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Technical Note

Reducing the gradient artefact in simultaneous EEG-fMRI by adjusting the subject's axial position

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ABSTRACT

Large artefacts that compromise EEG data quality are generated when electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) are carried out concurrently. The gradient artefact produced by the time-varying magnetic field gradients is the largest of these artefacts. Although average artefact correction (AAS) and related techniques can remove the majority of this artefact, the need to avoid amplifier saturation necessitates the use of a large dynamic range and strong low-pass filtering in EEG recording. Any intrinsic reduction in the gradient artefact amplitude would allow data with a higher bandwidth to be acquired without amplifier saturation, thus increasing the frequency range of neuronal activity that can be investigated using combined EEG-fMRI. Furthermore, gradient artefact correction methods assume a constant artefact morphology over time, so their performance is compromised by subject movement. Since the resulting, residual gradient artefacts can easily swamp signals from brain activity, any reduction in their amplitude would be highly advantageous for simultaneous EEG-fMRI studies. The aim of this work was to investigate whether adjustment of the subject's axial position in the MRI scanner can reduce the amplitude of the induced gradient artefact, before and after artefact correction using AAS. The variation in gradient artefact amplitude as a function of the subject's axial position was first investigated in six subjects by applying gradient pulses along the three Cartesian axes. The results of this study showed that a significant reduction in the gradient artefact magnitude can be achieved by shifting the subject axially by 4 cm towards the feet relative to the standard subject position (nasion at iso-centre). In a further study, the 4-cm shift was shown to produce a 40% reduction in the RMS amplitude (and a 31% reduction in the range) of the gradient artefact generated during the execution of a standard multi-slice, EPI sequence. By picking out signals occurring at harmonics of the slice acquisition frequency, it was also shown that the 4-cm shift led to a 36% reduction in the residual gradient artefact after AAS. Functional and anatomical MR data quality is not affected by the 4-cm shift, as the head remains in the homogeneous region of the static magnet field and gradients.

Introduction

Simultaneous electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) has become a widely used technique for studying brain activity. Applications of this technique are now far reaching, ranging from the study of brain networks associated with the resting state (Laufs et al., 2003) to the investigation of epileptic foci (Iannetti et al., 2002; Laufs and Duncan, 2007; Lemieux, 2004; Salek-Haddadi et al., 2002, 2003). Concurrent EEG-fMRI has also been extensively used to investigate the relationship between BOLD signal changes and evoked potentials (Debener et al., 2006; Eichele et al., 2005; Mobascher et al., 2009; Schubert et al., 2008; Strobel et al., 2008; Warbrick et al., 2009). The successful exploitation of the combined EEG-fMRI technique is remarkable given the very large artefacts that are generated in EEG data recorded during concurrent fMRI. The main confounding factors are the pulse artefact caused by pulsatile motion linked to the cardiac cycle (Allen et al., 1998; Debener et al., 2008; Ives et al., 1993; Yan et al., 2010) and the gradient artefact produced by the temporally varying magnetic fields required for MR imaging (Allen et al., 2000). Both of these artefacts are generally orders of magnitude larger than the neuronal activity of interest, but their inherent periodicity and known or measurable timings facilitate artefact correction by post-processing techniques, such as average artefact subtraction (AAS) (Allen et al., 1998, 2000). It is these techniques that underpin the successful implementation of combined EEG-fMRI.

Nevertheless, the contamination of raw EEG recordings made during continuous fMRI by artefact voltages that are many times larger than the signals of interest does pose a number of limitations on concurrent EEG recordings. These include the requirements for a large dynamic range and limited bandwidth. The disparity in the magnitude of the artefacts and signal of interest also means that very high

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performance in artefact correction is required, since a residual artefact can still completely swamp the neuronal signals, even if highly attenuated compared with the artefacts appearing in the uncorrected data. In this work, we focus on the gradient artefact, which is generally at least an order of magnitude larger than the pulse artefact, and describe a simple method, involving adjustment of the axial position of the subject, that can be used to reduce the amplitude of this artefact in the recorded data.

Use of the average artefact subtraction (AAS) technique, developed by Allen et al. (2000), to perform gradient artefact correction involves forming an average gradient artefact template and then subtracting this template from each occurrence of the gradient artefact in the EEG data. This requires accurate sampling of the gradient artefact waveform, which means that the artefact must be precisely sampled and smaller in magnitude than the dynamic range of the EEG system. The former requirement can be achieved through synchronisation of the MR scanner and EEG clocks (Mandelkow et al., 2006; Mullinger et al., 2008a), while the latter requires the use of an EEG system with a very high dynamic range and/or limiting of the amplitude of the gradient artefact.

The magnitude of the gradient artefact voltage depends on the rate of change of magnetic flux linked by loops effectively formed by the EEG leads and the conducting tissues of the head. To make an approximate estimate of the size of the gradient artefact, we assume an easily generated, average rate of change of magnetic field in the head of 20 T s^{-1} and an effective loop area of 50 cm^2. This yields an induced voltage of 100 mV, which is more than 10,000 times larger than a typical evoked response in an EEG recording. Accurate recording of EEG signals in the presence of such large artefact voltages would require a very large dynamic range and a large number of bits in signal digitisation. Fortunately, the power spectrum of the gradient artefacts is dominated by contributions that are much higher in frequency than the signals of most common interest in EEG recordings. This means that low-pass filtering can be used to reduce the gradient artefact voltages to a more manageable level in EEG recordings made during concurrent MRI without corrupting the EEG data. Hardware filtering of the voltages at the EEG amplifiers' inputs is usually therefore applied, and with a typical cut-off frequency of 250 Hz, the peak artefact voltage can be reduced by more than a factor ten, thereby reducing the dynamic range required to avoid amplifier saturation. With this level of filtering, it is still possible for typical gradient waveforms to cause amplifier saturation and further increases in the performance of the gradient systems used in MRI scanners will exacerbate this problem. Recording with a higher bandwidth provides benefits by allowing more accurate sampling of the rapidly varying gradient artefacts and is a necessity for those interested in measuring ultra-high frequency signals from the brain in combined EEG-fMRI experiments (Freyer et al., 2009). EEG systems incorporating hardware filters with a cut-of frequency of 1 kHz and higher are available, but they are more prone to saturation by the larger resulting gradient artefact voltages. In light of the above discussion, it can be seen that a reduction of the amplitude of the gradient artefact voltages produced during concurrent EEG/fMRI would be of significant value since it would allow a relaxation of the constraints on dynamic range and bandwidth that could be usefully exploited in many studies.

A further problem with the implementation of AAS and other techniques for gradient artefact correction arises when subject movement occurs during a study. Changes in subject position alter the morphology of the induced gradient artefacts, meaning that the artefact voltage waveforms recorded at each electrode vary over volume acquisitions. As a consequence, residual artefacts remain after AAS, since the average artefact template does not exactly characterise individual occurrences of the gradient artefact. This problem is often partially resolved by using a sliding time window to form the average artefact template (Allen et al., 2000; Becker et al., 2005). Moosmann et al. (2009) have recently taken this concept further, by using information about the occurrence of subject movements derived from the MRI realignment parameters, to guide the formation of templates, while Freyer et al. (2009) analysed the similarity of the artefact produced by a particular image acquisition to the artefacts generated during all other image acquisitions and then formed a varying correction template by weighted summation over a limited number of the most similar artefact waveforms.

Although these methods can improve the efficacy of artefact removal, the reduced number of repeated artefact waveforms that they may use in forming correction templates means that there is a greater risk that signals due to neuronal activity will be attenuated in the correction process (Mullinger et al., 2008b). Other sources of temporal instability in the generation or sampling of the gradient artefact voltages, including scanner timing errors and lack of synchronisation of the EEG sampling and gradient waveforms (Mandelkow et al., 2006; Mullinger et al., 2008a), also lead to partial failure of AAS. The large residual artefacts that arise as a consequence of this failure can easily overwhelm the signals of interest from the brain. Further digital filtering of the EEG data after artefact correction with AAS is therefore regularly employed to address this issue. This application of additional low-pass filtering, with a low-frequency cut-off that is often less than 80 Hz (Allen et al., 2000; Benar et al., 2007; Comi et al., 2005; Ertl et al., 2010; Gebhardt et al., 2008; Mayhew et al., 2010), restricts the range of brain signals that can be investigated in concurrent EEG-fMRI experiments. In particular, residual gradient artefacts can make recording activity across the gamma band (30–100 Hz) problematic in combined EEG-fMRI experiments (Ryali et al., 2009), while recording of ultra-high frequency activity currently requires interleaving of EEG and MRI data acquisition. Such interleaving can be achieved by using the stepping stone approach (Anami et al., 2003), but this requires non-standard modification of the imaging sequence used for fMRI data acquisition. Any steps that would reduce the intrinsic sensitivity to these residual gradient artefacts would therefore be highly beneficial for combined EEG-fMRI studies.

In recent work, we showed how the pattern of gradient artefacts induced on different leads by time-varying longitudinal and transverse gradients could be modelled analytically and numerically (Yan et al., 2009) based on knowledge of the lead paths and head position in the gradient fields. This modelling work provided some insight into ways in which the magnitude of the gradient artefact could be reduced. In particular, the models suggested that adjustment of the axial position of the subject's head in the scanner could reduce the overall amplitude of the gradient artefact. In essence, this involves positioning the subject so that the maximum rate of change of magnetic field produced by the time-varying gradients over the EEG leads is minimised. In the previous work (Yan et al., 2009), we partially confirmed the prediction of the simulations by measuring the gradient artefacts at two different axial positions but did not explore in any detail the benefits of subject repositioning for combined EEG-fMRI studies.

The aim of the study described here is therefore to measure the effects of the subject's axial position on the characteristics of the gradient artefacts and to assess the effect of optimal positioning on the residual artefact after AAS has been applied to data recorded during concurrent fMRI. The first part of the study focused on finding the axial position at which optimal reduction of the artefacts due to *x*-, *y*- and *z*- gradients is produced. This involved implementing a customised pulse sequence in which controlled gradient pulses were sequentially applied along the three Cartesian axes. In the second part of the study, we tested whether the gradient artefacts were reduced by adopting the optimal subject position in a typical EEG-fMRI experiment. We compared the gradient artefacts generated by a multi-slice EPI sequence (as used in the vast majority of fMRI experiments) when the subject was in the optimal axial position