An MRI Simulator for Effects of Realistic Field Distributions and Pulse Sequences, Including SAR and Noise Correlation for Array Coils

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Introduction: With the recent rapid increase in development of transmit and receive arrays, an MRI simulator that could consider the effects of all the pertinent electromagnetic fields could allow for robust hardware and sequence evaluation before the expensive and time-intensive implementation stage. While a variety of MRI simulators have been developed for a wide range of purposes [1-8], and an increasing number are available for public use [6-8], until now none have provided consideration of the RF electric fields for both noise correlation (in reception) and SAR (in transmission).

Methods: A versatile and robust simulation engine to solve the Bloch Equations with a finite difference approach through space and time was programmed in C++ using a previously-published method [1] to minimize the number of isochromats required. The engine can read files containing information pertaining to the sample geometry and MR properties, transmit RF magnetic (complex B_1^+) and receive RF magnetic (complex B_1^-) field distributions and associated complex electric (E_1) fields from any number of coils in transmission and reception, B_0 field distribution, gradient field distributions, and arbitrary pulse sequence. These files can be user-defined, selected from a library, or (in the case of sequence files for some common sequences) created by a separate Matlab-based "setup" GUI. The engine then calculates the resulting orientation and size of the magnetization vectors throughout space and time, and records the 1) signal intensity and 2) noise (considering noise correlation with electric field distributions of receive coils [2]) induced in each receive coil at each data acquisition time, as well as 3) the corresponding location in k-space (a trajectory map) to three separate files. The simulator is also able to calculate average specific absorption rate (SAR) and un-averaged SAR distribution for the given pulse sequence, even considering multiple transmit coils with different waveforms. The simulator engine is constructed with parallel computation capability that can be utilized on a multi-core desktop computer. Matlab-based GUIs that can examine files, aid in development of some simple sequences, launch the simulation engine, and reconstruct and display the final images for simple reconstruction methods serve as an intuitive interface to the simulation engine. All input and output files have easily-understood structures so that user-defined sequences and reconstruction algorithms can be implemented with minimal effort. Along with the software package, an expandable library of human phantoms and field distributions (currently containing tissue geometry distribution and realistic field distributions for both head and whole body models in volume coils and arrays at 3T and 7T) is provided.

Results: Here a variety of outputs of the simulator are shown for demonstration of basic capabilities. Figure 1 shows k-space and reconstructed images with different contrast due to TE and TR settings. Figure 2 shows simulated EPI images with and without consideration of realistic B_0 distribution at 3T. Figure 3 shows the arrangement of a transceive array around a head model. Figure 4 shows SAR distribution of the array during a specific pulse sequence. Figure 5 shows SENSE-reconstructed images illustrating effect of increasing acceleration factor on noise distribution and artifacts. Figure 6 shows dramatic improvement in excitation homogeneity by using a slice-selective array-optimized composite pulse [9] rather than a conventional pulse with quadrature-type drive at 7T.

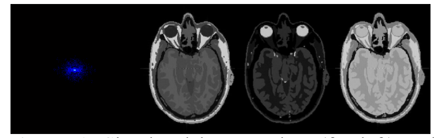

Figure 1. Simulated k-space data (far left) and reconstructed images from sequences with T_1, T_2, and proton density weighting through a high-resolution head model.

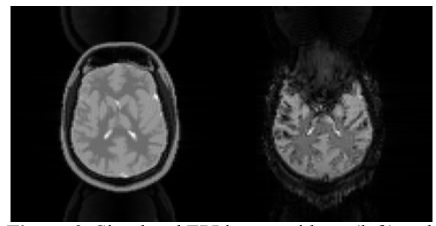

Figure 2. Simulated EPI image without (left) and with (right) consideration of B_0 inhomogeneity.

Figure 3. Geometry of 8 element transceive head array (MR Instruments Inc, MN, U.S.A.) and head model.

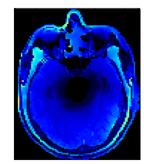

Figure 4. SAR distribution on axial plane for transmit array in figure 3 as calculated by simulator for a specific pulse sequence.

Discussion: With the rapid proliferation of transmit and receive arrays and the significant challenges associated with design of arrays and pulses to minimize noise correlation and SAR, a growing number of research groups are using electromagnetic field simulations to determine field distributions of coils and SAR distributions for array-specific pulses. While many groups also have their own tools for pulse design and SAR evaluation, often the pulse design tools are limited to low flip angle approximations and the SAR analysis is limited to worst-case approximation. Here we present a simulator designed for ease of use in implementing and evaluating such sequences and field distributions. Results shown here introduce the simulator and demonstrate some basic functionality related to transmit and receive RF arrays. Consideration of accurate B_0 and gradient field distributions is also included. It is important to note that this simulator is not limited by low flip angle approximations, and in principle can simulate a system at any field strength and with any number of coils with only a desktop computer. Future plans of this project include simulating temperature increase due to SAR and resulting frequency shift in the MR signal. The target release date of the software is May 1st 2010. It will be freely available through http://cnmrr.hmc.psu.edu.

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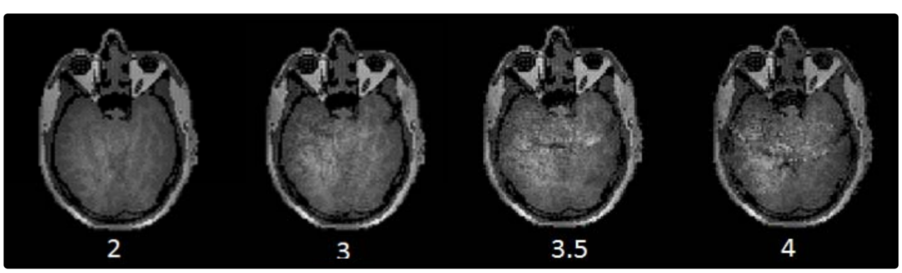

Figure 5. Demonstration of images generated with SENSE reconstruction at different reduction factors (numbers below images) using receive array shown in figure 3 with consideration of noise correlation.

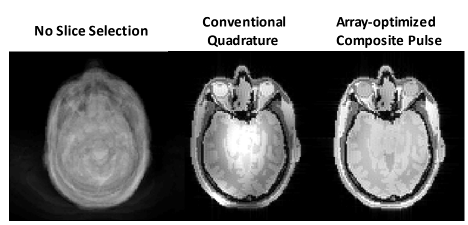

Figure 6. Results of a GRE sequence with slice-selective array-optimized composite excitation pulse (right) compared to results with the slice-select gradient turned off (left) and with a conventional excitation pulse (center) in a volume coil at 7T.