RF Heating of Gold Cup and Conductive Plastic Electrodes during Simultaneous MRI and EEG

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Introduction: The EEG electrodes typically used in clinical settings—epilepsy long-term monitoring (LTM) or intensive care units (ICUs)—are often removed prior to MRI scanning at 3T due to safety concerns regarding their heating by RF pulses. It would be advantageous to (i) leave these electrodes on during routine clinical MRI scans and (ii) be able to record directly from these electrodes during functional MRI scans, as originally demonstrated by Ives et al. [1]. Previous studies of RF heating of EEG electrodes and leads have either been at 1.5T or have employed EEG caps that are not typically used in clinical settings, e.g., see Nöth et al. [2]. Our goal therefore was to measure the temperature changes under two types of clinically used electrodes—gold cup electrodes (GCEs) and conductive plastic electrodes (CPEs)—during a variety of MRI scans at 3T, using watermelons as phantoms. For both electrode types, we found little heating (under 4°C) for all sequences when the wire lengths were multiples of ½ the RF wavelength and substantial heating (over 15°C) for high-SAR sequences when the wire lengths were at ¼ RF wavelength, consistent with the idea that RF standing waves established on the wires are the main cause of heating. Our results suggest that these clinical electrodes could be used safely in 3T MRI scanners, as long as the EEG wire lengths and the SAR of the MRI sequences are both carefully taken into consideration.

Methods: Three "mini" watermelons, with circumferences ranging from 20 to 23 inches, were recruited for this study. These watermelons were chosen for this study since (i) their size is comparable to the human head and (ii) their surfaces are conductive, like the human scalp and unlike most MRI phantoms. Either GCEs (for watermelons 1 and 3) or CPEs (for watermelon 2) were placed on the surface according to the 10-20 system (electrodes provided by Ives EEG Solutions Inc., Newburyport, USA). Three different configurations of electrode wire lengths were investigated: in the "short wire" configuration (Fig. 1, left), the 19 scalp EEG electrodes and 1 EKG electrode terminated at the black connectors (black arrow). In the "medium wire" configuration (Fig. 1, middle), the black connectors were connected, via braided wires (yellow arrow), to a BrainProducts interface box (blue arrow). In the "long wire" configuration (Fig. 1, right), the interface box was connected, via a ribbon cable (purple arrow), to a BrainAmp MR amplifier (Brain Products GmbH, Gilching, Germany), allowing EEG signals to be recorded. Temperatures were measured by placing four Neoptix T1 fiberoptic probes under the EKG, T3, Fp2 and T6 electrodes, with the fiberoptic cables connecting to a Reflex Signal Conditioner (Neoptix, Inc., Québec, Canada).

Fig. 1: Watermelon phantom with 19 scalp EEG electrodes and 1 EKG electrode (red arrow). The short, medium and long wire configurations (see text for description) are shown in the left, middle and right panels, respectively.

The watermelons were scanned on a Siemens 3T Trio scanner (Siemens Healthcare, Erlangen, Germany) with a variety of sequences, including MPRAGE, EPI, DTI, HASTE, FLAIR and TSE, using a 32-channel receive array coil and with parameters set to the typical values currently used at our institution for routine clinical scans. Of these sequences, TSE had the highest SAR and always produced bigger temperature increases than any other sequence, as would be expected from, e.g., Nöth et al. [2] (but see also Nitz et al. [3] and Baker et al. [4] on the limitations of whole-body SAR values as indicators of local heating). We therefore focus here on the results from the TSE sequence (TR/TE = 5500/89 ms, FOV = 192x220 mm, matrix 313x512, slice thickness 2.5 mm, FA = 120°, acquisition time 4m15s, scanner-reported SAR level = 0.34 W/kg).

Results and Discussion: Fig. 2 shows the temperature increases under the four electrodes during and immediately after TSE for watermelon 1 (with GCEs; top row) and watermelon 2 (with CPEs; bottom row), for the short, medium and long wire configurations. For both electrode types, substantial increases in temperature were seen for the EKG electrode in the short wire configuration (over 15°C), with little heating (under 4°C) in the medium and long wire configurations. The other three electrodes (T3, Fp2 and T6) showed temperature increases of less than 4°C for both electrode types and all wire-length configurations, with one exception: T6 CPE in the short wire configuration exhibited a 6°C increase. A

Fig. 2: Temperature changes under 1 EKG and 3 EEG electrodes for GCEs on watermelon 1 (top row) and CPEs on watermelon 2 (bottom row), for the short (left column), medium (middle column) and long wire (right column) configurations. (Note the higher temperature scale for the short-wire configuration.)

similar pattern of results was obtained when the GCE experiment was repeated with watermelon 3 (results not shown).

We noticed that the total EKG wire length was 2 ft, 4 ft or 8 ft in the short, medium or long wire configurations, respectively, corresponding to ¼, ½ or 1 RF wavelength at 3T. We therefore hypothesized that RF antenna effects [5], rather than electromagnetic induction [6], might explain most of the observed heating, since a ¼ wavelength standing wave would lead to a large current at the electrode-watermelon junction, but ½ or 1 wavelength standing waves would lead to very little current. To confirm this hypothesis, we conducted a follow-up experiment in which the electrode wire lengths were systematically varied from 1 ft to 8 ft, in 1 ft increments, and scanned a fourth watermelon with the TSE sequence at both 3T and 1.5T (Siemens Avanto scanner). For both electrode types and at both field strengths, we observed the most heating at ¼ wavelength (2 ft at 3T; 4 ft at 1.5T) and little heating at ½ wavelength (4 ft at 3T; 8 ft at 1.5T), consistent with heating due to the RF antenna effect.

Although further work is required to understand the relationship between the heating observed in these watermelon phantoms and heating in patients, certain conclusions from this work (such as the need to avoid ¼ wavelength wires) are highly likely to hold in patients, and could be immediately applicable to the design or re-design of clinical electrode sets that are safe to use in 3T MRI scanners.

References: [1] Ives et al. (1993) *Electroencephalogr Clin Neurophysiol* 87:417-20. [2] Nöth et al. (2012) *J Magn Reson Imaging* 35:561-71. [3] Nitz et al. (2005) *Invest Radiol* 40:773-6. [4] Baker et al. (2004) *J Magn Reson Imaging* 20:315-20. [5] Dempsey et al. (2001) *Clin Radiol* 56:457-65. [6] Lemi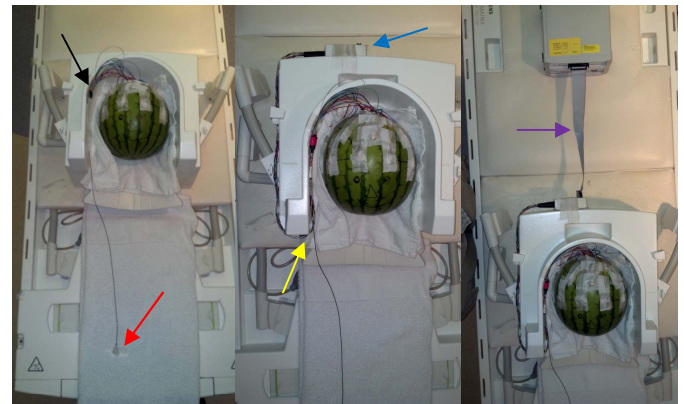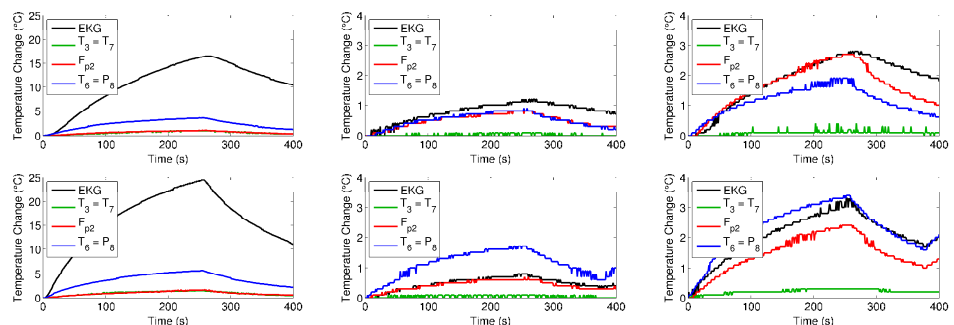eux et al. (1997) *Magn Reson Med* 38:943-52.