Ultra-fast electromagnetic field computation for RF shimming, parallel transmission and coil design

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Introduction

High field MR imaging suffers from non-uniformity and signal voids both in the RF transmit and receive fields and from the increased SAR deposition in the patient. The use of phase amplitude controlled coils enables the use of RF shimming or parallel transmission to alter the electromagnetic field distribution in the patient to improve the image quality and/or to reduce the SAR. Both methods require information about the electromagnetic field in the patient, but measuring the magnetic field is time-consuming and needs to be done for all coil elements individually. Even more problematic is the electric field which is not measurable inside a patient.

As an alternative to measuring the magnetic field, finite difference time domain (FDTD) calculations have become the standard. However, these calculations take a lot of time which makes them unsuitable for on-line MRI optimization. We present a Bessel Boundary Matching (BBM) method that is capable of calculating the electric and magnetic field inside a multi-layered patient anatomy in one or two minutes, thereby increasing the feasibility of both RF shimming and parallel transmission drastically.

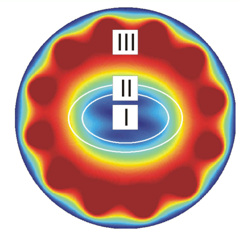

figure 1, quadrature E_Z field and setup for the BBM method.

Methods

The BBM method we present solves the Maxwell equations in two dimensions, which limits its use to regions where the field is essentially two-dimensional such as in the pelvic region, where both the electric and magnetic field vary slowly in the longitudinal direction. Such a two-dimensional field can be completely described in terms of the vector potential (A) by the 2D Helmholtz equation, which can be solved for each homogeneous region in- and outside the patient (figure 1). The general solution for each region is a summation of Bessel functions and has the general form shown below.

$$A_z(r,\theta) = F(r,\theta) + \sum_{l=1}^{N} C_l \left[\sum_{m=-M}^{M} a_m^l J_m(r) e^{im\theta} + \sum_{n=-M}^{M} b_n^l Y_n() e^{in\theta} \right]$$

F is a fundamental solution which takes the contribution of the antennas into account and is only non-zero in the region where the antennas are located. N is the number of antennas and M is the number of first (J) and second (Y) order Bessel functions that are included. C is the complex amplitude for the antennas and a and b are the Bessel coefficients. ξ is the complex permittivity.

The coefficients a and b of the Bessel functions are region dependent and are obtained by matching the solutions for the different regions at their interfaces with suitable boundary conditions. Matching is done with a least-square fit method (MATLAB), which allows the use of arbitrary boundary shapes. From the obtained solution for the vector potential we can compute the electric and magnetic field through respectively the time derivative and the curl.

The number of homogeneous regions and their shape can be arbitrarily chosen. The patient can for instance be divided in an inner layer with averaged muscle-organ properties and an outer layer of fat. The shape of the contours can be chosen to follow the real patient outline, which is illustrated in figures 3 and 5.

We validate the presented method by comparing the results with standard three-dimensional FDTD calculations.

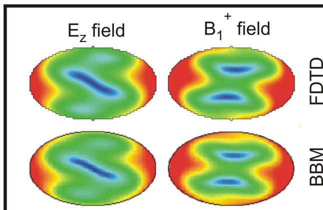

figure 2, Quadrature excitation in an ellipse calculated with FDTD and BBM method.

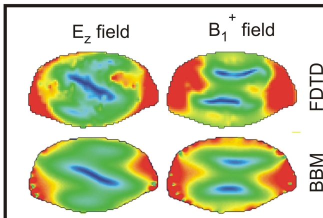

figure 3, Quadrature excitation in a patient model calculated with FDTD and BBM method.

Results

The presented BBM method is capable of calculating the electric and magnetic field and performing RF shimming in roughly 2 minutes for a coil of 12 antenna elements and 4 minutes for a coil of 32 elements. The method can be made even faster by using a low-level programming language instead of MATLAB. Preliminary results for two models are shown in figures 2, 3, 4 and 5 and are compared with standard three-dimensional FDTD results. The results show a very large correspondence for a quadrature excitation both for an ellipse (figure 2) and for a real anatomy (figure 3).

At the moment we have only considered the magnetic field for RF shimming, but the electric field can be included easily to reduce the average and peak SAR. The shimming results are presented in figures 4 and 5 for an ellipse and an anatomy respectively. We tested the validity of the optimal phase-amplitude settings that were found with the BBM method by applying these settings to the fields from the FDTD calculations. These results are also shown in figures 4 and 5.

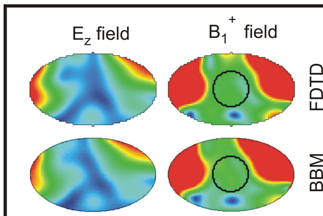

figure 4, Shim results in an ellipse with FDTD and BBM method.

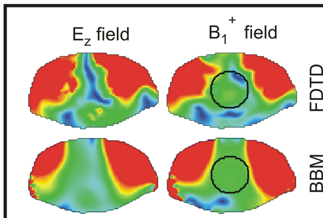

figure 5, Shim results in a patient with FDTD and BBM method.

Discussion and Conclusions

The presented method uses a description of the patient in different homogeneous regions rather than the detailed patient anatomy. This makes the BBM method very suitable for on-line RF shimming, since the body can be automatically segmented in an inner region predominantly consisting of average muscle and organ properties and an outer region consisting of fat. Figure 5 shows that the absence of a detailed anatomy does not alter the fields much and that the phase amplitude settings resulting from RF shimming in a model without detailed structure can also be applied to a model which does have such a detailed structure. The global field behaviour dominates over local field behaviour especially at higher field strengths due to effects such as the small penetration depth. This makes the inclusion of a detailed anatomy structure redundant for RF shimming of the B_1^+ field. The capability to calculate not only the magnetic field, but also the electric field in less than a minute opens up new possibilities to control the SAR both for on-line RF shimming and for parallel transmission.

Different coil properties such as the number of antenna elements and their distance to the RF shield can be optimized rapidly and their effect monitored for different patient sizes. This makes the BBM method very versatile and fast for the development of both surface and body coils.