Finite Element EEG and MEG Simulations for Realistic Head Models: Quadratic vs. Linear Approximations

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Most techniques for solving inverse EEG/MEG problems require accurate forward modeling. When using a realistic head model containing multiple conductivities, exact analytic solutions cannot be calculated but may be approximated by a technique such as the finite element method [1]. Most applications of the finite element method for solving EEG/MEG problems have used linear basis functions to interpolate within an element [2], which forces the electric potential in an element to be linear and the electric field to be constant. These constraints on the electric potential and field can introduce significant errors when solving for the electric field near a dipole source.

In this paper, we compare linear and quadratic finite element methods using a 3D tetrahedron model of a realistic anisotropic head with a current dipole as the source. We use a 6-component model for conductivity, differentiating between air, skin, skull, cerebral spinal fluid, gray matter, and white matter. The Poisson equation is solved to compute the electric currents and potentials throughout the entire volume and the magnetic field outside of the head. We numerically approximate Maxwell's equations with linear and separately with quadratic basis functions to determine which more realistically and accurately represents the non-linear electric and magnetic fields that emanate from the dipole.

We first verify our method on a 41,093-element isotropic sphere for which electric and magnetic fields can be computed analytically as a function of the distance of the dipole from the surface of the sphere. Our magnetic field computation error averages 0.33% compared to the analytic solution when using the quadratic elements; this contrasts with an error averaging 2.6% when using the linear elements. The total electric field in the spherical model improved by 3.1%, whereas the electric field near the dipole source improved from an 18% error when using the linear elements to a 6.7% error when the quadratic elements were used to calculate the electric field.

After verifying our method, we applied it to the 396,285-element realistic head model which had been created from a patient magnetic resonance image scan, and computed the electric and magnetic fields using both linear and quadratic elements; the same mesh model was used for both sets of calculations. The electric potential calculated when using linear elements results in a discrepancy of up to 73% when compared to the electrical potentials at the same electrodes calculated using quadratic elements. When quadratic elements are used, the electric potential on the cerebral cortex is much more focused, giving more accurate results than can be determined by using only linear elements. The magnetic field calculated at detector points outside of our head model demonstrates that the discrepancy between the field derived using linear elements and that using quadratic elements was 14%.

The use of our quadratic finite element method improves substantially the electric and magnetic fields calculated from an isotropic sphere. In a 3D anisotropic realistic head model, the large discrepancy between the linear and quadratic element calculations of the electric and magnetic fields, and the more tightly focused electric potential in the model employing quadratic elements, suggests that the use of a higher order and adaptive finite element method will be more useful in accurately solving both forward and inverse EEG/MEG problems than would be possible using linear elements alone.

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