A High Performance FDTD Scheme for MRI Applications

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Synopsis: In recent years, Magnetic Resonance technology has progressed towards improved image resolution and acquisition speed. As a result, obtaining analogous high-resolution images via an electromagnetic (EM) field analysis, which are required for both designing of MRI systems as well as for providing a valuable insight into the experimentally obtained results becomes more challenging. The reason is that the task of determining the distribution of induced eddy current in complex geometries involving both patients and magnet cryostats requires considering an increased number of unknowns. As a result, solving of the new problem becomes more computationally intensive both in terms of the required computer memory and processing time. In order to tackle this problem it is necessary to devise new computationally efficient computer algorithms. Here, we present an efficient parallel computational structure for the Finite-Difference Time-Domain (FDTD) algorithm, which is based on the pervasive Message-Passing Interface (MPI) library. Using this approach the computation and communication tasks are optimized. The power of the devised algorithm is demonstrated in two examples. These concern the analysis of low-frequency transient eddy currents using a recently proposed cylindrical FDTD routine [1, 3], and the interaction of RF-fields with the human body via the conventional FDTD method in Cartesian coordinates.

Method: The formulation of an FDTD algorithm for solving Maxwell's equations using Cartesian coordinates has already been reported in [2]. This formulation forms the basis for devising a parallel FDTD architecture for high frequency scenarios. The challenge concerns a low frequency region as the standard FDTD formulation suffers from a prohibitively long execution time. In our recently proposed scheme [1, 3] we have demonstrated a suitable adaptation of the Maxwell's equations to the low-frequency region. The high and low frequency FDTD schemes are transformed to the parallel computing architecture by dividing the computational domain into several sub-spaces. An additional memory is allocated to each sub-process in the sub-space boundary regions in order to establish correspondence of mirror fields to the neighbouring field components, as illustrated in Fig. 1(c). The computational complexity depends on the method of computing of coefficients and on the updating of EM field components for different types of regions. As shown in Fig. 1(a, b), the computational region is divided into different types of sub-regions, which decrease the memory consumption and the complexity of coefficient calculations. The pre-processing for coefficients reduces the computational time, as shown in Fig. 2 (b). Communication routines are efficient when communication routines are unblocked in this parallelism. We compare the proposed communication routine when the problem scale is gradually increased. As observed in Fig. 2 (c) the significant improvement in communication efficiency is obtained. Our optimisation algorithm emphasizes the whole computing performance, based on statistical tests of the execution efficiency on each parallel process, with the assumption of constant computational environment on the run time.

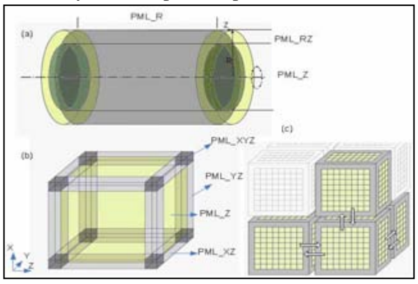

Fig.1 – Separation of the FDTD computing region: (a) cylindrical coordinate system; (b) Cartesian coordinate system; (c) The message communication routine mechanism in FDTD for 3 dimensional arrays.

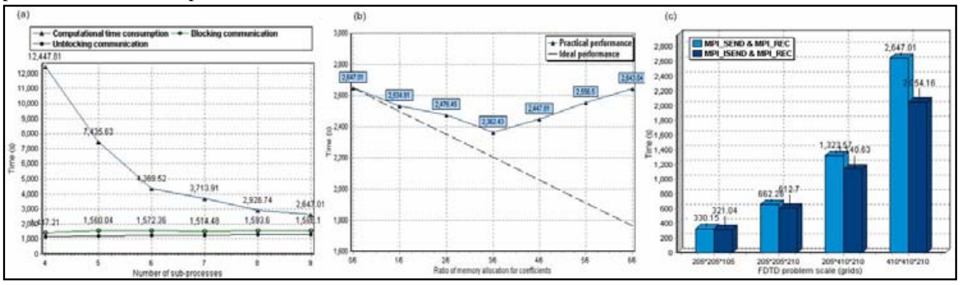

Fig.2 Performance of the parallel FDTD scheme.(a) The time consumption comparisons between computation and communication with increasing number of processes; (b) Time consumption according to the ratio of the occupied memory for coefficients. (For example, 5/6 means 5 out of 6 coefficients occupy additional memory for the pre-processing concern); (c) Time consumption for different communicating routines according to the increasing problem scale. All cases are based on 410×410×210 problem scale with 1000 FDTD time steps.

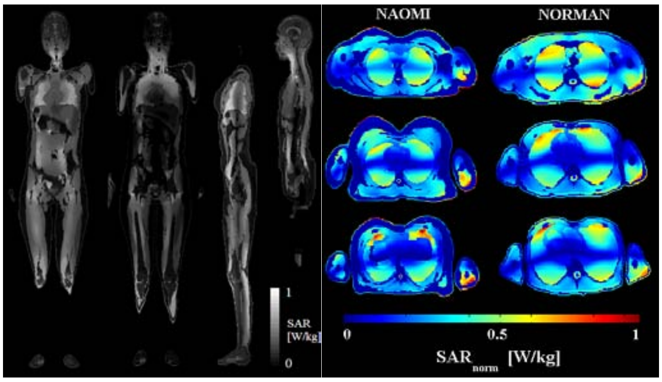

Fig. 3 – Normalized SAR profiles inside a female model (NAOMI, left) and comparisons of SAR between female and male model (NORMAN, right).

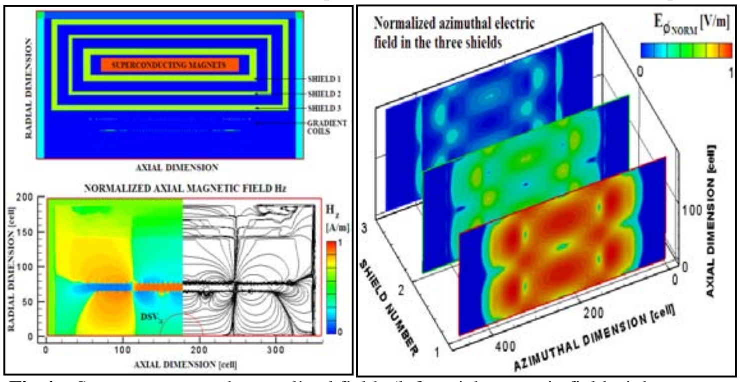

Fig.4 – System set-up and normalized fields (left: axial magnetic field; right: azimuthal electric field in the middle layer of each radiation shield).

Results and Discussion: We demonstrate the use of the proposed parallel FDTD scheme in the analysis of low frequency transient eddy currents in nearby conducting structures when pulsing magnetic field gradients. We assess the Specific Absorption Rate (SAR) during the interaction of RF fields with inhomogeneous human tissues (both female and male models) within a linearly polarized birdcage resonator model at 340 MHz. Fig. 3 shows a comparison of normalized SAR between the female (NAOMI) and male (NORMAN) voxel phantom in a birdcage resonator. Fig. 4 illustrates spatial normalized axial magnetic and azimuthal electric fields in the symmetric gradient coil system and radiation shields for a single gradient pulse of 10 T/m/s. The devised parallel routine on the cluster of processors was approximately 10 times faster than when a single processor was used.

Conclusion: An optimised and robust parallel FDTD scheme, which can be easily implemented using the MPI library, has been presented for MRI applications. Computational benefits of the proposed parallel FDTD structure has been demonstrated on two typical low and high frequency field problems. It has been shown that parallel computing can increase the computational efficiency and power. This is of considerable advantage to the advancement of MRI technology.

References:

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