MARIE: A MATLAB-Based Open Source MRI Electromagnetic Analysis Software

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Our Magnetic Resonance Integral Equation suite (MARIE) is a numerical software platform for comprehensive frequency-domain fast electromagnetic (EM) analysis of MRI systems. The tool is based on a combination of surface and volume integral equation formulations. It exploits the characteristics of the different parts of an MRI system (coil array, shield, and realistic body model), and it applies sophisticated numerical methods to rapidly perform all the required EM simulations to characterize the MRI design: computing the un-tuned coil port parameters, obtaining the current distribution for the tuned coils, and obtaining the corresponding electromagnetic field distribution in the inhomogeneous body for each transmit channel.

The underlying engine of MARIE is based on integral equation methods applied to the different domains that exist in traditional MRI problems (for example, except in interventional cases, the coil and body occupy separate spaces). The natural domain decomposition of the problem allows us to apply and exploit the best modeling engine to each domain. The inhomogeneous human body model is discretized into voxels and modeled by volume integral equation (VIE) methods. The homogeneous conductors that form the coil design and shield are tessellated into surface triangles (that allow the modeling of complex and conformal geometries), and modeled by surface integral equation (SIE) methods. Both models are coupled by applying standard dyadic Green functions. Due to the nature of integral equation methods, there is no need to model or discretize the surrounding air or non-electromagnetic materials, although the solution fields can be computed anywhere outside the discretized domain by applying the same free-space Green functions. Also, no boundary condition needs to be defined (integral equations satisfy the radiation condition by construction), which simplifies the setting of the problem for the user: the inputs are the voxelized definition of the inhomogeneous body model, the tessellated geometry of the coil design (which the external ports defined), and the frequency of operation.

Once the models are generated, fast numerical methods are applied to solve the complete system. A set of nested iterative methods with the appropriate preconditioning is used to solve the effect of each port. Fast Fourier transform (FFT) techniques exploit the regularity of the voxelized grid and accelerate the matrix vector products. Depending on the different scenarios for analysis, some numerical models or tasks can be pre-computed to accelerate the solution, and many strategies are used to reduce either computational time or memory consumption.

The software runs on MATLAB and is able to solve a complex scattering problem in ~2-3 min. on a standard single GPU-accelerated windows desktop machine. On the same platform, it can perform a frequency sweep of a complex coil in ~3-5 min. per frequency point. Furthermore, it can solve the complete inhomogeneous body and coil system in ~5-10 min. per port, depending on the model resolution and error tolerance required. Intended to be a development platform, it includes a simple and intuitive graphic user interface (see Figure 1 for a snapshot) for standard analysis and a set of well-documented scripts to illustrate how to use the core numerical functions to perform more advanced analyses, to allow experienced users to create their own analysis by using or modifying the existing code. The input of the body is voxel-based and can be read from simple files that define position and tissue properties. The input of the coil design is based on standard triangular geometric descriptions, widely popular and with multiple open-source mesh generators available. The underlying numerical routines can be used to generate standard results, such as the B1+, B1-, and E maps presented in Figure 2, or to address other relevant problems, such as the generation of ultimate intrinsic SNR and SAR on realistic body models, fast coil design and optimization, and generation of patient-specific protocols, among others.

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FURTHER READING


Figure 1: Snapshot of MARIE’s graphic user interface with body and coil models loaded, for which the simulation results are shown in Figure 2.

Figure 2: Comparison of the (left) B1+, (center) B1−, and (right) RMS(E) maps for a body model. Top maps are with SEM-CAD (SPEAG), bottom with MARIE.