Safety of simultaneous intra-cranial EEG-fMRI: Magnetic field gradient induced voltages

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Introduction EEG-correlated fMRI is used for the investigation of the haemodynamic responses of interictal epileptic discharges (IEDs) and generator localisation. Key questions remain as to the relationship between scalp-recorded IEDs, electrical activity within the brain and BOLD signal changes. In some patients with refractory epilepsy, electrodes are implanted in the brain to record from the cortical surface and deep structures to localise the epileptic focus. This could present a unique opportunity to study both fMRI and electrical signals simultaneously in the human brain and improve interpretation of less invasive EEG-fMRI in epilepsy patients. However, MR imaging of patients with implanted electrodes poses potential health risks one of which is imaging gradient induced currents that could result in undesired stimulation.

Methods A Perspex phantom, described previously [1], with a shape and dimensions approximating an adult human torso was filled to ~10cm with a semi-liquid gel (distilled water, poly-acrylic acid partial sodium salt 8g/L, sodium chloride 0.70 g/L) with electrical and thermal characteristics similar to those of human tissue [2]. Three depth electrodes, one grid and one strip electrode array were placed in a clinical relevant arrangement; for details see [1]. The intracranial electrodes tested are of a type commonly used for intracranial EEG (icEEG) monitoring in patients with epilepsy. The depth electrodes (Ad-Tech, Racine, WI) consist of Platinum contacts of 2.3mm length with a radius of 1mm, with nickel-chromium wires in polyurethane tubing leading to nickel-chromium tail contacts. The grids and strip electrodes consist of 4mm diameter platinum-iridium disks (2.3mm exposed) imbedded within a silicon sheet with stainless steel (316) wires and nickel-chromium tail contacts contained within polyurethane tubing. For this study, cables (Tech-Attach Cables, Ad-Tech) were attached to the electrodes with their respective connector blocks (Tech-Attach disposable connector blocks) as would be required for simultaneous recordings. These are effectively ribbon cables with specialist connectors that are between 80 and 120cm. All measurements were performed within a 3T Siemens Trio scanner and a head body transmit/receive coil. An EPI sequences was run with the following parameters: TR 2900ms; TE 30ms; echo spacing 500μs; 192mm FOV; matrix 64 x 64; 48 slices; requiring amplitudes of 25mT/m and slew rates of 160μs. Voltage measurements made with the cables connected and positioned so that they were next to the phantom body using a balanced coaxial probe [3] consisting of two 20:1 'low impedance' probes (950Ω resistors in series with 50 Ω coaxial cables), with shields from each probe periodically joined to minimise ground loops, connected to a 200 MHz digital oscilloscope (Tektronix TDS 2022, Beaverton, OR) configured with differential inputs. Voltages were measured between the cable terminations from two circuits, one between left and right sided depth electrodes and one around the grid electrode array, aiming to maximise the loop area (i.e. the worst-case). In order to assess the contribution of signals induced in the test-leads to the total voltages detected, a control measurement was performed in which the ends of the balanced probes were connected directly together but left in the same position as for all previous measurements and the scanner run as before.

Measurement position	RF-coil	peak-peak voltage (V)
		EPI gradients
depth	head	0.04
	body	0.03
grid	head	0.03
	body	0.03
control	head	0.01

Table 1 Max gradient induced voltage

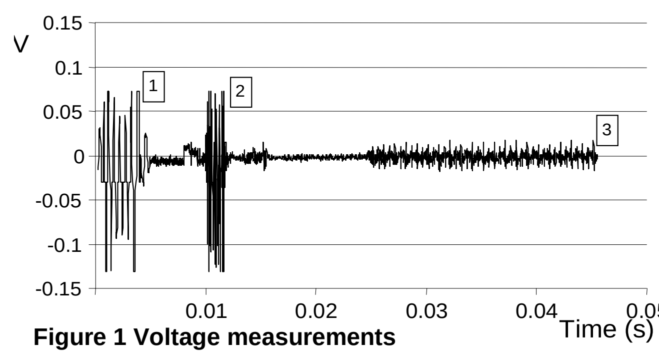

Figure 1 Voltage measurements the fat saturation pulse (1), the excitation pulse (2) and the EPI readout gradient switching (3).

Results The results are shown in table 1 and figure 1 with the main finding being that the measured switching magnetic field gradient induced voltages were small (0.04±0.01V).

Discussion The relevant safety guidelines for exposure to fluctuating electromagnetic fields in the range of gradient switching frequencies are: maximum allowed induced current of 0.1mA under normal conditions and 0.5mA under single fault conditions [4]. Voltage measurements were obtained at the cable terminations measuring the voltage induced across two different circuits comprising of the implant and the tissue. These measurements were primarily aimed at determining the likely voltages induced in these circuits due to gradient switching. During normal operation, the EEG amplifier's input impedance (typically >1MΩ) will limit the amount of current through the subject at low frequencies; for example, for the maximum induced electromotance observed in this study, 0.04V, the current is <0.04μA. However, in a fault condition, the majority of the impedance would be provided by the tissue and in this case larger currents could result. For both of the tested circuits (across depth and grid electrodes) a low voltage due to switching gradients was detected (0.04±0.01V). Assuming a conservatively low tissue impedance value of 500Ω, this corresponds to a current of 0.08mA, well below the medical devices limit for a single fault condition (0.5mA). This result is consistent with that reported in [5] for deep brain electrodes and an external pulse generator sited outside the scanner room with long connecting leads attached (the most similar data available) where a voltage of <0.5mV was detected. In summary, the measured induced currents from gradient switching are not large enough to cause damage or stimulation. This confirms that radiofrequency induced currents causing heating are the primary safety concern [1]. MRI of patients with these implants is 'off label' use, to our knowledge they do not have FDA or European certification for MRI safety.

References **1.** Carmichael DW, et al. J Magn Reson Imaging. 2008 Oct 28;28(5):1233-1244. **2.** Park SM, et al. IEEE transactions on magnetics, 2003; 39 (5): 3367-3371. **3.** Smith DC, 1993 High frequency measurements and noise in electronic circuits. Van Nostrand Reinhold, New York. **4.** IEC (2005) International Standard, Medical Equipment Part 1:. International Electrotechnical Commission 60601-1:2005, Geneva 2005. **5.** Georgi JC, et al. Magn Reson Med, 2004; 51:380–388.