Removal of Gradient Artefacts during Transient Head Movements for Continuous EEG-fMRI

José L. Ferreira[1], Ronald M. Aarts[1,2] and Pierre J. M. Cluitmans[1,3]
[1]*Department of Electrical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands*
[2]*Philips Research Laboratories Eindhoven, Eindhoven, The Netherlands*
[3]*Kempenhaeghe Epilepsy Center, Heeze, The Netherlands*

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Abstract: This paper presents a novel approach for removing gradient artefacts from the EEG signal recorded during continuous EEG-fMRI, which are influenced by transient head movements of the subject within the magnetic scanner. Transient head movements provoke abrupt changes in the gradient artefact waveform, in such a way that they compromise the estimation of an artefact waveform to be subtracted and achieve the EEG correction. According to our proposed methodology, a cubic spline waveform is used to model and represent the signal transitions components. This model is then used to change and approximate the shape of the EEG signal as homogeneous data, in order to improve the performance of the gradient artefact correction technique. The proposed approach also makes use of the signal slope adaption (SSD) method, combined with sum-of-sinusoids modelling for correction of the gradient artefact. Our methodology reveals to perform a robust and satisfactory removal of gradient artefacts under the occurrence of abrupt transient head movements.

1 INTRODUCTION

Albeit combination of EEG-fMRI constitutes a powerful and promising tool for brain activity mapping as well as cognitive studies and research, the occurrence of artefacts in the EEG signal still represents a challenge to be overcome in order to consolidate and broaden the range of application of such a technique (Moosmann et al., 2009; Ritter et al., 2010; De Munck et al., 2013). It is the case of the gradient or imaging acquisition artefact, which is induced in the electroencephalogram by the rapidly varying gradient magnetic fields of the fMRI equipment (Ritter et al., 2010). The gradient artefact has amplitudes (up to 10^4 μV) that can be much larger than those of the clinical EEG (up to 300 μV). It possesses a characteristic waveform, which is approximately the differential waveform of the gradient magnetic fields that originate the artefact (Anami et al., 2003; Ritter et al., 2010; Olson, 2010).

Because of the periodic and stationary nature of the gradient artefact waveform, correction methods based upon subtraction in time-domain and its variants have been proposed and successfully employed for artefact correction and subsequent EEG restoration (Allen, et al. 2000; Garreffa et al. 2003; Gonçalves et al., 2007; De Munck et al., 2013). In this way, the established average artefact subtraction (AAS) methodology proposed by Allen et al. (2000) has proven to be very effective for cleaning up imaging artefacts. However, as discussed by Yan et al. (2009), head motions of the subject within the fMRI scanner compromise its efficacy because of the alterations and transients that are inserted in the artefact waveform. Thereby, the averaging process results in an inaccurate estimation of the artefact template (Sun and Hinrichs, 2009; Koskinen and Vartiainen, 2009), which leads to arising residual artefacts in the corrected EEG.

The usage of a sliding average artefact template achieves to minimize this problem, decreasing the probability of movement within a particular averaging window. Nevertheless, in addition to increasing the risk of subtraction of a clinical event of interest of the EEG signal, the windows which coincide with the movement continue locally altered by using this approach (Yan et al., 2009). In order to circumvent that problem, Moosmann et al. (2009)

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propose a correction procedure that uses information related to head movement parameters from the fMRI to improve the accuracy of the artefact template. In the same way, Sun and Hinrichs (2009) describe a method whereby the considered epochs for template averaging are selected by weighting factors that account the influence of the head position and movement on the artefact shape. However, under the occurrence of abrupt head movements, the artefact correction obtained by those approaches could not achieve accurate artefact template estimation as well (Moosmann et al., 2009; Sun and Hinrichs, 2009). Moosmann et al. (2009) even mention the strong need for development of other correction methods which take the occurrence of abrupt head motions into account during simultaneous EEG-fMRI.

2 OBJECTIVES

Instead of using an artefact average template, Ferreira et al. (2013a) propose a gradient artefact correction methodology whereby the gradient artefact waveform is approximated by the sum of a set of sinusoids. According to Niazy et al. (2005), artefact frequencies overlap the EEG bandwidth in discrete harmonic frequency intervals (or frequency bins) whose fundamental corresponds to the inverse of the MR echo-planar slice time (*ST*) parameter. Such frequency components can be modelled as a sum of sinusoids waveforms which are then subtracted to obtaining the EEG restoration (El-Tatar and Fokapu, 2011; Ferreira et al., 2013a). An advantage of using such a modelling approach is that it does not require extensive calculation of MR parameters as well as time-alignment of the internal clocks of the EEG and fMRI equipments. Furthermore, estimation of the average waveform is not based upon an averaging process, in addition to predicting the artefact waveform variability over the time (Ferreira et al. 2013a).

The objectives of this paper are to investigate and adapt the methodology proposed by Ferreira et al. (2013a) for correction of gradient artefacts affected by abrupt signal transients provoked by head movements. In this way, we have proposed to model and represent those signal transients as cubic splines curves, which are used to modify and approximate the shape of the EEG as homogeneous data. This approach shows to improve the performance of the gradient artefact correction, as described in the sections Materials and Methods and Results. Moreover, the proposed methodology reveals itself to be robust to such signal transitions, as shown in the section Results.

3 MATERIALS AND METHODS

3.1 Subjects

The EEG recordings were collected simultaneously with the fMRI data for a research focused on epilepsy and post-traumatic stress disorder (PTSD) (Van Liempt et al., 2011; Ferreira et al., 2012; Ferreira et al., 2013a), jointly developed by the department of Psychiatry of Universiteit Medisch Centrum Utrecht, the Research Centre Military Mental Health Care in the Dutch Central Military Hospital in Utrecht, and the Department of Research and Development of the Kempenhaeghe Epilepsy Center in Heeze, The Netherlands.

The data were recorded from military veterans with PTSD which were in mission abroad through the outpatient clinic of the Military Mental Health Care. All participants were male and aged between 18 and 60 years.

3.2 Characteristics of the Used Data

Functional magnetic resonance imaging scanning was carried out using a 3 T Scanner (Philips, Eindhoven, The Netherlands) at Kempenhaeghe Epilepsy Center. An MRI-compatible 64 channel polysomnograph (MRI 64, MicroMed, Treviso, Italy) was used to collect one ECG channel, two EOG channels, one EMG channel and 60 EEG channels.

The subjects were scanned using a functional echo-planar imaging sequence with 33 transversal slices (thickness 3 mm, TE 30 ms, TR 2500 ms). EEG electrodes positioning was in accordance with the international 10-20 system electrodes placement. The sampling rate for signal acquiring was 2048 Hz (Ferreira et al., 2012).

3.3 Proposed Methodology for Signal Transients Modelling and Gradient Artefact Removal

Representative raw EEG excerpts containing abrupt transients caused by subject head movements were selected and processed in accordance with the algorithm block diagram of figure 1. Each step of the algorithm was implemented and applied to the EEG data in MATLAB environment.

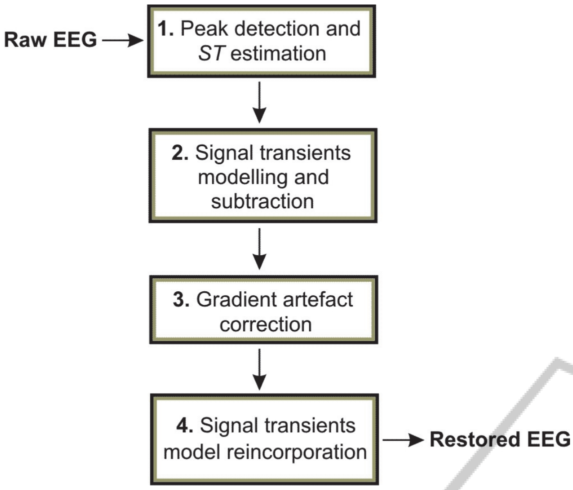

Figure 1: Block diagram structure of the proposed methodology for gradient artefact correction under transient head movements.

3.3.1 Peak Detection and *ST* Estimation

Implementation of the methodology illustrated in figure 1 requires the initial detection of the typical gradient artefact peaks, which are observed in the raw EEG data recorded within the MR scanner. Such detection is necessary for implementation of the signal transients modelling (step 2 of figure 1). Localization of those peaks are important for estimation of the echo-planar slice time (*ST*) as well, parameter used during the gradient artefact correction methodology proposed by Ferreira et al. (2013a) and applied in the step 3 of figure 1.

In order to detect the peaks, we used the peak detection algorithms proposed by Garreffa et al. (2003). Because of the EEG excerpts under analysis were contaminated with transients, making difficult the correct localization of the peaks, we have used the ECG signal recorded simultaneously with the EEG channels to perform the peak detection, as performed by Ferreira et al. (2012).

For the data under analysis, the value of *ST* was estimated at 155 ± 1 samples, which corresponds to the time interval of 75.68 ± 0.50 ms (Ferreira et al., 2012). The length of the raw EEG window was set as 32 × 155 samples (Ferreira et al., 2013a).

3.3.2 Signal Transients Modelling and Subtraction

The following equation was taken into account for representation of the raw EEG signal ($\mathbf{EEG_{raw}}$):

$$\mathbf{EEG}_{\mathbf{raw}} = \mathbf{EEG}_{\mathbf{true}} + \mathbf{S}_{\mathbf{trans}} + \mathbf{S}_{\mathbf{art}}, \qquad (1)$$

where $\mathbf{EEG_{true}}$ corresponds to the true EEG signal; $\mathbf{S_{trans}}$ corresponds to the signal transients introduced by the head movement; and $\mathbf{S_{art}}$ is the gradient artefact.

In order to model the signal transients, the EEG excerpts were divided into epochs (slices) whose length is equal to the time between the gradient artefacts peaks, *ST* (155 ± 1 samples), observed in the raw EEG. Afterwards, we have taken into account to average all samples of each epoch separately. Making the assumption that the gradient artefact waveform is stationary (i.e., it can be considered a slowly varying process from epoch to epoch) and has zero mean, that average only would run over values associated with the EEG signal and the signal transients. Thereby, the resulting average values associated with each epoch would correspond to the mean variation of the signal transients and low-frequency components related to the true EEG signal, from epoch to epoch. Figure 2a illustrates the implementation of such a procedure. The illustrative raw EEG excerpt shown in this figure was extracted from the recordings of one subject, electrode position F8:

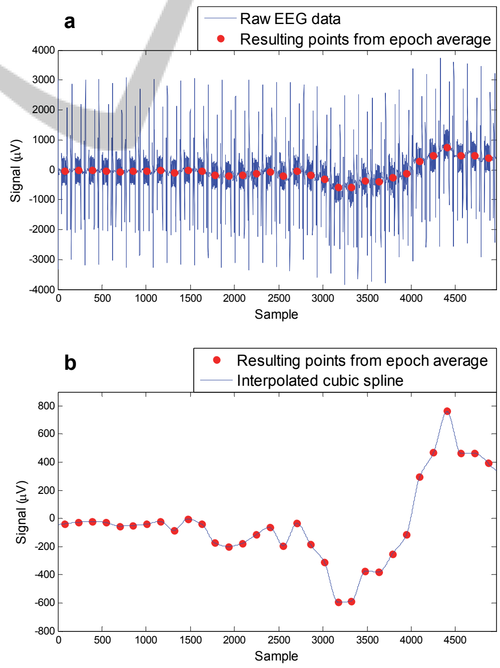

Figure 2: (a) Raw EEG data (blue trace) and resulting values from averaging of each epoch (red points); (b) resulting values from averaging each epoch (red points), approximated by a cubic spline curve (blue trace).

The average values were plotted in the middle of each epoch (red points). Such points have been plotted in figure 2b as well, together with a cubic spline curve which was used to fit those points in a time continuous sense. According to Wolberg and Alfy (1999), cubic splines are very useful to fit a smooth continuous curve to discrete data. The usage of cubic splines as interpolants is especially attractive because they make use of piecewise polynomials with low-order to interpolate the data. Moreover, the data can be modelled by respecting constraints of smoothness and monotonicity. The usage of cubic splines was proposed by Koskinen and Vartiainen (2009) to improve the artefact template estimation during application of the AAS method (Allen et al., 2000).

Therefore, the fitted spline also corresponds to the mean variation of the signal transients and low-frequency components associated with the true EEG signal from epoch to epoch. In turn, the frequency activity associated with the gradient artefact and the true EEG high-frequency components are contained in the signal resulting from the subtraction of the spline from the raw EEG of figure 2a. Such characteristics can be observed in figure 3.

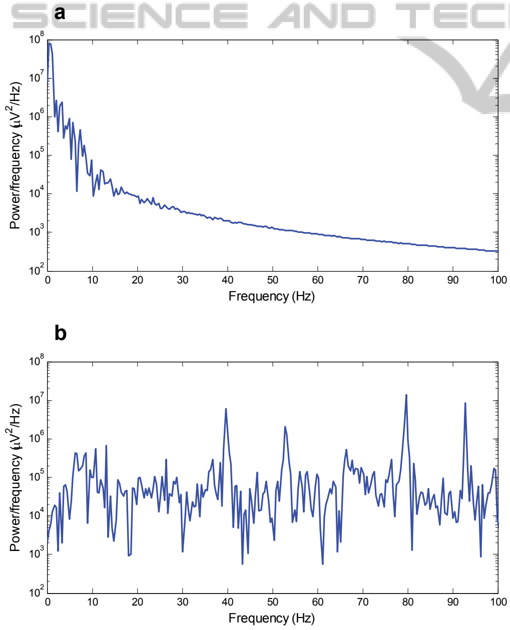

Figure 3: (a) Power spectrum of the fitted spline curve shown in figure 2b; (b) power spectrum of the subtraction of such a spline from the raw EEG of figure 2a. The gradient artefact frequencies are contained in (b).

Thereby, although transients in the EEG signal caused by abrupt head movements possess strong high-frequency components, they can be characterized as low-frequency activity in comparison with the gradient artefact frequency components. Hence, equation (1) was changed to equation (2):

$$\mathbf{EEG}_{\mathbf{raw}} = \mathbf{S}_{\mathbf{p}} + \mathbf{S}_{\mathbf{h}}, \tag{2}$$

where $\mathbf{S}_{\mathbf{p}}$ is the fitted spline, which corresponds to the sum of the signal transients $\mathbf{S}_{\mathbf{trans}}$ and the low-frequency components of the $\mathbf{EEG}_{\mathbf{true}}$; and $\mathbf{S}_{\mathbf{h}}$ corresponds to the sum of the gradient artefact $\mathbf{S}_{\mathbf{art}}$ and the high-frequency components of the $\mathbf{EEG}_{\mathbf{true}}$.

Therefore, according to equation (2) and figure 3, the gradient artefact correction should be applied uniquely in the signal $\mathbf{S}_{\mathbf{h}}$, which is the component of the raw EEG that, in fact, contains the artefact activity. Thus, there is no need to apply such correction in the $\mathbf{S}_{\mathbf{p}}$, in such a way that the inaccuracies introduced by the signal transients caused by the subject head movements during the application of the gradient artefact approach can be minimized.

To fit the cubic spline curve shown in figure 2, we have used the piecewise cubic Hermite interpolation method (Kreyszig, 2011; Fritsch and Carlson, 1980). According to the Hermite interpolation setup, given two points (x_j, y_j) and (x_{j+1}, y_{j+1}), they are linked by the cubic interpolating polynomial $H_j(x)$ with the following constraints:

$$\begin{aligned} H_j(x_j) &= y_j, \\ H_j(x_{j+1}) &= y_{j+1}, \\ H'_j(x_j) &= y'_j, \\ H'_j(x_{j+1}) &= y'_{j+1}. \end{aligned} \tag{3}$$

$H_j(x)$ is described as $(x_j \le x \le x_{j+1})$:

$$\begin{aligned} H_j(x) = a_j + b_j(x - x_j) + c_j(x - x_j)^2 \\ + d_j(x - x_j)^2(x - x_{j+1}), \end{aligned} \tag{4}$$

where the coefficients a_j, b_j, c_j, and d_j are calculated by taking into account the values of x_j, x_{j+1}, y_j, y_{j+1}, and certain slopes y'_j and y'_{j+1} at the two segment endpoints. These slopes are chosen in such a way that the shape and monotonicity within the data are respected. Finally, the piecewise interpolant is found by joining the J local cubic interpolants:

$$H(x) = \sum_{j=1}^{J} H_j(x). \tag{5}$$

In MATLAB, we have implemented the cubic Hermite interpolation method using the routine ‘`pchip`’.

3.3.3 Gradient Artefact Correction

As mentioned above, we used the gradient artefact correction methodology proposed by Ferreira et al. (2013a).

According to this method, initially a non-linear filter based upon the signal slope adaption (SSD) approach (Ferreira et al., 2013b; Ferreira et al., 2013c) is applied to the raw EEG in order to remove artefact high-frequency components. Here, we have applied this filter directly to the signal $\mathbf{S_h}$, as suggested earlier.

Because of such a filter is based upon the difference between consecutive samples of the signal, we observed that large signal slopes associated with abrupt signal transients affect the computational performance of the filtering processing. In similar way, estimation of the frequency components associated with the sum-of-sinusoids model (Ferreira et al., 2013a) can be affected by undesirable frequency activities inserted by those transients. We noticed that such drawbacks are minimized by using the signal $\mathbf{S_h}$ instead of the raw EEG, during carrying out the gradient artefact correction.

The resulting signal after removal of the gradient artefact constitutes the signal $\mathbf{EEG_{corct}}$.

3.3.4 Signal Transients Model Reincorporation

As the fitted spline model contains low-frequency components associated with the EEG signal, the signal $\mathbf{S_p}$ cannot be left out of the estimation of the restored EEG, $\mathbf{EEG_{rest}}$, but it must be reincorporated, as follows:

$$\mathbf{EEG_{rest}} = \mathbf{EEG_{corct}} + \mathbf{S_p}\,. \tag{6}$$

Therefore, the proposed methodology is specifically addressed to remove the gradient artefacts from the raw EEG. Thus, the baseline associated with the signal transients still remains in the restored EEG.

4 RESULTS

Figures 4 and 5 illustrate the application of the proposed methodology to remove the gradient artefact from the raw EEG excerpt of figure 2. In figure 4a, the raw EEG was reproduced from figure 2. It can be noticed that the beginning of the abrupt transient in this signal occurs around 188.5 s.

Figure 4b shows the signal $\mathbf{S_h}$, resulting from the subtraction of the fitted spline from the raw EEG. It can be noticed that $\mathbf{S_h}$ approximately possesses the shape of homogeneous data (i.e., data without abrupt transients caused by head movements) in comparison with the raw EEG signal. This fact, therefore, enables minimization of the influence of the signal transient components on estimation of the artefact waveform. In consequence, application of the gradient correction technique is performed in a more accurate way.

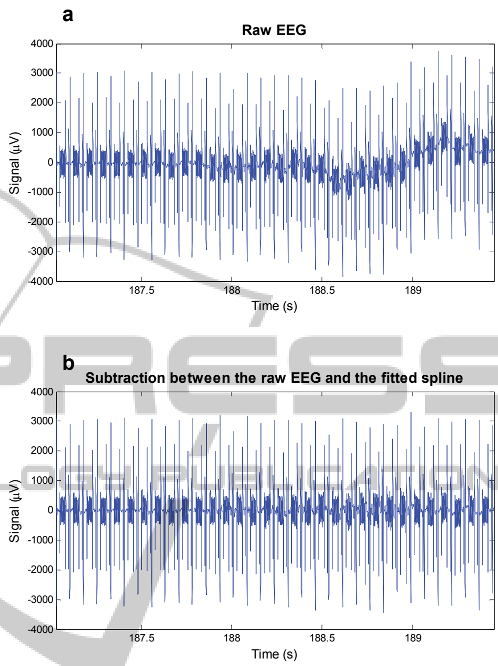

Figure 4: (a) Raw EEG data; (b) signal $\mathbf{S_h}$ resulting from the subtraction of the fitted spline curve depicted in figure 2b from the raw EEG. The signal $\mathbf{S_h}$ possesses an approximated homogeneous data shape in comparison with the raw EEG of (a).

In figure 5, the restored EEG after application of the proposed methodology is depicted. It can be observed that the gradient artefact was cleaned up. In figure 6, the restored EEG signal and the fitted spline are superimposed for comparison purposes. As can be observed, such curves are quite similar, with a cross-correlation equal to 0.995. This fact indicates that the restored EEG signal contains weak frequency activity associated with $\mathbf{S_h}$. It also confirms the idea that the points resulting from the average of each epoch (and the respective fitted spline) correspond to the mean variation of the signal transients and low-frequency components associated with the EEG signal, from epoch to epoch, as assumed during implementation of our approach.

Figure 7 depicts the power spectrum of the restored EEG. The frequency activity associated with the gradient artefact (figure 3b) was effectively attenuated. Finally, figure 8 reveals that the usage of

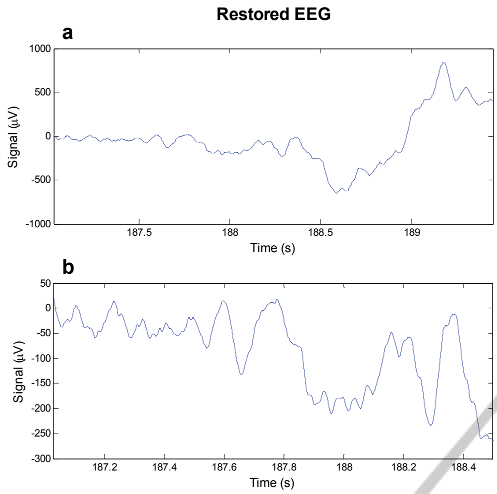

Figure 5: (a) Restored EEG data after application of the methodology depicted in figure 1; (b) Zooming in the signal (a) around 187.7 s.

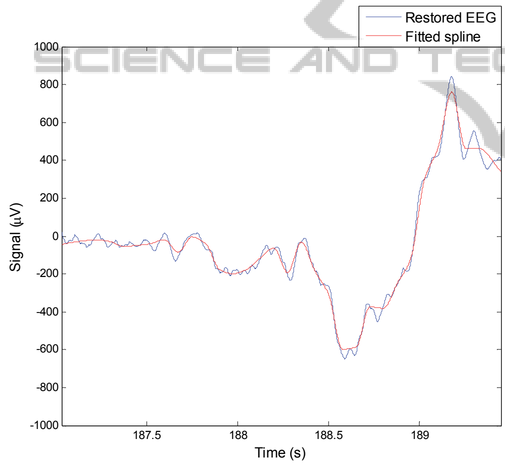

Figure 6: Restored EEG signal (blue trace) and fitted cubic spline curve (red trace). The cross-correlation between these curves is equal to 0.995.

the cubic spline for representation of the signal transitions can be employed to improve the gradient artefact correction obtained by the AAS method (Allen et al., 2000, Moosmann et al., 2009). For evaluation of this case scenario, we used this approach in the step 3 of figure 1 as well, after application of the non-linear filter by SSD (Ferreira et al., 2013b; Ferreira et al., 2013c) in the signals of figure 4. Taking into account the signal of figure 4b, it can be noticed that the EEG restoration obtained by both correction methods are quite similar (figure 8). In turn, considering only the AAS method, the artefact interference without subtraction of the spline was estimated at 21 μV pk-pk, whereas such interference was reduced to 13 μV pk-pk by performing the subtraction of the $\mathbf{S_p}$. Therefore, the subtraction of the spline proves to attenuate alterations or inaccuracies introduced in the artefact waveform estimative by the signal transients.

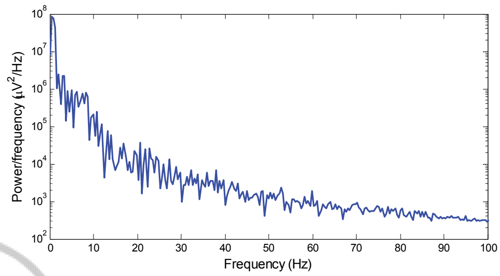

Figure 7: Power spectrum of the restored EEG signal.

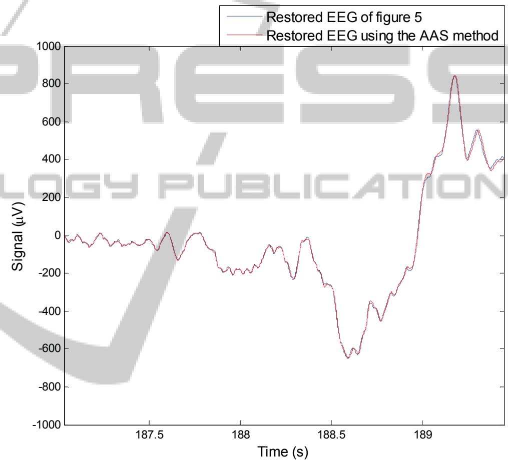

Figure 8: Restored EEG signal of figure 5 (blue trace) and restored EEG signal by the AAS method (red trace).

5 DISCUSSION

A number of approaches have achieved a satisfactory removal of gradient artefacts from the EEG signal recorded within the fMRI scanner during the occurrence of subject head movements. Nevertheless, the development of further correction techniques is still demanded to improve the quality of the EEG restoration in case of abrupt transients caused by the head motions (Moosmann et al., 2009; Sun and Hinrichs, 2009).

In this sense, we have proposed to model those signal transients by averaging the samples of each epoch into which the raw EEG was divided (figure 2). Such procedure also represents a moving-average filtering process of *ST* samples, which removes high-frequency components from the raw EEG, including those ones related to the gradient artefact activity. Hence, the cubic spline used to fit the resulting values from epoch averaging contains low-frequency components associated with the EEG signal and the signal transients per se, as depicted in figures 3 and 6.

As shown in figure 4, the representation of the signal transitions by cubic splines and the subtraction of the respective model from the raw EEG allow the data obtaining a homogeneous shape. This fact yields to improve the performance of the gradient artefact correction method by its application in the signal $\mathbf{S_h}$, instead of the raw EEG, which makes it robust to the signal transients. Hence, as shown in figure 5 and 7, application of the proposed approach achieves an effective removal of the gradient artefact under the occurrence of signal transitions caused by head movements.

Therefore, the subtraction and reincorporation of the spline model from the raw EEG data, according to the methodology depicted in figure 1, act as an artifice to preserve the signal transients and EEG low-frequency signal components from an unnecessary processing by the artefact correction method. The transients are responsible to introduce inaccuracies and alterations in the artefact waveform estimative and, in consequence, in the restored EEG (Yan et al., 2009). We have noticed that the proposed procedure is even useful during the occurrence of longer lasting head movements and homogeneous data correction. An additional advantage associated with using the cubic spline modelling is that eventual outliers which could be obscured in the epoch averaging process can be inserted in the interpolated curve as well, depending on the need, in order to obtaining a better representation of the signal transients. Those characteristics shall be better evaluated in future work.

It is noteworthy that instead of using splines, application of a low-pass filter in the raw EEG does not show to be adequate during implementation of the proposed methodology. The higher the cut-off frequency of the filter, the more is the amount of gradient artefact frequency components which remains in the signal $\mathbf{S_p}$, in case of using low-pass filtering. Thereby, the gradient correction method should be applied in $\mathbf{S_p}$ as well. On the other hand, a low cut-off frequency provokes insertion of frequency components associated with the transients in the signal $\mathbf{S_h}$, in such a way that those inaccuracies could continue being introduced in the restored EEG during the application of the gradient artefact correction approach.

Another advantage observed within application of the methodology described in figure 1 is that it does not require additional information associated with the head movements, quantified by using sensors or related to the fMRI equipment. Rather, according to the approach proposed in this work, such information is directly inferred from the EEG data during the signal transients modelling (step 2 of figure 1).

As shown in figure 8, the restored EEG of figure 5 and the restoration obtained by the application of the AAS method (Allen et al., 2000) in the step 3 of figure 1 are quite similar. Therefore, it indicates that the cubic spline can be employed for a satisfactory EEG restoration by the AAS method as well, during the occurrence of abrupt subject head motions. As a further suggestion for future work, the usage of the cubic spline for signal transients modelling shall be assessed within the application of other artefact correction methodologies.

6 CONCLUSIONS

In this work, we have proposed a novel method for removing gradient artefacts from the EEG signal recorded within the fMRI scanner under the occurrence of abrupt subject head movements.

The proposed approach makes use of a cubic spline curve to model signal transients caused by the head motions. The subtraction and reincorporation of such a model is used to change the EEG data shape, which reveals to improve the performance of the employed gradient artefact correction method.

Our methodology shows to perform an effective and robust removal of the gradient artefact from the EEG signal during the occurrence of abrupt signal transients caused by head movements. Therefore, such an approach constitutes a promising tool for a satisfactory EEG correction within studies and patients in scenarios in which it is difficult to prevent those types of movements.

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