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A Series of Notched–Noise embedded Chirps for Objective Frequency Specific Hearing Examinations

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***Abstract*— Chirp-evoked auditory brainstem responses (ABRs) have shown a better performance compared to click-evoked ABRs, due to their temporal organization which compensates for the traveling wave delay achieving a synchronous discharge of the cochlea. In this paper we present the development and evaluation, in healthy subjects, of a series of notched noise embedded frequency specific chirps to evoke ABRs. Results of the ABRs using Phase Synchronization Stability are also reported. The assessment of frequency specific responses by using noise embedded chirps was possible, and the PSS analysis supported previous findings which stated that low frequency channels are better for the recognition and analysis of chirp-evoked ABRs. Accordingly, future analysis can be done to make a faster recognition of frequency specific chirps-evoked ABRs.**

I. INTRODUCTION

From cochlear mechanics is known that the cochlea is tonotopically organized [1], this means that low frequencies components of a traveling wave take a longer time to reach their sensation locus (resonance place) (apex) than the high frequency components (base). Neely et. al. [2] reported Wave V latency curves and showed that the latency and amplitude of the wave V were related to the intensity and the frequency of the stimulus. Later, Dau et. al. [3] created a chirp stimuli that was designed to compensate the temporal dispersion of the basilar membrane (BM) by using the linear cochlear model of de–Boer [1]. More chirps have been developed using otoacoustic emissions (OAE) data, wave V–latencies fitted curves [2], and auditory steady state responses (ASSRs) [4], [5]. The commonly used methods to assess frequency specific responses and check the integrity of the cochlea are, e.g., pure tone-evoked ABRs, ASSRs, and lately, methods such as the stacked ABRs [6]. The authors in [7] and [8] developed frequency specific chirps. In particular, [8] calculated a low-frequency chirp, evaluated and compared against a pure tone. The resulting ABRs showed a larger wave V for the chirp-evoked ABRs. In [7] a series of band limited chirps was constructed, using the same approach as in [3]. Moreover, frequency windows to limit the bands of the chirps were employed. The authors obtained ABRs and concluded that the threshold estimations were similar to pure-tone stimuli without masking but different from the reported for tone-burst using noise masking. In [8] is concluded that the low-frequency chirp evoked larger Wave V-amplitudes at low and medium levels than a tone pulse with similar duration and magnitude spectrum.

We showed recently in [9], that to be independent from amplitude fluctuations one can focus on Phase Synchronization Stability (PSS) measures exclusively. The aim of the present work is to develop a series of frequency specific chirps, similar to the ones in [7] but instead of symmetric frequency window, using amplitude functions that result in flat spectrum chirps (see [3]) which also assure smooth onset and offset of the chirps. Furthermore, the stimuli will be embedded in notched filtered noise adjusted to the frequency characteristics of each chirp. This will avoid the contribution of other areas of the cochlea than the intended ones. We present the development, and results of the chirps, the ABRs obtained using this stimulation paradigm and their analysis using PSS. The assessment of frequency specific ABRs could serve not only for hearing threshold determination but also for hearing aid fitting purposes.

II. METHODS

New chirps series: Based on the chirp created and tested by [3], [4], a broadband chirp, referred as approximated chirp in the same references, was calculated for the frequency range of 0.1-10 kHz (central frequency at 5250 Hz). This range of 9.9 kHz, which was the total operation range, served to generate the frequency specific chirps. With this range 5 bands were created (2^n, n $\in \{1, 2, \ldots, 5\}$) and then centered on standard frequencies for audiograms (250, 750, 2k, 4k, 8k Hz). In ascending order, the smaller bands correspond to the low central frequencies and the larger bands correspond to the higher frequencies respectively, see Fig. 1. The rational here is to combine an amplitude envelope that results in a flat frequency spectrum stimuli, such as [3], (for details we refer to [10], [3]), combined with masking notched filtered noise. With the previously stated and making sure that each stimulus starts and ends with zero, it is presumed that the effect of an abrupt onset and offset of each stimulus is then diminished. The chirps were then adjusted to the model in order to have zero values at their beginning and at their end. For this series of chirps it was desirable to have as many cycles as possible in each stimulus. Thus, the duration criteria, besides the condition of 0 at the beginning and at the end, was taken according to a minimum number of cycles. In [8] the authors used 3 "half-Waves" chirp, which we took

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as criteria of minimum number of half cycles to have in the chirps. The resultant chirps were slightly different from the first calculated bands (the frequencies changed less than 20%), and they remained under the tolerance limits according to the initial values. A special consideration was done for the two chirps that had the higher frequency bands. The range of both chirps were added, and one chirp (instead of two) was constructed. Therefore we had finally 4 frequency specific chirps. The reason to design this one chirp out of two was because the model did not allowed the criteria of 3 half-cycles for the second last high-frequency chirp. Therefore, a fourth chirp covered the ranges of these two chirps. This limitation of the model and possible improvements will be discussed further on this paper. The final waveforms, durations, bands, and center frequencies, as well as the de–Boer model can be seen in the Fig. 1. For identification purposes, the chirps are called Ch1, Ch2, Ch3, and Ch4, according to their frequency range, where Ch1 is for the stimulus with the lowest frequency band and Ch4 is for the chirp with the highest frequency band, for the broadband chirp the abbreviation is B-bCh. The final central frequencies are: 302, 813, 1915, 6725 Hz, for Ch1 to Ch4 respectively. It is important to mention that the final chirps included inside their range, the standard audiogram frequencies. The bands and corresponding durations are: [108-490] Hz and 6.19 ms for Ch1, [495-1135] Hz and 2.02 ms for Ch2, [1230-2600] Hz and 0.88 ms for Ch3, and [2950-10500] Hz and 0.51 ms for Ch4. All the chirps had alternating polarity (one time the stimuli started with positive values the next time with negative values) and a repetition rate of 20 Hz.

Notched masking noise: For the masking notched noise files, white noise as recommended in [11], was created. We used the software MATLAB (The Mathworks Inc., USA) for that purpose. The noise was band-passed filtered for the frequency range of 0.1-10 kHz, afterwards it was notched filtered using digital finite impulse response filters. The cutoff frequencies of the notch filters fitted the limits of the respective chirp. The noise in all conditions was 20dB peak equivalent Sound Pressure Level (pe SPL) smaller than the corresponding intensity of the chirps. After calibration (for details see the subsection of calibration below), the noise was added to the stimuli and then presented to the subject. Note that the noise was not added to the broadband chirp because in this case we intend to stimulate the entire cochlea. All the stimuli were calculated digitally and converted to a sound file with a sampling frequency of 44.1 kHz.

Calibration: The setup and stimuli were calibrated according to [12], [13]. For this purpose, the peak equivalent (pe) SPL had to be calculated for each type of stimulus. The peak voltage of each stimulus was measured using a digital oscilloscope (TPS 2014, Tektronix, USA), and the equivalent reference sinusoidal wave (to calculate the pe SPL) was produced by a function signal generator (33220A, Agilent, USA). A sound level meter (type 2250, Brüel & Kjær, Denmark) measured the pe SPL via a prepolarized free field 1/2" microphone (type 4189, Brüel & Kjær, Denmark) connected to an artificial ear (type 4153, Brüel & Kjær,

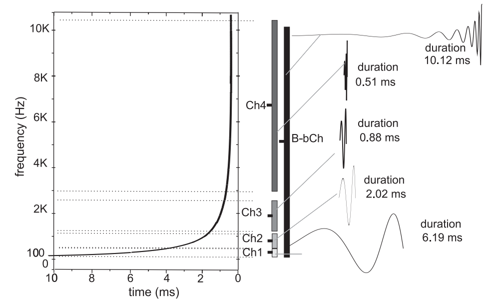

Fig. 1. Frequency specific chirps. Thick black line: model of de–Boer, which served for the generation of the chirps. The resulting waveforms, bands and duration of the chirps are also shown. Where, Ch1 corresponds to the chirp with the lowest frequency band, and Ch4 corresponds to the chirp with the highest frequency band. B-bCh is a broadband chirp.

Denmark). The artificial ear was simultaneously coupled to the headphones (HDA–200, Sennheiser, Germany) while reproducing the reference sinusoidal wave.

Subjects, Experiments and Preprocessing: For the experiments we had ten volunteers (mean age 25.1 years with a standard deviation of 2.96 years; 4 female, 6 male), with no history of hearing problems and normal hearing thresholds (below 15 dB (HL)); which was checked by an audiogram carried out before the experiments. After a detailed explanation of the procedure, all subjects signed a consent form. The time for one complete experiment was approx. 2.0 h including the time for the preparation of the subject and electrodes placement. Passive Ag/AgCl electrodes (Schwarzer GmbH, Germany) were attached as follows: ipsilateral to the stimulus at the right mastoid (A1), common reference at the vertex (Cz) and ground at the upper forehead (Fpz). The electrode labels are according to the standard 10–20 system. Impedances were maintained below 5kΩ in all the measurements. The subjects were instructed to lay on a bed in an acoustically insulated room trying to remain quiet, with the eyes closed, and sleep if possible. The headphones (the same used in the calibration) were placed and after verifying correct impedances, the lights were turned off. Subsequently, ABRs were obtained using the broadband chirp and next, using the noise embedded frequency specific chirps for the intensity levels of 50, 40, and 30 dB pe SPL. In total 15 files were recorded. In each recording and condition 3000 sweeps, i.e., the response to an individual stimulus, free from amplitude artifacts (artifacts were removed by an amplitude threshold (15μV) detection) were recorded. The measurement sequence was identical for each subject. The electroencephalographic activity was acquired by a high–end 24 bit biosignal amplifier (gUSBamp, gTec, Austria) using a sampling frequency of 19.2 kHz. The data was subsequently filtered using a band–pass filter from 0.1 to 1.5 kHz.

Post-processing – Time–Scale Phase Synchronization: For the determination of the PSS, we need an adaptation of the derived phase locking measure between two signals to our problem. Let $\psi_{a,b}(\cdot) = |a|^{-1/2}\psi((\cdot - b)/a)$ where $\psi \in L^2(\mathbb{R})$ is the wavelet with $0 < \int_{\mathbb{R}} |\Psi(\omega)|^2 |\Psi(\omega)|^{-1} \mathrm{d}\omega < \infty$ ($\Psi(\omega)$ is the Fourier transform of the wavelet), and

$a, b \in \mathbb{R}$, $a \neq 0$). The wavelet transform $\mathcal{W}_\psi : L^2(\mathbb{R}) \longrightarrow L^2(\mathbb{R}^2, \frac{\mathrm{d}a\mathrm{d}b}{a^2})$ of a signal $x \in L^2(\mathbb{R})$ with respect to the wavelet ψ is given by the inner L^2–product $(\mathcal{W}_\psi x)(a, b) = \langle x, \psi_{a,b} \rangle_{L^2}$. We define the synchronization stability $\Gamma_{a,b}$ of a sequence $\mathcal{X} = \{x_m \in L^2(\mathbb{R}) : m = 1, \ldots, M\}$ of M sweeps by

$$\Gamma_{a,b}(\mathcal{X}) := \frac{1}{M} \left| \sum_{m=1}^{M} e^{\imath \arg((\mathcal{W}_\psi x_m)(a,b))} \right|. \qquad (1)$$

Note that (1) yields a value in $(0, 1)$. For a more detailed explanation in the extraction of phase synchronization stability we refer to [9]. Phase synchronization stability of the collected ABRs was calculated using different values of the scale a.

III. RESULTS AND DISCUSSION

Auditory Brainstem Responses and Stimuli: Measurement examples of one subject for the different conditions are shown in Fig. 2 as single sweep matrix representation, i.e., the amplitude of the sweeps is encoded in a color-scale map (bright colors represent large values and dark colors represent small values), and as thick white and gray lines, the averages for the time domain waveforms. Each line represents the average of 1500 responses to show reproducibility as waveform. In the same Fig. the offset of the stimuli are subtracted, so the responses are aligned to the offset of their respective stimuli. The columns correspond to the responses for a specific intensity level (from left to right, 50, 40 and 30 dB pe SPL), and the rows 1, 2, 3, 4 and 5 correspond to the responses of Ch4, Ch3, Ch2, Ch1, and, B-bCh respectively. The 6th row is the addition of the responses from Ch1 to Ch4. And the last 7th row is the same addition but with prior alignment of the waves V. The trace of the Wave V over the different chirps can be extracted from the color-scale map. From these last rows 5, 6 and 7, can be seen that after an alignment of the responses, the broadband chirp can be improved. Theoretically, after an improvement of the B-bCh, the summation of the band-chirps responses would not necessarily differ from the response obtained using the new B-bCh, and a re-alignment would not be necessary. The previously stated would mean that we manage to stimulate in a better and completely synchronized way.

The Fig. 3, shows the group delay as well as the latency curves obtained from the grand average of the latencies of the wave V (overall the subjects), for the different intensity levels and stimuli. The chirps, shown in Fig. 1, were developed to stimulate specific areas along the cochlear partition, and the advantage of a flat spectrum is to stimulate with the same intensity all the fibers of the auditory nerve that are of interest. The fact that notched noise was added to the stimulus, and that the chirps were calculated to start and end exactly with zero, was done to avoid stimulation of undesired areas of the cochlea. The study reported in [8] obtained ABRs responses under a similar paradigm like the one used in this work but only one low frequency chirp was tested and not a series that cover the entire auditory range. It could be

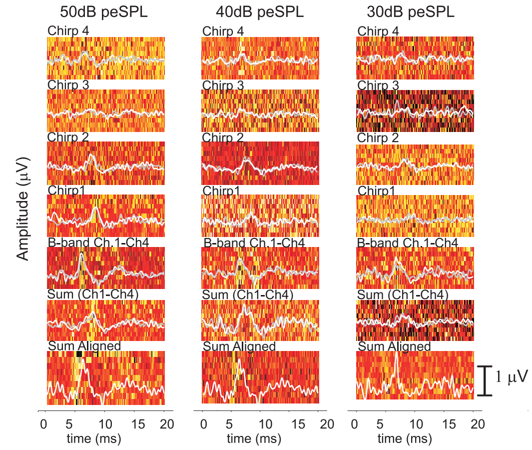

Fig. 2. ABRs measurements collected from one subject for different stimulation conditions. The columns correspond to the responses for a specific intensity level (from left to right, 50, 40 and 30 dB pe SPL), and the rows 1, 2, 3, 4 and 5 correspond to the responses evoked by the Ch4, Ch3, Ch2, Ch1, and B-bCh respectively. The row number 6 corresponds to the summation of the averaged responses of the ch1, ch2, ch3 and ch4, and the 7th row corresponds also to the same summation but after alignment of the waves V. Each averaged is represented by two lines (white and gray) to show reproducibility, and they are placed above its respective single sweep matrix representation, i.e., the amplitude of the sweeps is encoded in a color-scale map.

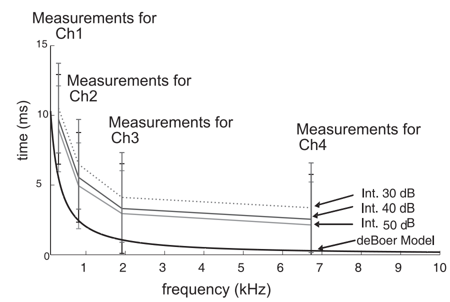

Fig. 3. Wave-V Latency curves: Average latencies obtained from all the subjects and for all stimulation conditions. Gray continuous line: for the intensity level of 50 dB pe SPL, black continuous line: for the intensity level of 40 dB pe SPL, and gray dot-dashed line: for the intensity level of 30 dB pe SPL. For these curves, 5 ms were subtracted from the preliminary average value. Those 5 ms represents the neural component and it is not considered on the mechanical model which is represented as a black thick line in the figure. The error bars indicate standard deviation.

argued that an alternative paradigm using a broadband chirp combined with noise could limit the response to the bands of interest. Nevertheless, there are no results or comparisons for the approach presented here. In Fig. 2 and Fig. 3, the larger latencies corresponding to the low frequency chirp (Ch1) stimulations are clearly noticeable compared as to the latencies of the responses for the high frequency chirp (Ch4). In Fig. 3, the relation frequency-intensity of the stimuli and the latency of the wave V can be seen. For the highest intensity used in this experiments (50 dB pe SPL), the latencies are in general smaller as compared to the ones for lower intensities. It can also be extracted how the latencies decrease as the frequencies of the stimuli increase. Note that the latencies plotted have a subtraction of 5 ms which is due fact that this 5 ms represents the neural component, see [2], which is not considered in the mechanical model plotted with a thick black line. These results represented for the first time by frequency specific chirps the fact that the tonotopical organization of the cochlea is related to the time that takes for a traveling wave to reach their sensation locus along the cochlea partition. We can conclude that we were able to extract frequency specific responses under the designed paradigm.

Scale Phase Synchronization: The Fig. 4, shows the grand average (overall the subjects) of the PSS for the different stimulation conditions, with M=3000 (sweeps), in (1). The columns correspond to the PSS for a specific intensity level (from left to right, 50, 40 and 30 dB pe SPL), and the rows 1, 2, 3, 4 and 5 to the chirps Ch4, Ch3, Ch2, Ch1, and, B-bCh respectively. Dark and bright colors represent small and large amplitude values, respectively. For the calculation we used the symmetric 6th–derivative of Gaussian function as the wavelet, and the value of the scale a ranged from 20 to 60 with increments of 5. Fig. 4 shows that the latency shift of the wave V is easily noticeable in the PSS, specially for larger scales. The motivation to analyze the PSS was to find out if the scale a to analyze frequency specific chirp-evoked ABRs would be different than the ones used for broadband chirps, [10]. In Fig. 4 it can be seen that, for all the conditions the PSS is higher in the range of Wave V and it becomes larger for the values of $a \geq 40$, where a = 40 corresponds to the frequency of 288 Hz. This is consistent to our previous findings in [14], where for Gabor Frame Phase Stability (GFPS) analysis of chirp-evoked ABRs the channels with the highest energy of the ABRs corresponded to the frequency ranges of [160-230] and [320-480] Hz. In Fig. 4, for the B-bCh, the PSS of the wave V is higher even for the small values of a, which is supported by the fact that more fibers of the VIII–th nerve are stimulated. It can be concluded that the scale for the analysis of frequency specific chirp-evoked ABRs not necessarily need to be different from the scale for broadband chirp-evoked ABRs, although this last ones can be analyzed using smaller values of a. Consequently the presented series of chirps can be used in our PSS scheme for the early hearing threshold detection in [9].

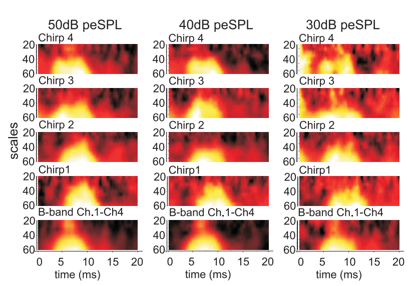

Fig. 4. The grand average overall the subjects of $\Gamma_{a,b}(\mathcal{X})$ (the scale a ranges from 20 to 60 with increments of 5), for the different stimulation conditions. The left, center and right columns correspond to the intensity levels of 50, 40 and 30 pe SPL, respectively. The rows from top to bottom, correspond to the chirps Ch4, Ch3, Ch2, Ch1 and B-bCh, respectively.

IV. CONCLUSIONS AND FUTURE WORK

In this work we developed a series of notched–noise embedded frequency specific chirps, which allowed the acquisition of frequency specific ABRs, with an identifiable wave V for the different intensity levels. The PSS of frequency specific chirp-evoked ABRs reflected the presence of the wave V for all stimulation intensities. The scales that resulted in higher PSS are in line with previous findings reported in [10], where broadband chirp-evoked ABRs were analyzed. Part of the future work includes to evaluate the notched noise embedded chirps with patients with different types of hearing loss, and make a comparison against the commonly accepted methods. Future analysis can be done to make a faster recognition of frequency specific chirps-evoked ABRs [9]. The model used to calculate the series of chirps is considered as first order approximation of the basilar membrane behavior. Further improvements related to the stimuli can be done by making the chirps intensity specific, using e.g, the latency plots reported in [2].

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