GPU accelerated FDTD solver and its application in B1-shimming

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Introduction   FDTD is widely used for EM analyses in MRI applications, due to its simplicity and efficiency in wave modelling and its ability to handle field-tissue interactions[1]. However, contemporary MRI problems, such as high field-tissue interaction modelling requires high performance computing. Conventional CPU-based FDTD calculations offer compromised computing performance without expensive super-computer support. This study extends our recent works on CPU-base FDTD simulations[1] into a Graphics Processing Unit (GPU)-based parallel-computing framework[3], producing substantially boosted computing efficiency at only PC-level cost. The new computational strategy enables intensive computing feasible for solving forward-inverse EM problems in modern MRI, as illustrated in the high-field B_1-shimming investigation presented herein. Moreover, the new rotating RF excitation technique proposed here can compensate for B_1 inhomogeneities while simultaneously controlling SAR, and as such, may have a number of applications in high-field MRI.

GPU accelerated FDTD solver   GPU technology meets the demands of increased computational power and its applications have exploded in recent years. GPU is designed with massively parallel, many-core multi-processors, taking advantage of parallel threading to enable multi-computing operations simultaneously. The parallel FDTD program is implemented with NVIDIA's single Tesla C1060 card[3]. The device is capable of 933 GFLOPs/s of processing performance and comes standard with 4 GB of GDDR3 memory at 102 GB/s bandwidth. It contains 240 processor cores with core clock of 1.296 GHz. To simplify many-core programming, the standard Compute Unified Device Architecture (CUDA) C programming environment is used. For the FDTD algorithm, the memory management has been a major issue. In a GPU device, three different types of memory are accessible: global memory, registers, and shared memory. Although the latter two are fast to access, the large-capacity global memory is used in this study, due to large arrays being usually required for representing the heterogeneous EM properties of a patient model in MRI. The transition from a CPU-based FDTD code to multithreaded GPU-based code is realized by dividing the whole computation domain into multiple blocks and by calculating the E- and H- field components in each sub-domain with a different thread. The impact of the number of threads and thread block sizes on computing efficiency is tested and we conclude that 256 threads are favourable for our MRI applications. In this modelling study, the GPU-enabled FDTD computing is proven to be 30~60 times faster than the same implementation on a single PC.

MRI application- B_1-shimming   In this application, the distortion of the RF field caused by biological samples is considered by introducing a 3mm-resolution, realistic human head model[1], while using an unshielded single-loop rotating RF coil (RRFC)[2] operating at 470MHz for RF transmission study. The coil-load model setup is illustrated in Fig.1(a). The coil parameters are: R=14.7*cm*, Length = 15*cm*, opening angle of the loop=32*degree*; rotating speed=2000*rpm*. The EM fields produced by the single-loop rotating coil were emulated by 100 coils evenly distributed around the sample, with an incorporation of phase-shift due to sequential motion. The B_1-shimming was realized by solving an ill-posed linear system equation for loop currents at each angular position during rotating RF transmission. The optimization procedure is detailed in a companion study[4]. In the first step, to obtain the coil sensitivity profiles (see Figs.1(b),(c)) for the construction of the linear system, 100 FDTD simulations were carried out and each calculation took about 26*sec* using GPU computing. By contrasting, the simulation time with the DELL precision 3500 (quad cores) would typically take about 15 mins to complete. In the simulation, 123 uniformly distributed field points in the *z*=0 plane were sampled with targeted B_1-field of (1+i) and minimized E-fields. In the second step, the source profiles of the RRFC can be determined within one minute by optimization. Fig.1(d) shows the optimized current profiles. Figs.1(e),(f) shows comparative results in terms of B_1-fields and SAR values between the standard birdcage-mode excitation and optimized rotating excitation. The results clearly indicate a huge enhancement in B_1 homogeneity and that all the RF heating "hot spots" have been removed from the central slice.
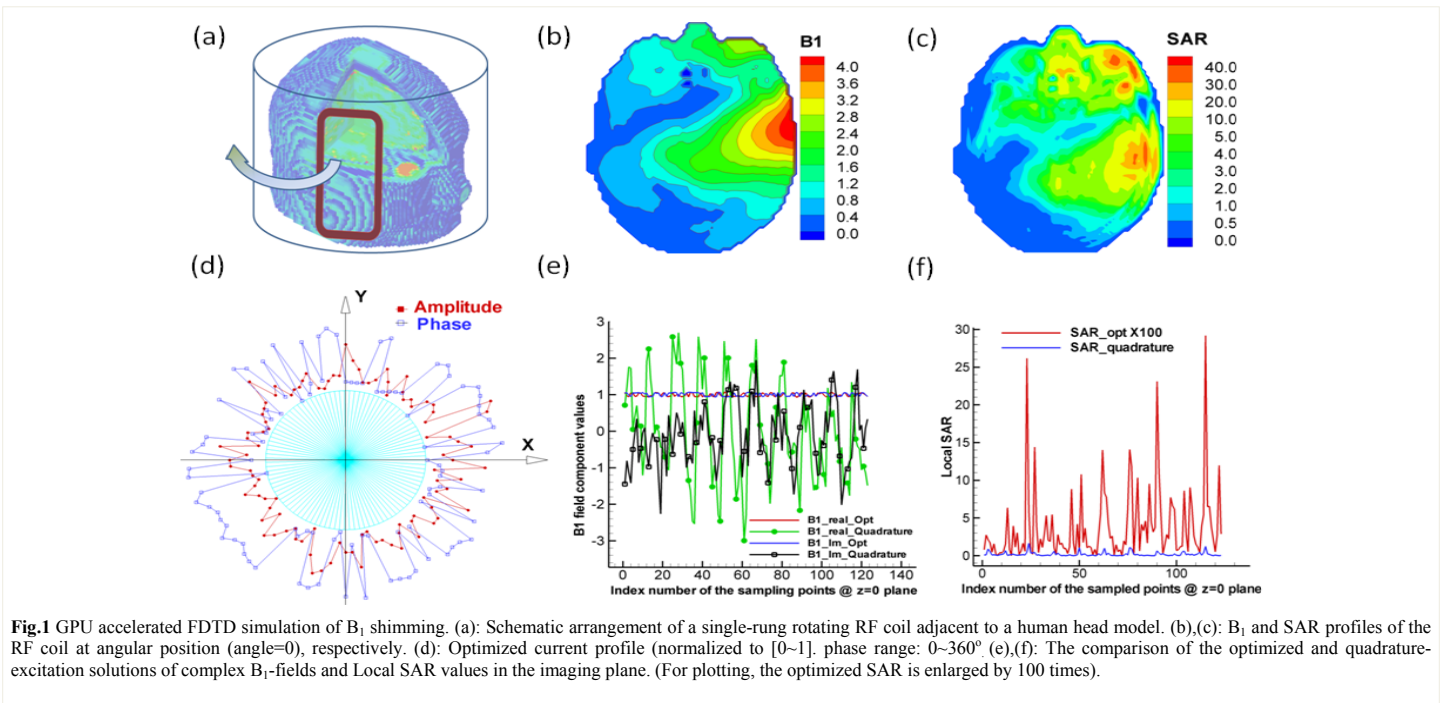

Fig.1 GPU accelerated FDTD simulation of B_1 shimming. (a): Schematic arrangement of a single-rung rotating RF coil adjacent to a human head model. (b),(c): B_1 and SAR profiles of the RF coil at angular position (angle=0), respectively. (d): Optimized current profile (normalized to [0~1]. phase range: 0~360° (e),(f): The comparison of the optimized and quadrature-excitation solutions of complex B_1-fields and Local SAR values in the imaging plane. (For plotting, the optimized SAR is enlarged by 100 times).

Conclusion   The GPU technology can drastically accelerate FDTD simulations for MRI applications. We will continue to optimize the parallel implementation of the FDTD on GPUs by utilizing the fast memory access, data reuse and thread redesign. The parallel FDTD solver enables us to investigate the high-frequency RF problem, inverse EM designs and high-resolution tissue-field interactions as well as the effect of EMFs on surrounding coils/conductors, which previously was impractical.

Reference   [1] Liu,Beck,Fitzsimmons,Blackband,Crozier, *Phys Med Biol* 50:5281-91 (2005). [2] Trakic,Wang,Weber,Li,Poole,Liu, Crozier, *JMR*, *in-press* (2009). [3] http://www.nvidia.com/object/product_tesla_c1060_us.html. [4] Liu,Weber,Trakic,Wang,Crozier, *ISMRM*, *submitted* (2010).