Simultaneous EEG–fMRI: evaluating the effect of the cabling configuration on the gradient artefact

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Received 27 January 2015
Accepted for publication 23 February 2015
Published 3 June 2015

Abstract

EEG recordings made in combined EEG–fMRI studies are corrupted by gradient artefacts (GAs) resulting from the interaction of the EEG system with the time-varying magnetic field gradients used in MRI. The dominant contribution to the GA arises from interaction with the leads of the EEG cap and the human head, but artefacts are also produced in the cables used to connect the EEG cap to the amplifier. The aim of this study is to measure the effects of the connecting cable configuration on the characteristics of the GA. We measured the GA produced on two different cable configurations (a ribbon cable and a cable consisting of wires that are twisted together to form a cylindrical bundle) by gradient pulses applied on three orthogonal axes and also characterized the effect of each cable configuration on the GA generated by a multi-slice echo planar imaging sequence, as employed in typical EEG–fMRI studies. The results demonstrate that the cabling that connects the EEG cap to the amplifier can make a significant contribution to the GA recorded during EEG–fMRI studies. In particular, we demonstrate that the GA generated by a ribbon cable is larger than that produced using a twisted cable arrangement and that changes in the GA resulting from variation in the cable position are also greater for the ribbon cable.

Keywords: simultaneous EEG–fMRI, artefact correction, gradient artefact, cabling, ribbon cable

(Some figures may appear in colour only in the online journal)
1. Introduction

Simultaneous electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) allows investigation of brain activity with the high temporal resolution of EEG and the good spatial precision of fMRI. However, simultaneous EEG–fMRI measurements are technically challenging because the two techniques interfere with one another. The greatest problem for the successful implementation of simultaneous EEG–fMRI is the influence of the MR scanning on EEG signal quality. The gradient artefacts (GAs), produced by the interaction of the temporally varying magnetic field gradients with the EEG cabling and the electrically conducting structures in the human head (Allen et al 2000), are a significant confounding factor since the GA produced by standard fMRI sequences are many orders of magnitude larger than the neuronal signals. This means that the EEG amplifiers used in simultaneous EEG–fMRI experiments need to have a large dynamic range to accommodate the induced artefacts voltages without saturating. Since the strongest contributions to the GA occur at frequencies above a few hundred Hz, low-pass filtering, with a typical cut-off frequency of 250Hz, is generally applied at the amplifier’s inputs so as to reduce the GA significantly, without significantly corrupting the EEG data. Using such filtering, the peak GA voltage can be reduced by more than a factor ten. However, even with this level of filtering, it is still possible for typical gradient waveforms to cause amplifier saturation especially when using long EEG leads.

In the absence of saturation, the GA can be removed in post-processing by creating a template of the average artefact and subtracting this from each GA occurrence (Allen et al 2000). The large discrepancy between the magnitude of the artefacts and neuronal signals means that a very high degree of artefact correction is required, since a small residual artefact can easily swamp the neuronal signals. Problems in GA correction occur when the position of the subject’s head or of the EEG cabling changes during data acquisition, since changes in the positions of the wire paths with respect to the magnetic field gradients alters the GA. As a consequence, the average template no longer properly represents each occurrence of the GA and residual artefacts remain after correction using average artefact subtraction (AAS).

The above discussion indicates the motivation for finding methods to reduce the amplitude and variability of the GA at source. Yan et al (2009) previously showed how the pattern of GA induced on different leads could be modelled based on knowledge of the lead paths and head position in the gradient fields. This work suggested that a reduction in the magnitude and variability of the artefacts induced in the cabling could be achieved by using a twisted cable instead of the flat ribbon cable, currently employed by a leading EEG manufacturer, to complete the connection from the EEG cap to the amplifier. A twisted cable minimizes the effective area of cable wire loops, so that the rate of change of net magnetic flux produced by the time-varying magnetic field gradients is minimized (figures 1(a) and (b)). The aim of this experimental work is to measure the effects of the connecting cable configuration on the characteristics of the GA. Two, 1 m long cable configurations were studied: a ribbon cable in which the wires run in parallel, effectively forming loops of large area; and a cable consisting of wires that are twisted together to form a cylindrical bundle of around 1 cm diameter.

The first part of the study focused on measurement of GA amplitude for both cables using a customised pulse sequence in which controlled gradient pulses were sequentially applied along the three gradient axes. We then tested the effect of each cable configuration on the GA generated by a standard fMRI sequence, as used in typical EEG–fMRI studies.
2. Methods

Thirty-two channels of EEG data were recorded using a BrainAmp MR-plus EEG amplifier (Brain Products, Germany) with Vision Recorder (Version 1.10) in conjunction with a Philips Achieva 3 T MR scanner (Philips Medical Systems, The Netherlands). The EEG data were sampled at 5 kHz, with synchronization of the EEG and MR scanner clocks (Mandelkow et al 2006, Mullinger et al 2008a), and the trigger pulses from the MR scanner marking each slice acquisition were recorded by the EEG system.

A 1 m-long ribbon cable and a similar length twisted cable (figure 1(a)), both running axially along the centre of the magnet bore, were used to connect the EEG amplifier to the EEG cap. Both cables were attached to a wooden, cantilevered beam mounted on a stand placed on the floor of the scanner room so as to ensure that they were kept straight and isolated from scanner vibration. The ribbon cable was oriented such that the normal to the ribbon’s surface was in the AP direction. The EEG amplifier was isolated from scanner vibrations by sitting it on a table just outside the bore of the magnet (Mullinger et al 2008b). The EEG cap carried 31 electrodes following the extended international 10–20 system, with the reference electrode positioned at FCz. EEG recordings were made with the cap placed on a 19 cm-diameter-spherical agar phantom (fabrication as described by (Yan et al 2009)) and on the head of a human subject. The additional electrooculography (EOG) channel electrode was attached beneath the left eye of the subject.

2.1. Study 1

In order to assess how the cable configuration affected the magnitude of the GA produced by the three orthogonal gradients, EEG recordings were made during execution of a modified echo planar imaging (EPI) sequence, which incorporated three additional gradient pulses applied sequentially in the anterior–posterior (AP), right–left (RL), and foot–head (FH) directions prior to each slice acquisition, as described by Mullinger et al (2011). This experiment was carried out with the EEG cap on the agar phantom and the cable arrangements were positioned such that the phantom was placed at iso-centre in the FH and RL directions (equivalent to the z- and x-coordinates of the MR-system) and at a fixed position just below iso-centre in the AP direction. To characterize the effect of changes in cable position on the GA, recordings were made with each cable assembly located at two AP positions, separated by 5 mm. The EEG amplifier was operated with a frequency range of 0.016–1000 Hz to enable full characterization of the artefacts produced by the customized gradient pulses. The GA from thirty pulses applied along each gradient axes was recorded for each cable arrangement.
2.2. Study 2

To evaluate the effect of cable configuration on the GA generated in typical fMRI studies, EEG data were recorded during a standard EPI sequence. Data were acquired for both cables with the EEG cap on the head of a human subject (with approval from the local research ethics committee and informed consent of the volunteer). The subject was positioned such that the Fp1 and Fp2 electrodes coincided with the iso-centre of the scanner in the RL and FH directions. Data were again recorded with the cabling at two positions, separated by 5 mm in the AP direction. To prevent saturation of the EEG amplifiers, data were filtered to a frequency range of 0.016–250 Hz, as is typically used in EEG–fMRI studies. For each cable type and position, EEG data were recorded for a 2 min period while a standard axial, multi-slice EPI sequence (TR = 2 s, TE = 40 ms, 64 × 64 matrix, 3 mm isotropic resolution, flip angle = 85° and SENSE factor = 2) was executed. Twenty transverse slices were acquired with equidistant temporal spacing in each TR period.

3. Analysis

Initial data processing and analysis were carried out in Brain Vision Analyzer2 (Version 2.0.1; Brain Products, Germany) while MATLAB (The MathWorks) was used for further quantification of differences in induced GAs between cables and positions.

3.1. Study 1

Each gradient pulse in the customized EPI sequence commenced with a 10 ms period during which the gradient ramped up linearly to a value of 20 mT m−1 giving a rate of change of gradient, dG/dt, of 2 T m−1 s−1. This was followed 10 ms later by a 10 ms period during which the gradient ramped down to zero with dG/dt = −2 T m−1 s−1. To form a robust measure of the artefact voltage on each channel, the difference in the average voltage over the central 5 ms of the two ramp periods was evaluated (Mullinger et al 2011). The strength of the GA was characterized by calculating the range and the root-mean-square (RMS) amplitude of this measure across the 31 channels connected to scalp electrodes.

3.2. Study 2

EEG data were baseline corrected before calculation of the average slice artefact for each channel. The RMS amplitude of the voltages across channels was then calculated at each time point of the slice artefact waveform. To evaluate the change in the GA due to AP movement of the cabling, the difference of the average slice artefact waveforms recorded at the two positions was taken and the RMS of this difference waveform across channels was then calculated at each time-point. The RMS amplitude of the resulting difference waveform was also calculated over the 100 ms slice-TR-period so as to give a single measure of the GA produced for each cable type and position.

4. Results

4.1. Study 1

Figure 2 shows the variation with channel number of the GA voltage generated by the three orthogonal gradients when the ribbon (figure 2(a)) and twisted (figure 2(b)) cables were
Figure 2. Artefacts produced on different channels when the cables were connected to the EEG cap placed on the spherical agar phantom, and exposed to RL, AP and FH gradients varying at $2 \text{T m}^{-1} \text{s}^{-1}$.

(a) Ribbon cable positioned with 0 mm AP shift; (b) twisted cable positioned with 0 mm AP shift; (c) difference between voltages recorded using the two cables (figures (a) and (b)); difference between the voltages recorded at the two AP positions using the ribbon cable (d) and twisted cable (e).
connected to the 32-electrode EEG cap which had been placed on the phantom. The pattern of voltage variation with channel number is complex in both plots, reflecting the dominant effect of the voltages induced in the EEG leads and phantom. However, there are some differences in the artefact voltages for the two cables, particularly for the AP gradient, which result from the different contributions of the two cables to the GA. These produce small differences in the RMS voltage amplitude over leads for the ribbon/twisted cables, which took values of 1915/1918 µV, 1363/1212 µV and 678/704 µV for the RL, AP and FH gradients respectively. The effect of the cabling on the GA is more obvious in figure 2(c), which shows the result of taking the difference of the voltages generated when using the ribbon cable and the twisted cable (i.e. figures 2(a) and (b)), so that the voltages produced by the EEG cap are cancelled out. The difference is largest for the AP gradient and varies approximately linearly with channel number, spanning a range of 1623 µV. For comparison, the difference voltage ranges for the RL and FH gradients are 153 µV and 105 µV, respectively. Figures 2(d) and (e) show the difference in the GA voltages produced at the two different cable positions for the ribbon and twisted cables respectively. It is evident that the change in GA voltage produced by a 5 mm AP change in cable position is larger for the ribbon cable, particularly when the FH gradient is applied. The RMS amplitude of the voltage difference between positions for the ribbon/twisted cable took values of: 15/8 µV, 26/28 µV and 75/12 µV for the AP, RL and FH gradients, respectively. The voltage change produced by the shift in AP position of the ribbon cable shows a linear variation with channel number for the FH gradient spanning a range of 243 µV.

4.2. Study 2

Figure 3(a) shows the RMS amplitude of the voltage across channels recorded when the two different cables were connected to the EEG cap placed on the subject’s head and exposed to the gradients of the EPI sequence. The RMS amplitudes are generally smaller for the twisted cable than for the ribbon cable during the periods of peak artefact generation. This is reflected in the voltage ranges across time and channels, which take values of 8520/8161 µV for the ribbon cable/twisted cable. The effect of changes in cable position in the AP direction on the GA induced by the EPI sequence is shown in figure 3(b). This shows that the largest changes in artefact voltage due to cable movement occur at times when the slice select (−0–10 ms) and crusher gradients (−55–65 ms) are applied. These are also the times when the largest artefact voltages are generated (see figure 3(a)). It is also evident that the changes in GA due to changes in the AP position of the ribbon cable over these time ranges are much larger than those produced when the twisted cable’s AP position changes. The RMS and range values of the difference waveforms for the ribbon/twisted cables took values of 32/18 µV and 509/332 µV.

5. Discussion

The measurements reported here show that the cabling that is used to connect the EEG cap to the amplifier can make a significant contribution to the GA recorded during EEG–fMRI studies and that adjusting the form of this cabling can make a substantial difference to the amplitude of the induced artefacts. We argue below that the pattern of variation of the difference in the GA voltages in the ribbon and twisted cables (figure 2(c)) indicates that the artefacts induced in the ribbon cable are larger than those produced in the twisted cable. The measurements also show directly that changes in the GA resulting from changes in cable position are greater for the ribbon cable. These findings result from the fact that the magnetic flux linked
by the loops formed by the leads in the ribbon cable is much larger than that produced in the twisted cable when both cables are exposed to field gradients. Key features of the measurements are the largest differences in the GA voltages induced in the two cables result from application of the AP gradient (figure 2(c)), the largest changes in GA voltages with the AP position of the ribbon cable result from the FH gradient, and in both cases the relevant voltages show an approximately linear variation with channel number. In the experimental set-up used here, the lead that is connected to the reference electrode is positioned at the centre of the ribbon cable and the normal to the ribbon surface points in the AP direction (figure 1(b)). Consequently the loops formed by the wires in the ribbon cable lie in the x–z plane and thus mainly link flux resulting from the y-component of the magnetic field (i.e. the component of the field aligned with the AP direction). Magnetic fields with a significant y-component are present when the AP and FH gradients are applied: in the region where the field gradients are homogeneous $B_z = G_{yz}$ for the AP gradient ($B_z = G_{yz}$) and $B_z = -G_{yz}/2$ for the FH gradient ($B_z = G_{yz}$) is applied. Also, as shown in figure 1(b), the distance between individual wires
and the wire that is connected to the reference electrode varies linearly with channel number in the ribbon cable. Consequently the area of the loop formed by an individual wire and the reference wire also increases linearly with channel number, being large and positive for wire 1, changing polarity between wires 14 and 16 and taking a large negative value for wire 31. A linear variation of GA amplitude with channel number is therefore expected when a time-varying AP gradient is applied to the ribbon cable, as a result of the linear variation with channel number of the effective $x$–$z$ loop area in the cable, and hence of the average flux linked by $B_r$ along the length of the cable. No such ordered variation is expected in the twisted cable because of its more complex wire paths. The fact that the linear variation of voltage with channel number is strongly manifested in the plots of the difference in GA due to the AP gradient recorded with the two cables (figure 2(c)) indicates that the GA produced in the ribbon cable must be much larger than that produced in the twisted cable for this gradient. It is difficult to show the difference in GA amplitude in the two cables more directly since GA are induced in any conducting structures that are used to terminate the cables, so that any single measurement of the GA will always show the superposition of artefacts in the cabling and terminating structures (e.g. figures 2(a) and (b)). However it should be noted we generated similar difference plots to those shown in figure 2(c) when the cables were terminated using the Brain Products ‘signal tester box’ (data not shown).

The linear variation with channel number of the change in voltage induced by the FH gradient for an AP shift of the ribbon cable (figure 2(d)) can also be explained by the cable geometry. It results from the variation of $B_r$ with AP position that is produced by the FH gradient, which means that the average flux linked by each cable loop varies linearly with both channel number and AP position of the ribbon cable. Scaling the values shown in figure 2(d) indicates that changing the position of the ribbon cable by just 1 mm would produce a $\sim 30 \mu V$ change in the artefact voltage at the relatively low slew rate of $2 T m^{-1} s^{-1}$ (the gradient system of the scanner is capable of generating a slew rate of $200 T m^{-1} s^{-1}$).

The GA voltages generated by the different gradients when the cables are connected to the EEG cap on the conducting spherical phantom show complex patterns of variation with channel number (figures 2(a) and (b)). Although the EEG cap makes a larger contribution to the GA than the ribbon cable, the difference of the GA recorded using the two different cables (figure 2(c)) shows that the GA does contain a significant contribution from the cabling particularly, when the AP gradient is applied. By comparing the GA induced by the AP gradient in channels 1–5 and 27–31 for the two cable configurations (figures 2(a) and (b)) it is clear that the addition of the ribbon cable contribution significantly changes the amplitude of the artefact induced in these channels by the AP gradient and therefore will change the overall spatial distribution of the GA. This effect largely explains previously reported discrepancies between experimentally recorded and modelled GA data (Yan et al 2009).

The interaction of the artefact voltages induced in the ribbon cable and the EEG cap clearly depends on the design of the EEG cap and the correspondence of lead number in the ribbon cable and electrode position on the cap. Since this correspondence is arbitrary, we could potentially connect leads and electrodes in a way which minimizes the overall size of the GA. For example, since the largest positive (negative) voltages due to the AP gradient are produced on channels 1–5 (27–31) of the ribbon cable (figure 2(c)) and the largest negative (positive) voltages due to the same gradient interacting with the EEG cap are produced on the right (left) side of the head (see figure 7 (Yan et al 2009)), channels 1–5 (27–31) should be connected to the electrodes on the right (left) side of the head to minimize the overall magnitude of the GA due to the AP gradient. By reducing the maximum induced voltages in the EEG system in this way, the demands on amplifier dynamic range could be reduced. Further work is needed to explore how significant a reduction in GA range could be achieved using this approach.
The results obtained when recordings were made during execution of the EPI sequence (figure 3(a)) show that the RMS amplitude of the GA across channels is generally larger for the ribbon cable and this is particularly the case around times of 27–32 ms, when the pre-excision pulse is applied in the phase-encoding direction. This is expected, since phase-encoding was applied in the AP-direction in this experiment and the AP gradient generates the largest voltages in the ribbon cable (figure 2(c)). It is worth noting that the RMS amplitude of the artefact across channels generated around times of 55–65 ms is slightly larger for the twisted cable than for the ribbon cable. This is most likely because the artefact generated in the ribbon cable is opposite in sign to the artefact from the EEG cap on some channels, thus reducing the RMS amplitude. When the ribbon cable is moved by 5 mm in the AP direction while attached to the EEG cap on the subject’s head, the largest changes in the RMS artefact amplitude across channels occur around times of 0–10 ms, when the slice select gradients, are being played out and at times of 55–65 ms, when crusher gradient pulses are applied (figure 3(b)). This sensitivity arises because the largest changes in the voltages induced in the ribbon cable due to changes in AP position occur when a FH gradient is applied, and the EPI data were acquired here with axial slice orientation, meaning that the slice gradient was applied in the FH direction. The crusher gradients also include a strong contribution along the FH direction. Figure 3(b) indicates that small changes in the ribbon cable position can generate large variations in the GA induced by the EPI sequence. This variation would cause problems for artefact correction schemes such as AAS that require the artefact waveforms to be invariant across repeated EPI slice acquisitions. These plots make clear the importance of fixing the ribbon cable position in EEG–fMRI experiments so that large movements cannot occur and also so that the cabling does not move as a result of vibrations stemming from time-varying gradients or from the magnet cryo-cooler system. The arrangement used here, employing a cantilevered beam mounted on the floor of the scanner room, forms a straightforward way of limiting cable movement.

6. Conclusions

This work has shown that the form of cabling used to connect the EEG cap to the amplifiers can have a significant effect on the GA generated in EEG–fMRI experiments. In particular the GA induced in a ribbon cable can be much larger than those produced using a twisted cable in which the effective area of the loops that are sensitive to magnetic flux changes are much reduced. Using the twisted cable rather than the ribbon cable reduces the variation in the GA due to changes in cable position. This sensitivity to positional changes of the ribbon cable highlights the need to isolate this cable from all movement when performing EEG–fMRI experiments.

References

Allen P J et al 2000 A method for removing imaging artifact from continuous EEG recorded during functional MRI Neuroimage 12 230–9
Becker R et al 2005 Visual evoked potentials recovered from fMRI scan period Hum. Brain Mapp. 26 221–30
Debener S et al 2008 Properties of the ballistocardiogram artefact as revealed by EEG recordings at 1.5, 3 and 7T static magnetic field strength Int. J. Psychophysiol. 67 189–99
Krakow K et al 1999 EEG-triggered functional MRI of interictal epileptiform activity in patients with partial seizures Brain 122 1679–88
Lemieux L. et al 1997 Recording of EEG during fMRI experiments: patient safety Magn. Res. Med. 38 943–52
Mandelkow H et al 2006 Synchronisation facilitates removal of MRI artefacts from concurrent EEG recordings and increases usable bandwidth Neuroimage 32 1120–6
Mullinger K J et al 2008a Improved artefact correction for combined electroencephalography/functional MRI by means of synchronization and use of VCG recordings J. Magn. Reson. Imaging 27 607–16
Mullinger K J et al 2008b Exploring the feasibility of simultaneous EEG/fMRI at 7 T Magn. Reson. Imaging 26 968–77
Mullinger K J et al 2011 Reducing the gradient artefact in simultaneous EEG–fMRI by adjusting the subject’s axial position Neuroimage 54 1942–50
Mullinger K J et al 2012 Identifying the sources of the pulse artefact in EEG recordings made inside an MR scanner Neuroimage 71 75–83
Yan W X et al 2009 Understanding gradient artefacts in simultaneous EEG/fMRI Neuroimage 46 459–71
Yan W X et al 2010 Physical modeling of pulse artefact sources in simultaneous EEG/fMRI Hum. Brain Mapp. 31 604–20