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Audiometric Threshold Screening Method Using Envelope Detection Filters of Intensity Ramping Click Auditory Steady-State Responses

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***Abstract*—The Auditory Steady-State Responses (ASSR) elicited by click stimuli can be utilized for hearing screening as is traditionally done with click-evoked Auditory Brainstem Responses (ABR). In a typical ASSR or ABR hearing screening, several recordings at different intensities are required to find the response threshold. In this study the use of binaural click stimulus with time ramping intensity produces dual-ear evoked potentials in only one recording session, decreasing significantly the recording time. To achieve this performance a one second sweep consisting of repetitive click stimuli, with logarithmically ramping up intensity, is presented to one or both ears simultaneously. Unique repetition frequencies for each ear are used in order to differentiate the responses coming from each ear. The stimuli sweep is repeated and the EEG data corresponding to each sweep is averaged until a pre-specified residual noise level is achieved. Hilbert-transform-based envelope detection filters in the time domain are used to estimate the signal and noise energy around the main stimulation rate. Because the stimulus time-intensity functions are known, thresholds can be estimated from the response onset time position by estimating the significance of the signal to noise ratio. Preliminary results indicate a strong agreement of the obtained thresholds with behavioral thresholds.**

I. Introduction

SINCE hearing problems interfere with learning, speech and language development, the first three years of life are critical for early identification and intervention of hearing loss [1], [2]. Additionally, the cost of people to society who cannot communicate is high. In the last decade, since the National Institutes of Health consensus statement on the Early Identification of Hearing Impairment in Infants and Young Children (NIH Consensus Statement, 1993), a great deal of emphasis has been given to hearing screening to assess possible hearing loss. Electrophysiological tests such as Auditory Brainstem Responses (ABR) and Otoacoustic Emissions (OAE) provide objective tests for determining hearing thresholds in children, newborns and other difficult-to-test subjects.

Recently, Auditory Steady-Sate Response (ASSR) technique has been introduced in detecting the hearing thresholds. ASSRs are evoked electrical potentials that are recorded using scalp electrodes and are elicited using continuous or long duration auditory stimuli. The response is considered stable in a steady state sense when the temporal window is much longer than the duration of a single stimulus cycle [3]. Since ASSRs are evoked by fast stimuli, the transient response to any stimulus overlaps with the response to the following stimuli [3], [4], [5], [6]. As a result, individual stimulus responses produce a steady behavior over time and can be detected by the spectral energy corresponding to the rate of stimulus presentation. Response detection is achieved by comparing the signal estimate at the repeating frequency with the noise estimate levels of adjacent frequencies [7], [8].

In a typical threshold detection session using ASSR, a number of responses must be recorded, each one obtained with constant stimulus intensity. The process is repeated until the smallest detectable response, the electrophysiological threshold, is recorded. In screening, the basic aim is to obtain reliable measurement in a time efficient manner. In this study, instead of evoking ASSR by a stimulus at constant intensity, we introduce ramping intensity click stimuli generated using an increasing intensity function with the recording cycle. This method reduces recording time and increases threshold accuracy. Using dual ear stimulation by presenting the sequence of clicks at different presentation rates for each ear, the time required for the procedure can be further decreased.

II. Methodology

A. Intensity Ramping Click Stimulus

The click stimulus used in this study is prepared such that its intensity increases linearly in terms of hearing level (in dB HL). At the top of Fig.1 stimulus intensity is shown in linear scale. The middle part shows the same stimulus intensity in dB HL. The bottom part shows the ASSR obtained in response to intensity ramping click between 0 and 50 dB HL. In Fig. 2, the spectrogram of the same data is shown with time-domain response at the bottom and frequency-domain response at the left of the figure. Although the visual threshold for the time domain response is quite high (0.5 s = 25 dB HL), the spectrographic visual threshold observed at

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80 Hz indicates 10 dB HL (0.1 s) showing the value of spectrographic approach.

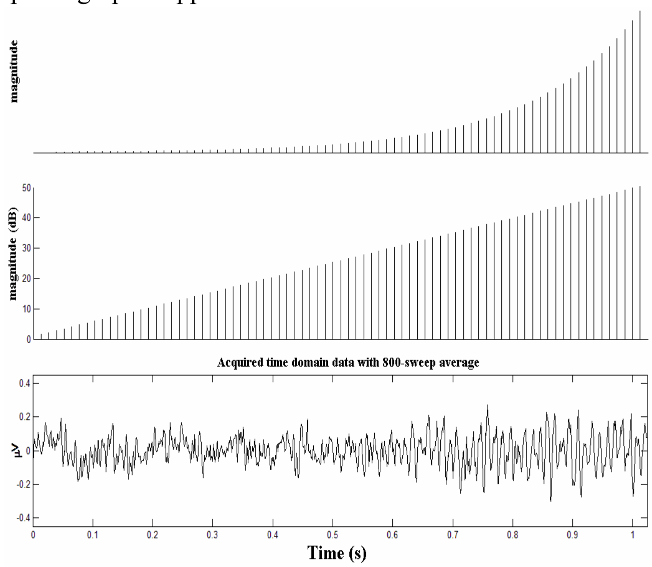

Fig. 1. Intensity ramping of click stimulus changing between 0 and 50 dB HL plotted in arbitrary units (top), in dB HL (middle). Bottom figure shows the ASSR in response to this stimulus obtained by averaging 800 sweeps (Subject 1).

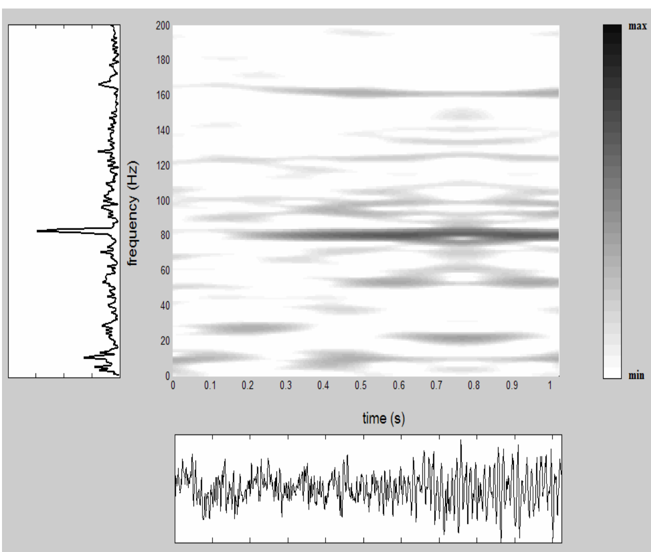

Fig. 2. Spectrogram of the obtained ASSR in response to ramping click stimulus at 80 Hz after 800-sweep average.

B. Envelope Detection Filters

ASSRs elicited by repeating clicks with intensity ramping shows increasing amplitude characteristic as well. We used time domain envelope detection filters [9], [10] to extract the ASSR from the raw recordings contaminated with residual EEG noise. These filters are tuned to the stimulation repeating frequency (f_0). Discrete time envelope detection filters are implemented by the following equations:

$$y_1(k) = \sum_{i=0}^{M-1} s(k-i)h_1(i) \quad (1)$$

$$y_2(k) = \sum_{i=0}^{M-1} s(k-i)h_2(i) \quad (2)$$

$$h_1(k) = \frac{1}{M}\cos(2\pi\frac{f_0}{f_s}i)W_M(i) \quad (3)$$

$$h_2(k) = \frac{1}{M}\sin(2\pi\frac{f_0}{f_s}i)W_M(i) \quad (4)$$

where $W_M(i)$ is a Blackman window with length M, f_s is the sampling rate, $s(k-i)$ is the response signal, and $h_1(i)$, $h_2(i)$ are the wavelet's filters. Temporal and spectral characteristics of the wavelets are shown in Fig. 3. The signal envelope is then estimated as:

$$a(k) = \frac{1}{0.21}\sqrt{(y_1(k))^2 + (y_2(k))^2} \quad (5)$$

Window sizes are selected according to the trade-off specified by the time-frequency uncertainty principle. In this study right and left ears are stimulated at rates of 85 Hz and 95 Hz, respectively and recorded data are analyzed using these wavelets.

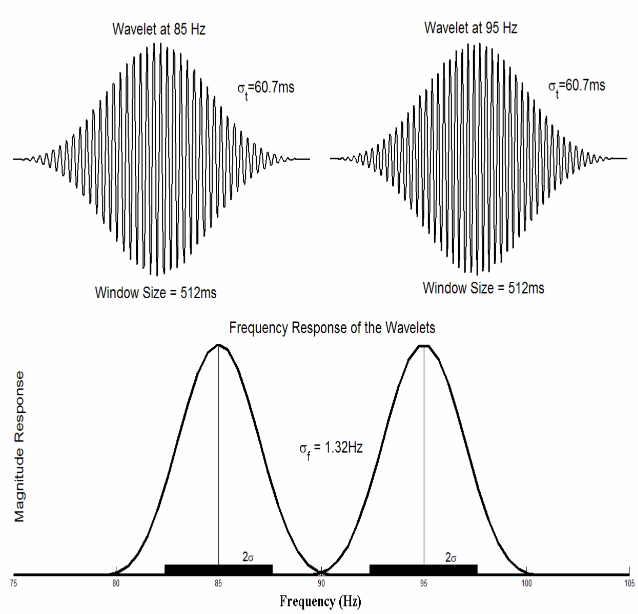

Fig. 3. Cosine wavelets used in envelope detection filters with corresponding frequency responses. Time and frequency standard deviations are chosen such that energy separation is better than 95%.

C. Recordings

ASSR recordings were acquired from six subjects (12 ears) with binaural intensity ramping click stimulation. In order to investigate the sweep averaging effect, one extra session was performed with monaural stimulation. Gold cup surface electrodes were used. In dual-ear testing, four electrodes were placed on the mastoids (two negative electrodes), Cz (positive electrode), and low forehead (ground electrode). Scalp recordings were amplified 100,000 times and sampled at 1000 Hz using 16 bits. Band-pass filter settings were set to 30-300 Hz (6 dB/oct). Sweep time duration was selected as 1024 ms. For each channel, two 1024 sample buffers were recorded, for even and odd sweeps separately. Odd-even sweep averaging was used to estimate residual noise of the response.

III. Results

Acquired responses were analyzed in the time domain using envelope detection filters. Basic criterion for detecting threshold values was separating the signal response from the residual noise. Using a split-sweep buffer technique, a signal estimate was obtained by the addition of these two buffers whereas the residual noise estimate was obtained by taking the difference of same two buffers. The signal and noise estimates were filtered with the envelope detection filters. In order to find the threshold, noise floor (n_{th}) in the envelope was computed by the following equation:

$$n_{th}^2 = \frac{1}{N} \int w(f) \left| \tilde{\varphi}_n(f) \right|^2 df \qquad (6)$$

where $\tilde{\varphi}_n(f)$ is the frequency response of the noise estimate inside the corresponding window ($w(f)$) of frequency response of the time domain wavelet. N is the length of the frequency window. n_{th} is the RMS value of the corresponding noise estimate falls in to the window of the frequency domain wavelet. By comparing the filtered signal estimate and the RMS noise estimate, a threshold point was identified as the first response point in which the signal was significantly different from the noise. In order to get significant difference, 95%-significance-level F-test was used and minimum significant amplitude level values were obtained. Signal amplitudes bigger than significance level were considered to be significantly different than the noise. Since the stimulus time-intensity functions were known, after determining the significant values, the one at the intersection point with the significance level was estimated as the threshold.

Using intensity ramping ASSR technique, we studied the effect of the number of averaged sweeps. As it is seen in Fig. 4, even after averaging 800 sweeps, threshold compared to 80 sweeps threshold does not change much.

Dual-ear intensity ramping click ASSRs were recorded from six subjects. The results are shown in Table I. Click stimuli rates were selected to be 85 Hz for right ear and 95 Hz for the left ear.

First four subjects (I-IV) shown in Table I have normal hearing. The left ear of Subject V, who has normal hearing in both ears, was made to simulate conductive hearing loss by sponge plugging in the ear tube. Subject VI had a border-line mild hearing loss.

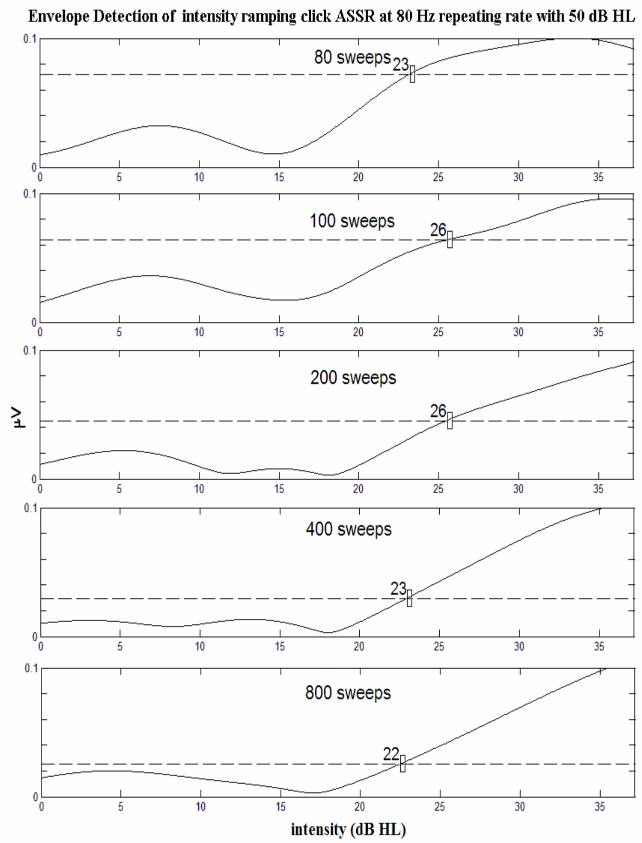

Fig. 4. Effects of the number of sweeps averaged on thresholds. This data were obtained using single channel recording with single ear stimulation. Solid line is the signal response and the dashed line is the RMS noise level with 95% significance level.

Averages of the differences between behavioral thresholds and physiological thresholds for all ears were found to be 8.9 dB HL for 200-sweep-average and 5.3 dB HL for 800-sweep-average. Standard deviations were found to be 7.6 dB HL and 5.8 dB HL, respectively. This result shows that increasing the number of sweeps averaged improves the threshold detection reliability of the system. 200-sweep-average, however, can still be used for threshold detection with slightly increased error but much reduced recording time duration.

Table I

	200 SWEEPS				800 SWEEPS			
SUBJECT	RE	Δ	LE	Δ	RE	Δ	LE	Δ
I	25	25	4	4	11	11	12	11
II	11	4	20	16	9	2	13	9
III	6	-1	19	14	15	8	14	9
IV	10	10	10	9	8	8	8	7
V	-2	-2	45	5	-6	-6	34	-6
VI	18	10	37	13	13	5	29	5

Click hearing thresholds for the right ear (RE) and the left ear (LE) of six subjects and the differences (Δ) from the behavioral thresholds for 200-sweep and 800-sweep averages in dB HL.

In Fig. 5 and Fig. 6 response detection plots for normal hearing (Subject 4, right ear) and simulation conductive hearing loss (Subject 5, left ear) are given, respectively.

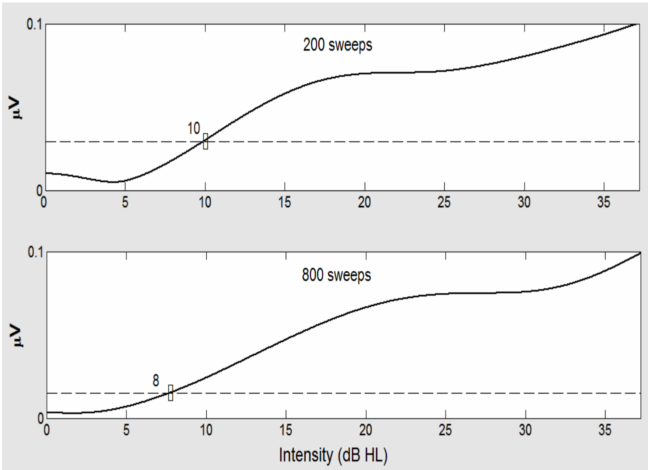

Fig. 5. Response detection plots for dual-ear intensity ramping click ASSR for right ear of Subject 4 for 200 and 800 sweep averaging.

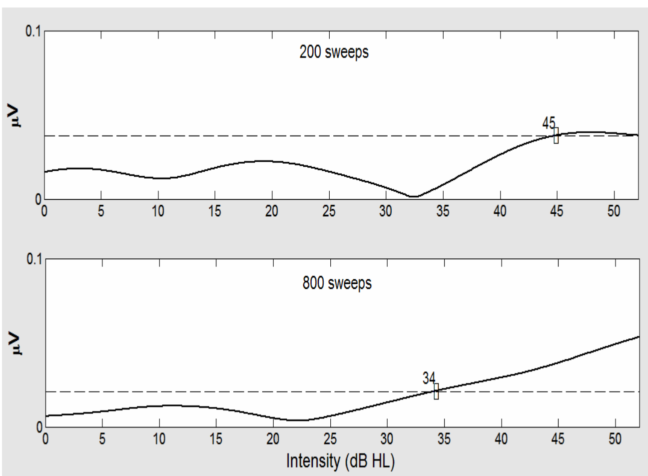

Fig. 6. Response detection plots for dual-ear intensity ramping (0-70 dB HL) click ASSR for left ear of Subject 5 for 200 and 800 sweep averaging. Data were acquired using conductive hearing loss simulation. Behavioral threshold was found to be 40 dB HL after the simulation.

IV. Discussion

Conventional hearing screening methods provide only a pass/fail assessment of hearing with respect to a set criterion (generally 35 dB HL). Testing methods, on the other hand, use step-up or step-down techniques with a preset intensity increment (generally 10 dB) for determining the threshold. Such testing methods actually require long recording times for accurate threshold determination. In this study, we developed a ramping method that finds the threshold fairly accurately without increasing the testing time. This ramping method uses smaller intensity increments (around 1 dB) thus giving more accurate results. More extensive testing in larger populations is required to assess the precision of the proposed method. If the preliminary results are confirmed, the audiologists will be able to get reliable hearing thresholds in small amount of time that is currently required in traditional methods.

In patients with hearing loss we expect responses with smaller amplitudes embedded in residual EEG noise. Thus, threshold detection is made more difficult. The most difficult aspect of this study was establishing a balance between the time and frequency uncertainty of the response detection. The use of long time-domain filters (512 samples) decreases the resolution (in dB) of the resulting threshold. Shorter time-domain filters have the effect of a wider frequency response, diminishing the frequency resolution. However, due to the use of one stimulus per ear, the spectral resolution of these filters is not as critical as compared to multi-frequency stimulation. The use of longer acquisition time windows can further improve the accuracy of the method but at the cost of longer acquisition time.

V. Conclusion

This study demonstrates that intensity ramping click ASSR technique can be effectively used for audiometric threshold determination. By applying this approach to dual-ear, the recording time required for testing can be decreased. With further development, intensity ramping ASSR technique can be adapted in detecting frequency-specific thresholds to obtain an audiogram for a subject.

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