Fast SAR Estimation via a Hybrid Approach

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Introduction: Estimation of local specific absorption rate (SAR) is a major challenge in high-field (>3.0 Tesla) multi-channel transmission systems. Conventional Finite-Difference Time-Domain (FDTD) method is often inefficient to give subject-specific results. Recent studies significantly speed up the process by applying Ampere's law to obtain electrical field distributions via measured transverse B_1 fields [1]--[3]. The drawback is that only the longitudinal electrical fields can be recovered via experiments, which may yield a large discrepancy [2]. If all three components of the magnetic field are known, results obtained from rigorous FDTD and those via Ampere's law bear little differences [3].

It was well known that magnetic field distributions of RF coils are not strongly affected by tissue inhomogeneity. The profiles can be fairly well captured by using homogeneous phantoms filled with an equivalent medium [4], especially at 3.0 Tesla. Thus it is possible to develop fast SAR evaluation approaches by calculating magnetic fields in a homogeneous phantom, and then applying Ampere's law in the same phantom but filled with inhomogeneous tissues. We studied this approach by applying fast surface integral-equation method (SIE) [5] and a fast field interpolation scheme. We only demonstrate the resulting electric field distributions, which are actually required in SAR computations.

Methods: This method includes three major components: 1) applying fast integral-equation method to obtain magnetic field distributions in a homogeneous phantom (filled with a single equivalent medium) 2) calculate magnetic fields at a set of Cartesian grid points 3) replace the single medium with inhomogeneous tissues and apply Ampere's law (Eq. (1)) to calculate electric fields. The last step is accomplished via standard finite-difference scheme for simplicity.

$$\vec{E} = \nabla \times \vec{H} / (\sigma + i\omega\varepsilon) \quad (1)$$

In the first step, a multi-level Adaptive Cross Approximation (ACA) method [6] was applied to compress matrices and speed up matrix/vector multiplications in iterative solvers. The SIE method yields current distributions and one needs to obtain magnetic fields at a set of Cartesian grid locations in order to compute electric fields. Straight-forward computation involves millions of grid locations and CPU time is unaffordable. Instead, we construct tetrahedral meshes inside and outside of the phantom and only compute magnetic fields on the vertices. Magnetic fields at finite-difference grid points were obtained through linear interpolation. In typical head imaging problems, this approach is at least two to three orders of magnitude faster than straightforward field computations.

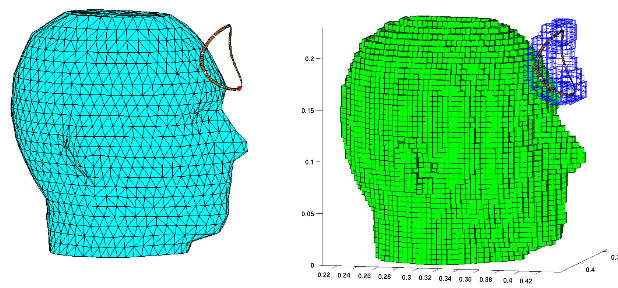

Fig 1. The coil and head model in the SIE method (left) and the corresponding model in the finite-difference computation of Ampere's law (right). Blue wires in the right figure show the reserved boundary for tetrahedral meshes.

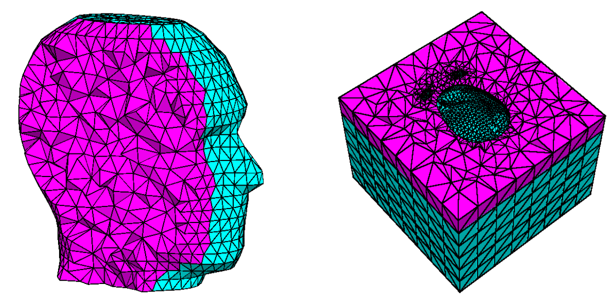

Fig. 2: A cut through the tetrahedral meshes inside (left) and outside (right) of the head phantom. Pink color denotes the cross-section of tetrahedral meshes. Note that coil conductors are excluded from the meshes (right).

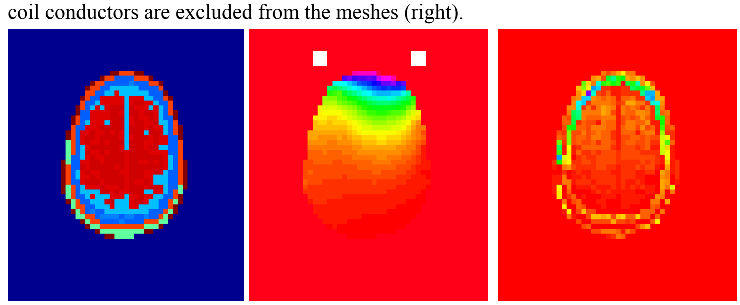

Fig 3: The anatomy (left), the B1+ field distribution calculated by the SIE method (middle), and the electric field distribution calculated via Ampere's law (right). The two white blocks in the middle figure denote coil conductor locations.

Results and Discussion: We investigated the electric fields generated inside a human head by a 7.0 Tesla surface coil. A 5-mm^3 inhomogeneous human head model (Duke from Virtual Family Models) was applied. The surface of this inhomogeneous model was extracted and used in SIE simulations (Fig. 1). The head model was filled with a dielectric that has ε_r = 52 and σ=0.552 S/m, which resembles the white matter at 7.0 Tesla. On a 3.0 GHz AMD processor, the simulation takes 30 seconds to finish. Next, tetrahedral meshes both inside and outside of the human head were constructed by constrained Delaunay method, which took less than one second. There were 2,398 vertices and 10,633 tetrahedrons in the interior, 4,363 vertices and 18,916 tetrahedrons in the exterior. The meshes are shown in Figure 2. Magnetic fields were computed on the vertices, which took 74 seconds. Subsequent interpolation on finite-difference grids took 10 seconds. Note that only magnetic fields surrounding the head are required to compute electric fields on the surface of the head. Thus the outside region can be significantly reduced, although we have chosen not to do so in order to demonstrate coil locations. In the extreme case where only tetrahedrons inside the head were involved, field computation and interpolation took less than 40 seconds. Finally, electric fields were computed by replacing the homogeneous phantom with the original inhomogeneous phantom and applying Ampere' law, which took less than a second. Figure 3 shows the results in one axial slice. We notice that strong electric fields are associated with tissue discontinuities.

Conclusion: We presented a fast SAR simulation approach by combing integral-equation method and Ampere's law. Combined with fast subject modeling, this method may provide a viable approach for subject-specific SAR estimations.

References: 1) Katscher AA et. al. Proc ISMRM 2008, 1191. 2) Cloos M.A. and Bonmassar G. Proc ISMRM 2009. 3) Buchenau S. et. al. Proc ISMRM 2009 4798. 4) Yang Q.X.et. al.MRM 2004 Nov;52(5):1016-20. 5) Wang and Duyn, Phys. Med. Biol. 51:3211-3229 (2006). 6) Wang S., et.al. Proc ISMRM 2009, 507.