Fast E_1, B_1 and SAR simulation with the use of graphics processors

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Introduction: Specific Absorption Rate (SAR) is a dominant constraint in high field MR, and has been a topic of much recent interest with developments of parallel transmission systems (pTx). While real-time estimates of local SAR over large volumes as well as SAR-constrained pTx RF design are highly desirable goals, it is both difficult to control and computationally burdensome to compute. Steady advances in graphics cards for game developers have enabled dramatic speedups in computationally heavy tasks for computer graphics, and some of this functionality is applicable for faster numerical SAR simulation compared to general CPUs. In this study, we present the use of Compute Unified Device Architecture (CUDA) enabled graphics cards in Finite Difference Time Domain (FDTD) simulations for SAR computation. We show that using this framework can speed up computation by at least an order of magnitude compared to regular CPU computation. This will allow us to estimate SAR, B_1, and E_1 fields quickly for instances where SAR estimation for parallel transmission imaging of individual subjects (if head models are reshaped to fit the subject) is necessary [1], or for optimizing coil designs based on these estimates. A fast FDTD computation would also significantly speed up iterative optimizations of coil design over a geometric parameter space.

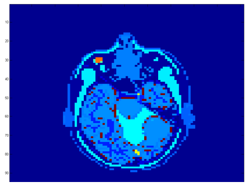


Figure 1. Tissue-Segmented Head Model

Figure 2a. $|B_1(t)|^2$ vs. simulation time at center grid point (blue) and point near coil 1 (red). Steady state is achieved in 2-3 cycles for an input 300 MHz sinusoid.

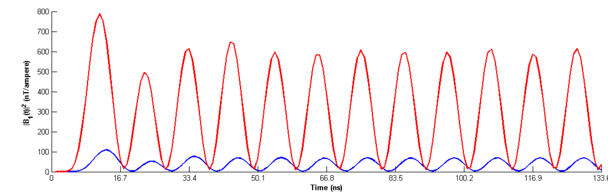
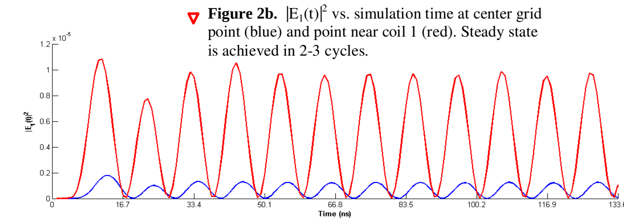


Figure 2b. $|E_1(t)|^2$ vs. simulation time at center grid point (blue) and point near coil 1 (red). Steady state is achieved in 2-3 cycles.



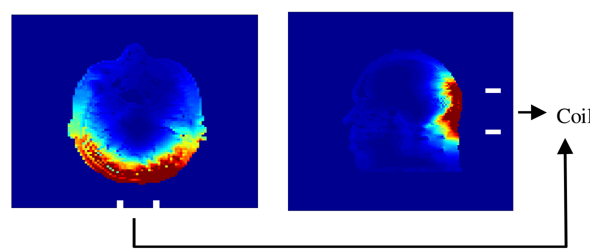


Figure 2c. $|\mathbf{B}_1^+(\mathbf{r})|$ axial and sagittal plots after 80,000 time steps for coil 1 driven with unit ampere sinusoid current. Quantitative map shows B field inhomogeneity.

Methods: FDTD with Uniaxial Perfect Matching Layer (UPML) boundary conditions was coded on a NVIDIA GeForce 9800 GX2 (2 GPUs with 512 MB configurable memory on each GPU, approximate retail cost \$200-\$300) using the NVIDIA CUDA framework. FDTD equations were CUDA optimized by use of two kernel functions, one for the E field update equations and another for the B field update equations. FDTD simulations were run on a high-resolution (1x1x3 mm^3) multi-tissue human head model, which is obtained via segmentation of anatomical MRI data [4]. Each of the segmented tissues in the model are assigned both a density, ρ (kg/m^3) and electrical conductivity, σ (S/m). Figure 1 shows an axial slice of the human head model. A parallel transmit coil was modeled by placing $P = 8$ copper loop elements at 45° increments along a 20-cm-diameter cylindrical surface centered on the head [2,4]. Each loop element had an edge length of 10 cm with no input resistance, for computational simplicity and more accurate simulation results. The spatial resolution (256x256x128 cells) was $\Delta x = \Delta y = 1$ mm, $\Delta z = 3$ mm and time step resolution $\Delta t = \Delta x / 2c \approx 1.67$ps. To obtain each individual transmit channel field profile, each channel was driven with a 1-ampere peak-to-peak 300-MHz sinusoid, while leaving all other channels without current to obtain steady-state electric and magnetic fields per ampere of input current per coil. The absorbing boundary conditions (UPML) were 10 cells deep [5] and a perfect electrical conductor covering the outside of the entire grid. The UPML had a polynomial grading of order 4 and maximum reflection error of e^{-16}. E fields obtained from FDTD simulation were then input into optimized SAR calculation algorithms [2,3]. SAR for parallel transmission with current pulses $a_p(t)$ played on channel p computed at any vector location $\mathbf{r}$ can be solved by numerical integration [2]:

$$\mathrm{SAR}(\mathbf{r}) \approx \frac{\sigma(\mathbf{r})}{2\rho(\mathbf{r})}\frac{\Delta_t}{\mathrm{TR}}\sum_{n=0}^{N_t-1}\|\mathbf{E}(\mathbf{r},n\Delta_t)\|_2^2 = \frac{\sigma(\mathbf{r})}{2\rho(\mathbf{r})}\frac{\Delta_t}{\mathrm{TR}}\sum_{n=0}^{N_t-1}\left\|\sum_{p=1}^{P}a_p(n\Delta_t)\mathbf{E}_p(\mathbf{r})\right\|_2^2$$

where $\rho(\mathbf{r})$, σ $(\mathbf{r})$ is the density and electrical conductivity, respectively, Δ_t is the integration time step, and $\mathbf{E}_p(\mathbf{r})$ is the r.m.s. E field at steady state on channel p when driven by unit ampere (peak value) sinusoid. Computation of $\mathbf{E}_p(\mathbf{r})$ and $\mathbf{B}_p(\mathbf{r})$ via FDTD involves the time step update of E and H fields to be sequential in a leap-frog manner [5]. Each update for each cell in a grid can be run in a parallel manner since each field component being updated in a grid cell depends on neighboring cell field components. Optimization of memory handling and GPU architecture allows for fast computation of each update with only overhead cost of storing maximum 6 field arrays (256x256x128 floats). UPML material properties can be broken up for each of the different edge regions of the grid (8 corner elements, 8 non-corner edge PML layers, and 6 faces). With multiple GPUs (Tesla or more advanced architecture), it is possible to run different channels simultaneously for FDTD simulation. Current card model allows only 2 channels to be excited separately but computed simultaneously.

Results and Discussion

Figure 2a plots $\|\mathbf{E}_1(t)\|^2$ and $\|\mathbf{B}_1(t)\|^2$, magnitude squared of both fields with only one coil element (coil $p=1$) driven with 1A 300-MHz current over ~6 cycles of the sinusoid (1 period = 12,558 time steps of Δt) at the volumetric center of the grid. Similarly, Figure 2b plots $\|\mathbf{E}_1(t)\|^2$ and $\|\mathbf{B}_1(t)\|^2$ over the same ~6 cycles of the sinusoid at a different point on the same center sagittal slice. In both figures, steady state is reached after about only two cycles of the sinusoid. Figures 2c plots the B_1^+ magnitude maps (axial and sagittal center slices) after 80,000 time steps for only one coil driven by unit ampere (peak to peak) current. The runtime for 20,000 time steps (~1.5 cycles at 300 MHz) is 40 minutes (an order of magnitude faster than most CPU processing run times) on the present graphics card model and the runtime increases linearly with number of time steps used to update the field equations. The presented data support the idea that using CUDA for parallel implementation of FDTD can help alleviate time constraints on SAR computation and iterative coil optimization.

References: 1) Setsompop, K. *Ph. D Thesis, MIT EECS*, 2008. 2) Zelinski et al. Specific Absorption Rate Studies of the Parallel Transmission of Inner-Volume Excitations at 7 Tesla. *JMRI*, 2008. 28(4). 3) Zelinski et al. Designing RF Pulses with Optimal Specific Absorption Rate (SAR) Characteristics and Exploring Excitation Fidelity, SAR and Pulse Duration Tradeoffs. *ISMRM* 2008. 4) C. Gabriel. "Compilation of the dielectric properties of body tissues at RF and microwave frequencies," Brooks Air Force, Brooks AFB, TX, Tech. Rep. AL/OE-TR-1996-0037, 1996. 5) Taflove et al. Computational Electrodynamics. © 2000. ***Acknowledgements:*** *NIH R01EB006847, R01EB007942, NCRR P41RR14075, Siemens Medical Solutions, Dr. Qianqian Fang(MGH), Dr. Leonardo Angelone (MGH), Prof. Giorgio Bonmassar.*