The sensitivity of the ce-chirp auditory brainstem response in estimating hearing thresholds in different audiometric configurations

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Background
CE-Chirp is a new broadband stimulus that permits the energy from the stimulus to reach the whole regions of the cochlea at approximately the same time.
Aim
Comparison of auditory brainstem response (ABR) thresholds obtained by using click stimulus, broadband CE-Chirp and 500 Hz, 1, 2, and 4 kHz narrow band CE-Chirp stimuli to those obtained by behavioral hearing thresholds in adults with normal hearing and with varying configurations of sensorineural hearing loss (SNHL).
Patients and methods
Ten adult patients with normal-hearing thresholds, whose age ranged from 19 to 50 years, with a mean age of 30.4±9.1 years constituted a control group (group 1). Thirty adult patients with different configurations of SNHL constituted group 2, whose age ranged from 18 to 65 years, with a mean age of 32.5±9.8 years. All cases and controls were subjected to pure-tone audiometry, click, CE-Chirp and four narrow band CE-Chirp (at 500, 1000, 2000, and 4000 Hz) evoked ABRs.
Results
ABR thresholds to chirps have a relationship closer to behavioral hearing thresholds than ABR thresholds to clicks in individuals with normal-hearing thresholds and SNHL. Wave V mean latencies at threshold in response to click stimuli were earlier than those obtained using CE-Chirp in both groups. Wave V mean amplitudes at threshold with CE-Chirp were significantly larger than those with click in both groups. Wave V amplitude increased and latency decreased as the stimulus frequency increased in both groups.
Conclusion
There are evidences to suggest that ABR recording in response to CE-Chirps provide an efficient tool for estimating hearing thresholds in normal-hearing thresholds and individuals suffering from SNHL in comparison to click stimuli. The use of CE-Chirp had the potential to provide high sensitivity and accuracy for frequency-specific thresholds estimation in young children and difficult to test adults.

Keywords:
auditory brainstem response, click, hearing threshold, narrow band CE-Chirp, sensorineural hearing loss

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Introduction

The auditory brainstem response (ABR) is used to indirectly evaluate auditory thresholds in adults and infants. The ABR is an onset-sensitive neural response that is beneficial in assessing the integrity of the auditory system through the level of the brainstem [1]. Click stimuli are considered ideal for eliciting ABRs because of their abrupt onset, which results in widespread neural synchrony within the central auditory system, ensuring clear and repeatable waveforms. However, the temporal properties of normal cochlear mechanics give rise to a place/frequency cochlear delay, thanks to the traveling wave [2].

The concept of the chirp was first used in auditory electrophysiology by Shore and Nuttal [3], and has since been studied intensively for its use within the auditory field by Elberling *et al.* [4]. The CE-Chirp is a family of stimuli designed to compensate for this cochlear travel delay and provide enhanced neural synchronicity [5].

Chirp stimuli are based on cochlear delay models that presume normal cochlear function with normal cochlear frequency-place mapping and frequency tuning. Delay models have been based on (a) a linear description of the mechanical properties of the cochlea [6], (b) tone-burst ABR latencies [7], (c) stimulus-frequency otoacoustic emission latencies [8], and (d) derived-band ABR latencies [4,9,10]. Thus, one may assume that chirp-stimuli characteristics, which are advantageous for recording ABRs from normal-hearing patients may not show the same effects in patients with different types and degrees of hearing impairments [2].

The broadband CE-Chirp is designed using a delay model based on derived-band ABR latencies. Decomposing the broadband CE-Chirp into four components, filtered versions of the CE-Chirp were created with center frequencies 500, 1000, 2000, and 4000 Hz [4]. These stimuli, called narrow band chirps (NB CE-Chirp) were obtained by decomposing the CE-Chirp and constitute a subset of the CE-Chirp [11]. In the frequency domain, Elberling *et al.* [4] showed that the chirps give a shorter detection time and higher signal-to noise ratio than the click when auditory steady state to chirp and to a click stimulus are compared at two levels of stimulation (30 and 50 dBnHL) and at a rate of 90/s in 49 normal-hearing patients.

The drop in response amplitude of the chirp ABR over the click ABR for higher levels of stimulation in normal-hearing individuals implies that there might be an upper level of stimulation beyond which the chirp is no longer more effective than the click. Compared with the click stimulus, using the chirp in ABR recording, the response amplitude can be increased by a factor of 1.5–2.0 [5].

Aim

The purpose of this study was to evaluate the potential of the chirp stimulus in providing accurate and clear ABR measurements, by comparing thresholds for ABRs using click, broadband CE-Chirp, 500 Hz NB CE-Chirp, 1 kHz NB CE-Chirp, 2 kHz NB CE-Chirp, and 4 kHz NB CE-Chirp stimuli, to those obtained using behavioral hearing thresholds in adults with normal hearing and in individuals with varying configurations of sensorineural hearing loss (SNHL).

Patients and methods

This study is a case–control design that was conducted on two groups: Group 1 consists of 10 adult patients with normal hearing sensitivities, their average pure-tone hearing thresholds less than 20 dBHL and their age ranging from 19 to 50 and of both sexes. Group 2 consists of 30 patients with different configurations of SNHL and their age ranging from 18 to 65 and of both sexes.

Inclusion criteria

All participants in this study were above 18 years, all patients had SNHL varying from mild to profound in severity and with different configurations. There was no evidence of retrocochlear affection.

Exclusion criteria

None of the patients in this study or the control groups had any past history of external or middle ear pathology.

Those participants were recruited from patients referred to the Audiology Clinics of Beni Suef University Hospital for audiological evaluation. The study was approved by the ethics committee of the department and informed consents were obtained from all participants in both groups. The study period was from June 2015 to May 2017.

All participants who participated in this study were subjected to: (a) full history taking, (b) otological examination, (c) audiological evaluation using a clinical audiometer (model Orbiter 922; Otometrics, Madsen, Denmark), in a sound treated room (Amplisilence model E), and TDH 39 earphones calibrated according to the ISO standards. Tonal audiometry in the frequency range 0.25–8 kHz was tested. Speech audiometry including speech reception threshold using Arabic spondee words [12] and word discrimination score, using, Arabic phonetically balanced words [13]. (c) Immittancemetry was done using GSI 33 Grason-Stadler (USA), calibrated according to the ISO standards, using single-frequency tympanometry with a probe tone of 226 Hz. Click and CE-Chirp-evoked ABR were performed using Interacoustics, Eclipse 'EP15' (Denmark).

Surface electrodes were placed as follows: reference electrodes were placed on the right (A2) and left (Al) mastoids, the active on the scalp at the vertex (Fz position of the 10–20 International System of electroencephalography electrode placement) and the ground electrode on the lower mid-frontal area (Fpz position). Ag/AgCl electrodes filled with conductive paste were fixed to skin that was abraded with a skin preparation gel. Electrode impedances were less than 5 kΩ, and interelectrode impedances were less than 2 kΩ.

The patient was in relaxed state. ABR measurements were carried out using different stimuli: click, broadband CE-Chirp, NB CE-Chirp at500Hz, 1, 2, and 4 kHz. Clicks and CE-Chirps were presented monoaurally through TDH 39 headphones at an intensity level starting at 100 dBnHL. Clicks were presented at a rate of 21.1 stimuli per second in rarefaction polarity. Chirps were presented at a rate of 44.1 stimuli per second using alternate polarity. Filters of 100 Hz–3 kHz were used during the recording with averages of 1200 sweeps. Intensity was decreased to 20 dB until no response was obtained and it was increased by 10 dB steps until response thresholds were defined. At each intensity level, two recordings were obtained, and run consisted of 1200 sweeps, to ensure the replicability of the waveforms.

Statistical analysis

Data were analyzed using the software, statistical package for the social sciences, version 20 (USA), and then processed and tabulated. Frequency distribution with its percentage and descriptive statistics with mean and SD were calculated. χ^2, t test, correlations were done whenever needed. P values of less than 0.05 were considered significant.

Results

The current study was conducted on 10 adult patients (20 ears) with normal hearing sensitivity whose age ranged from 19 to 50 years, with a mean age of 30.4 ±9.1 years (group 1). They comprised six (60%) women and four (40%) men. The second group (group 2) comprised 30 patients (60 ears) with SNHL varying from mild to profound in severity and with different configurations. Eighteen (30%) ears had SNHL limited to the high-frequency region, 12 (20%) ears had SNHL with sloping configuration, 12 (20%) ears had SNHL with flat configuration, 12 (20%) ears had SNHL with trough configuration, and six (10%) ears with profound left corner) and their age ranging from 18 to 65 years, with a mean age of 32.5±9.8 years. They comprised 17 (56.6%) women and 13 (43.3%) men. There was no statistically significant difference between the two groups as regards age and sex.

Table 1 shows that there were statistically significant differences between thresholds at pure-tone audiometry (PTA) at 2 and 4 kHz and click ($P<0.05$) and between thresholds at click and CE-Chirp, also between thresholds at PTA and NB CE-Chirp at 500 Hz. While there were no statistically significant differences between thresholds at PTA and CE-Chirp and between thresholds at PTA and NB CE-Chirp at 1000, 2000, and 4000 Hz ($P>0.05$) in the control group.

Table 1 Comparison between thresholds obtained with pure-tone audiometry, CE-Chirp, click, and narrow band CE-Chirps at 500 Hz, 1, 2, 4 kHz in group 1

Threshold at	Mean±SD	*P* value
PTA	20.3±2.4	0.054
CE-Chirp	22.3±3.02	
PTA at 2 and 4 kHz	20.5±3.2	0.001*
Click	25.5±4.6	
Click	25.5±4.6	0.004*
CE-Chirp	22.3±3.02	
PTA at 500 Hz	19.5±3.2	0.035*
NB CE-Chirp at 500 Hz	21.8±3.4	
PTA at 1000 Hz	21.3±3.2	0.748
NB CE-Chirp at 1000 Hz	21.5±2.9	
PTA at 2000 Hz	19.8±4.4	0.184
NB CE-Chirp at 2000 Hz	21.5±2.4	
PTA at 4000 Hz	21.3±3.2	0.072
NB CE-Chirp at 4000 Hz	23.3±4.4	

NB, narrow band; PTA, pure-tone audiometry. *This means that value is statistically significant.

Table 2 Comparison between thresholds obtained with pure-tone audiometry, CE-Chirp, click, and narrow band CE-Chirps at 500 Hz, 1, 2, 4 kHz in group 2

Threshold at	Mean±SD	*P* value
PTA	53.9±15.9	0.084
CE-Chirp	55.3±16.6	
PTA at 2 and 4 kHz	61.8±16.3	0.001*
Click	67.5±15.1	
Click	67.5±15.1	0.001*
CE-Chirp	55.3±16.6	
PTA at 500 Hz	42.5±15.6	0.001*
NB CE-Chirp at 500 Hz	46.9±15.3	
PTA at 1000 Hz	48.6±21.5	0.001*
NB CE-Chirp at 1000 Hz	51.4±21.1	
PTA at 2000 Hz	56.8±18.7	0.001*
NB CE-Chirp at 2000 Hz	60.6±18.2	
PTA at 4000 Hz	63.5±13.8	0.444
NB CE-Chirp at 4000 Hz	64.1±14.7	

NB, narrow band; PTA, pure-tone audiometry. *This means that value is statistically significant.

Table 2 shows that there were statistically significant differences between thresholds at PTA at 2 and 4 kHz and click ($P<0.05$) and between thresholds at click and CE-Chirp, also between thresholds at PTA at 500, 1000, and 2000 Hz and NB CE-Chirps at 500, 1000, and 2000 Hz. But there were no statistically significant differences between thresholds at PTA and CE-Chirp and between thresholds at PTA at 4000 Hz and NB CE-Chirp at 4000 Hz ($P>0.05$) in the patients group.

Table 3 shows that there were no statistically significant differences between wave V latency at

thresholds obtained using click and that with CE-Chirp in the control group as *P* value more than 0.05. However, there was a statistically significant difference between wave V latency at threshold obtained with click and that with CE-Chirp in the patients group as *P* value less than 0.05.

Figure 1 shows the mean and SD of wave V latency at threshold obtained with 500 Hz NB CE-Chirp,1 kHz NB CE-Chirp, 2 kHz NB CE-Chirp, and 4 kHzNB CE-Chirp in both groups. Wave V latency at 500 Hz NB CE-Chirp was delayed more than that obtained at 1 kHz NB CE-Chirp which is delayed more than that with 2 kHz NB CE-Chirp and wave V at 2 kHzNB CE-Chirp was delayed than that obtained with 4 kHz NB CE-Chirp. The differences were not statistically significant in group 1 as *P* value more than 0.05, but were statistically significant in group 2 ($P<0.05$).

Table 4 shows that the amplitudes of wave V obtained with CE-Chirp were higher than that obtained with click. This difference was statistically significant in both patients and control groups ($P<0.05$).

Figure 2 shows the mean and SD of wave V amplitude at threshold obtained with 500 Hz NB CE-Chirp,1 kHz NB CE-Chirp, 2 kHz NB CE-Chirp, and 4 kHz NB CE-Chirp in both groups. Wave V amplitude at 500 Hz NB CE-Chirp was smaller than that obtained at 1 kHz NB CE-Chirp which is smaller than that with 2 kHz NB CE-Chirp and wave V at 2 kHz NB CE-Chirp was smaller than that obtained with 4 kHz NB CE-Chirp. The differences were statistically significant in both groups as *P* value less than 0.05.

Discussion

The CE-Chirp is a new broadband stimulus designed to enhance the wave V of ABR through adjustment of the stimulus frequency composition. This adjustment counteracts the temporal dispersion of the traveling wave inherent in the cochlea by presenting a lower

Table 3 Comparison between wave V latency (ms) at thresholds with click and CE-Chirp in the control and the patient groups

Groups	Latency	Mean±SD	*P* value
Control (*n*=20)	Click	8.2±0.9	0.11
	CE-Chirp	8.5±0.5	
Patients (*n*=54)	Click	6.8±0.72	0.03*
	CE-Chirp	7.1±0.76	

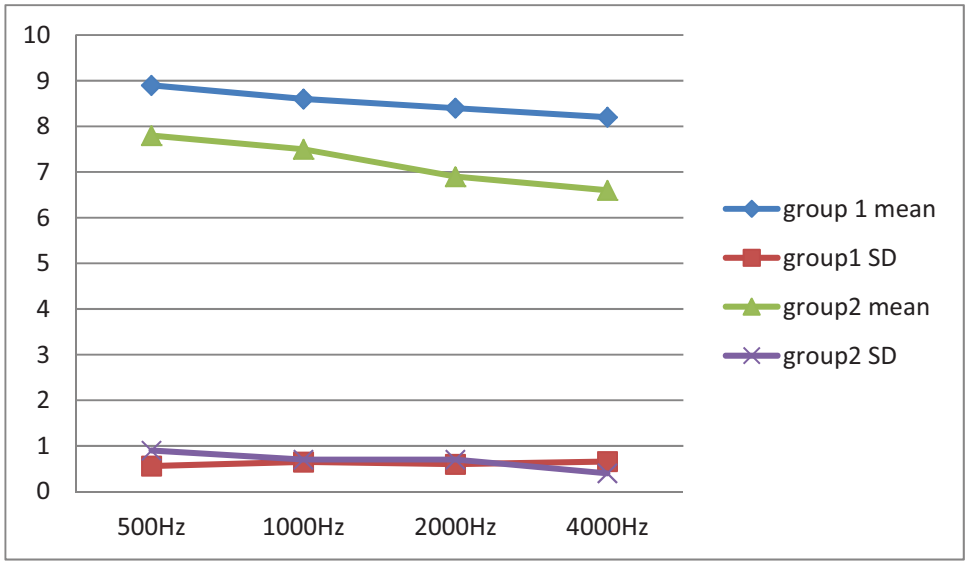
Six ears with profound sensorineural hearing loss left corner out of 60 ears of the patients group. *This means that value is statistically significant.

Table 4 Comparison between wave V amplitude (nV) at threshold with click and CE-Chirp in the control and patient groups.

Groups	Amplitude	Mean±SD	*P* value
Control (*n*=20)	Click	247±54.9	<0.001*
	CE-Chirp	425±63.8	
Patients (*n*=54)	Click	252±74.2	<0.001*
	CE-Chirp	344±76.8	

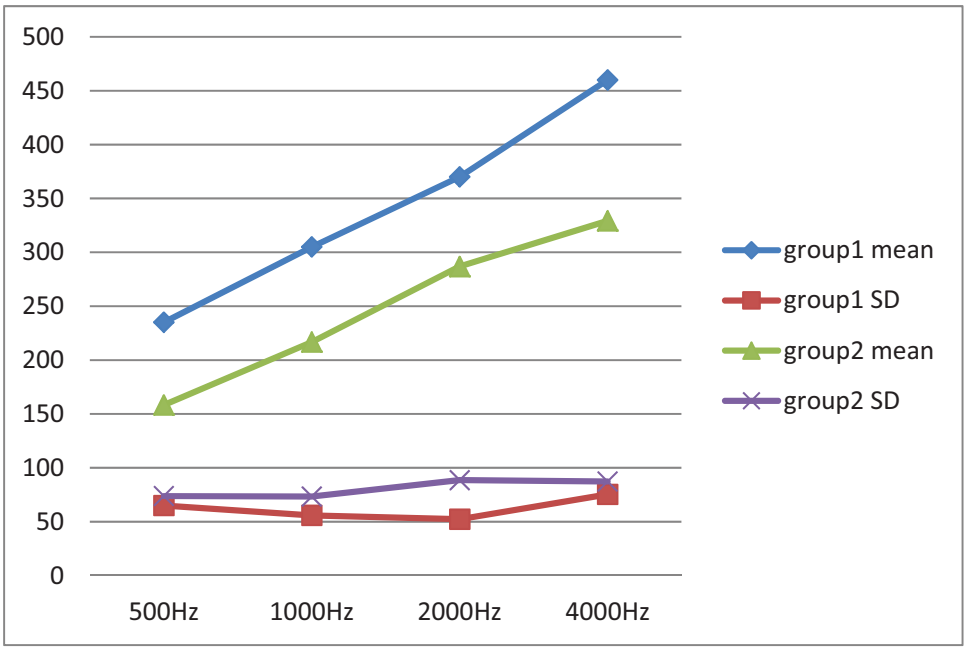
Six ears with profound sensorineural hearing loss left corner out of 60 ears of cases group. *This means that value is statistically significant.

Figure 1



Mean and SD of wave V latency (in msec) at 500 Hz NB CEchirp, 1 kHz NB CE chirp, 2 kHz NB CE chirp and 4 kHz NB CE chirp in the control group (group 1) and the patients group (group 2). NB, narrow band.

Figure 2



Mean and SD of wave V amplitude (in nvolt) at 500 Hz NB CEchirp, 1 kHz NB CE chirp, 2 kHz NB CE chirp and 4 kHz NB CE chirp in the control group (group 1) and the patients group (group 2). NB, narrow band.

frequency energy before a higher frequency energy resulting in an increased wave V amplitude [14].

For a chirp stimulus, there is an apparent representation of a wider range of frequencies in the neural response compared with a click stimulus. The apparent result of this broader stimulation pattern is the observation of neural responses closer to behavioral thresholds [15,16].

In the present study we found that the mean ABR thresholds to CE-Chirp were higher than the mean PTA thresholds with a mean difference of 2 dBnHL, although, this difference was not statistically significant in group 1 (Table 1). This may refer to a narrower auditory filter shape of the normal auditory system that may lead to increased fluctuations in neural response, which may contribute to a decrease in synchronous neural activity at lower-intensity levels [15,16].

Also, the mean ABR thresholds to CE-Chirp were insignificant higher than the mean PTA thresholds with a mean difference of 1.4 dBnHL in group 2 (Table 2). Maloff and Hood [17] in their study on 25 normal-hearing adults and 25 adults with mild to severe SNHL found that ABR thresholds to chirp did not differ significantly for the hearing loss groups and related that to the design of the chirp stimuli and the fact that all of the participants in these groups had flat or sloping hearing loss.

In our study, we also found that the mean ABR thresholds to click were statistically significantly higher than the mean PTA thresholds at 2 and 4 kHz with a mean difference of 5 dBnHL in group 1 (Table 1).This was in agreement with Maloff and Hood [17] who reported that the mean ABR thresholds for click were significantly higher than the mean PTA thresholds by 6.56 dB and Gorga *et al.* [18] who found that click ABR thresholds can average 10–20 dB higher than the overall PTA thresholds in an normal-hearing patients.

The mean ABR thresholds to click stimuli were significantly higher than the mean PTA thresholds at 2 and 4 kHz with a mean difference of 5.7 dBnHL in group 2 (Table 2). Gorga *et al.* [18] stated that click ABR can average only 5–15 dB higher thresholds than overall PTA thresholds in the SNHL population. They mentioned that it is possible that better agreement between ABRs to clicks and audiometric thresholds for the SNHL group may exist because at low-intensity levels the physiologic response may be dominated by lower-frequency regions where hearing is more normal in patients with sloping hearing losses. In addition, an impaired auditory filter is characteristically broader and the slope of the filter skirt is shallower compared with a normal auditory system [15,16,19].

In this work, the author noticed that in both groups ABR thresholds to clicks were significantly higher than ABR thresholds to CE-Chirps (Tables 1, 2). The chirp

designed by Dau *et al.* [14]was to account for the functional relationship between stimulus frequency and place of maximum displacement and the traveling wave velocity along the partition as derived by de Boer [6]. This adjustment for temporal spacing of frequency components theoretically excites a maximal number of nerve fibers simultaneously and provides maximum synchrony of discharge across the frequency spectrum. Thus, the unique design of the chirp stimulus may allow for larger amplitudes and lower ABR thresholds compared with the click stimulus [14].

In this study, we found that the mean ABR thresholds to 500 Hz NB CE-Chirp, 1 kHz NB CE-Chirp, and 2 kHz NB CE-Chirp were significantly higher than the mean PTA thresholds at 500, 1000, and 2000 Hz in both groups (Tables 1, 2), while the mean ABR thresholds to 4 kHz NB CE-Chirp were insignificantly higher than the mean PTA thresholds at 4 kHz in both groups (Tables 1, 2). So the CE-Chirp and the NB CE-Chirp hearing thresholds fell within 5 dBnHL of the corresponding PTA thresholds.

The mean wave V latency at threshold utilizing click stimuli was found to be shorter than that with the CE-Chirp, but this difference was not statistically significant in group 1 (Table 3). Rodrigues and Lewis [20] who compared the latencies of wave V on ABR recording obtained with click and CE-Chirp stimuli in 12 adults with normal hearing totalizing 24 ears found that at higher intensities (80 and 60 dBnHL) the CE-Chirp stimulus presented shorter latencies than those observed with click stimulus. In lower intensities (40 and 20 dBnHL) the opposite occurred; click latencies were shorter than those obtained with CE-Chirp stimulus. Petteri [21] found that in normal-hearing patients, the chirp latencies were either approximately the same or smaller than the click latencies.

We also observed that wave V latency at threshold with click was shorter than that with CE-Chirp with a mean difference of 0.3 ms and this difference was statistically significant ($P<0.05$) in group 2 (Table 3). Maloff and Hood [17] compared the click and chirp mean latency-intensity functions in normal-hearing patients and SNHL patients. Steeper slopes were associated with the chirp ABR and SNHL groups. They explained this steeper slopes associated with the chirp ABR by that at higher-intensity levels the neural response is dominated by higher and lower frequency regions.

Don *et al.* [9] stated that the neural response to chirps at lower-intensity levels is likely dominated by lower-frequency cochlear regions, which are characterized by longer latencies. The steeper slopes associated with the SNHL groups may be caused by a delay in the cochlear filter buildup time as this is dependent on the amount of hearing loss and stimulus level.

In this study, we found that wave V amplitudes at threshold with CE-Chirps were significantly larger than those with clicks in both groups (Table 4). Rodrigues and Lewis [20], who recorded responses for intensities (80, 60, 40, 20 dBnHL), found that the amplitudes obtained with the CE-Chirp stimulus were significantly larger than those obtained with clicks for all intensities except at 80 dBnHL. They suggested that when a chirp stimulus is used there is a broadening of sound wave propagation along the cochlear partition at high intensity levels. This likely affects regions along the basilar membrane to respond in an asynchronous manner and results in reduced amplitudes.According to latencies and amplitudes of wave V at threshold obtained with NB CE-Chirps, we found that wave V latency at the 500 Hz NB CE-Chirp was prolonged than that obtained at 1 kHz NB CE-Chirp which is delayed than that with 2 kHz NB CE-Chirp and wave V at the 2 kHz NB CE-Chirp was delayed than that obtained with the 4 kHz NB CE-Chirp. The differences were not significant in the control group as $P>0.05$ but were significant in the patients group ($P<0.05$) (Fig. 1). The researcher in this study found that wave V amplitude at the 500 Hz NB CE-Chirp was smaller than that obtained at the 1 kHz NB CE-Chirp, which is smaller than that with the 2 kHz NB CE-Chirp and wave V at the 2 kHz NB CE-Chirp was smaller than that obtained with the 4 kHz NB CE-Chirp. The differences were significant in both groups as *P* value less than 0.05 (Fig. 2).

Bell *et al.* [22] who used band-limited chirp stimuli that compensate for frequency-dependent cochlear delays found that wave V amplitude increased and latency decreased as stimulus frequency increased. The decrease in latency is consistent with high-frequency responses arising from basal regions of the cochlea. Another study done by Hamada *et al.* [23], which was conducted on 30 young adult patients with normal hearing sensitivity and 30 patients with moderate degree of SNHL using low-frequency (1000 Hz), high-frequency (4000 Hz) chirp, and click stimuli at 20 and 10 dBSL (relative to the behavioral threshold) found shorter latency of wave V with the high-frequency chirp than the low-frequency chirp and

the wave V amplitude was larger with the high-frequency chirp in both groups.

Conclusion

This study has shown that the CE-Chirp has the potential to be used in determining physiologic response thresholds in adults with normal thresholds and those with SNHL of variable configurations. ABR thresholds to chirps stimuli have a closer relationship to behavioral hearing thresholds than ABR thresholds obtained in response to click stimuli in individuals with normal hearing thresholds and those with SNHL. The wave V amplitude increased and latency decreased as the NB CE-Chirp frequency increased. A study with a larger sample of participants, including children and infants, is suggested to explore this potential further.

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Conflicts of interest

There are no conflicts of interest.

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