Can a Spherical Model Substitute for a Realistic Head Model in Forward and Inverse MEG Simulations?

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Abstract

Although the human head is not a sphere, models using spheres have been employed to simplify forward and inverse magnetoencephalographic (MEG) calculations. We compared the normal component of the magnetic field calculated at 61 detectors and the localization accuracy of 5 different spherical models to the results obtained using the finite element method (FEM) in a realistic head model. The spherical models used were an analytic equation for a single homogeneous sphere; a FEM single homogeneous sphere; concentric FEM spheres with skin, skull, and brain conductivity layers; concentric FEM spheres with skin, skull, CSF, gray, and white matter conductivity layers; and an overlapping sphere head model. No spherical model proved to be consistently the most accurate in determining forward magnetic field values or in localizing the 5 different dipoles used. Forward and inverse results for the spherical models tended to correspond more closely with the realistic model results for dipoles located near the surface of the head than for those deep inside the head. Large discrepancies in calculated magnetic field values and localization errors for some dipoles, however, limit at least these 5 spherical models as substitutes for the realistic head model in forward and inverse MEG calculations.

1 Introduction

Magnetoencephalographic (MEG) models that use homogeneous spheres in simulating the magnetic fields emanating from current electric dipole neuronal activity possess the advantage that forward problems can be reduced to a closed form analytic solution, and inverse calculations need not account for volume currents [6]. With more realistic, homogeneous, anisotropic, nonspherical head models, however, volume currents become of critical importance in calculating magnetic fields [7], a closed form solution is not easily computed, and approximations such as a finite element method (FEM) must be used. To determine how well spherical models with their simplified mathematics can substitute for a realistic model, we compared the calculated normal component of the magnetic field at the detectors and the inverse solution accuracy of 5 spherical models with results obtained using data generated from dipoles placed in a realistic head model. The spherical models employed were a single homogeneous sphere calculated using either an analytic equation or a FEM model, 3 or 5 concentric spheres in which each layer contains a different conductivity, and the overlapping sphere model of Huang, et. al. [2].

2 Methods

The finite element realistic head model was created from 256 volume magnetic resonance image (MRI) slices and consisted of 72,745 nodes, 406,493 elements, and 61 magnetic field detectors placed over the head. The model consisted of five conductivity values: skin (s=1.0 S/m), skull (s=0.05 S/m), cerebrospinal fluid (CSF) (s=4.62 S/m), gray matter (s=1.0 S/m), and white matter (s=0.43 S/m) [5]. The sphere models were least-squared fitted to the skull of the MRI slices. The single homogeneous spheres calculated by the analytic equation and by the FEM had radii of 100mm and conductivities of the white matter. The 3 sphere model consisted of conductivities of the skin (radius=100mm), skull (radius=92mm), and white matter (radius=80mm), whereas the 5 sphere model consisted of conductivities of the skin (radius=100mm), skull (radius=92mm), CSF (radius=80mm), gray matter (radius=72mm), and white matter (radius=52mm). The overlapping sphere model locally fits a sphere to the portion of the head that is closest to each magnetic field detector when calculating the field value at that particular detector [2].

According to Sarvas [6], the magnetic field (B(r)) outside of a homogeneous sphere enclosing a dipole with moment Q can be calculated as follows:

$$B(r) = \mu_o (FQ \times r' - Q \times r' \cdot r\nabla F) /4pF^2$$

where μ_o is the homogeneous magnetic permeability, r' is the coordinate of the dipole, r is the point of detection, $F = |a|(|r||a| + |r|^2 - r' \cdot r)$, $a = r' - r$, and

	Analytic Sphere	Homogeneous Sphere		3 Concentric Spheres		5 Concentric Spheres		Overlapping Spheres
		Linear	Quad	Linear	Quad	Linear	Quad	
Left Occipital	5.3%	5.4%	5.3%	5.4%	5.3%	5.4%	5.3%	10.8%
Right Frontal	7.8%	7.5%	7.8%	7.5%	7.8%	7.7%	8.4%	9.3%
Left Hippocampus	15.1%	15.2%	15.1%	15.1%	15.2%	15.8%	16.6%	10.9%
Right Temporal	23.7%	23.6%	23.7%	23.6%	23.8%	23.6%	24.0%	18.4%
Left Thalamus	>100%	>100%	>100%	22.0%	21.2%	21.1%	21.2%	72.2%

Table 1 Linear and quadratic forward MEG errors. Errors are 1-(correlation coefficient) expressed as percent.

$\nabla F = (|a|^2/|r|+a\cdot r/|a|+2|a|+2|r|)r - (|a|+2|r|+a\cdot r/|a|)r'$. This equation was used for the magnetic field values calculated for the homogeneous sphere with the analytic equation and for each of the spheres in the overlapping sphere model.

The other models used the FEM to approximate the magnetic field value at each detector according to the following equation:

$$B(r) = (\mu_0/4\pi)[Q \times (r-r')/(r-r')^3 - \Sigma \sigma_j \oint_{Gj} \nabla f \times (r-r')/|r-r'|^3 dv']$$

where G is the conductive region of the brain [1].

The SCIRun Problem Solving Environment [4] was used to drive the forward and inverse MEG simulations. Placing a dipole within the realistic head model 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.

3 Results

The five current electric dipoles that were used individually in the forward and inverse MEG calculations were located in the left occipital cortex, the right posterior frontal subcortical white matter, the left hippocampal cortex, the right medial temporal white matter, and the left medial thalamus adjacent to the third ventricle, the latter being placed at the center of the homogeneous sphere. Each dipole's distance from the closest magnetic detector was as follows, respectively: 53.6mm, 65.9mm, 94.5mm, 95.9mm, 104.6mm. Magnetic field values at detectors as predicted by forward MEG calculations for each of the 5 spherical models were correlated to the solutions obtained from the realistic model with the dipole at the same position (Table 1). Calculations requiring the FEM were performed with both the linear FEM and the more accurate quadratic FEM [8]. The inverse MEG solutions for each of the 5 spherical models were compared to the true dipole source position; localization errors are listed in Table 2. Inverse simulations using the 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.

4 Discussion

The discrepancy between magnetic values predicated by the spherical models and those determined by the realistic model generally was greater for dipoles remote from the nearest detector (i.e. "deep" in the head) than for those close to a detector (i.e. in a more superficial location), although Table 1 shows some variablity exists. The location of the left thalamic dipole in the center of the homogeneous sphere proved particularly difficult for the homogeneous spherical models to accomodate, as a dipole in such a location produces no external magnetic field [6]; large errors resulted when the realistic head magnetic values were correlated with the zero or near zero field strengths as calculated from both homogeneous sphere models and the overlapping sphere model.

The spherical models' difficulties with "deeper" lying dipoles also is reflected in the inverse data. The general trend seen in Table 2 is that the discrepancy between the location calculated using the spherical models and the true dipole position increases as dipole distance from the nearest detector increases; as with the forward data, some variability in this trend also exists. Again, the central location of the left thalamic dipole proved especially troublesome for the spherical models, with large localization errors found for most models. Although the relative discrepancies in forward results and the inverse localization errors for a given dipole and model tended to be similar, with larger forward discrepancies suggesting greater

	Analytic Sphere	Homogeneous Sphere	3 Concentric Spheres	5 Concentric Spheres	Overlapping Spheres
Left Occipital	7.0mm	7.7mm	7.7mm	5.6mm	8.2mm
Right Frontal	14.4mm	14.5mm	14.7mm	10.9mm	9.93mm
Left Hippocampus	25.2mm	41.5mm	41.5mm	50.6mm	38.2mm
Right Temporal	47.9mm	22.7mm	15.1mm	31.9mm	22.7mm
Left Thalamus	59.9mm	80.8mm	80.6mm	34.7mm	85.9mm

Table 2 Inverse source localization errors.

localization errors, this also was not invariable, as shown for the left occipital and right frontal data for the overlapping spheres, and for the right temporal and left thalamic data for both the 3 and 5 concentric spheres.

The lesser discrepancies found in the results from dipoles in more superficial sites may reflect the complex geometry of the realistic brain. Concentric spherical models with uniform conductivity layers may best suit a superifical dipole where the magnetic field must cross only relatively uniform layers of brain, CSF, skin, and skull to affect the nearest detectors where the largest measured fields often occur and which most heavily influence the forward and inverse solutions. In contrast, magnetic fields emanating from "deeper" dipoles must cross multiple conductivity layers, frequently more than once due to the geometry of the gray matter, white matter, and CSF in the brain and its sulci, before reaching a detector. Homogeneous spherical models try to simplify the geometry and remove the need to consider volume currents. But the head is not a sphere, and volume currents do exist in the data derived from an inhomogeneous anisotropic geometrically complex head. The discrepancies in the results obtained from the homogeneous spherical models may derive from the simplifications of the models being too great, especially for "deeper" dipoles, when using magnetic field forward data encumbered by volume currents. Although the quadratic FEM is more accurate than the linear FEM [8], the discrepancy in the spherical models' results for some forward solutions when compared to realistic model data was greater for the quadratic than for the linear method; this trend may suggest that the errors inherent in the simplifications introduced by the spherical models may be even greater than suspected by the linear FEM alone.

Depending on the level of accuracy desired, the potentially large discrepancies in the data generated by each of the 5 spherical models when compared to the realistic model may make these spherical models unreliable substitutes for the realistic model. No one model proved consistently superior to the others in forward simulations or in inverse localizations. Taken either individually or as a group, the results of the 5 spherical models generally were more accurate for superficial than for "deep" loci. But even in the separate groupings of superficial and "deep" dipoles, no one model consistently demonstrated lower magnetic field value discrepancies or improved localization ability, and the most accurate model for any given dipole position was unpredictable.

5 Conclusion

Although at times MEG spherical models can accurately localize a dipole based on realistic model magnetic field forward data, large discrepancies in localization at other times make at least the 5 spherical models presented in this paper not interchangeable with the realistic head model, especially when the dipole source position is unknown *a priori*. Depending on the level of accuracy desired, discrepancies in calculated magnetic field values and localization errors for some dipoles may limit at least these 5 spherical models as substitutes for the realistic head model in forward and inverse MEG calculations.

4 References

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