Reducing the gradient artefact in simultaneous EEG-fMRI by adjusting the EEG cap lead configuration

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Introduction

EEG data recorded simultaneously with fMRI acquisition are contaminated by large voltages generated by the time-varying magnetic field gradients. The resulting gradient artefact (GA) can be more than 3 orders of magnitude larger than signals of interest from the brain. Correction of the GA generally relies on the use of low-pass filtering to attenuate the large, high-frequency voltage fluctuations produced by the gradient waveforms, followed by subtraction of a GA template produced by averaging over many repeats of the artefact waveforms [1]. The average artefact subtraction (AAS) process relies on the EEG system having a large enough dynamic range to characterise the artefact voltages and also on invariance of the artefact waveform over image acquisitions. Saturation of the amplifiers, changes in subject position or variation in the timing of the gradient waveforms cause these conditions to be violated, leaving unwanted residual GA after AAS. Previous work [2] suggested that changing the EEG cap lead layout and the position where the cable bundle leaves the cap could reduce the GA amplitude. Here, through simulations and experimental investigation we evaluate the effect of modifying the lead paths on the magnitude of the GA and the residual artefact after AAS.
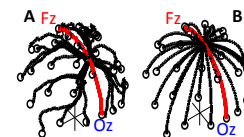

Figure 1: Lead paths used in simulation for standard cap (A) and modified cap (B). The convergence point was altered along the midline (red line).

Methods

Simulation: Numerical calculations were performed using previously described methods [2]. The head was modelled as a sphere and the lead paths formed great circles starting from each electrode and converging to a point from which the cable bundle leaves the cap (Fig. 1B). The position of the convergence point was moved along the midline (between Fz and Oz) (Fig. 1, red line) and also in a right-left direction between electrodes T7 and T8 (in each case a 100 positions were tested). For each configuration, the GA due to gradients applied in the Anterior-Posterior (AP), Right-Left (RL) and Foot-Head (FH) directions were simulated and the range and root-mean-square (RMS) amplitude of the induced GA across electrodes were calculated. The results were compared with GA simulations using the real lead paths from a standard EEG cap, as previously described [2].

Experimental: EEG data were recorded at 3T using two different 32-electrode EEG caps, a BrainAmp MR-plus EEG amplifier and Brain Vision Recorder software (Brain Products, Munich).The electrode positions in both caps followed the extended 10-20 system. The first EEG cap had standard lead configurations with the cable bundle leaving the cap mid-way between Cz and Pz (Fig 1A). The second cap used the optimal lead paths and cable bundle position identified from the simulations (Fig 1B). Artefact voltages were first measured using a 19-cm-diameter, saline-loaded spherical agar phantom [2] and then on a human head. To identify how the lead paths affected the magnitude of the GA produced by the three orthogonal gradients, EEG recordings were made during execution of a sequence in which gradient pulses with a slew rate of 2 $Tm^{-1}s^{-1}$ were sequentially applied in the AP, RL and FH directions (30 repeats, 1 kHz low pass filter). The range and RMS amplitude of the artefacts across electrodes were calculated for each cap and gradient direction. EEG data were also recorded over a 6-minute period whilst a standard axial, multi-slice EPI sequence was executed (84×84×20 matrix, 3×3×4 mm^3 voxels) with TR/TE =2s/40ms. During the scanning, the phantom was manually rotated and the subject cued to move their feet for 5s every 30s, generating cumulative movements of less than 4/1mm in amplitude in the phantom/head, to allow evaluation of the effect of small movements on the GA. A low-pass filter cut-off of 250 Hz was used in this case to avoid saturating the EEG amplifiers. Data were exported to Matlab both before and after AAS had been carried out in Brain Vision Analyzer2. Since subject positioning is also known to effect GA amplitude [3] 7/3 repeats of each measurement were made on the phantom/subject with the phantom/subject removed and then returned to the scanner each time. Positioning was kept as similar as possible between repeats with Fp1&Fp2 placed axially at isocentre each time [3].
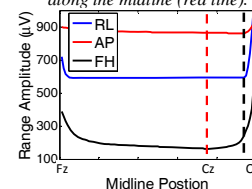

Figure 2: Variation of the range of the average GA (over electrodes) with cable bundle position for simulated RL, AP&FH gradients. Standard (black dashed line) and modified (red dashed line) cable bundle positions.
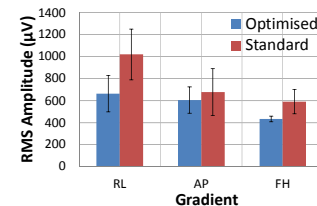

Figure 3: Variation of the average measured GA (RMS over electrodes) with standard and modified caps for gradients applied in the RL, AP&FH directions. Errors are the standard deviation across repeated measures.

Results

Simulation: Figure 2 shows that changing the lead paths by moving cable bundle position along the midline produces a decrease in the range of the GA for the FH gradient, but little change for the RL or AP gradients compared with the conventional position of the cable bundle (Fig 2, black dashed line). Similar results were seen for the RMS measures. From these simulations, a sensible compromise position was found to be with the cable bundle at Cz (Figs 1B & 2, red dashed line). When compared with real lead paths, the modified cap design produced a decrease in the range/RMS of the simulated GA of 48/40% and 1/0% for the FH and AP gradients respectively, with a 9/6% decrease/increase for the RL gradient. Moving the cable bundle off the midline in the RL direction did not reduce the GA measures.

Experimental: Figure 3 shows the GA measured with the standard and modified cap on the phantom, indicating that the most significant GA reduction is for the FH gradient, as predicted from the simulations. Similar results were found on the subject. Figure 4 demonstrates that, for both the phantom and subject, the modified cap most significantly reduces the amplitude of the GA due to an EPI sequence over the temple regions. The signals after AAS which occur at multiples of the 10 Hz slice repetition frequency are dominated by residual GA. Taking the RMS of these signals and averaging over leads and repeats measured on the phantom yielded values of 11±3 µV/5±1 µV for the standard/modified cap respectively. However, no significant differences between caps were seen for the subject data which yielded values of 3.7±0.5 µV/4±2 µV for the standard/modified cap respectively.
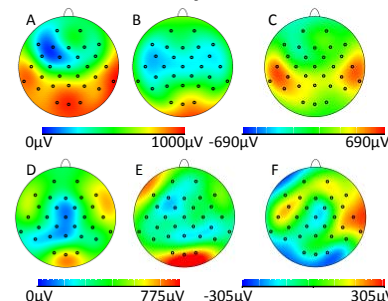

Figure 4: Maps of the RMS (over time) of the GA produced by a multi-slice EPI acquisition with the standard cap (A&D); modified cap (B&E) on the phantom (A-C) and the subject (D-F). Panels C&F show the difference, A−B and D−E, respectively.

Discussion

Here we have shown, through simulations and experiments, that modifying the lead paths and cable bundle position can have a significant effect on the amplitude of the induced GA. Simulations indicated that: (i) lead paths formed from great circles converging at electrode Cz produce the largest reduction in the overall GA (Figs. 1B & 2); (ii) the largest reduction occurred for the FH gradient, which was also reflected in the experimental measures (Fig 3). Using the standard EPI sequence we showed experimentally that the modified lead configuration reduced the GA amplitude most significantly in the temple regions, although some electrodes, primarily in the mid-frontal area, showed small increases in GA amplitude in the modified cap (Fig 4). This pattern of reduction, which most likely relates to the strong variation in the RL direction of the GA due to the FH gradient [2], would make the modified cap of particular use in studies focusing on auditory areas. This finding also suggests that other lead configurations could be used to minimise the GA at different electrodes depending on the cortical areas of interest. Since the greatest GA reductions for the modified lead configuration are seen over the temple regions, where the pulse artefact (PA, linked to the cardiac cycle) is largest, it is possible that this configuration may also reduce the PA amplitude. The results also indicate that the reduced GA amplitude in the modified cap can reduce the residual artefacts after AAS, since in the experiments on the phantom, a 55% reduction in the RMS of the data at the harmonics of the GA after AAS was seen when compared with data from the standard cap. The lack of a significant difference in the residual artefacts measured on the subject with the two caps may be due to the relatively small cumulative movements compared with the data from the phantom. Experiments on a greater number of subjects are planned to test fully the effect of using the modified cap in EEG-fMRI.

References [1] Allen *et al*. Neuroimage 12:230,2000 **[2]** Yan *et al* Neuroimage 46:459,2009 **[3]** Mullinger *et al* Neuroimage 54:1942, 2011