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Electromagnetic Simulation Helps Design Next Generation of MRI Equipment

The Project: Gain a better understanding of how the RF transceiver interacts with the nuclei in MRI systems in order to be able to design the next generation.

The Solution: Use electromagnetic simulation software to demonstrate how these interactions occur.

By Dr. Christopher M. Collins

A new generation of high definition magnetic resonance imaging (MRI) machines is enabling researchers to gain a far more accurate understanding of the metabolic pathways of the human brain and how these pathways are affected by disease. This new generation is generally known as 7-Tesla, which refers to the strength of the static magnetic fields generated by the machines. These fields are used to cause the nuclei in the body to wobble, or precess, so that a radio frequency (RF) transceiver can detect their movement and generate images. This new generation of machines operates at a much higher frequency than conventional MRI, requiring a better understanding of how the RF transceiver interacts with the nuclei. Electromagnetic simulations were critical in demonstrating how these interactions occur, which has provided important insight in the design of the new generation of machines.

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How MRI Works

MRI is based on the fact that a moving electric charge produces a magnetic field. In MRI, a static magnetic field is used to align the spinning protons in hydrogen within the body. Most of the protons align with the field while a slightly smaller number align against the field so they are spinning in the opposite direction. Just as gravity causes a top to wobble, the magnetic field causes the protons to precess at a certain resonance frequency which depends on the strength of the static magnetic field. An RF pulse is applied at the resonance frequency. Its energy is absorbed by the protons which then move to a higher energy state. When the pulse ends, the proton retransmits the absorbed RF energy at the resonance frequency, producing the MRI signal.

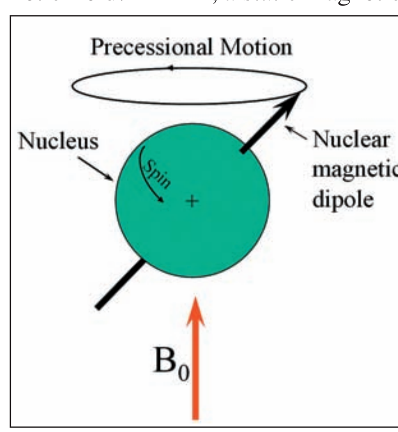

Figure 1: Nuclei precess when a static magnetic field B_0 is applied.

Due to the nature of this nuclear precession, it is the circularly polarized components of the RF fields that are important in communicating with the nuclei. Until fairly recently, there was disagreement about which circularly polarized field components were important in communicating with the nuclei. There was some evidence and theory indicating that the RF magnetic field component rotating in the same direction of nuclear precession was important during excitation and the component that rotated in the opposite direction of nuclear precession was important during signal reception. To many working in the field of MRI, this seemed counterintuitive. They were convinced that the component that rotated in the same direction as nuclear precession should be the active component during both excitation and reception.

Moving to the Next Generation

This discussion was of only theoretical interest during the first few generations of MRI equipment. But it became much more important as MRI moved to higher static magnetic fields in order to increase the signal-to-noise-ratio (SNR) and improve the resolution of the resulting images. The latest 7-Tesla MRI machines have a field strength which is 140,000 times stronger than the earth's magnetic field. This field is

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typically generated by a magnet that holds between 400 and 500 kilometers of superconducting wire. The earlier generation of MRI machines mainly detects variations in the concentration and physical characteristics of hydrogen in the body. High field magnets permit the detection of many more elements such as carbon and phosphorous, unlocking new potential for physiological discoveries. The more detailed images provided by these machines could lead to earlier diagnosis and treatment of a variety of diseases including multiple sclerosis and Alzheimer's disease.

The use of stronger magnetic fields increases the speed at which nuclei precess. This, in turn, increases the resonance frequencies, which produce wavelength effects that can result in clearly different distributions of the two circularly polarized components produced by even very simple RF coils. The question about whether only the field component that rotated with precession or both field components were involved in generating an MRI image suddenly became a significant issue in equipment design, particularly in the design of the RF coils. With my experience using XFdtd, electromagnetic simulation software created by Remcom Inc., and active collaborations with researchers who had access to an early 7-Tesla MRI system at the University of Minnesota, I was uniquely positioned to find the answer.

Simulation Goes Beyond Physical Experiments

It would have been difficult or impossible to determine the answer to the question using experimental techniques alone because a physical magnetic field cannot be separated into its individual components. However, I had been using electromagnetic simulation software in related research designed to ensure the safety of the new generation of 7-Tesla MRI machines. Electromagnetic simulation has the important advantage of allowing us to mathematically separate the components of a magnetic field and investigate the impact of the different components separately or in combination with each other.

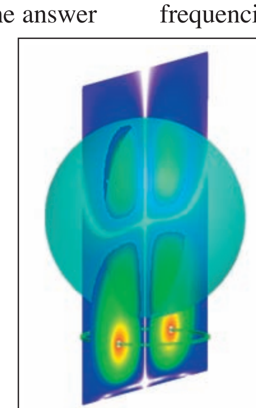

Figure 2: Model of a sphere and simple RF coil showing electrical fields through the center of the problem region.

As an example of our work in MRI safety, Michael Smith of Pennsylvania State University and I used electromagnetic simulation to calculate the RF magnetic field (B_1), specific absorption rate (SAR), and SNR as a function of frequency between 64 and 345 MHz for a surface coil against an anatomically accurate human chest. SAR measures tissue exposure to RF fields and is a standard in evaluating MRI safety. The calculated B_1 field distributions were in good agreement with previously published experimental results up to 175 MHz, especially considering the dependence of field behavior on subject anatomy. Calculated SNR in the heart agreed well with simple theory for low frequencies. Above 175 MHz, however, the trend in SNR with frequency began to depend largely on location in the heart. At frequencies above 175 MHz, limits on SAR also began to be an issue in some common imaging sequences.

I use Remcom's XFdtd electromagnetic simulation software for my MRI safety studies because it has demonstrated the ability to provide outstanding accuracy in simulation of MRI. XFdtd is used by all three of the leading producers of MRI equipment and its results are considered to be sort of a standard in this type of simulation. XFdtd is based on the finite difference time domain (FDTD) method. According to the Federal Communications Commission of the United States, "Currently, the finite difference time domain (FDTD) algorithm is the most widely accepted computational method for SAR modeling."[1]

Case in Point

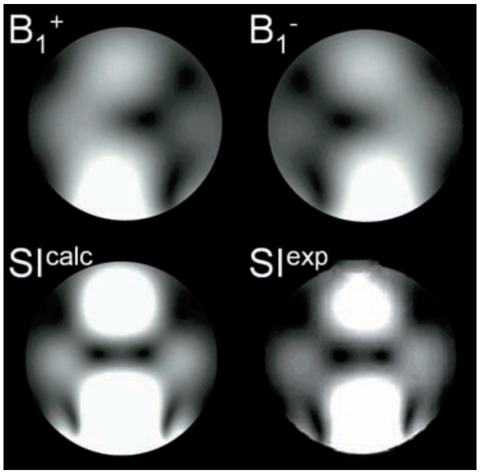

Figure 3: Images generated by simulation and physical experiments.

Answering the Question

My colleagues at Penn State and I used XFdtd to create a simple model that mimics MRI of a human head. The model includes a 16 cm diameter sphere filled with saline solution to represent the head. Below the sphere is a single 10 cm diameter circular loop of wire tuned to resonance at 300 MHz, the frequency used by the new generation of 7-Tesla MRI machines. The RF coil is used to excite the nuclei and receive signals from them. In the simulation, I excited the loop as if to transmit to the hydrogen nuclei in the water. I used XFdtd to separate the resulting RF fields in the sphere into the part that was circularly polarized in the same direction as the nuclear precession (B_1^+) as well as the part that was circularly polarized in the opposite direction (B_1^-). I used these two components of the field to simulate an MRI image. Meanwhile, my collaborators at the University of Minnesota also performed a physical experiment that matched the simulation conditions.

▶ Simulation often enables researchers to investigate applications and effects that cannot be measured experimentally.

At 300 MHz, there are significant wavelength effects in the spherical sample, resulting in unusual RF field patterns. The results for the RF field components rotating with and opposite nuclear precession are shown respectively in the images marked B_1^+ and B_1^- in Figure 3. I compared these distributions to the experimental image, marked SI^{exp} shown in the lower right hand corner of Figure 3. Upon simulating the same situation with XFdtd, we found that neither the circularly polarized magnetic field component rotating with nuclear precession (B_1^+) nor that rotating opposite nuclear precession (B_1^-) could be used alone to predict this experimentally acquired image. However, when the distributions of both components were combined in the appropriate way, the resulting simulated image 'SI^{calc}' matched the experimental one very well.

The match between SI^{calc} and SI^{exp} indicates that both components are involved in producing the MR image. Since the time we performed this demonstration, the need for considering the component that rotates opposite nuclear precession has become well accepted and is now an integral part of the prediction of MRI signal for hardware and pulse sequence engineering. This application clearly indicates the value of electromagnetic simulation in designing future generations of MRI equipment. Simulation often enables researchers to investigate applications and effects that cannot be measured experimentally. The result provides insights and understanding that help to improve the design of medical equipment.

Reference

[1] OET Bulletin 65. "Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields." Supplement C.

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