Volume and Surface Coils

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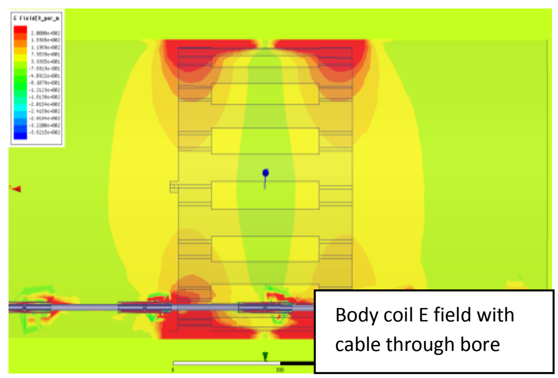
Highlights:

- Transmit volume RF coils are designed to create a uniform circularly polarized B1+ field inside the imaging volume
- E fields in the transmit coils need to be minimized where possible to conform to SAR standards
- Receive surface RF coils are designed for maximum SNR, and reside inside the Transmit coil
- Decoupling circuits are needed in both designs to prevent coupling of RF energy between the transmit and receive coils
- Baluns are needed in both designs to minimize cable shield currents which would otherwise be induced by the tangential E fields generated by the Transmit coil

Target Audience: Anyone who wants to improve understanding of RF coils in MRI systems

Objective: Understand the critical design criteria for different types of coils and how to achieve them

Good reference books: I recommend the following references: (1) and (2) to learn about electro-magnetic fields and how they interact with matter, (3) to learn about the behavior of electronic circuits and transmission lines at RF frequencies.



Body coil E field with cable through bore

Volume Transmit coils

The purpose of a transmit RF coil is to efficiently generate a uniform circularly polarized RF magnetic field throughout the imaging volume. This field is required to flip the magnetization vector by a uniform angle. If possible we would like the RF field to drop rapidly outside the imaging volume to prevent artifacts from non linear areas of the gradient fields that are superimposed on the DC magnetic field which also become non uniform outside the imaging volume.

In practice, most MRI systems have a birdcage resonator invented by Hayes et al. (4). We will go over its design and frequency response. Since this coil has cylindrical symmetry it is easy to generate the circularly polarized fields required for best uniformity and best efficiency (5). Typical B1 fields needed for excitation are on the order of 20 µT. The flip angle is proportional to the integral of the RF pulse. Bandwidth requirements limit the pulse width to a few ms. The peak RF currents in the body transmit coil are about 65 Amps, peak voltages 2 KV, and power needed for a 200 LBS patient around 30 KW at 128 MHz. You will learn how to design the coil to cope with these levels and how to make sure that legally required SAR limits are not exceeded. The SAR is a direct consequence of the E fields generated by the transmit coil inside the patient. The E fields partially depend on coil type and placement of capacitors. Those same E fields will also induce standing waves on cables that run in and out of the body coil, in particular the drive cables for the body coil if they are not part of the RF shield. Where the cables pass through an area of high E field e.g. the area between the endring and the shield, voltages and currents can be induced that hurt the performance of the body coil.

At frequencies where the wavelength in the patient becomes similar or shorter than the size of the patient, interference effects result in non-uniform excitation. You will learn how to visualize these effects and how to compensate for it using transmit coil arrays that provide more degrees of freedom to manipulate the field uniformity. This comes at the expense of efficiency and sometimes SAR.

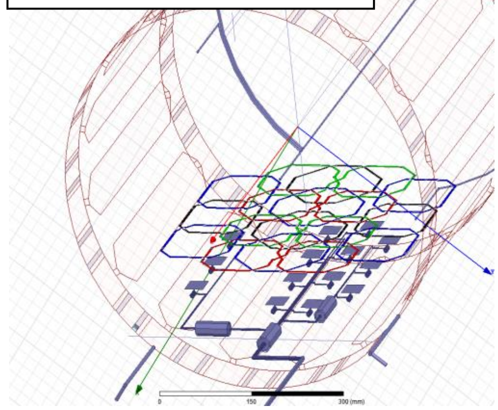
The RF shield

The RF body coil is surrounded by an RF shield that separates the RF space from the gradient coil space. The gradient coil is very lossy at the RF frequencies and has a plurality of modes that can interfere with the proper operation of the RF coil. Ideally the RF shield has low impedance at the RF frequencies such that the body coil Q is maintained, but it should have high impedance at 1-10 KHz, since this is the frequency associated with the gradient switching time. The high impedance will prevent gradient eddy currents in the shield (heat). We can achieve both by designing the shield with slits that do not interfere with the RF current pattern yet impose an impedance on the gradient eddy currents.

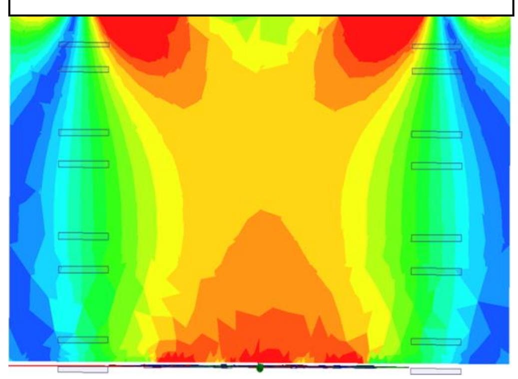
Surface receive coils

Unlike the transmit coils, the main goal of the receive coil is not B1 uniformity, although it may be important for some (Head coil e.g.), but it is maximizing SNR. You will learn how to minimize the coil losses, such that the main noise contribution in the image is from the losses in the patient's tissue. Today most receive coils have integrated preamps. These preamps have a low Noise figure of less than 0.3 dB, and an amplification of >26 dB such that the Noise figure of this preamp dominates the entire receive chain. The preamp also plays an important role in decoupling of different coil elements in the Receive array (6). In case the preamp input impedance is very low, it can be placed in series with a tank circuit to effectively decouple the array elements or when the preamp input impedance is high, it can be placed directly in series with the array elements.

FEM model of Body coil plus Rx array



B1+ of body coil with Rx array, in sagittal plane



During the transmit pulse the Receive coils and cables are exposed to the B and E fields generated by the Body transmit coil. The coil elements are decoupled from the Body coil fields by tank circuits and switches, in most cases PIN diode switches, that switch the Rx array elements off during the transmit pulse.

There are many cables connecting the receive array to the system's receive chain. Since the cables traverse the body coil's E field, voltages and currents will be induced on the cable shields. They will depend on the cable routing with respect to the body coil frame of reference, the cable length, cable shield ground points, and the body coil's E field magnitude and direction. These induced cable currents can interfere with Rx coil array performance, but more importantly they can cause patient warming if the cable gets close to the patient. The standard way of attenuating these currents is the Balun, a narrow band tank circuit that is connected to the cable shield in multiple places.

Interactions

- As may already be clear from the discussion of E fields, the RF coils interact with any metallic object residing in its E field, especially if that object has a length close to half a wavelength or a multiple thereof. We can think of ECG leads, EEG leads, Pacemaker leads, Neuro stimulator leads, system and coil cables.
- Interactions between body coil and Rx array, even if every element in the array is decoupled. The decoupling circuits in an array element turn the element into a number of open ended conductors in which the E fields may induce currents. Parasitic reactance between decoupled coil elements may provide alternate pathways for the RF current to flow, distorting the transmit field uniformity.
- The body coil interacts with the patient. If the design is very sensitive for perturbation the body coil symmetry may be affected since patients typically do not have cylindrical symmetry

Discussion

I have summarized the many aspects of transmit and receive coil design. I do not have the space to go into detail on every aspect in this syllabus, but I will attempt to do so in my lecture, which will be recorded. I encourage everyone to ask me questions during my lecture, or at the email address provided.

References

(1) B Bleaney and B I Bleaney, Electricity and Magnetism, Clarendon press
(2) J D Jackson, Classical Electrodynamics, Wiley
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(6) P B Roemer et al, the NMR phased array, MRM 16, 1990, p192