COMPUTER ASSISTED MAGNETIC RESONANCE IMAGING (MRI) SIMULATION ON THE BASIS OF MR SYSTEM COMPONENTS

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Introduction:
Computer simulations for MRI tend to focus on different application areas. Traditionally, design of MR system components, such as the main magnet, gradients and RF coils is done using the finite-difference time-domain (FDTD) [1] and finite element (FEM) [2] methods. In doing so, certain generic specifications are followed in the belief that this will minimize imaging artifacts, when the system is put together and pulse sequences are run. Likewise, pulse sequence developers have simulated spin responses with Bloch equation solvers to predict the outcome of the imaging process, usually assuming idealized gradients and RF [3-7]. Here, we propose to combine both approaches, where system design files are used to calculate the electromagnetic fields using commercial FEM simulation software. This field information provides the input for the Bloch solver and thus allows the prediction of image quality based on different combinations of MR applications and system components. Such approach comes at the cost of enormous computation times. Here we present the basic concept of the simulator together with methods to speed up the field simulation using model symmetry and adaptive time sampling and the Bloch solver due to parallelization on a graphics-processing unit (GPU). Proof of principle and preliminary results are demonstrated for a simplified setup using a cylindrical magnet and gradient Helmholtz and saddle coil pairs.

Materials and Methods: The presented simulator is composed of four major categories (Fig.1): pulse sequence design, transient field simulation for solving the Maxwell equations and including relevant MR system components, the Bloch solver for simulating the spin responses and finally signal generation together with image reconstruction. Already existent MR product pulse sequences are flexibly accessed without additional implementation changes by dumping the waveform memory and application parameters to file. This way, the exact timing and amplitude values as well as gradient and RF waveform shapes are obtained. The waveforms are used as current input function that drives the transient field simulation: temporally varying for gradients, remaining constant for the magnet. The FEM simulation is performed using Maxwell3D (Version 12.0.1, Ansoft Corporation, LLC, 2008), which is particularly used for designing and analyzing electromechanical structures [8]. Within Maxwell3D, the net magnetic field $B_{net}(r,t)$ is position (r) and time (t) dependent and adds the time varying gradient field $B_{x,y,z}(r,t)$ to the static main magnetic field B_0. In this setup, a uniform RF field B_1 is considered. Computational performance of meshing the design is dependent on model size and complexity. Reducing both through setting symmetry boundary conditions scales down the number of mesh tetrahedrons and hence speed up total solving times. In addition, reducing the total number of transient iterations through adaptive time sampling increases solving performance. In general, intervals with no or constant gradient activities are less densely sampled. The resulting field maps together with the RF pulse is the input for the Bloch solver, where other application parameters such as T_1, T_2, chemical shift or off-resonance effects can be additionally set. To speed up solving the Bloch equations, the solver is realized on a graphics-processing unit (GPU), where the GPU is considered as computational device for computational intensive and highly parallel computations. Here, each spin is processed by an individual task on the GPU resulting in increased solving performance. The output signal is reconstructed using the fast Fourier transform (FFT).

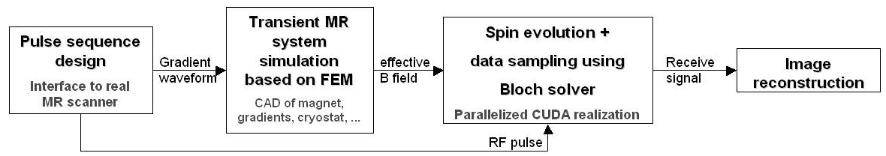

Fig1: Schematic overview of the simulation tool containing pulse sequence design, magnetic field simulation based on CAD files, Bloch solver and image reconstruction.

Results: The general workflow of the simulation tool together with the interfaces to Maxwell3D and the GPU Bloch solver is controlled via a graphical user interface implemented using Matlab (The Mathworks Inc.,Cambridge, MA, Version R2007b). The shown results are demonstrated using a gradient echo (GE) sequence (resolution=64x64, field of view=20cm, receiver bandwidth=15.625kHz, flip angle=90°, max. gradient strength=0.04T/m and TR=15ms). For proof of principle, a simplified MR system setup has been modeled including a cylinder as magnet, Helmholtz and saddle coil pairs as z, x and y gradients respectively. Wire windings, material properties and coil geometry and arrangement were adapted to set static field strength to 3T and maximum gradient field strengths to 0.04T. The design is split into one-eighth part (Fig.2) to fully utilize the symmetry boundary conditions. This reduced adaptive meshing times from 15min to about 1.3min, and solving times from 1min to 8sec. Originally, the GE sequence is sampled every 4us resulting in 3600 sampling steps and 8h solving times. Here, adaptive time sampling (Fig.3) reduced the number of time step iterations to 518 and resulted in a total solving time of 1h9min. The GPU Bloch solver itself is implemented on a GeForce 8800 GT (Nvidia, Santa Clara, CA) graphics card with 512MB of memory on a PC with 8 GB of memory and a 3.20 GHz processor running Windows XP x64 edition. The GPU code was written in C and compiled using CUDA [9]. For one phase encoding step, the parallel approach resulted in solving times of 1.63s, which is 6 times faster than our conventional reference solver. Six field of view corner points of the Maxwell3D simulated field maps were linearly spaced to generate the time and position dependent field map. The simulated signal overlaps with the reference signal with an accuracy of 10^{-8} (Figures4&5).

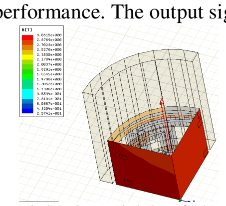

Fig2: One eighth of the simulation setup with B_0=3T in XZ and YZ plane respectively.

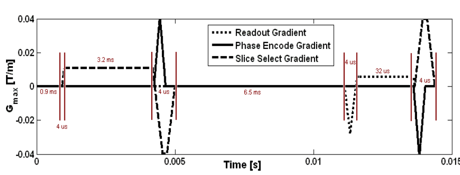

Fig3: The simulated GE sequence including: slice select, readout and phase encoding gradient. The adaptive time sampling intervals and their varying time step sizes are shown.

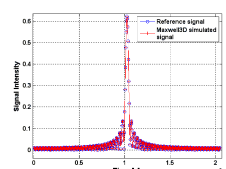

Fig4: Simulated signal of one phase encoding step: Reference vs. Maxwell3D signal.

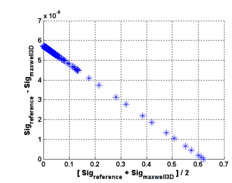

Fig5: Mean value compared to difference of Maxwell3D and reference signal.

Discussion and Conclusion: The developed simulator offers a simple and flexible tool to involve design files of different MR system components within full MR application simulations. The interface to real MR applications allows interchangeably evaluating different pulse sequences together with varying MR system designs. Hence, this simulator provides a basis to evaluate hardware related artifact sources and their impact on image quality. Using symmetry boundary conditions and adaptive time sampling schemes within the FEM field simulation together with a parallelized implementation of the Bloch solver significantly speed up the performance of the simulator. Mesh resolution mainly influences accuracy of the simulation results, but also simulation time. Regions of interest, e.g. close to cryostat or shielding, require high-resolution meshes with high numbers of mesh tetrahedrons. A parallelization of the mesh is not possible yet. Having a parallelized or distributed setup for the solving itself might speed up the simulation tool. The future goal is to analyze causes and effects of Eddy currents. Within Maxwell3D, Eddy current effects can be examined for each model component independently. Hence, the resulting fields B_{EC} will be additionally considered within B_{net}. The current work in progress contains simplification and meshing of real gradient coils, where field simulations are verified using experimentally measured field maps.

References:
[1] Trakic et. al, MRM 57, p.1119, 2007, [2] Shi et. al, IEEE Tran. Med. Im. 34, p.671, 1998, [3] Bittoun et. al, MRI 2, p.113, 1984, [4] Summers et. al, MRM 3, p. 363, 1986, [5] Brenner et. al., ISMRM 1997, #2052, [6] Yoder et. al, MRI 22, p. 315, 2004, [7] Benoit-Cattin et. al., JMR 173, p. 97, 2005, [8] http://www.ansoft.com/products/em/maxwell, Oct. 2008, [9] http://www.nvidia.com/object/cuda_home.html#, Oct. 2008