Simultaneous EEG-fMRI: evaluating the effect of the EEG cap cabling configuration on the gradient artefact.

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Introduction: EEG data recorded during simultaneous EEG-fMRI experiments are contaminated by large gradient artefacts (GA). The amplitude of the GA depends on the area of the wire loops formed by the EEG leads, as well as on the rate of switching of the field gradients [1-3]. Average artefact subtraction (AAS), the method most commonly used for GA correction, relies on the EEG amplifier having a large enough dynamic range to characterise the artefact voltages [4]. Low-pass filtering (250 Hz cut-off) is generally used to attenuate the high-frequency voltage fluctuations of the GA, but even with this precaution channel saturation can occur, particularly during acquisition of high spatial resolution MRI data. Previous work [2] has shown that the ribbon cable, used to connect the EEG cap and amplifier, makes a significant contribution to the GA since the cable geometry produces large effective wire-loop areas. However, by appropriately connecting the wires of the ribbon cable to the EEG cap it should be possible to attenuate the artefact voltage by producing partial cancellation of the cap and cable contributions [2]. Here, we test this hypothesis experimentally, with the aim of reducing the overall voltage range of the GA, thus increasing the spatial resolution that can be achieved without amplifier saturation.

Methods: Combined EEG-fMRI experiments were carried out on a Philips Achieva 3T MR scanner using the BrainAmp, EEG amplifier, with a 5 kHz sampling rate, Brain Vision Recorder software (Brain Products, Munich, Germany) and a 32-channel EEG cap. The ribbon cable (1 m long) was attached to a cantilevered beam centred in the magnet bore running parallel to the z-axis, as previously described [5], with the cable lying in the horizontal plane. Previous work has shown that anterior-posterior (AP) gradients induce the largest range of GA in the ribbon cable, with the largest positive (negative) voltages induced on channels 1-5 (28-32) (Fig. 1A)[2]. The contribution of the EEG cap to the GA due to an AP gradient shows a right-left pattern of variation (Fig. 1B) [1]. Therefore connecting the channels of the ribbon cable which generate large positive GA (1&2) to channels TP9&T7 on the EEG cap and similarly for negative channels will reduce the overall magnitude of the GA due to an AP gradient. Here, EEG data were acquired with the standard wire-electrode configuration and then with the optimised configuration on a head-shaped agar phantom [1,3] and on three subjects (with ethical approval) to evaluate the GA reduction produced by rewiring of the EEG cabling.

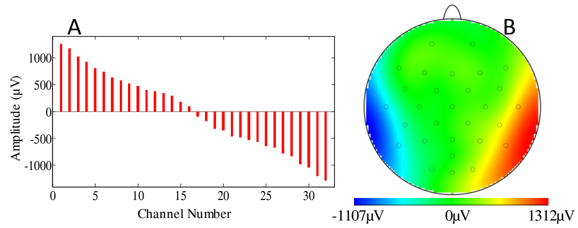

Fig. 1: (A) Variation over channels of the difference in the voltages recorded using the ribbon cable on application of AP gradient. (B) Map of the artefact voltages induced on the EEG cap (excluding ribbon cable) on a head shaped phantom.

Study 1: To test the efficacy of reducing the GA due to the three orthogonal gradients, EEG data were recorded (frequency range: 0.016-1000 Hz) with both cap-cable configurations during the execution of a customised EPI sequence in which gradient pulses with a slew rate of 2 $Tm^{-1}s^{-1}$ were sequentially applied in the Right-Left (RL), AP and Foot-Head (FH) directions, prior to each slice acquisition (30 repetitions) [3].

Study 2: EEG data were acquired (frequency range: 0.016-250 Hz) whilst performing a standard, multi-slice EPI sequence (20 slices, TR/TE=2000/40ms, 30 volumes). The first EPI sequence acquired axial slices, as is typical in whole brain fMRI (80×80 matrix, 3×3×3 mm^3 voxels); the second EPI sequence acquired high-resolution coronal slices, as are employed for fMRI of visual cortex (160×120 matrix, 1.5×1.5×0.5 mm^3 voxels).

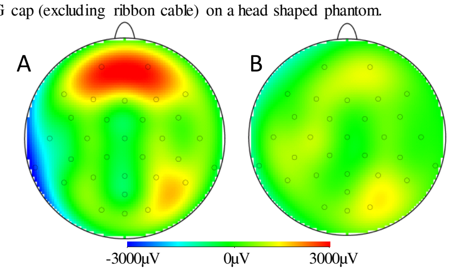

Fig. 2: Overall artefact maps induced by AP gradient on the head-shaped phantom: before (A) and after (B) re-wiring the cap-cable configuration.

Results and Discussion

Study 1: The average GA amplitudes (RMS across leads) for the head-shaped phantom before/after modifying the cabling were found to be 622/617, 1681/873 and 465/447 μV, for the RL, AP and FH gradients, respectively. A similar pattern of voltages was also observed in the data from human subjects, where the average GA amplitudes were 1497/1503, 2028/874 and 831/669 μV, for the RL, AP and FH gradients before/after modifying the cap. This indicates that the induced GA is reduced significantly for the AP gradient after re-wiring the cap-cable configuration with small reductions or no significant change in the GA induced by other gradients. Figure 2 shows the reduction in the amplitude of the GA induced by an AP gradient as a result of re-wiring the cap-cable connections. These results show that interference of the GA voltages from the EEG cap and ribbon cable greatly reduces the overall range of voltages induced in the EEG system by an AP gradient (average range 5790/2547 [phantom] 7951/3813 μV [subjects] before/after re-wiring). The negative voltages were reduced more than the positive voltages (79% compared with 43%) as a consequence of the non-linear distribution of voltages induced on the EEG cap due to slight differences in lead paths for different channels.

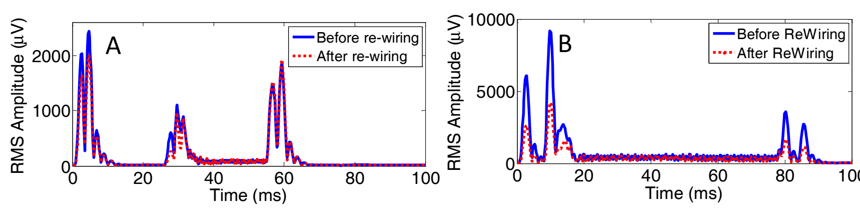

Fig. 3: Average RMS across leads of the average slice artefact before (blue) and after (red) re-wiring for axial EPI slice acquisition (A) and for coronal EPI slice acquisition (B) across all subjects.

Study 2: Figure 3 shows the average RMS over leads of the average induced GA over an EPI slice acquisition before and after re-wiring. For the axial acquisition (Fig 3A) the average RMS of the GA summed over 100 ms of the artefact on the subjects, resulted in a GA reduction from 482±21 μV using the standard configuration to 432±23 μV after re-wiring. For the coronal EPI acquisition, the slice orientation means that the AP gradient has a much greater influence on the overall GA, with the largest changes induced by the slice select and crusher gradients. This was reflected in the RMS of the artefact over time for coronal acquisition (Fig 3B) which on average was found to be reduced from 1575±18 μV before re-wiring to 761±14 μV after. The greatest advantage of re-wiring the conventional EEG cap is the large reduction of the range of the EEG signal recorded (the average range values over subjects for axial acquisition before/after modification were 12305±629/10523±1092 μV and for coronal acquisition were 31726±440/ 19120±84 μV). In the case of coronal acquisition two channels were saturated with the standard cable configuration, but there was no saturation after rewiring.

Conclusion: Interference between gradient artefacts induced in the EEG cap and in the cabling connecting the cap to the amplifier can be used to minimize the overall range and RMS amplitude of the GA. Here by modifying the connections of the EEG cap to a 1 m ribbon cable we were able to reduce the range of the GA for a high-resolution coronal EPI acquisition by a factor of ~ 1.7 and by a factor of ~ 1.2 for a standard axial EPI acquisition. These changes could potentially be translated into a reduction in the required dynamic range, an increase in the EEG bandwidth or an increase in the achievable image resolution without saturation, all of which could be beneficially exploited in EEG-fMRI studies. The re-wiring could also prevent the system from saturating when small subject movements occur using the standard recording bandwidth. Our focus here was on reducing the GA due to the AP gradient, but alternative cabling schemes which additionally reduce the overall GA from RL and FH gradients can also be envisaged, and will be explored in future work.

References: (**1**) W. X. Yan *et al,* NIMG 46, 459 (2009), (**2**) M. E. H. Chowdhury *et al,* ISMRM 2012, Abstract#2322, Australia, (**3**) K. J. Mullinger *et al,* Front. Neurosci. 8, 226 (2014), (**4**) P. J. Allen *et al,* NIMG 12, 230 (2000), (**5**) K. J. Mullinger *et al,* JoVE, 76, e50283 (2013).