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Assessment of auditory threshold using Multiple Magnitude-Squared Coherence and amplitude modulated tones monaural stimulation around 40 Hz

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ABSTRACT

Background and Objective: The use of objective detection techniques applied to the auditory steady-state responses (ASSRs) for the assessment of auditory thresholds has been investigated over the years. The idea consists in setting up the audiometric profile without subjective inference from patients and evaluators. The challenge encountered is to reduce the detection time of auditory thresholds reaching high correlation coefficients between the objective and the conventional thresholds, as well as reducing difference between thresholds.

Methods: This paper evaluated the use of the Multiple Magnitude-Squared Coherence (MMSC) in Auditory Steady-State Responses (ASSRs) evoked by amplitude modulated tones around 40 Hz, attaining objective audiograms, which were, later, compared to conventional audiograms. It was proposed an analysis of the electroencephalogram signals of ten subjects, monaurally stimulated, in the intensities 15, 20, 25, 30, 40 and 50 dB SPL, for carrier frequencies of 0.5, 1, 2 and 4 kHz. After the detection protocol parameters variation, two detectors were selected according to behavioral thresholds.

Results: The method of this study resulted in a Maximum detector with correlation coefficient $r = 0.9262$, mean difference between the objective and behavioral thresholds of 6.44 dB SPL, average detection time per ear of 49.96 min and per stimulus of 2.08 min. Meanwhile, the Fast detector presented coefficient $r = 0.8401$, mean difference of 6.81 dB SPL, average detection time of 28.20 min per ear and 1.18 per stimulus.

Conclusions: The results of this study indicate that the MMSC use in the auditory responses detection might provide a reliable and efficient estimation of auditory thresholds.

1. Introduction

The necessity for auditory system evaluations induced the development of behavioral audiological exams. These exams require active participation of the patient and are capable of detecting auditory losses which may impact the human social well-being. However, current approaches to stimulate the behavioral auditory thresholds might not always offer reliable or even possible answers, as is the case of children and other people incapable of responding to the exam.

There are several methods that use Evoked Potentials (EP) – a local variation on the electric field of a neural structure, due to an external stimulus [1] – to estimate auditory thresholds, such as the Slow Cortical Potential audiometry (SCP) [2] and the Brainstem Evoked Response Audiometry (BERA), widely used in children [3]. Though, even with the attempt of some methods to increase their specificity in frequency, such precision is not possible on the whole range of frequencies used in audiometry [4,3]. SPC and BERA still rely on the subjective judgment of the waveforms by an examiner.

The electroencephalogram (EEG) collected through electrodes placed in the scalp, allows to indirectly measure a EP [5]. According to [6], the sinusoidal amplitude modulation of a continuous tone (AM tone) exemplifies a stimulus that evokes an Auditory Steady-State Response (ASSR), characterized by an energy increase in the frequency of the modulating signal in the EEG signal power spectrum [7], which solves the specificity of the frequencies used in audiometry [8]. However, since the EEG measures several other potentials and due to the low signal-to-noise ratio (SNR), it is necessary to use Objective Response Detection (ORD) techniques [9].

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ORD techniques use statistical tests to define the presence or absence of a specific response, which allows automatic detections, without the intervention of patients or evaluators [10]. Among the ORDs, the Magnitude-Squared Coherence (MSC) stands out from other techniques because it has a high efficiency in EEG periodic stimulation [11, 12]. In order to improve the detection, multivariate techniques, which add more channels to the detection test, are used. The Multiple Magnitude-Squared Coherence (MMSC) is an example of a multivariate technique that extends the MSC to multiple channels [13].

Currently, ASSRs are widely studied in the 70–110 Hz range, even though the first ASSRs presented were stimulated with repetition frequencies near 40 Hz [14]. Moreover, these ASSRs with frequencies near 40 Hz show amplitudes two to three times more intense than those in the 70–110 Hz range, which could be very useful in auditory thresholds estimations. Furthermore, since the discovery that ASSRs could be clinically applied to evaluate hearing [14] through analysis in the frequency domain [15], several studies have been made aiming to estimate audiograms automatically, as observed in [2,16,17]. In general, two approaches have been studied: monaural simple estimation and binaural multiple estimation. The most used response detection methods vary among: detection methods based on Component Synchrony Measure – CSM [18–22]; detection methods based on Spectral F-test – SFT [23–27,12]; detection method using Magnitude-Squared Coherence – MSC [12] and its multivariate version, Multiple Magnitude-Squared Coherence – MMSC, employed in this research.

In this work, an audiogram estimations of normal hearing subjects are presented, through monaural stimulation of amplitude modulated tones in the around 40 Hz, using MMSC. Later the results were analyzed and compared to conventional audiometry.

2. Mathematical background

2.1. Multiple Magnitude-Squared Coherence (MMSC)

The MMSC is obtained when the MSC technique is extended to multiple channels, as a way of increasing the detection rate. For a multivariate linear system, the MMSC of a periodic and deterministic stimulus in each window x[n], synchronized with N electrodes $y_i[n]\,(i = 1,\ 2,\ \ldots,\ N)$, is given by [26]:

$$\widehat{\mathrm{MMSC}}(\mathrm{f}) = \frac{\mathrm{V^H(f)\hat{S}_{yy}^{-1}(f)V(f)}}{\mathrm{M}}, \tag{1}$$

where f is the frequency, M is the number of windows used and the spectral matrices $\mathrm{V^H(f)}$ e $\mathrm{\hat{S}_{yy}^{-1}(f)}$ as defined as:

$$\mathrm{V^H(f)} = \left[\sum_{i=1}^{M} \mathrm{Y_{1i}(f)} \quad \sum_{i=1}^{M} \mathrm{Y_{2i}(f)} \quad \ldots \quad \sum_{i=1}^{M} \mathrm{Y_{Ni}(f)} \right] \tag{2}$$

$$\mathrm{\hat{S}_{yy}(f)} = \begin{bmatrix} \mathrm{\hat{S}_{y1y1}(f)} & \mathrm{\hat{S}_{y1y2}(f)} & \cdots & \mathrm{\hat{S}_{y1yN}(f)} \\ \mathrm{\hat{S}_{y2y1}(f)} & \mathrm{\hat{S}_{y2y2}(f)} & \cdots & \mathrm{\hat{S}_{y2yN}(f)} \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{\hat{S}_{yNy1}(f)} & \mathrm{\hat{S}_{yNy2}(f)} & \cdots & \mathrm{\hat{S}_{yNyN}(f)} \end{bmatrix}, \tag{3}$$

with "H" denoting the Hermitian operator of the matrix; $\mathrm{Y_{ji}(f)}\,(\mathrm{j} = 1,\ 2,\ \cdots,\ \mathrm{N})$ is the Discrete Fourier Transform of the ith signal window of the channel j, and $\mathrm{\hat{S}_{yp\ yq}(f)}$ is the crossed power spectral density estimation of the electrodes p and q ($p,\ q = 1,\ 2,\ \ldots,\ N$), given by:

$$\mathrm{\hat{S}_{yp\ yq}(f)} = \sum_{i=1}^{M} Y_{pi}^{*}(f)\ Y_{qi}(f) \tag{4}$$

For the null hypothesis H_0, the MMSC presents central beta distribution with N and M-N degrees of freedom, and can be represented by [27]:

$$\widehat{\mathrm{MMSC}}_{\mathrm{N}}(\mathrm{f})|_{H_0} \sim \beta_{(\mathrm{N},\ \mathrm{M-N})}\ . \tag{5}$$

In this manner, the detection threshold is achieved by:

$$\widehat{\mathrm{MMSC}}_{\mathrm{crit}} = \beta_{\mathrm{crit}\ (\alpha,\ \mathrm{N},\ \mathrm{M-N})}, \tag{6}$$

where β_{crit} is the critical value of the beta distribution for a given significance level α. Thus, the ASSR is detected when $\widehat{\mathrm{MMSC}}(f) > \widehat{\mathrm{MMSC}}_{\mathrm{crit}}$.

3. Materials and methods

3.1. Subjects

A total of ten adult individuals participated of this study, six females and four males, with age between 18 and 34 years (24 ± 4.7 years). The subjects had their auditory threshold determined through the conventional tonal audiometry (Hughson-Westlake - HW, modified [28]), which spends approximately 5 min for the two ears. Exclusively individuals with normal hearing and without history of neural dysfunction participated in this study.

The subjects signed the consent form before submitting to the experimental procedure, according to the protocol approved by the Local Ethics Committee.

3.2. Stimuli

The auditory stimuli were digitally generated in Matlab®, with 24-bit resolution. The stimuli consist in pure sinusoidal tones modulated in amplitude and are created by the multiplication of a sinusoidal carrier, with frequency f_c, by a modulation sinusoidal signal, with frequency f_m. The carrier has high frequency while the modulation signal has low frequency. For a maximum amplitude A and modulation depth λ, the AM signal may be described as [29]:

$$\mathrm{x(t)} = \frac{\mathrm{A} \cdot \sin(2\pi \mathrm{f_c t}) \cdot (\lambda \cdot \sin(2\pi \mathrm{f_m t}) + 1)}{(1 + \lambda)} \tag{7}$$

A modulation depth of 1 (100%) was used and the amplitudes (or tones intensities) were adjusted to 15, 20, 25, 30, 40 and 50 dB SPL[1]. The modulation signals varied between 35 and 48 Hz and were fixed *a priori* in order to fit an integer number cycles in a 1024 points window, this avoids spread spectrum in objective detection of ASSRs [29]. Each stimulus exposition time was defined as 9 minutes and 58 seconds for all tested intensities.

The stimuli application was performed monaurally, through a shielded cable coupled to an insert earphone E-A-R Tone 5A (Aearo Technologies). For the system calibration, the artificial ear Brüel & Kjäer model 4152 was used coupled to a sound level meter Brüel & Kjäer model 2250, with the aid of a Larson Davis microphone model 2575.

3.3. Data acquisition

For the EEG signals acquisition, the BrainNet BNT 36 (Lynx Tecnologia, Brazil) amplifier was used. The *Ag/AgCl* noninvasive electrodes, with 10 mm diameter, were connected to the signal amplifier and placed on the scalp of each subject, with the assistance of an electrolytic gel.

The electrodes positions were defined according to the International 10–20 System, with reference to electrode O_Z and ground on F_{pZ}, in the derivations: $F_7, T_3, T_5, F_{p1}, F_3, C_3, P_3,\ O_{1,}$,

[1] Sound Pressure Level, where: dB SPL = 20 log (P_0/ P_{ref}), where P_0 is the pressure in μPa and P_{ref} = 20 μPa.