Construction and Validation of a Probe for Electric Field Measurements in Gradient Coils

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Introduction: During magnetic resonance imaging, gradient coils produce a linearly varying magnetic field that is switched in magnitude and direction many times per second. This changing magnetic field produces an electric field, and the electric fields experienced in the bore of the magnet can be an important safety consideration. Simulations of the electric field have focused on the induced vector potential, because it is a simple analytic calculation, and more recently on more sophisticated scalar potential calculations [1-3]. However it can be difficult to directly determine the actual electric field experienced, because electric field measurements can be hard to do, especially in air.

Theory: Electric field may be thought of a being composed of the contributions of two types of potential, the vector potential and the scalar potential. These combine to produce a net electric field. The vector potential, and in the case of gradient coil induced electric fields, is the contribution of the changing magnetic field to the total. The second term, is the potential due to a non-homogenous charge distribution. Charge accumulation can occur at the surface of a conducting object, such as a human body, inside the coil. Even in an empty coil charge accumulation in the current carrying wires can produce a large electric field [4].

However, in air, even a large electric field can be difficult to detect. For a cylindrical rod probe tip situated in a sinusoidally oscillating electric field the current induced along the conductor can be described by [5]:

$$i(t) = -8r\varepsilon_0\omega E\sin(\omega t)l$$

Where r is the radius of the conductor, ε_0 is the permittivity of free space, ω is the angular frequency of the applied electric field, E is the magnitude of the electric field, and l is the length of conductor exposed to the field. For a probe tip of 0.5 mm in diameter, and 2mm in length situated in a 10V electric field oscillating at 1 kHz, the current is in the order of hundreds of femtoamps – a magnitude of current that is a challenge to detect.

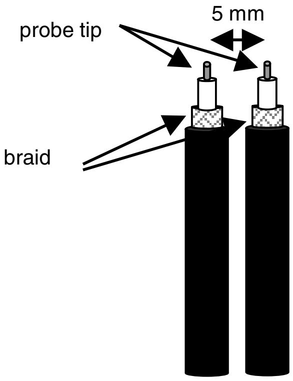

Figure 1: An illustration of the electric field detector made from 2 co-axial cables

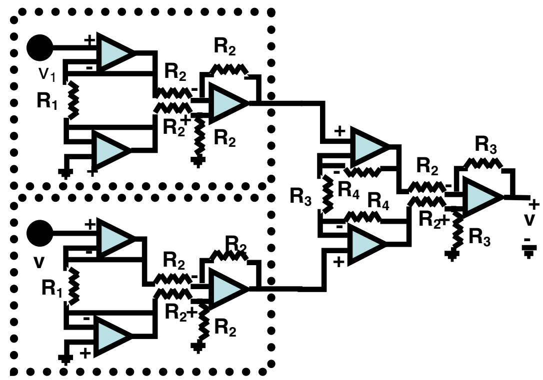

Figure 2: Circuit diagram for electric field detection. A = TL081 Operational Amplifier. R= 510 kΩ; R= 100 kΩ; R= 560 kΩ; R= 4 kΩ

Methods: An electric field probe was constructed using two pieces of co-axial cable. An illustration of this probe is shown in Figure 1. The silver centers of the coaxial cable were exposed to a 3mm length and the braid was grounded. The tips of the coaxial cables were separated by 5 mm and fixed in place. The ends of the cables were attached directly to an amplifier circuit, and the output of the instrument amplifier was sent to a computer for processing in LabView. The probe was designed to measure electric fields in both saline solutions and in air.

The probe was calibrated by placing it between two conducting plates, and inducing a sinusoidally oscillating electric field. The output of the probe was connected to a cascaded instrument amplifier, the exact circuit is illustrated in Figure 2. The frequency response of the probe-circuit combination was measured for frequencies ranging between 100 Hz and 100 KHz as well as the phase delay of the output. A plot of amplification vs .frequency is shown in Figure 3. The results of these calibration measurements were used to create a Labview application that accepted the output of the probe-circuit system and adjusted the amplitude and the phase of each frequency component to match the induced electric field.

The probe was used to measure the electric field in the X-Y plane over top of a head gradient coil. The probe-tip was positioned by hand, in both the X and Y orientations. 5 readings were taken for each location, and the surface of the coil was measured with a 2cm X 2cm sample spacing. A shield was constructed out of strips of aluminum foil in order to separate the scalar potential effects. Measurements on the same plane were taken with the shield placed between the gradient coil and the probe.

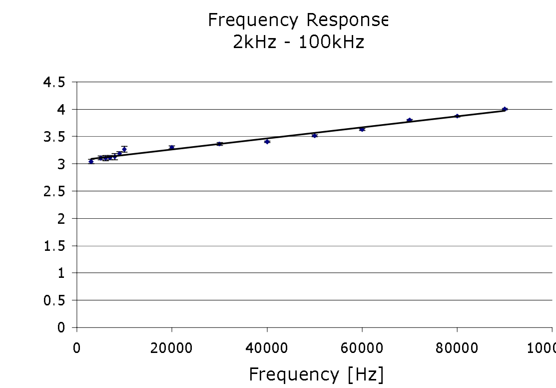

Figure 3: Amplitude of probe-circuit system as a function of signal frequency

Results and Discussion: Figure 4 shows a line of the electric field measurements taken at a 42 degree angle across the face of the gradient coil. The shielded electric field profile followed the simulation of vector potential for the gradient coil. However, the unshielded electric field – the field due to the scalar potential – was very large. These results have implications for any electric field dependant MR investigation – such as the investigation of peripheral nerve stimulation. Stimulation experiments conducted in the absence of an RF coil, or some shielding of the patient from the scalar potential that would otherwise be present during MRI operation may not produce accurate stimulation thresholds. It is critical for actual electric field measurements to be made in order to validate electric field simulations and we believe this work represents a the first attempts to do so in MRI gradient coils. Although the probe works very well in saline solution, we are continuing to work on improving the sensitivity in air.

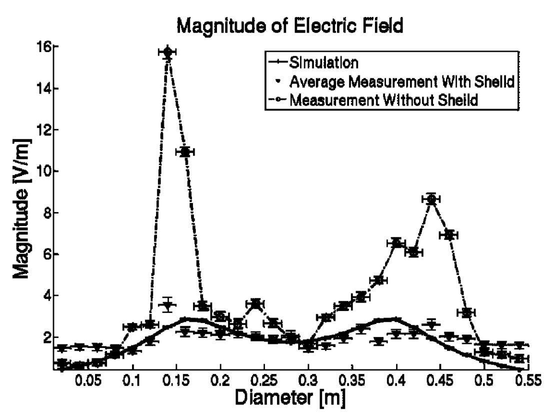

Figure 4: Comparison of measured electric field with shield to simulation.

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