RF safety assessment of simultaneous EEG-fMRI at 7T MR

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Target audience: Researchers interested in RF safety of EEG/7 T MR setup using EM simulations and optical temperature measurements

Purpose: For simultaneous EEG-fMRI applications [1] at ultra-high field (7 T), subject safety is a major concern due to the probable RF interactions between the EEG materials and the RF coil[2]. Electromagnetic simulations using realistic head models allow the estimation of high-resolution SAR distributions across the head, but only a small number of studies have been devoted to this approach [3-5]. In this study, an exact model of a 64-channel EEG cap with all electrodes, resistors, metallic wires and connectors and the RF coil was simulated, and B_1^+ and SAR distributions across the human head evaluated with/without the presence of the EEG cap. Simulation results were complemented by experimental B_1^+ and temperature measurements from a human subject with simultaneous EEG acquisition, using both RF volume and surface coils.

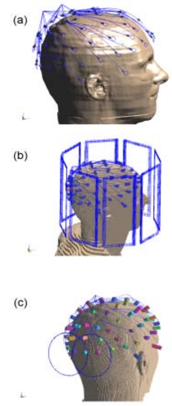

Fig.1 a) Geometric model consisting of a realistic human head and a set of 64 ring electrodes, safety resistors and leads simulating the EEG cap; the wire branching was designed according to the real cap, terminating in two connectors close to the head; Voxel mesh obtained from the full geometrical model, including the electrolyte gel and (b) head array and (c) surface coil.

Methods: Finite difference time domain (FDTD) simulations were performed on SEMCAD X (SPEAG, Zürich, Switzerland) to evaluate the impact of a custom 64-channel EEG setup (EasyCap, Herrsching, Germany) on B_1^+ and SAR distributions on the realistic human meshed model Duke from the Virtual Family [6] using an 8-channel transmit/receive loop head array (Rapid Biomedical, Rimpar, Germany) or in-house built two-channel surface loop coil. For the RF coils (Fig.1b-c), the copper strips of the loops were modeled as perfect electric conductors (PEC), with capacitors and voltage sources inserted on each loop to ensure excitation of the circularly polarized mode. EEG ring electrodes were designed as a set of 64 PEC loops, connected to PEC leads via 5kΩ resistors. The leads converged in 8 branches towards the 2 connectors, standing approximately 2cm above the scalp (Fig. 1a). Wire branches and connector positions were modeled according to the real cap, with specific care taken to ensure that no wires/electrodes were in physical contact with each other or with the skin. Contact with the scalp was modeled with small cylinders mimicking the Abralyte gel (Fig. 1b-c), with dielectric properties measured from a real sample (DAKS, SPEAG, Switzerland). The simulation model was meshed in a non-uniform grid of approximately 8MCells, with voxel steps ranging from $0.3{\times}0.40{\times}0.3mm^3$ to $69{\times}78{\times}85mm^3$ for the loop array (Fig. 1b), and for the surface coil with voxel steps ranging from $0.4{\times}0.2{\times}0.1mm^3$ to $38{\times}50{\times}42mm^3$ (Fig.1c). A harmonic excitation at 297.2 MHz was applied, and steady-state conditions were achieved within 30 periods of simulation time. Perfectly matched layers in medium strength were used at the edges of the FDTD domain. The resulting B_1^+ and SAR maps, with and without the cap, were normalized to a 1W delivered power and exported to Matlab (Mathworks, Natick MA, USA) to be resampled into a uniform grid. For comparison, MR measurements were performed on an actively-shielded Magnetom 7T head-only scanner (Siemens, Erlangen, Germany). SA2RAGE (64 sagittal slices, $2.0{\times}2.5{\times}2.0mm^3$ voxels, TR/TE=2400/1.4ms, TI_1/TI_2=65/1800ms, α_1/α_2=4°/11°), was used for B_1^+ field mapping [7]. Temperature fluctuations were assessed during a 16min session with two consecutive 8-min fMRI runs: a sinusoidal gradient-echo EPI sequence (25 axial slices, $1.5{\times}1.5{\times}1.5mm^3$ voxels, TR/TE=2000/25ms, α=78°, 90% of SAR limit), followed by a spin-echo EPI sequence (20 slices, $1.5{\times}1.5{\times}1.5mm^3$ voxels, TR/TE=5000/44ms, α=90°, 95% of SAR limit).

Results: For the 8-channel coil, peak local SAR was 0.43 W/kg normalized to 1 W power without the EEG cap. Decreasing to 0.39 W/kg normalized after placement of the cap. Similarly, for the surface coil, with the introduction of the EEG cap, the peak local SAR value decreased from 0.73 W/kg to 0.66 W/kg. The validity of the FDTD simulations was assessed by comparing the estimated B_1^+ maps with MR measurements performed on a human subject, with and without the EEG cap in place (Fig. 2). In general, both experimental and simulated maps exhibit similar field distributions, with higher efficiency in the center and occipital regions for the 8-channel coil and higher at the region close to the surface coil, and both showed an overall decrease in B_1^+ strength with the introduction of the EEG cap – approximately 13% in the MR data, compared to 8.0% in simulations for the volume coil and 22% in the MR data, compared to 11% in the simulation for the surface coil. Local effects occurring closer to the skin effectively differed in location and shape (Fig. 2, arrows 1&2), with measurements displaying slightly wider intensity variations than simulated maps, including decreases down to 0 B_1^+ and increases up to approximately 1.8× the nominal flip angle where it is observed in only low SAR regions. For both coils, the temperature increase on the electrodes was max. 0.8 °C during 16 min. acquisition (Fig.3).

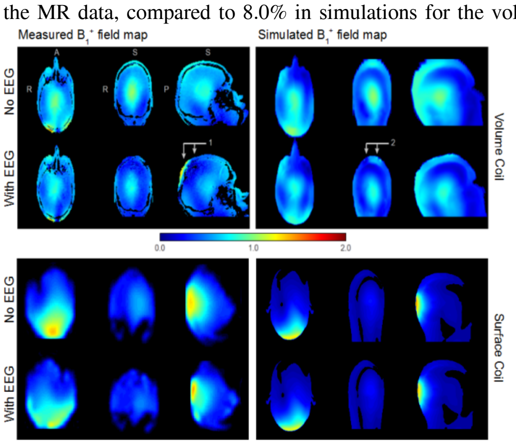

Fig.2 Comparison of experimental (left column) and simulated (right column) B_1^+ field distributions with and without the EEG cap. The B_1^+ field distributions are expressed as a fraction of the nominal flip angle. Arrows 1 and 2 indicate more accentuated local variations occurring near the skin.

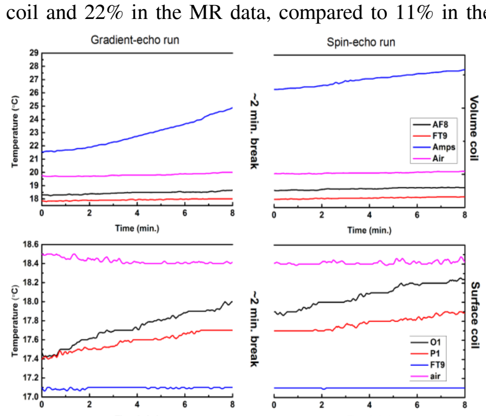

Fig.3 Temperature fluctuations during an 8min-long GE-EPI acquisition followed by an 8-min-long SE-EPI run. The two runs were separated by approximately 2min, which included shimming and adjustment procedures for the SE run. Temperature monitoring was performed in cap electrodes (AF8 and FT9 for volume and O1, P1, FT9 for surface), in between the two EEG amplifiers, and suspended inside the bore above the phantom.

Discussion and Conclusion: Relying on the validated FDTD simulations, no RF safety concern is raised for simultaneous EEG-fMRI at 7 T MR with the current setup. However, with the introduction of the EEG cap, a pronounced RF shielding effect is found, which leads to a decrease in the RF efficiency in the subject. When the EEG cap is present, the $SAR/(B_1^+)^2$ value increased by 15% for the volume coil and by 33% for the surface coil. This implies that, while some RF-losses are incurred with the introduction of the EEG cap, there are no safety concerns for EEG-FMRI at 7T with these setups, although scan parameters might need to be adapted to compensate for the drop in RF efficiency. References: [1] Laufs, Neuroimage 2012 [2] Lemieux *et al.* 1997. [3] Angelone *et al.* Bioelectromagnetics 2004 [4] Angelone *et al.* MRI 2006 [5] Jorge *et al* Neuroimage 2015 [6] Christ *et al.* Phys Med Biol 2010 [7] Eggenschwiler *et al.* MRM 2012.