

Fast GPU FDTD Calculations: Towards Online SAR and B1+ Assessment and Control

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Introduction:

One of the main drawbacks of high field MRI is its inherent higher SAR deposition. To address this issue multiple channel RF transmit systems are under development which allow a higher level of control over the electromagnetic fields. Although the individual magnetic excitation fields (B1+) can be mapped, the accompanying electric fields per element cannot be measured. This information is crucial for SAR control via RF shimming or the design of parallel transmit RF pulses for spatially tailored excitation within SAR constraints [1]. In this study we propose a novel implementation of the finite-difference time-domain (FDTD) method, based on parallel computing using graphical processing units (GPU). We show that with an accelerated implementation the total computing time for a 2 channel 7T head coil becomes sufficiently short to perform online SAR computations.

Methods:

Since in the FDTD method the field to be updated only depends on the field from the previous time-step (leapfrog scheme), it is well possible to parallelize the problem. The parallel FDTD scheme was implemented on a GPU (NVIDIA's graphics card GTX 285) using the CUDA language [2]. The computational domain was truncated with perfectly matched layers (PML) using the auxiliary variable technique [3]. The discrete Fourier transform (DFT) of both electric and magnetic fields inside the head are calculated on-the-fly at the desired frequency. The developed software also implements capacitors and resistors, required to simulate an MRI coil. The software was tested against previously validated FDTD simulations [3, 4]. As a test case we simulated a 7T high-pass birdcage coil ($f = 298$ MHz, Nova Medical detunable head transmit coil) with a head model [4] containing 13 tissue types and a $2.5 \times 2.5 \times 2.5$ mm³ voxel size. The total domain size was $0.4275 \times 0.4275 \times 0.3225$ m resulting in a simulation domain of $171 \times 171 \times 130$ cells, plus 8 PML cells in each direction. In order to guarantee convergence of the DFT, 20000 time-steps were taken.

Results:

The total simulation time was 380 seconds against 2 ½ hours with the original CPU software. That includes the DFT of both electric and magnetic fields components. Figures 1 and 2 show SAR and B1+ distributions, respectively. If the resolution is $5 \times 5 \times 5$ mm³, the total domain size is $86 \times 86 \times 65$ cells and the total number of required time steps is 10000, reducing the total simulation time to 41 seconds.

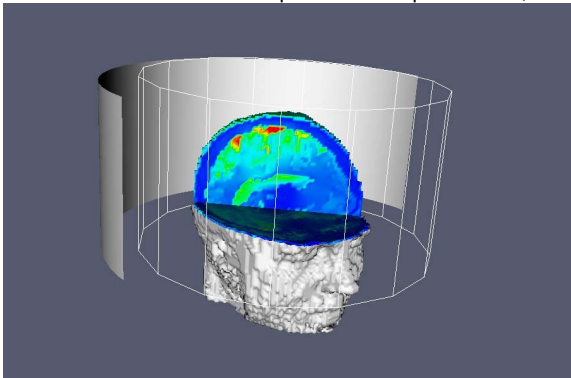


Figure 1: Computed SAR distribution inside the head model

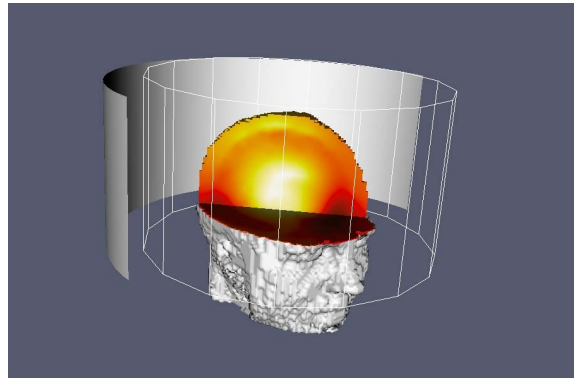


Figure 2: Computed B1+ inside the head model

Discussion:

The EM distribution can be simulated within minutes, or even in less than a minute, as opposed to hours using regular CPU software. This opens the possibility of online SAR estimation and reduction *during* the procedure. As an example, Figure 3 shows the SAR distribution after RF shimming while Figure 4 shows the SAR distributions with regular quadrature excitation. In both cases, SAR was normalized for a 90 degrees pulse in the centre of the head with a rectangular pulse of 1 ms and a 5% duty cycle. Although the simulation takes 7 minutes, this can be decreased even further by using multiple GPUs. To complete the implementation, we should be able to obtain the patient's dielectric model. When this final step is taken, the increased speed of the FDTD simulations can be used online, to calculate B1+ and electric fields for parallel RF transmission.

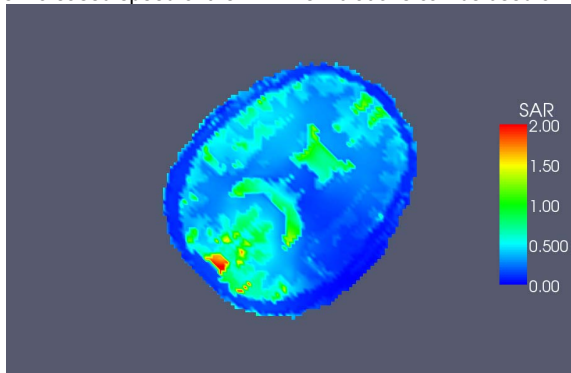


Figure 3: Computed SAR after RF shimming.

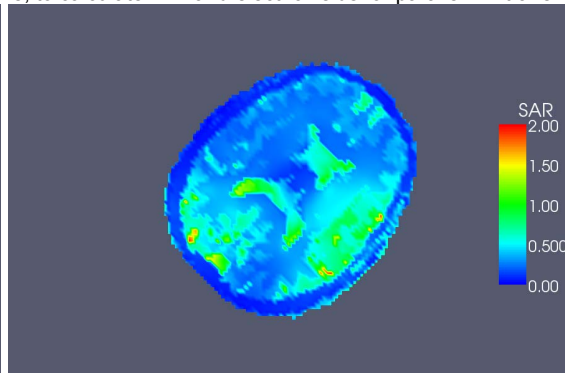


Figure 4: Computed SAR with quadrature excitation.

Conclusion:

We showed a parallel implementation of FDTD-PML on a GPU. This reduced calculation times by a factor of 25 or more, to the order of minutes (7 minutes for 3.8M voxels) without changing the simulation outcomes. Now, online SAR assessment and control is almost feasible. The next step towards online EM computations is creating a sufficiently accurate dielectric patient model based on (pre) images of the patient in the scanner.

[1] van den Bergen *et al*, Ultra fast electromagnetic field computations for RF multi-transmit techniques in high field MRI. *Phys Med Biol.* (2009) **54**:1253-64.

[2] www.nvidia.com/object/cuda_home.html

[3] Correia and Jin, On the Development of a Higher-Order PML, *IEEE Trans Antennas Prop.* (2005) **53** 4157-63

[4] Van Leeuwen *et al.*, Calculation of change in brain temperatures due to exposure to a mobile phone *Phys. Med. Biol.* (1999) **44** 2367-79.