UNI- AND MULTI-VARIATE COHERENCE-BASED DETECTION APPLIED TO EEG DURING SOMATOSENSORY STIMULATION

A.F.C. Infantosi, D.B. Melges, A.M.F.L. Miranda de Sá and M. Cagy

Biomedical Engineering Program, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
PO Box 68510, Zip Code 21941-972

afci@peb.ufrj.br, dmelges@peb.ufrj.br, amflms@peb.ufrj.br, mcagy@peb.ufrj.br

Abstract: The Magnitude-Squared Coherence (MSC) and Multiple Coherence (MC) were applied to EEG signals during somatosensory stimulation of the right posterior tibial nerve (at motor threshold) acquired from derivations [Fpz'-Cz'] and [C3'-C4'] of 10 adult volunteers. Detection was identified based on the null hypothesis of response absence rejection – when the estimates exceed the respective critical values (significance level $\alpha = 0.05$ and $M = 100$ epochs). By considering the frequencies from 30 to 60 Hz, the maximum detection percentage with MSC was in 90% of volunteers for [Fpz'-Cz'], 70% for [C3'-C4'] and 100% with MC (36.8-57.9 Hz). The latter rate was also reached when both derivations are considered together but just at 42.1 Hz. Hence, both techniques could be considered suitable for somatosensory evoked potential detection.

Introduction

The Somatosensory Evoked Potential (SEP) has been used in the clinical diagnostics and monitoring during surgical procedures, such as carotid endarterectomy [1] and spinal cord surgery [2], to name a few. During surgeries, the patient status changes are evaluated based on percentage variations of the pre-operative SEP amplitude and/or latency [3]. This analysis is conducted by visual inspection of the coherent (stimulus-synchronized) average of a number of post-stimulus epochs. Hence, since this method depends on the experience of the observer and is subjective, Objective Response Detection (ORD) techniques have been proposed to statistically infer about the response presence with a known maximum false-detection rate.

The Magnitude-Squared Coherence is a frequency-domain ORD technique and has been used to detect response elicitated by auditory [4], visual [5] and somatosensory [6] stimulation. Although the only way of augmenting the detection rate using only a signal with fixed signal to-noise ratio (SNR) is by increasing the number of epochs used in the estimates, the probability of detection can be improved for fixed data length if more than one EEG lead is used, provided such exhibit not very different SNR [7]. According to this, an extension of Coherence for the multivariate case, i.e. using two or more EEG derivations, has been used and considered as a promising tool for evoked potential monitoring during surgical procedures [7]. This work aims at comparing the performance of Magnitude-Squared Coherence (MSC) and the Multiple Coherence (MC) in stimuli-response detection.

The coherence-based approach as ORD techniques

The MSC between a periodic signal (stimuli) and a random one (EEG) can be estimated using only the latter [5]:

$$\hat{\kappa}^2(f) = \frac{\left|\sum_{i=1}^{M} Y_i(f)\right|^2}{M\sum_{i=1}^{M}\left|Y_i(f)\right|^2} \tag{1}$$

where "^" superscript denotes estimate, $Y_i(f)$ is the Fourier Transform of i^{th} window of EEG signal and M is the number of epochs. The statistical distribution of $\hat{\kappa}^2(f)$ is related to the F-distribution with 2 and 2M-2 degrees of freedom for the null hypothesis (H_0) of response absence. The critical value for a given significance level (α) and M can be obtained as [5]:

$$\hat{\kappa}^2_{crit} = \frac{F_{crit\ 2,2M-2,\alpha}}{M-1+F_{crit\ 2,2M-2,\alpha}} \tag{2}$$

where $F_{crit\,2,\,2M\text{-}2,\,\alpha}$ is the critical value of the above F-distribution.

The Multiple Coherence between a periodic signal and a set of N random ones ($y_j[k]$, j = 1..N) is given as [5]:

$$\hat{\kappa}^2_N(f) = \mathbf{V}^H(f)\hat{\mathbf{S}}^{-1}_{yy}(f)\mathbf{V}(f)\big/M \tag{3}$$

where $\mathbf{V}(f) = \left[\sum_{i=1}^{M} Y^*_{1i}(f) \quad \sum_{i=1}^{M} Y^*_{2i}(f) \quad \cdots \quad \sum_{i=1}^{M} Y^*_{Ni}(f)\right]^T$;

H and T superscript mean, respectively, Hermitian and the transposed matrix; and the p^{th}-row, q^{th}-column element of $\hat{\mathbf{S}}_{yy}(f)$ is $\hat{\mathbf{S}}_{yp\,yq}(f) = \sum_{i=1}^{M} Y^*_{pi}(f)Y_{qi}(f)$.

The critical value for a significance level α, M epochs and N signals can be expressed as [5]:

$$\hat{\kappa}^2_N crit = \frac{F_{crit\,\alpha,2N,2(M-N)}}{\left(\dfrac{M-N}{N}\right)+F_{crit\,\alpha,2N,2(M-N)}} \tag{4}$$

ISSN: 1727-1983 © 2005 IFMBE

For both techniques, the detection is obtained based on the rejection of the null hypothesis (H_0) of response absence, which is reached when the estimates values exceed the respective critical values ($\hat{\kappa}^2(f) > \hat{\kappa}^2 crit$ or $\hat{\kappa}_N^2(f) > \hat{\kappa}_N^2 crit$).

Material and Methods

EEG during somatosensory stimulation was obtained from [Fpz'-Cz'] (Fpz': mid-point between Fpz and Fz according to the International System 10-20; Cz': 2 cm posterior to Cz) and [C3'-C4'] (2 cm posterior to C3 and C4, respectively) from ten adult volunteers aged between 23 and 45 (mean: 27.4, standard deviation: 6.8 years) with no symptoms of neurological pathology and with normal SEP. The volunteers were lied down in the supine position with eyes closed. Stimuli (200 μs width pulses) were applied to the right posterior tibial nerve at the motor threshold level (the lowest intensity that produces feet interior muscle involuntary contraction) and rate of 4.91 Hz (to avoid responses at 60 Hz and harmonics) using the stimulator of the MEB 9102 (*Nihon Koden*). A ground electrode was positioned on the poplitea fossa. The signals were band-filtered within 1 - 1000 Hz with the bioamplifier Opti-Amp V. 8000D® (*Intelligent Hearing System*) and digitized with a 12-bits analog-digital converter (DaqPad1200® of *National Instruments*) at the sampling rate of 3000 Hz. Surface gold electrodes were used for recording and stimulation.

In order to avoid the stimulus artifact, which is wide-band and stimuli-synchronized, the first 10 ms were discarded and a 190 ms-windowing (spectral resolution of 5.26 Hz) was applied. MSC and MC were estimated for the acquired signals using (1) and (3) with $M = 100$, $N = 2$ and $\alpha = 5\%$. Furthermore, an automatic artifact rejection algorithm (AARA) was used in order to avoid high variance (low signal-to-noise ratio) epochs. Based on the standard deviation (*sd*) of twenty seconds of noise-free background EEG (reference for signal levels), selected by visual inspection, epochs with more than 5% of continuous samples or more than 10% of any samples exceeding ±3 *sd* (threshold containing approximately 99.5% of samples assuming EEG amplitude as normally distributed) were automatically rejected.

Results

The application of the ORD techniques to the EEG during stimulation of volunteer #1, stimulated with 10.6 mA, is illustrated in Figure 1 and indicates the response detection in the frequency band from 31.6 to 57.9 Hz for MC ($\hat{\kappa}_2^2(f) > \hat{\kappa}_2^2 crit = 0.0470$, with $M = 100$, $N = 2$ and $\alpha = 0.05$) and within 31.6 – 52.6 Hz and 31.6 - 47.7 Hz for MSC ($\hat{\kappa}^2(f) > \hat{\kappa}^2 crit = 0.0298$, with $M = 100$ and $\alpha = 0.05$) in [C3'-C4'] and [Fpz'-Cz'], respectively. For volunteer #8, stimulated with 15.6 mA, as can be noticed in Figure 2, it was possible to reject the null hypothesis for MC in the frequency range from 26.3 to 63.2 Hz (except for 31.6 Hz) and at 26.3, 36.8, 42.1 Hz for MSC in the derivation [C3'-C4']. The MSC application to [Fpz'-Cz'] resulted in detection only for a single frequency (47.4 Hz) with low estimate value. On the other hand, detection was obtained within 36.8-63.2 Hz for MC and 42.1-47.4 Hz for MSC in the derivation [Fpz'-Cz'] of volunteer #3, stimulated with 16 mA. However, for [C3'-C4'] it was only possible to reject H_0 with low MSC-values to 42.1, 57.9, 63.2 Hz (Figure 3).

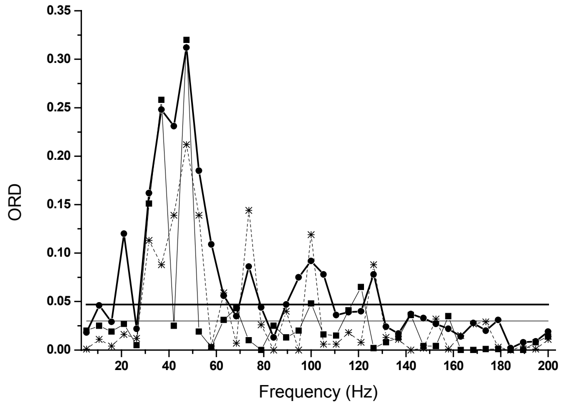

Figure 1: For volunteer #1, stimulated with 10.6 mA, $\hat{\kappa}_2^2$ (●), $\hat{\kappa}_2^2 crit$ = 0.0470 (thick horizontal) and $\hat{\kappa}^2$ of [Fpz'-Cz'] (■) and [C3'-C4'] (*), $\hat{\kappa}^2 crit$ = 0.0298 (thin horizontal), for $M = 100$, $\alpha = 0.05$.

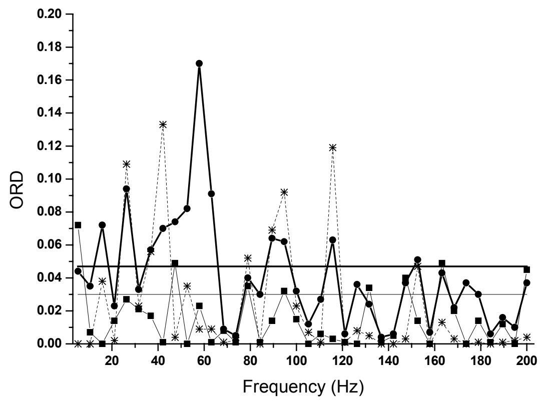

Figure 2: Idem Figure 2, for volunteer #8, stimulated with 15.6 mA.

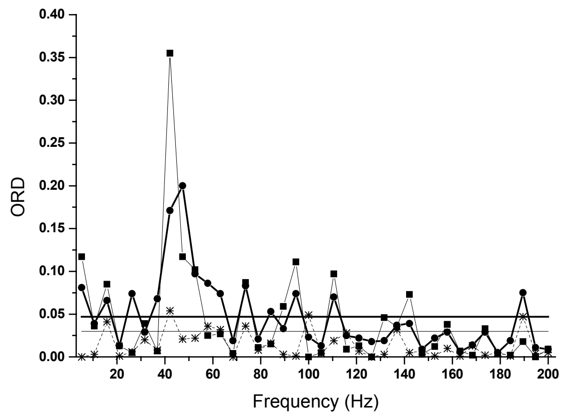

Figure 3: Idem Figure 2, for volunteer #3, stimulated with 16 mA.

ISSN: 1727-1983 © 2005 IFMBE

False detection was expected to occur in a 5% rate (α). The results in these three Figures described above are compatible with such values (estimates exceeding the critical values that were not pointed out as detection in the examples).

The percentage of volunteers for whom it was possible to detect the response, for each frequency within the range of 26.3 - 63.2Hz, using MC and MSC of each derivation is shown in Figure 4. The percentage when both derivations are considered together (significance level $\alpha = 0.0253$ for each derivation resulting in a "logical-OR detector" – LORD, with false-alarm rate of $\alpha = 0.05$) is also presented.

In the range between 30 to 60 Hz, the MSC detection achieved at least 60% of volunteers ([Fpz'-Cz'] or [C3'-C4']), although it was never higher than 90%. By considering the same range, the MC reached detection for all volunteers, with worst result at 31.6Hz (80% of volunteers). On the other hand, LORD obtained minimum detection rate of 70%. However, it was capable of detecting stimuli response for 100% of volunteers at 42.1 Hz.

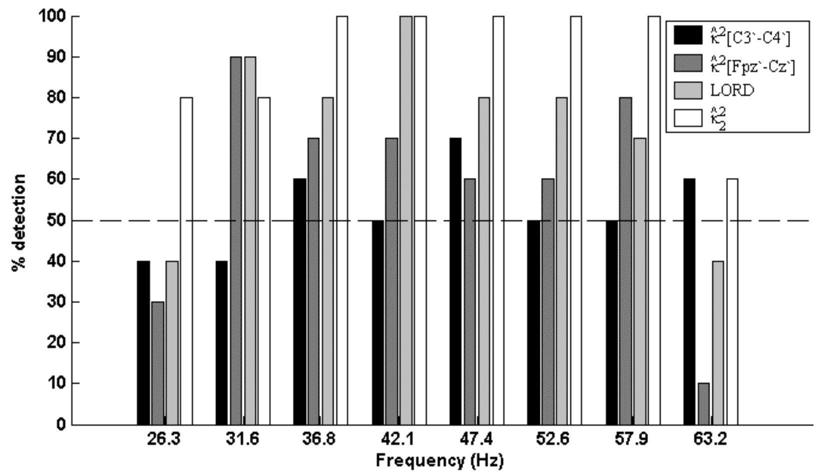

Figure 4: Percentage of volunteers for whom the stimuli-response was detected: $\hat{\kappa}^2$ of [C3'-C4'] (black) and [Fpz'-Cz'] (dark grey), LORD (light grey) and $\hat{\kappa}_2^2$ (white). Horizontal dashed line represents detection for 50 % of volunteers.

Discussion

Both MSC and MC indicate that the frequencies from 30 to 60 Hz (within the gamma band) are adequate for SEP monitoring as evidenced by higher percentage of detection for the volunteers. Frequencies within this range (30-45 Hz) have already been reported as a SEP characteristic [6].

The maximum percentage detection with the MSC was in 90% of volunteers for [Fpz'-Cz'], 70% for [C3'-C4'] and 100% with both "LORD" (47.1 Hz) and MC (36.8-57.9 Hz). By considering the frequencies from 30 to 60 Hz, MC detection percentage was often higher than MSC and LORD, except for 31.6 Hz. Therefore, for these frequencies (except 57.9 Hz), the LORD detected response in a higher number of volunteers than the MSC.

Hence, better results were found with MC, especially when noise affected one derivation. In this case, low MSC-values can be found, while the second derivation used in MC computation may ensure a suitable detection rate as described in [5]. This advantage is particularly relevant for studying the response to lower stimuli intensity.

In spite of the results achieved with MC, it is possible to verify cases for which the MSC exceeds MC-values as can be noted for [Fpz'-Cz'] of subject #3 (Figure 3). As reported in [8], there are cases for which higher number of signals did not lead to increase in the detection rate with Component Synchrony Measure (an ORD technique that uses only phase information), which was explained by large differences in the SNR of signals or highly correlated background activities in the derivations recorded. These could also explain higher MSC than MC-values. Nevertheless, there was no volunteer for whom it was possible to detect response with MSC but not with MC.

In addition, the use of both derivations in MC calculation implies a greater overhead for the automatic artifact rejection algorithm because this estimate is not calculated when at least one of the two derivations epochs reaches the rejection criterion. On the other hand, it is worth noting that MC showed to be more robust, i.e. less biased by noisy epochs, when the AARA is not used.

For derivations with fixed SNR-values, the detection rate is known to be improved by increasing the number of epochs (M) for MSC and MC. However, such increase leads to larger data lengths, which could result in non-stationary records as assumed for the ORD techniques calculation. Moreover, the larger the used M value, the slower the SEP changes tracking by the ORD techniques, as it seems that M works as a inertia (or memory) for epoch-to-epoch SEP variation tracking. The SEP morphology visual inspection is usually proceeded with average of M=500 to 2000 epochs [9] (using 4.91 Hz, the stimulation time varies from 100 to 400 s). In this work, M=100 epochs (about 20 seconds of EEG) were used and it is still possible to detect stimuli-response with the techniques presented. However, higher M-values should result in lower estimates variance and detection rate increase.

For MSC, the detection percentage for [C3'-C4'] derivation was lower than that obtained for [Fpz'-Cz'] within the frequencies of interest (30-60 Hz), except at 47.2 Hz. This could be probably due to noisy epochs (not rejected by the AARA) contaminated by myogenic artifatcs (neck musculature tension and swallowing) that usually affect [C3'-C4'] and result in MSC low values. Hence, other derivations monitoring should be considered, as pointed out in some studies according to which the commonly used SEP derivations are often suboptimal for morphological analysis [10]. This could also be true for frequency domain analysis. In fact, the derivation selection is related to the inter-individual variability and is an important issue as evidenced by the examples provided in the present work (Figures 1-3).

As reported in [7], MC could be useful in surgery monitoring, provided that signals from different derivations exhibit similar signal-to-noise ratio. This assumption was justified by the interhemisphere symmetry when EEG during photic stimulation was collected from homologue sites over the occipital (visual) cortex [7, 11]. However, as SEP derivations are registered over different lobes (distinct sensory processes related areas) it should be better investigated for this potential. Also in this case, other derivations could be more adequate [10]. In addition, although the probability of detection for MC can be enhanced by considering more than two derivations [7], it is worth noting that the improvement is only expected if suitable derivations are considered, i.e. stimuli-related derivation.

Conclusions

The MSC and MC showed to be capable of identifying somatosensory stimuli response at the motor threshold. Based on both techniques, the frequency range within 30-60 Hz (gamma band) was considered suitable for SEP monitoring.

When two or more derivations (related with stimulus) are available, as a general rule, it is better to use MC than choosing monitoring one derivation with MSC. In this study, only when both derivations are considered together (LORD with $\alpha = 0.05$), the detection was obtained for all volunteers in 42.1 Hz, which was reached by MC within the range 36.8-57.9 Hz.

These techniques are experience-independent and have a maximum false-detection rate established *a priori* (significance level α), and could be useful for patient responsiveness monitoring during surgeries and in the post-operative period.

Intermediary intensities should be investigated, since it is more suitable in the post-operative period, when the motor threshold is inconvenient (uncomfortable) as the patient is aware.

Acknowledgement

To CAPES, CNPq and FAPERJ for the financial support and to the Military Police Central Hospital of Rio de Janeiro for providing infrastructure support.

References

[1] FLORENCE G., GUÉRIT J-M., GUEGUEN B. (2004): 'Electroencephalography and somatosensory evoked potentials to prevent cerebral ischaemia in the operating room', *Neurophysiologie Clinique*, **34**, pp. 17-32.

[2] JOU I-M., HSU C-C., CHERN T-C., CHEN W-Y., DAU Y-C. (2003): 'Spinal somatosensory evoked potential evaluation of acute nerve-root injury associated with pedicle-screw placement procedures: an experimental study', *Journal of Orthopaedic Research*, **21**, pp. 365-372.

[3] LINDEN, R. D., ZAPPULLA, R., SHIELDS, C. B. (1997): 'Intraoperative evoked potential monitoring', in Chiappa, K.H. (Ed): 'Evoked Potentials in Clinical Medicine', (Raven Press, New York), pp. 601-638.

[4] DOBIE R. A., WILSON M. J. (1989): 'Analysis of Auditory Evoked Potentials by Magnitude-Squared Coherence', *Ear and Hearing*, **10**, pp. 2-13.

[5] MIRANDA DE SÁ, A. M. F. L., FELIX L. B., INFANTOSI A. F. C. (2004): 'A matrix-based algorithm for estimating multiple coherence of a periodic signal and its application to the multichannel EEG during sensory stimulation', *IEEE Transactions on Biomedical Engineering*, **51**, pp. 1140-1146.

[6] TIERRA-CRIOLLO C. J., INFANTOSI A. F. C. (2002): 'Determinação da Banda de Máxima Resposta para Estimulação do Nervo Tibial', Anais do XVIII Congresso Brasileiro de Engenharia Biomédica. São José dos Campos (SP), Brasil, 2002, **5**, pp. 476-479.

[7] MIRANDA DE SÁ, A. M. F. L., FELIX L. B. (2002): 'Improving the detection of evoked responses to periodic stimulation by using multiple coherence – application to EEG during photic stimulation', *Medical Engineering & Physics*, **24**, pp. 245-252.

[8] MIRANDA DE SÁ, A. M. F. L., FELIX L. B. (2003): 'Multi-channel evoked response detection using only phase ionformation', *Journal of Neuroscience Methods*, **129**, pp. 1-10.

[9] MISULIS, K. E. (1994): 'Averaging', in MISULIS, K. E. (Ed): 'Spehlmann's Evoked Potential Primer', (Butterworth-Heinemann, Boston), pp. 25-37.

[10] MCDONALD D. B., STIGSBY B., ZAYED Z. A. (2004): 'A comparison between derivation optimization and Cz′-FPz for posterior tibial P37 somatosensory evoked potential intraoperative monitoring', *Clinical Neurophysiology*, **115**, pp. 1925-1930.

[11] COULL B. M., PEDDLEY T. A. (1978): 'Intermittent photic stimulation clinical usefulness of non-convulsive responses', *Electroencephalography and Clinical Neurophysiology*, **44**, pp. 353–63.

ISSN: 1727-1983