Modification of a Standard MR-compatible EEG Cap for Improved EEG Neurofeedback with Simultaneous fMRI

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Target audience: Researchers employing simultaneous EEG-fMRI, as well as persons interested in non-invasive brain neuromodulation using EEG neurofeedback, real-time fMRI neurofeedback, and their multimodal integration.

Purpose: The problem of real-time removal of artifacts from EEG data recorded simultaneously with fMRI has been a subject of attention and research. It is particularly important for applications of EEG neurofeedback (EEG-nf) with simultaneous fMRI, e.g. [1,2]. The average artifact subtraction method [3], implemented, for example, in the BrainVision RecView software (Brain Products, GmbH), can quite accurately remove MR artifacts in real time. However, this method may be less efficient for cardioballistic (CB) artifacts due to cardiac profile variability, random head movements, and distortions of the ECG signal. Furthermore, no similar technique exists for random-motion artifacts. Various approaches have been proposed to address this problem. One advanced method uses a special EEG cap with multiple reference electrodes connected to a reference layer approximating scalp conductivity [4]. A simpler approach involves the use of several reference wire loops [5]. These techniques aim at reducing artifacts for all EEG channels. However, most EEG-nf methods utilize signals from only a small number of specific EEG electrodes. For example, frontal EEG asymmetry nf [1,2,6,7] uses signals from two frontal electrodes (usually F3 and F4). Therefore, accurate real-time removal of EEG-fMRI artifacts is crucial for the EEG-nf channels, and is not essential for the rest of EEG channels. Here we describe a simple modification of a standard MR-compatible EEG cap that can substantially improve quality of EEG-asymmetry-nf provided simultaneously with fMRI.

Methods: We modified a 32-channel MR-compatible EEG cap (BrainCap MR from EASYCAP GmbH) by adding two reference contours for EEG channels F3 and F4 (Fig. 1). We denote these contours as R3 and R4. Each reference contour is formed by a wire that follows the corresponding electrode's lead, goes around that electrode (F3 or F4) as well as Fz, and connects to the Ref electrode's lead through a non-magnetic resistor (50k, 0.4W). This wire segment approximates an *effective* spurious conductive path that exists between the electrode (F3 or F4) and the Ref due to scalp conductivity. The other end of the wire is connected to the lead of TP9 (for R3) or TP10 (for R4) at the location where all the EEG leads come together in the bundle. The electrodes TP9 and TP10 are disconnected and unused. The modified EEG cap be used as a regular EEG cap, except that acquisition channels TP9 and TP10 record artifacts induced in the reference contours R3 and R4. The size and shape of R3 and R4 can be optimized to better approximate the random-motion and CB artifacts picked up by F3 and F4. The modified EEG cap was tested in the GE Discovery MR750 3T MRI scanner with an 8-channel receive-only head coil. Three healthy male subjects participated in the tests, and followed the real-time fMRI-nf training procedure [1]. A single-shot gradient echo EPI sequence with FOV/slice=240/2.9 mm, *TR/TE*=2000/30 ms, SENSE *R*=2, image matrix 96×96, flip=90°, 34 axial slices, was employed for fMRI. An MPRAGE sequence with FOV/slice=240/1.2 mm, *TR/TE*=5.0/1.9 ms, *TD/TI*=1400/725 ms, SENSE *R*=2, image matrix 256×256, flip=10°, 128 axial slices per slab, was used for anatomical imaging. Concurrent EEG recordings were performed using a BrainAmp MR from Brain Products GmbH in 0.016–250 Hz frequency band with 0.1 μV resolution and 5 kS/s sampling rate. Offline EEG data analysis was performed in the BrainVision Analyzer 2. MR artifacts were removed using the average artifact subtraction method. The data were then downsampled to 250 S/s sampling rate (4 ms interval) and band-pass filtered between 5 Hz and 35 Hz to select the alpha and beta EEG bands relevant for EEG-asymmetry-nf [1,2,6,7]. The reference signals were fitted to the EEG data using a general linear model, $V_{F3}(t)=a\cdot V_{R3}(t)+b\cdot V_{R4}(t)+e(t)$ (and similar for F4). The model was applied to a 520 s long EEG dataset, and corrected data for channels F3 and F4 were obtained by subtracting the reference waveform fits.

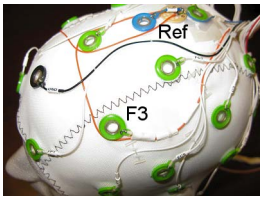

Fig. 1. Modified EEG cap: reference contour for channel F3 (orange).

Results: No MRI distortions or signal losses in either EPI or MPRAGE images were observed with the modified EEG cap. Fig. 2A shows a representative subject's EEG data for channels F3 and F4 before and after the correction using the reference signals from R3 and R4. Both random-motion and CB artifacts are visibly reduced after the correction. The signals' temporal standard deviations are reduced by factors 2.2 and 2.6 (−6.8 dB and −8.3 dB) for channels F3 and F4, respectively. Fig. 2B demonstrates that the reference signals from contours R3 and R4 provide relevant information about the artifacts picked up by EEG channels F3 and F4.

Conclusion: Our results demonstrate that a simple modification of a standard MR-compatible EEG cap can substantially improve quality of the EEG signals needed to provide EEG-asymmetry-nf inside an MRI scanner. More tests are under way to ensure that the performance is consistent and robust. The proposed signal correction can be applied in real time after the MR average artifact subtraction and before the CB average artifact subtraction. The information provided by the reference channels can also be used to perform EEG-assisted retrospective motion correction of the simultaneously acquired fMRI data [8].

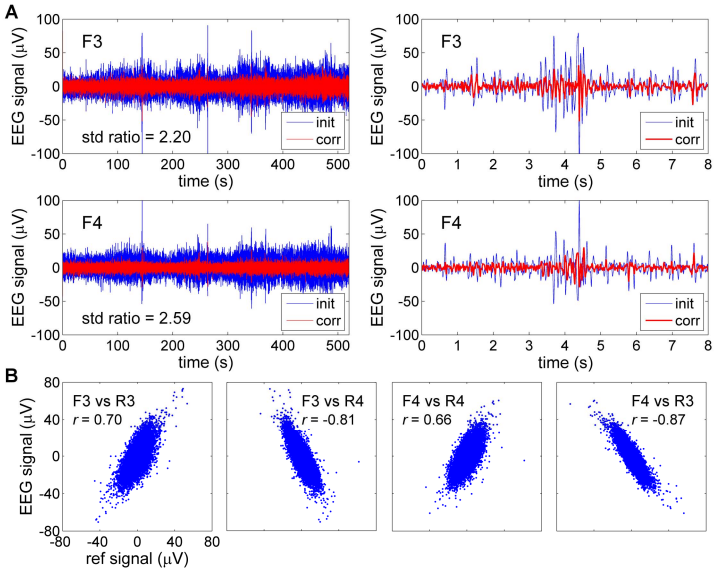

Fig. 2. A) Signals from frontal EEG channels F3 and F4 following removal of MR artifacts before (blue) and after (red) the correction of random motion and CB artifacts using the reference signal subtraction. The figures on the right show the same signals in 140...148 s time interval. B) Correlations between the signals from F3 and F4 (before the correction) and the reference signals from R3 and R4.

References: [1] V. Zotev et al. *NeuroImage* 2014, 85:985. [2] M. Cavazza et al. *OpenAccess Ser. Informatics* 2014, 41:42-60. [3] P.J. Allen et al. *NeuroImage* 2000, 12:230. [4] W.J.R. Dunseath. U.S. Patent 7715894. [5] R.A.J. Masterton et al. *NeuroImage* 2007, 37:202. [6] J.J.B. Allen et al. *Psychophysiol.* 2001, 38:685. [7] F. Peeters et al. *PLoS ONE* 2014, 9:e91837. [8] V. Zotev et al. *NeuroImage* 2012, 63:698.