Dielectric shimming in MRI

Addressing RF interference problems

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Strong magnetic background fields are of great interest in Magnetic Resonance Imaging (MRI), since images with high spatial resolution can be obtained at reduced scanning times. Strong background fields may cause RF interference effects, however, and these effects can severely degrade the quality of an MR image. This problem can be partly resolved using various advanced and mostly expensive techniques, but there is also a cheap and practical solution, namely, dielectric pads. The main goal of our project is to develop a tool that allows us to efficiently design effective dielectric pads for High Field MRI.

For about 2 years we have been working on a project in Magnetic Resonance Imaging or MRI. This project is in joint collaboration with the C.J. Gorter Center for High-Field MRI at the Leiden University Medical Center and addresses interference effects that may be encountered in High-Field MRI. Such interference effects severely degrade the quality of an MR scan, but fortunately can be avoided through the use of dielectric pads. Specifically, by placing high-permittivity pads in a neighborhood of a body part that needs to be imaged, interference effects may disappear and high-quality MR images are obtained. Dielectric pads are a practical and cheap solution and work really well provided these pads are properly designed. In this article, we discuss the approach that we have developed in our project to systematically design effective dielectric pads in MRI.

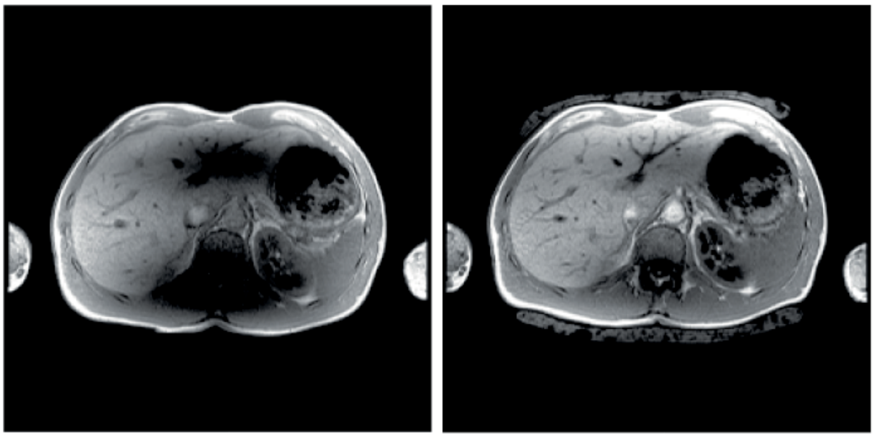


Figure 1: *Left: MR image of a slice through the abdomen obtained without any dielectric pads. Signal voids in the anterior and posterior of the abdomen are clearly visible. Right: MR image of the same slice through the abdomen, but this time obtained with dielectric pads. The signal voids have disappeared due to the presence of high-permittivity pads.*

Introduction

Magnetic Resonance Imaging is a well-known technique that is used to create detailed images of the anatomy of the body. The first MR scanner dates from the early 70's and although significant improvements have been achieved, the fundamentals remain the same. Below, we briefly discuss these fundamentals.

Basically, the key component of the scanner is the main magnet. This superconducting solenoid produces a static uniform magnetic field on the order of 1.5 - 7T, which is up to 200,000 times the Earth's magnetic field. When a person is positioned in the bore it causes the hydrogen nuclei in our body (protons) to spin around this static magnetic field, which is known as precession. The angular frequency of this precession is referred to as the Larmor frequency and it is linearly related to the static magnetic background field. For typical field strengths of 1.5T, 3T, and 7T the corresponding Larmor frequencies are 64 MHz, 128MHz, and 298 MHz, respectively.

By transmitting a circular polarized magnetic field – the so-called B_1^+ field – with an RF coil operating at the Larmor frequency, we are able to exert some torque on the magnetic moments of the nuclei such that they absorb energy. This works since the circular polarized field rotates with the same angular velocity as the hydrogen nuclei, i.e. they are at resonance. When the RF field is switched off, the nuclei return to their equilibrium position, emitting energy while they do. This energy is emitted in the form of RF radiation and is picked up by a receiver coil. Finally, an image of the interior of the body is obtained by applying some basic Fourier transformation techniques on the received signal [1].

There is great interest in High-Field MRI, since it leads to an increased Signal-to-Noise Ratio (SNR) and consequently a higher spatial resolution or shorter scanning times or both. There are some downsides too, however, one of which is that the Larmor frequency increases as well and therefore the RF wavelength decreases. For 3T (128 MHz) the wavelength in free space is about 2.3 meter, and inside the body it decreases to about 0.25 meter. Since the wavelength now becomes comparable with the dimensions of the body, we have to deal with destructive (and constructive) interference effects. The destructive interference effects cause signal voids inside the body, since the B_1^+ field distribution is simply too weak at these particular locations. As a result the MR image contains dark spots and the anatomy is not visible anymore at some locations, see Figure 1 (left) for the scan and Figure 3 (right) for the corresponding simulated B_1^+ field. In the scan there are clearly some signal voids in the anterior and posterior of the abdomen. We would like to remove these voids from the image by having a homogeneous B_1^+ field throughout the complete Region of Interest (ROI). To this end, we tailor or shape the B_1^+ field through a process called shimming. There are basically two shimming techniques available, namely, active and passive shimming. Active shimming uses multiple transmit antennas or local transmit antennas to bring the source closer to the ROI. Most of the active shimming techniques require additional hardware and are often quite expensive. Passive shimming techniques, on the other hand, do not use active current driven coils and use dielectric materials instead. These materials induce a secondary magnetic field that allows us to reshape the total RF field inside the human body.

Dielectric pads

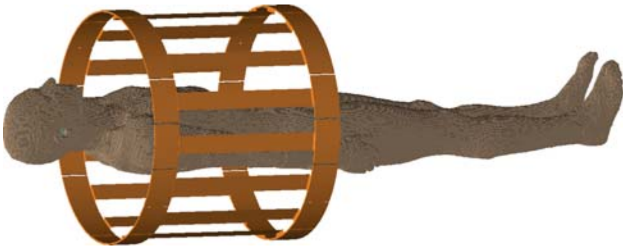
Our project focuses on the use of passive dielectric shimming using dielectric pads [2]. These pads (see Figure 2) have a high relative permittivity in the order of 80 - 300. Fabricating these pads is relatively cheap, and they can be used in existing MRI systems, i.e. no additional hardware

Figure 2: *High permittivity pad with a relative permittivity of 200 and dimensions 13x16x1 cm^3. The material of the pad is a mixture of calcium titanate, barium titanate, and deuterated water.*

is required. The dielectric pads affect the B_1^+ field in a ROI and may significantly improve the quality of an MR image. An example of the effect of a well-designed dielectric pad is shown in Figure 1 (right). Here, one pad is placed on the anterior and another on the posterior of the abdomen. The quality of the MR image is drastically improved, as the anatomy is visible

"Fabricating these pads is relatively cheap, and they can be used in existing MRI systems."

again. The design of the dielectrics is not trivial, however, and patient dependent as well. For example, scanning the inner ear of a male requires a dielectric pad different from a pad needed to scan the inner ear of a female. Furthermore, the d



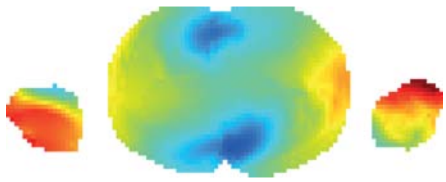


***Figure 3:** On the left side a typical simulation configuration, created with Remcom XFdtd software. The birdcage antenna around the human voxel model emits the RF field. The right figure depicts the B_1^+ field for a transverse slice around the liver. The signal voids (blue) are clearly visible in the anterior and posterior.*

volume of the subject and the ROI have a significant influence on the design as well, since wavelength effects are typically more severe for larger volumes.

Normally, standard commercial electromagnetic fields solvers are used to design effective dielectric pads. These solvers can easily be used to model common MR configurations, i.e. the RF coil combined with a virtual voxel model of the human body, as shown in Figure 3. Simulations are commonly carried out for a wide variety of dielectric pads with different parameters (i.e. location, geometry, and constitution). Such simulations are computationally intensive with very long associated simulation times. Designing a proper dielectric pad for a single ROI and for a single virtual voxel model often takes hours and sometimes even days to complete. This approach is obviously very cumbersome and the main objective of our project is to significantly speed up the design process.

Approach towards solution

The dielectric pad is in most cases small compared with the dimensions of the body and introduces a small perturbative term in Maxwell's equations. By exploiting this feature, we are able to speed up the process of evaluating dielectric pads. However, to find a pad that meets certain design criteria, many different pads still need to be evaluated. To formalize the search for an optimal pad, we therefore pose our design problem as an optimization problem and computation times can be reduced even further by incorporating reduced-order modeling techniques in the optimization procedure. This approach allows us to systematically design dielectric pads within a couple of minutes instead of hours or days. Our tool is presently used in several clinical applications to produce high quality MR images of the cerebellum and the inner ear. The combination of electromagnetics, modeling, optimization, and the collaboration with the C.J. Gorter Center for High-Field MRI makes it a really enjoyable and exciting project. c

[1] McRobbie, Donald W., et al. MRI from Picture to Proton. Cambridge University Press, 2007.

[2] De Heer, P., et al. "Increasing signal homogeneity and image quality in abdominal imaging at 3 T with very high permittivity materials." Magnetic resonance in medicine 68.4 (2012): 1317-1324.