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Comparison of three-shell and simplified volume conductor models in magnetoencephalography☆

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ABSTRACT

Experimental MEG source imaging studies have typically been carried out with either a spherically symmetric head model or a single-shell boundary-element (BEM) model that is shaped according to the inner skull surface. The concepts and comparisons behind these simplified models have led to misunderstandings regarding the role of skull and scalp in MEG. In this work, we assess the forward-model errors due to different skull/scalp approximations and due to differences and errors in model geometries.

We built five anatomical models of a volunteer using a set of T1-weighted MR scans and three common toolboxes. Three of the models represented typical models in experimental MEG, one was manually constructed, and one contained a major segmentation error at the skull base. For these anatomical models, we built forward models using four simplified approaches and a three-shell BEM approach that has been used as reference in previous studies. Our reference model contained in addition the skull fine-structure (spongy bone).

We computed signal topographies for cortically constrained sources in the left hemisphere and compared the topographies using relative error and correlation metrics. The results show that the spongy bone has a minimal effect on MEG topographies, and thus the skull approximation of the three-shell model is justified. The three-shell model performed best, followed by the corrected-sphere and single-shell models, whereas the local-spheres and single-sphere models were clearly worse. The three-shell model was the most robust against the introduced segmentation error. In contrast to earlier claims, there was no noteworthy difference in the computation times between the realistically-shaped and sphere-based models, and the manual effort of building a three-shell model and a simplified model is comparable. We thus recommend the realistically-shaped three-shell model for experimental MEG work. In cases where this is not possible, we recommend a realistically-shaped corrected-sphere or single-shell model.

Introduction

In magnetoencephalography (MEG), the electrical activity of the brain is studied via magnetic field that is measured outside the head. The MEG signal is understood to arise from chemically-driven ionic currents that flow inside and in the vicinity of postsynaptic dendrites (e.g., Hämäläinen et al., 1993). These ionic currents produce a primary magnetic field and a charge distribution. The charges give rise to an electric field that drives currents in conducting medium, and these secondary currents generate a secondary magnetic field. A MEG measurement thus reflects both the chemically-driven neural currents and the secondary currents driven by the electric field.

In source analysis, the neural generators are estimated from measured MEG signals. To do this, the source activity, secondary currents, and sensors need to be modeled. These form a forward model that gives the sensor-level signals for a modeled source distribution. In macroscopic scale, the chemically-driven source activity is modeled as primary current distribution that is typically discretized into a set of current dipoles. Computing the magnetic field of a current distribution using the Biot–Savart law is a straightforward task; however, to compute the secondary currents (also called the volume currents), the electric potential distribution in the head has to be solved first. This so-called volume conduction problem is solved using quasi-static Maxwell equations (e.g., Sarvas, 1987). The electric potential and thus also the secondary currents and magnetic fields depend on the conductivity profile of the head.

The head can be coarsely divided into three regions of homogeneous conductivity (*three-shell model*): the inside of the skull, the skull, and the scalp. Such a three-shell model is common in experimental electroencephalographic (EEG) and combined EEG + MEG source analysis, but in sole experimental MEG it is rarely applied; instead,

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simplifications based on the low conductivity of the skull and the near-spherical head are frequently used. Some simplifications have been previously shown to produce very similar results to those obtained with the three-shell model, but at reduced computational cost and workload (Hämäläinen and Sarvas, 1989; Huang et al., 1999). In this study, we take a fresh look at whether these model simplifications are justified.

MEG volume conductor models

In this section, we describe briefly the MEG volume conductor models that are typically used in experimental brain research of anatomically normal subjects and that are implemented in common analysis toolboxes. In addition, we review how these models were motivated and verified and motivate the model comparison carried out in this study.

Sphere-based models

In sphere-based models, the global or local conductivity profile of the head is assumed spherically symmetric, or a spherical model serves as a starting point for a more detailed model. For sensors outside the spherical volume conductor, magnetic field generated by a dipolar source inside the conductor can be computed analytically (Sarvas, 1987). The spherically symmetric conductor possesses some special properties:

1. Radial sources produce no external magnetic field.
2. A radially symmetric conductivity profile has no effect on external magnetic fields.
3. The radial component of the magnetic field of a tangential dipole is identical to that in the free space or infinite homogeneous volume conductor.

Due to point 2, the model has only three free parameters: the coordinates of the origin.

There are in principle three ways for applying the spherical model to MEG: In the *global sphere* approach, a sphere is fitted so that the curvatures of the skull and sphere match as well as possible. The global sphere typically follows the skull and scalp geometry well around the central sulcus, but in frontal and occipital lobes the fit is then poor. In the *locally optimal sphere* approach, a sphere is fitted to the skull curvature around the region of interest (ROI), and typically only sensors close to the ROI are used. In the *local spheres* approach (Huang et al., 1999), separate spheres are fitted for each sensor, following the local skull geometry.

Global or locally optimal spherical models (both often called “single sphere”) have been used in all pre-90 s MEG source modeling studies and are still popular today. Single-sphere models have been successful in classical functional source localization tasks, in which a focal source is sought using a dipole model; typical applications include the localization of somatosensory or motor responses (e.g., Gallen et al., 1995; Mauguiere et al., 1997). For example, clinically-approved commercial source localization techniques usually utilize single-sphere models. However, the use of single-sphere model requires strong prior information about the source locations, and if there are separate source regions far from each other, a single sphere may not fit the geometry well enough. The local-spheres (or multi-sphere) model is supposed to fix these shortcomings and be valid for all sources and sensors. It is implemented in FieldTrip (Oostenveld et al., 2011) and BrainStorm (Tadel et al., 2011) toolboxes.

Corrected sphere

In the *corrected-sphere model* (Nolte, 2003), one sphere is fitted globally to the inner skull boundary and the model is corrected with a harmonic function based on the inner skull geometry and boundary conditions derived from the realistically-shaped single-shell model (see Realistically-shaped models section). The correction factors are computed analytically using a series solution. The corrected-sphere model is implemented in the FieldTrip toolbox and is the recommended method for building the MEG forward model in the SPM toolbox (www.fil.ion.ucl.ac.uk/spm). The corrected-sphere model is in these toolboxes confusingly called the “single-shell model”.

Realistically-shaped models

In realistically-shaped models, the conductivity profile of the head is modeled by extracting conductivity boundaries from anatomical MR (or CT) images, and the field computation is carried out numerically.[1] In experimental use, the most popular realistically-shaped model is the *single-shell model* (Hämäläinen and Sarvas, 1987, 1989), where only the shape of the inner skull boundary is modeled; the skull and scalp are assumed insulating and thus to be omitted and the volume inside the skull is assumed homogeneous. There are two motivations for omitting the skull and scalp: first, since the skull conductivity is much lower than that of the brain, most of the currents driven by the neural activity reside inside the skull, and the contribution of the weak currents in the skull and scalp on MEG signal is assumed negligible. Second, in a spherically symmetric head, the skull and scalp would not have any effect on external magnetic fields, and as the head resembles a sphere to some extent, the contribution of currents in the scalp and skull to the MEG signal is likely to be small. The single-shell model, solved with the boundary element method, is the default MEG head model in the MNE software (Hämäläinen, 2009).

The *three-shell model* is the most realistic head model routinely used in experimental MEG. The model comprises homogeneous compartments of brain, skull, and scalp. Numerical computations are typically carried out with the boundary element method (BEM), and the numerical problems due to the sources close to the poorly-conducting skull can be alleviated formulating the BEM using the isolated source approach (ISA) (Hämäläinen and Sarvas, 1989; Stenroos and Sarvas, 2012). The three-shell model is available, e.g., in MNE, ASA (www.ant-neuro.com), Curry (www.neuroscan.com), and BrainStorm analysis packages; in addition, three-shell model can be implemented with, e.g., Helsinki BEM library (Stenroos et al., 2007) and OpenMEEG (Gramfort et al., 2011) toolboxes.

The main challenge in constructing a realistically-shaped forward model is the segmentation of the skull: Because of good contrast for the brain, T1-weighted MR image sets are typically used for constructing the head model. However, T1-weighted MR has poor contrast for the skull, and thus especially automatic segmentation tools produce rather different and often erroneous results. Even though the errors due to the inaccurate skull boundary segmentation are typically associated with realistic models only, they also affect spherical models, as the spheres are fitted to the modeled skull boundary (or, worse, to the sensor geometry if no MR images are available).

Model comparison and validation

In the first MEG model-comparison study by Hämäläinen and Sarvas (1987), *single-sphere* models fitted locally were compared to a *single-shell* realistically-shaped BEM model (222 vertices). The BEM was first verified in a homogeneous sphere (152–382 vertices). Then, fields for dipoles in three brain regions were simulated in both spherical and BEM models. Field topographies were visually compared, and dipole localization errors due to the spherical approximation were studied using the BEM model as the reference. It was concluded that for occipital dipoles the spherical and single-shell models gave similar results, but for temporal and frontotemporal sources the differences were large and the spherical model was considered to give misleading results.

[1] The Nolte corrected-sphere model can also be interpreted as a realistically-shaped model.