Measurement of Electric Fields Induced in a Human Subjects due to Alternating Magnetic Gradient Fields and Natural Body Movements in Static Magnetic Fields

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Introduction: It is well known that electric fields are induced in the human body due to changes in magnetic field with time. At high rates-of-change of magnetic field this can cause peripheral nerve stimulation (PNS), magnetophosphenes, vertigo, and metallic taste [1, 2]. Analytic calculations and numerical modelling have been used to estimate the magnitude of the electric fields induced in the body during magnetic field gradient switching and natural movements in the environment of scanner magnets[3, 4, 5]. What have been missing so far are reliable *in-vivo* measurements of the induced electric field, which would allow the numerical and analytic models to be verified. Here, we demonstrate via experiments carried out on a saline-filled cylinder exposed to time-varying gradients that dipole probes can be used to measure the induced electric fields, before going on to report the first electric field measurements at the skin surface of the torso, head and tongue during natural movements of the subject around the magnet. Electric fields induced by gradient switching were also measured on the torso whilst the subject lay in the magnet or stood at the end of the magnet bore.

Theory: The electric field measured by a dipole probe can be thought of as originating from two contributions, namely the gradient of the scalar electric potential, V, and the temporal derivative of the magnetic vector potential, **A** (which is related to the magnetic field by $\mathbf{B} = \nabla\times\mathbf{A}$).[6]. For a true measurement of the electric field, the wires forming the dipole should lie on a short straight line, **l**, between the terminating electrodes, which in turn make a low impedance contact with a conductive medium. The electrode spacing should also be small in comparison with the length scale over which the electric field varies. Under these circumstances, the potential measured by an amplifier connected to the dipole probe is $(\nabla V + \partial\mathbf{A}/\partial t).\mathbf{l} = -\mathbf{E}.\mathbf{l}$,

Figure 1: (a) Saline phantom & short dipole probe in gradient coil . (b) Dipole probes used for measurements on human subject.

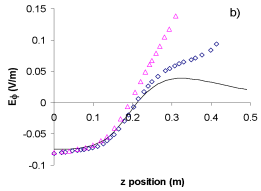

Figure 2: Analytic and measured electric field in cylinder due to transverse gradient switching.

Methods: Three separate dipole probes were constructed for the measurements described here and are shown in Fig. 1: (i) a short dipole of 20mm length with silver point contacts suitable for measurements in saline phantoms; (ii) a single 25 mm dipole with 6 mm silver disc electrodes; (iii) a dual channel probe with orthogonal 30mm dipoles embedded in a silicone rubber mould to ensure reliable contact to the skin. All probes were connected to a BrainVision recorder EEG amplifier and acquisition system (Brain Products, Germany). An additional probe to detect magnetic field variations based on three, orthogonal, 6mm diameter coils was also connected to the amplifier. Star-quad, low-noise microphone cable was used to connect the probes to the amplifier. This served to cancel out voltages induced by movement of the cable. An insert head-gradient coil set was placed on the floor and a saline cylindrical phantom of 260mm diameter placed inside (Fig. 1). The transverse gradient was driven so as to produce rate-of-change of 13.2 $\mathrm{Tm^{-1}s^{-1}}$ and the induced electric fields were measured in a transverse plane and along an off-centre axial line. A Philips 3T Achieva scanner was used for the *in-vivo* experiments. Electrode paste (Ten20, DO Weaver, USA) was applied to the silver electrode discs of the dual-dipole sensor before it was attached to either the chest or upper abdomen of the subject. The magnetic field sensor was fixed adjacent to the dipole sensor. Switched gradient measurements used an echo-planar imaging (EPI) sequence with an extra controlled rise-time pulse (10 T/m/s) applied on one of the X,Y and Z gradient axes whilst the subject was positioned such that their head was at the iso-centre of the magnet. To evaluate the effect of natural movements around the scanner, the subject stood at the bore end and performed a sequence of actions: bending and leaning into the magnet, walking across the bore of the magnet and executing body rotations. To investigate the effect of head movements (nodding, rotating and shaking) the dual sensor was fixed to the forehead. The single channel dipole sensor was also applied to the tongue during head movement, but no electrode paste was used. The subject clamped the probe using their own mouth.

Subject /Sensor location	Action or gradient axis	Peak dB/dt (T/s)	Peak E (V/m)	Geometric multiplier (m)
At bore end /on abdomen	Rotating body 90 degrees	1.08 ± 0.05	0.17 ± 0.01	0.15 ± 0.02
At bore end /on abdomen	Bending into bore	1.06 ± 0.05	0.13 ± 0.01	0.13 ± 0.01
At bore end / on forehead	Rotating head about vert. axis	0.61± 0.03	0.046 ± 0.02	0.077 ± 0.003
In magnet / on abdomen	Z (foot/head)	1.35 ± 0.07	0.19 ± 0.01	0.14 ± 0.02
In magnet / on abdomen	X (right/left)	0.51 ± 0.03	0.090 ± 0.005	0.18 ± 0.02

Table 1: Summary of typical magnetic fields, induced electric fields and multipliers for chosen example actions.

Results: Measured values of the off-axis electric field induced in the cylindrical phantom by transverse gradient switching are plotted against axial position in Fig 2. The analytic solution for an infinite cylinder is also shown [6]. A typical measurement of the electric field variation during a natural movement (leaning into magnet) is shown in Fig. 3. In this case the azimuthal component of the electric field is largest as the rate of change of the magnetic field along the subject's head-foot axis is greatest. Measurements made during the EPI sequence are shown in Fig. 4 Table 1 summarises some of the results obtained in this study. The typical measured values of |d**B**/dt| and |**E**| are given together with the geometrical multiplication factor which links the dominant component directions.

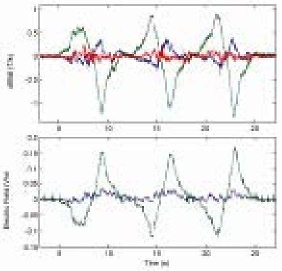

Figure 3: Temporal variation in magnetic fields (upper) and torso electric fields induced (lower) when leaning into magnet 3 times

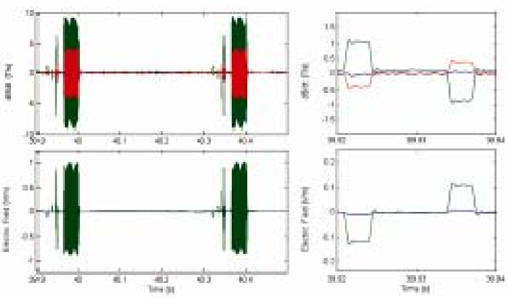

Figure 4: Measured rate of change of magnetic field (upper) and electric field induced in torso (lower) during EPI sequence. Right graph shows time segment spanning the 10 T/m/s gradient pre-pulse

Conclusions: The sensor described in this work can reliably measure surface electric fields induced *in-vivo* during natural movements and gradient switching coving a frequency range of 0.1 Hz to 800 Hz. The geometrical multiplier for the torso of a male subject was found to lie in the range of 0.1 to 0.15 m, which corresponds well to previous assumptions[1]. The measured values of **E** are of similar order to those predicted by simple analysis or numerical modelling [7]. For natural movements close to the bore of a 3T magnet, current densities induced in the body exceed proposed regulatory limits [5].

References: [1] Irnich, W., Mag. Res. Med., 1995. **33**(5):619-623. [2] Schenck, J.F., Med. Phys., 1992. **19**(4):1089-1098. [3] Bencsik, M., Phys. Med. Biol., 2002. **47**(4):557-576. [4] Liu, F., Concepts Mag. Res., 2002. **15**(1):26-36. [5] EU, *Directive 2004/40/EC* [6] Glover, P.M., Phys. Med. Biol., 2007. **52**:5119-5130. [7] UK HSE report RR570 http://www.hse.gov.uk/research/rrpdf/rr570.pdf