Removing the gradient artefact caused by 3D EPI in simultaneous EEG-fMRI experiments using a gradient model fit.

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Introduction: EEG recordings made during fMRI are corrupted by gradient artefacts (GA) produced by the temporally-varying field gradients used in image acquisition. Average Artefact Subtraction (AAS) [1], which is the most widely used method for GA correction, requires the GA to be highly stable across repeated acquisitions of the sequence so that a representative average artefact template can be produced. As subject movements produce changes in the GA, it is important to form the template for GA correction over the shortest possible time window [2]. It is also beneficial to be able to average across a large number of repeats of the GA in forming the template in order to attenuate other signals (e.g. brain activity and pulse artefact). This is relatively straightforward for multi-slice, 2D-EPI acquisitions because the GA is nominally the same in every slice acquisition and thus repeats on a time scale of 0.1 s or less. In contrast, 3D-EPI sequences are problematic because they employ a pulsed phase-encoding (PE) gradient, which is applied in the slice direction with an amplitude that varies cyclically over successive EPI acquisitions. Consequently, the GA template for AAS has to span all of the TR-periods of the volume acquisition, which could be more than 10 s in total duration. This increases the probability that the GA morphology will significantly change between volume repetitions as a result of movement and thus makes it harder to include a significant number of averages in forming the template. Such effects have limited the use of MR sequences involving phase encoding during concurrent EEG-fMRI recording. This is unfortunate as 3D-EPI, used in conjunction with parallel imaging speed-up in two dimensions, can offer significant benefits for high spatial-resolution fMRI [3], opening up interesting possibilities for combined EEG-fMRI studies. Here, we therefore explore the use of the gradient model fit (GMF) method [4] in modelling and correcting the cyclically-varying GA due to the phase-encoding gradient in 3D-EPI (as well as the constant aspects of the artefact and the changes in the GA due to changes in head position which were considered previously [4]). The aim is to make feasible the implementation of simultaneous EEG-fMRI studies using 3D-EPI.

Theory: A model of the GA for each lead can be generated by recording the artefacts induced by the gradient and RF waveforms during a 3D-EPI sequence in which four of the five elements of the 3D-EPI sequence (read, blip, phase-encoding, slice and RF) are nulled in turn; thus providing five models per lead. Each model spans a single TR-period, and the artefact measured in any TR-period of the full 3D-EPI sequence will be formed from a superposition of the five models, with changes in the weightings of the different elements of the model reflecting cyclic-variation of the phase-encoding gradient and the effect of changes in head position on the GA [4]. The 3D-EPI GA can therefore be corrected by fitting the models to the GA measured in each TR-period and then subtracting the fit.

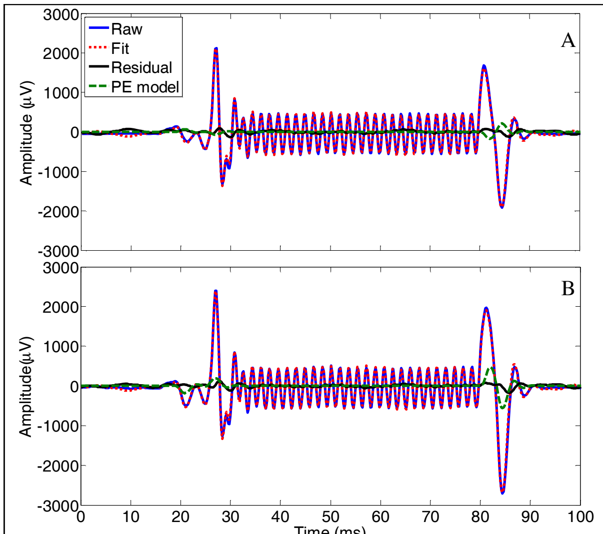

Fig. 1: GA from channel O2 (blue) acquired on the phantom during first (A) and last (B) TR period in volume acquisition with entire model (red) and phase-encode (green) fitted to each TR period. Black line show the residual artefact after GMF.

Methods: EEG recordings were made on a head-shaped agar phantom [5] and three subjects (with ethical approval) in a Philips Achieva 3T MR scanner using a Brain Products EEG system (32-channel cap, BrainAmp MR plus, 5 kHz sampling rate, with clock synchronization [6]). Data were acquired with a 0.016-250Hz frequency range to prevent amplifier saturation. A 3D-EPI pulse sequence was customized so that the five artefact waveforms (read, blip, PE, slice and RF) could be individually recorded at the start of the scan. 612 repeats of each of these waveforms (each spanning one TR-period) were acquired, prior to acquisition of 66 volumes of standard 3D-EPI data (80 slices, 102 PE steps, 160×160 matrix, 1.5mm isotropic resolution, TR/TE = 100/40ms, SENSE factor = 2.3).

Analysis: Models of the four GA components and the RF artefact were formed in MATLAB by averaging over repeats acquired at the beginning of the sequence and subsequently performing a weighted-average over channels. The models were used to form a General Linear Model (GLM) which was then adaptively fitted to each repetition (TR-period) on each channel in the EEG data. This contained an additional sixth model which was of constant amplitude to model any variations in baseline [4]. A regularised least-squares fit was calculated and used to estimate the scaling parameters for each component. The model waveforms were then scaled and subtracted from the EEG data for the corresponding TR-period. AAS was applied using Analyzer2 (Brain Products) after GMF to remove any residual GA which was constant over TR-periods. This was done by forming a sliding template over TR-periods (102 averages, one volume repetition), assuming that GA changes due to the PE gradient and subject movement had been removed by the GMF correction.

For comparison of the GMF-AAS method against a standard correction method, AAS was also applied to the raw EEG data using a template formed by averaging over all (66) volume artefacts (since the PE gradient prevents averaging over shorter repetition periods). After correction of the GA using each of the methods, the pulse artefact was also corrected using AAS for the subject data. The relative performance of each method was assessed by focussing on the 10 Hz harmonics of the GA. The attenuation of the power at each harmonic using either correction method (GMF-AAS or conventional AAS) compared with the raw data was found for each channel then averaged over channels and subjects.

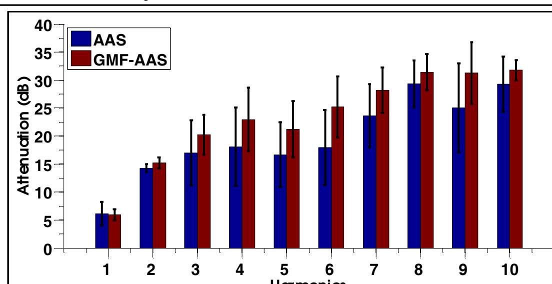

Fig. 2: Attenuation of the raw signal power using conventional AAS (blue) and GMF-AAS (red) for artefact correction for first 10 ten harmonics of the GA (occurring at multiples of TR^{-1} = 10 Hz), averaged over channels and subjects. Error bars: standard deviation over subjects.

Results and Discussion: Figure 1 shows the raw data (blue) acquired from a single channel (O2) on the phantom during two different TR-periods within a volume acquisition, along with the overall model fit (red). The small residuals (black) indicate the excellent fit that was achieved for both TR-periods despite the clear difference in the form of the GA due to the different PE gradient amplitudes. The difference is particularly evident from the scaled models of the PE GA (green) formed in the two TR-periods, which show features linked to PE around t = 30 ms and to phase-rewinding around t = 80 ms; the PE model weighting changed by a factor of -2.69 across these TR-periods. The greater artefact attenuation achieved when using GMF-AAS compared with AAS is shown in Figure 2 for the data from the human subjects. The improvement in GA correction was consistent over the harmonics of the GA up to 100 Hz for all subjects. These results show that the GMF approach can be used to correct GA in EEG recordings made during execution of a high-resolution 3D-EPI sequence, and that the combination of GMF-AAS provides better artefact attenuation than use of AAS with a template spanning the whole volume acquisition. It is worth noting that the approach described here can also potentially open up the use of other MRI sequences involving PE in EEG-fMRI studies.

References: **[1]** Allen *et al.* Neuroimage 12:230, 2000, [**2**] Mullinger *et al.* Neuroimage 54:1942, 2011 [**3**] Poser *et al.* Neuroimage 51:261, 2010, [**4**] Spencer *et al,* ISMRM, abstract#2083, Australia (2012), [**5**] Yan *et al,* NIMG 46, 459 (2009); [**6**] Mandelkow *et al.* Neuroimage 32:1120, 2006.