81mm	0.54mm	4.09mm	8.00mm	8.56m	8.51mm
Right Globus Pallidus	4.78mm	0.98mm	3.81mm	2.73mm	4.53mm	4.53mm	1.44mm	10.20mm	10.41mm

discrepancy between the varied conductivity model and the baseline conductivity model of 0.14±0.11%; a change in the conductivity by 50% produced a difference of 0.513±0.414%. Changing the white matter conductivity by 25% produced a variance between the models of 0.20±0.24%, and a change by 50% resulted in a difference of 0.99±0.71%.

The inverse MEG solutions for each of the varied conductivity models were compared to the true dipole source position; localization errors are listed in Table III and Table IV. Inverse simulations using the baseline realistic head model resulted in 0mm error for all dipoles, as would be expected since the forward data used in the inverse study were derived from the same model.

For the source localization study, a change in the gray matter's conductivity by 25% resulted in an average position error of 1.66±1.97mm, and a change by 50% produced an error of 2.21±2.81mm. Changing the white matter conductivity by 25% resulted in an average position error of 2.19±2.86mm; a change by 50% produced an error of 4.99±3.21mm. When all models with varied conductivities are considered, the greater localization errors found for changes in white matter conductivity differed from the smaller errors found by changing gray matter conductivity significantly ($p<0.01$, Student's t-test).

The dipoles used in the source localization study can be divided into two groups: dipoles that are >84mm from the nearest detector (i.e. "deep" in the head), and dipoles that are <66mm to a detector (i.e. in a more superficial location). When all models with varied conductivities are considered, the position error of the "deep" dipoles was significantly greater than was the error of the superficial dipoles ($p<0.02$, Student's t-test); the error was also significantly greater for "deep" dipoles for the model in which the white matter conductivity varied ($p<0.01$) and tended to be greater for "deep" dipoles for models in which the gray matter varied ($p<0.08$). For example, for the "deep" dipoles, a change of the white matter conductivity by 25% resulted in a position error of 3.45±3.70mm, and a change by 50% produced an error of 5.14±2.50mm. For the superficial dipoles, a change of the white matter conductivity by 25% resulted in a position error of 0.94±1.10mm, and a change by 50% produced an error of 4.85±4.22mm. For the "deep" dipoles, a change of the gray matter conductivity by 25% resulted in a position error of 2.83±2.11mm, and a change by 50% produced an error of 3.94±3.19mm. For the superficial dipoles, a change of the gray matter conductivity by 25% resulted in a position error of 0.49±0.99mm, and a change by 50% produced an error of 1.71±1.35mm.

Errors increase if the conductivity of both the gray and white matter are changed simultaneously. For the forward problem, a simultaneous change of the gray matter by 25% and the white matter by 25% resulted in a variance of 0.45±0.43%; a simultaneous change of the gray matter by 50% and the white matter by 50% produced a variance of 2.40±2.81%. For the inverse problem, a change in the gray matter conductivity by 25% and the white matter conductivity by 25% resulted in a position error of 2.42±2.62; a change in the gray matter conductivity by 50% and the white matter conductivity by 50% produced an error of 9.74±9.28mm.

IV. Discussion

Discrepancies in the magnetic values predicted by models with changes in the white matter conductivity value generally were greater than those determined by models with changes in the gray matter conductivity value, although Tables I and II show some variability exists. The magnetic field resulting from dipoles in the study that were located in the gray matter, however, generally were more influenced by a change in gray matter conductivity than by a change in white matter conductivity. Conversely, the magnetic field resulting from the dipoles that were located in the white matter generally were more influenced by a change in white matter conductivity than by a change in gray matter conductivity.

Although errors can occur with changes in the conductivity value for either gray or white matter, on average the source localization error resulting from changes in the gray matter were significantly less ($p<0.01$) than those resulting from changes in the white matter. As with the forward studies, when a dipole was located in the gray matter, the source localization error generally was larger when the gray matter conductivity value was changed than when the white matter conductivity value was changed. When a dipole was located in the white matter, the source localization error generally was larger when the white matter conductivity value was changed than when the gray matter conductivity value was changed.

The volume of the white matter in the brain is much larger than the volume of the gray matter. The integral portion of equation (1) applies to the entire volume of the brain, and conductivity value changes in the larger white matter volume of the brain would be expected to have a greater affect on the total magnetic field than would changes in the smaller volume gray matter. In both the forward and source localization problems, changes in the white matter's conductivity value resulted in a larger affect on the magnetic field than did changes in the gray matter's conductivity value.

The conductivity of the area directly surrounding the dipole had a greater influence on the resulting magnetic field than did the area further away from the dipole. The greater influence of the dipole's local environment would be expected from the integral portion of equation (1) that calculates volume currents. As the distance between the dipole and volume element decreases, the denominator portion of the equation, $|\mathbf{r}-\mathbf{r}'|^3$, decreases and the influence of the local region's conductivity on the total magnetic field increases.

The error associated with localizing "deep" dipoles was substantially different from the error associated with localizing more superficial dipoles. Indeed, dipoles that were "deep" in the head were generally more influenced by changes in conductivity values, whether they were changes in the gray matter or white matter, than were more superficially located dipoles. The smaller localization errors found with superficial dipoles would be expected based on equation (1), which implies that superficially located dipoles should produce magnetic fields with relatively low contributions from volume currents or influence from conductivity.

When gray and white matter conductivity values were changed simultaneously, substantially larger errors occurred in both the predicted magnetic fields and in the source localization of the dipoles than when the values were changed individually. This is an expected result since two sources of error now exist in the model that can inaccurately influence the magnetic field. Although most of the source localization errors that occurred when the conductivity value of the gray or white matter was individually changed by 25% or 50% were less than the accuracy of MEG, the errors that occurred when both were varied together were often greater than MEG's accuracy. A change of conductivity values of 25% or 50% may seem large, but the difference between the largest and smallest reported conductivity values of the gray and white matter vary by as much as 200% and 50%, respectively [2-6]. If the brain is treated as a homogeneous volume conductor, then the conductivity of the gray and/or white matter may vary up to 200% and 50%, respectively, of the correct conductivity, as well. Further, conductivity changes in pathologic states are largely unknown, but could be expected to even exceed 200% in some circumstances, such as porencephalic cysts.

Conductivity values of the gray and white matter tissues do influence the magnetic field resulting from a dipole in the brain. The conductivity of the tissue directly surrounding a dipole influences the resulting magnetic field more than does tissue that is farther away, and "deep" dipoles generally are more influenced by inaccurate conductivity values than are dipoles that are more superficially located. Although inaccuracies in a single tissue's conductivity value results in a small localization error, inaccuracies in multiple tissues may have substantial affects on dipole source localization.

V. CONCLUSION

Changes in conductivity values for the gray and white matter individually can alter the calculated magnetic fields and influence source localization accuracy in MEG realistic head models. Altering both gray and white matter conductivities simultaneously causes even greater discrepancies in calculated results compared to a model with baseline conductivities. Although a 50% change in conductivity may seem large, different investigators have published conductivity values for brain tissue that can vary by this amount or more, and changes of this size or greater can occur in the brain pathologic states. This study suggests that accurate gray and white matter conductivities may be important for MEG source localization in human brain.

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