ORIGINAL ARTICLE
J Audiol Otol 2022;26(4):182-191
pISSN 2384-1621 / eISSN 2384-1710
https://doi.org/10.7874/jao.2021.00689

Effects of Ambient Acoustic Noise on Auditory Brainstem Response to Level-Specific Chirp and Click Stimuli in Normal-Hearing Adults

Ahmad Aidil Arafat Dzulkarnain[1], Balqis Aqilah Mat Rahed[1], Fatin Amira Shahrudin[1], Fatin Nabilah Jamal[1], and Mohd Normani Zakaria[2]

[1]Department of Audiology and Speech-Language Pathology, Kulliyyah of Allied Health Sciences, International Islamic University Malaysia, Pahang, Malaysia
[2]Audiology Programme, School of Health Sciences, Universiti Sains Malaysia, Kelantan, Malaysia

Received December 16, 2021
Revised February 16, 2022
Accepted April 4, 2022

Address for correspondence
Ahmad Aidil Arafat Dzulkarnain, PhD
Department of Audiology and Speech-Language Pathology, Kulliyyah of Allied Health Sciences, International Islamic University Malaysia, Jalan Sultan Ahmad Shah, 25200 Kuantan, Pahang, Malaysia
Tel +609-570-5402
Fax +609-571-6776
E-mail a.aidil@gmail.com

Background and Objectives: Despite few reports on the influence of ambient acoustic noise on auditory brainstem response (ABR) to click stimuli, its effects on ABR to level-specific (LS) stimuli have not been systematically investigated. This study aimed to investigate the influence of ambient acoustic noise on ABR findings using both LS chirp and click stimuli. **Subjects and Methods**: Twelve normal-hearing adults participated in this repeated measure design study. The ABRs were acquired at 80, 50, and 30 dBnHL using two stimuli (LS chirp and click) under two conditions (quiet and noise). The ABRs under noise conditions were acquired using babble noise and white noise. The noise level was set at 55 dBA. Two-way repeated measure analysis was used to identify the main effects of the test conditions, stimulus types, and their interactions at a 95% confidence level. **Results**: No significant influence of ambient acoustic noise on ABR findings was identified at all intensity levels. No significant difference was found in the number of signal averages to reach the 0.04 μV residual noise as stopping criteria among the ABRs recorded with different types of stimuli and test conditions. The ABR waves I and V amplitudes were larger with LS chirp than with click stimulus. **Conclusions**: Ambient acoustic noise has no significant influence on ABR findings and the ABR test time based on the 55 dBA noise level used in this study.

J Audiol Otol 2022;26(4):182-191

Keywords: Acoustics; Noise; Evoked potentials; Auditory; Brain stem.

Introduction

Auditory brainstem response (ABR) is a useful assessment tool in estimating hearing threshold and determining the pathological sites along the auditory pathways. It is a known fact that ABR, specifically, and auditory evoked potential test, in general, are highly affected by ambient acoustic noise. Ambient acoustic noise refers to any noise or activities other than the true ABR signal that may reduce the accuracy of the ABR findings [1]. Ambient acoustic noise can influence the testing because ABR is typically performed as a far-field recording and the neural activities are captured together with the physiological and surrounding noise [2]. The basic principle in ABR is to conduct the test in a controlled and quiet environment where the patient is always advised to be calm, and all noise interferences should be minimized or permanently turned off. Noise can eventually hamper the ABR recording, where the whole acquired ABR signals would be rejected (if exceeding the maximum artefact rejection level) or the signal averaging process needs to be extended to reduce the amount of noise interference [2]. This could lead to extra testing time to record an ABR. A higher amount of noise may also lead to misinterpretations of the ABR results as it is difficult to separate the noise from the true ABR signal [2].

While maintaining a minimal ambient acoustic noise is a mandatory requirement for an ABR recording, in certain situ-

ations, the ABR still needs to be conducted in an uncontrolled environment with a higher level of ambient acoustic noise, such as in the universal newborn hearing screening. In this application, the designated testing room should be sound-treated [3]. However, not all postnatal ward is equipped with these facilities. Alternatively, a room with the lowest electrical interference and the lowest ambient acoustic noise level was used [4]. The reported ambient acoustic noise level was varied across studies at the range between 40 and 90 dBA with the noise spectrum in certain facilities that was prominent at lower frequency regions [4,5]. This level is considerably high for an ABR test, and the ambient acoustic noise could possibly affect the accuracy of the ABR results [4,5]. Despite this fact, only a few studies have systematically investigated the influence of ambient acoustic noise on the ABR findings using the standard ABR click stimulus [5-7] and one study conducted the test using speech token in the background noise [8]. The influence of ambient acoustic noise has also been studied in the auditory steady-state response (ASSR) [1] and otoacoustic emission [9].

Smith, et al. [9] investigated the effects of speech babble noise on transient evoked otoacoustic emissions (TEOAE) at several intensity levels among 30 normal-hearing adults. As the intensity levels of the speech babbles increased, the TEOAE findings were significantly affected but the passing criterion that was based on the signal-to-noise ratio (SNR) remains unchanged, providing that the speech-babble noise is below 70 dBA. Kei, et al. [1] investigated the effects of ambient acoustic noise in the ASSR test using speech-babble at 55 and 75 dBA among 31 normal-hearing adults. The results showed that the ASSR thresholds were not shifted when the speech-babble was presented at 55 dBA but significant change to the threshold was noted when the noise intensity level was increased to 75 dBA.

The literature investigating the influence of ambient acoustic noise on the click ABR results showed mixed findings depending on the noise intensity levels [5,7]. Richmond, et al. [5] investigated the influence of ambient acoustic noise from the neonatal intensive care unit on the ABR findings among 10 adults and infants at multiple intensity levels. The authors found that the increase in the noise levels up to 60 dBA did not significantly change the ABR results recorded at the supra-threshold level. When the noise level exceeded 60 dBA, some of their normal-hearing infant participants' ABRs were absent close to the threshold levels (20 and 30 dBnHL). The ABR wave V latencies were also increased as the intensity levels of ambient acoustic noise increased. Similar findings were found by Kim, et al. [7] that conducted a study among 104 young adults where the ABR wave V amplitudes and latencies were significantly smaller and delayed in 85 dBnHL white noise condition compared to the ABR recorded in quiet conditions.

BinKhamis, et al. [8] investigated the influence of background noise on the speech evoked ABR among 12 normal-hearing adults. This study found that the speech evoked ABR latencies became longer with a smaller peak of speech ABR amplitude in noise conditions compared to quiet conditions. The required number of sweeps was also higher in noise conditions compared to quiet conditions. In addition, some studies investigated the influence of continuous masking noise that was presented directly from supra-aural or insert phone concurrently with the click or tone burst stimuli to the recorded ABRs [6,10,11]. For example, Burkard and Sims [6] investigated the influence of broadband noise presented at an intensity ranging between 20 and 70 dBHL ipsilaterally to the ABR elicited from 115 dBpeSPL click stimulus. Similar to studies investigating the influence of ambient acoustic noise, the ABR wave V latencies were found to be increased and the ABR amplitudes reduced as the noise level increased.

A few studies did mention the influence of background noise but did not systematically investigate its effect on the ABRs finding. Those studies evaluated the effectiveness of a novel signal averaging technique and SNR estimation to overcome the background noise or to measure remaining residual noise level [12-14]. Elberling and Wahlgreen [14] evaluated their novel Bayesian averaging analysis that gave a certain weight to the acquired ABR signals based on the quality of the ABR recording. The authors evaluated the effectiveness of the algorithm based on the number of averaging required to reach the criterion to stop the ABR recording. The study did not mention or evaluate how the noise could be directly affecting the ABR recording in terms of the results or its test-retest stability.

To our knowledge, there are no known studies that investigated the influence of ambient acoustic noise using the latest chirp stimulus to elicit ABR. In the past 10 years, there was a significant trend in testing ABR using chirp, as the stimulus was shown to improve neural synchrony. The most cited chirp to elicit ABR is the level dependent chirp, which is also known as level-specific (LS) chirp [15]. Similar to its predecessor stimuli, LS chirp was designed by adjusting the onset of low- and high-frequency signals to ensure all nerve fibres be excited at the same time [15-17]. This enhanced all ABR peak amplitudes (I, III, and V) as opposed to the previous chirp that is only capable to enhance wave V and only at lower intensity levels with the absence or lower wave I and III amplitudes [15-18]. In the ABR to LS chirp stimulus, the duration of stimulus presentation varied according to the intensity level, where the duration is short at the supra-threshold level and is long at threshold

levels to minimize the upward spread of excitation [16,17,19]. With this arrangement, the ABR to LS chirp is as reliable as the ABR to click with the representation of all ABR peaks at a high-intensity level along with larger amplitudes [17,20-22].

Given the abilities of the ABR elicited from LS chirp stimulus to generate robust ABR amplitudes, it is of interest to know if the ABR from LS chirp could be less susceptible to ambient acoustic noise compared to ABR from click stimulus. This information is important since the ABR from LS chirp stimulus has been recommended to be used in the hearing screening procedure that may be subjected to certain levels of ambient acoustic noise [23]. The present study has two main objectives. The primary objective was to systematically assess the influence of ambient acoustic noise on the ABR findings, and the secondary objective is to determine if the ABR elicited from the LS chirp stimulus was less susceptible to ambient acoustic noise than the ABR elicited from the click stimulus.

Subjects and Methods

Study participants

Twelve normal-hearing adults with ages between 23 and 25 years old (mean=24, standard deviation=0.426) participated in this study. Given the smallest mean differences in the ABR amplitudes obtained from this study at 0.06 μV and standard deviation of 0.05, the sample size of 12 used in this study was translated into 96% power of the study (acceptable) at a 95% confidence level. Written consent was obtained from the participants before the testing procedure. This study received ethical clearance from the Institutional Ethics Committee of the International Islamic University Malaysia with an approval number of 172/19. The study participants were healthy without any chronic illness or under medications that can influence the ABR findings. The participants were required to have a normal hearing and middle ear function as reflected from their pure tone audiometric thresholds and tympanometry testing, respectively. Both pure tone audiometry and tympanometry tests were conducted using Interacoustics AC40 diagnostic audiometer (Interacoustics, Middlefart, Denmark) and GSI TympStar middle ear analyser (Grason-Stadler, Eden Prairie, MN, USA), respectively. Their behavioural threshold was equal to or less than 20 dBHL at a octave frequency between 250 Hz and 8,000 Hz and all participants had a type A tympanogram. All participants also have normal acoustic reflex thresholds that are less than 105 dBHL at 500, 1,000 and 2,000 Hz in both ears for ipsilateral and contralateral recordings.

Procedures

The ABR procedure was conducted in a sound-treated room that has been electrically shielded specific for auditory electrophysiology assessments following the American National Standards Institute (ANSI) standard (ANSI S3.1-1999 and ANSI S3.6-2004) [24,25]. The ABR was performed using Interacoustics Eclipse auditory evoked potential equipment with the EP 25 module (Interacoustics). The participant's skin was cleaned using a Nu-prep skin preparation gel at the high and lower forehead as well as at the mastoid of both ears. Next, disposable silver chloride electrodes (Ambu Neuroline 720, Ballerup, Denmark) were placed in these four areas. The non-inverting electrode was placed at the high forehead, the ground electrode at the lower forehead, and inverting electrodes were placed at both mastoid prominences as illustrated in Fig. 1. The absolute impedance for all electrodes was checked and maintained below 5 kΩ with a balance inter-electrode impedance. The ABR was conducted using two channels functions where the first channel recorded the ABR from the ipsilateral configuration and the second channel recorded the ABR from the contralateral configuration. Only the ABR from the ipsilateral configurations were taken for the final analysis and the contralateral ABRs were used to resolve any discrepancy in the waveform analysis for wave IV and V complexes [26]. Eclipse ER-3A (Interacoustics) insert phones were then placed on both ear canals of the study participant for stimulus presentation.

The participants were asked to be in the supine position during the test. They were encouraged to sleep and were instructed to remain relaxed while closing their eyes to reduce any noise or myogenic artefact that can affect the testing as well as to ensure the recording was of good quality with high reliability. The ABR was elicited using 0.1 ms click and standard commercialised LS chirp at 80, 50 and 30 dBnHL intensity levels presented from Eclipse ER-3A insert phones. The output of the click and LS chirp stimuli were calibrated by Interacoustics

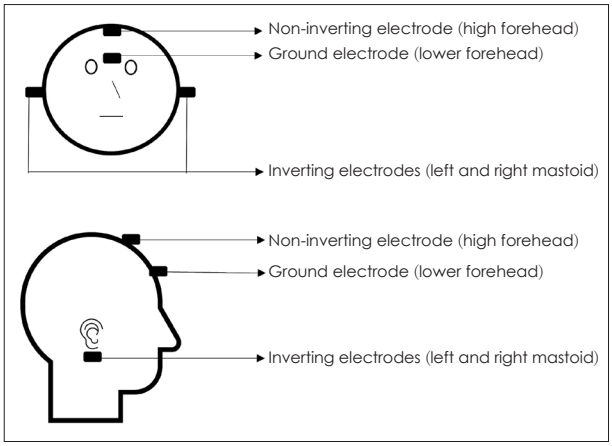

Fig. 1. Electrode's configurations (ipsilateral montage) for two-channels auditory brainstem response recordings from front view (top) and side view (bottom).

(manufacturer) following the reference-equivalent threshold sound pressure level (RETSPL) from ISO 389-6:2007 [27] and Physikalisch-Technische Bundesanstalt (PTB; Braunschweig, Germany) for click and LS chirp, respectively. Based on this, the reference levels of 0 dBnHL were set at 35.5 dBpeSPL for the click and 31.5 dBpeSPL for the LS chirp. The stimulus rate was set at 33.1 stimuli/sec using alternating polarity. Only the right ear was tested while the white noise (as masker) was presented on the non-test ear at 40 dB lower than the actual intensity level of the test ears to avoid the participation of the non-test ear, especially at the high-intensity levels.

The study participants' ABRs were acquired separately in a quiet condition and two noise conditions. The external noise was presented using a speaker that was located 1 meter from the bed at 90 degrees from the right ear. In noise conditions, babble noise and white noise were used. Six talker-babbles were used to generate the ambient acoustic of babble noise. The babble noise was generated from three male and three female English native speakers of 60 seconds loop recording with any silent gaps that were removed and normalized. The original energy spectrum of the recording is illustrated in Fig. 2. The white noise is a continuum frequency that was equally distributed over a whole range of hearing to provide ambient acoustic noise during the ABR testing. The white noise spectrum was within 31.5 Hz to 16,000 Hz. Both noise levels were presented at 55 dB(A). This ambient acoustic noise was chosen based on the maximum noise level at neonatal care nursery as reported from a previous study [5]. The noise output was filtered and played using the Audacity software version 2.0 (Pittsburgh, PA, USA) that was controlled using a laptop. To ensure a constant level of ambient acoustic noise, the output from the speaker was measured continuously during the testing to obtain an average SPL on A- weighted scale using Bruel & Kjaer Type 2325 sound level meter (SLM) (Nærum, Copenhagen, Denmark). The SLM was placed near the participant's right ear and was pointed towards the speaker that was placed 1 meter away from the bed. The order of testing condition, type of stimuli and the intensity presented for each participant were randomized to avoid any bias during the study.

The ABR signals were averaged using the Bayesian-weighted averaging technique until the residual noise leave reached 0.04 μV. The artefact rejection was set at 40 μV with a band-pass filter of 100−3,000 Hz to remove unwanted activities from the recorded responses. Every ABR was recorded twice to ensure wave repeatability and only the data from the initial waveform were included in the final data analysis.

ABR analysis

The presence or absence of the wave was consensually determined by two observers (1st and 2nd authors) to ensure correct peak labelling. Only ABR waveforms with high quality that have an SNR of 3:1 was accepted for analysis (e.g., the wave V amplitude of the ABR signal is 3 times larger than the amplitude of the residual noise). Amplitudes of waves I, III, and V were determined from the peak to the following trough, whereas the absolute latencies were measured from the 0 ms reference time window to the peak of each respective wave. The number of averages under different test conditions for each stimulus was determined by the total number of sweeps that are required to reach the test stopping criteria of 0.04 μV

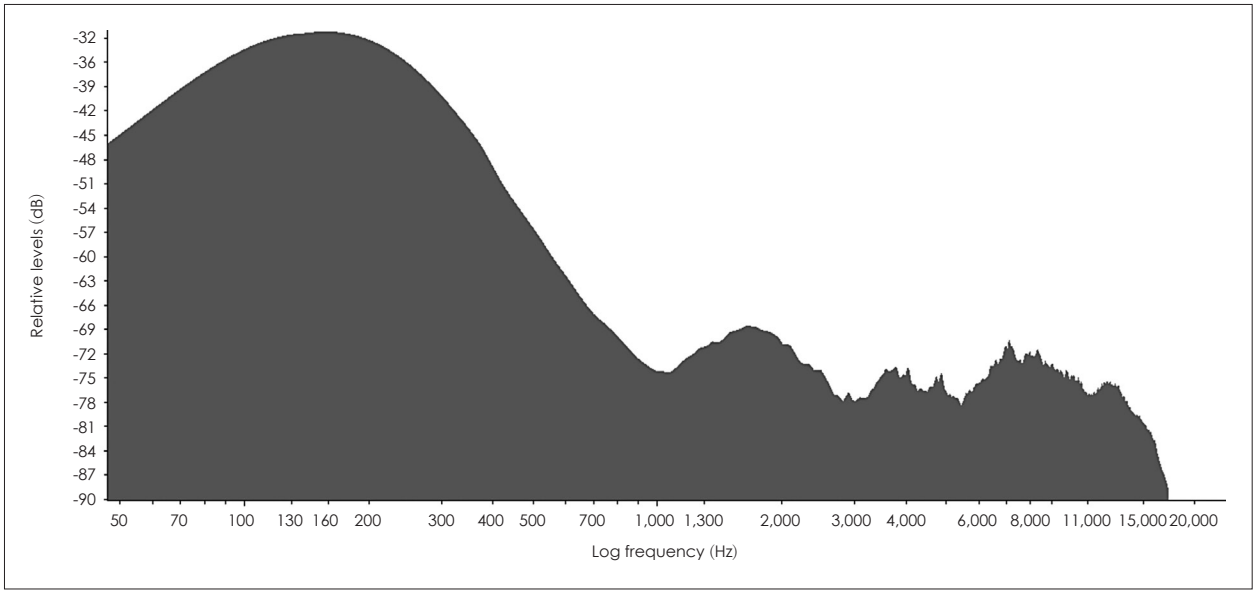

Fig. 2. Frequency spectrum of babble noise.

of the residual noise level.

Statistical analysis

The statistical analysis was conducted using the SPSS version 20.0 (IBM Corp., New York, NY, USA) and the significance level was set at a 95% confidence interval. The variables of this study are as follows: 1) ABR amplitudes and absolute latencies of waves I and III (80 dBnHL) and V (all intensity levels) and 2) the number of averages to reach the 0.04 μV residual noise level.

The mean differences of waves I, III, and V amplitude and absolute latencies among the ABRs elicited from LS chirp and click stimuli at three intensity levels (80, 50, and 30 dBnHL) with three test conditions (babble noise, white noise, and quiet) were statistically compared using two-way repeated measures analysis of variance (RM ANOVA). A pairwise comparison approach with Bonferroni correction was applied to each finding that reaches a significant level to account for multiple-comparison corrections. The number of averages comparison among ABRs to LS chirp and click stimuli at three intensity levels and three test conditions were analysed using the non-parametric Friedman test because of the breach of parametric assumptions, including non-normal data distribution and inhomogeneous variance. The post-hoc analysis using Wilcoxon signed-rank test was then performed with multiple comparisons adjustments should significant findings be found. The initial significance value of 0.05 was further divided by six levels of probabilities (3 polarities × 2 stimuli), resulting in the adjustment of the significance level to p=0.008.

Results

The ABR waveforms were present in all participants when elicited with both stimuli in three different test conditions and three intensity levels. Waves I, III, and V were identified in all participants at 80 dBnHL. At 50 and 30 dBnHL, wave V was identified in all participants in ABRs elicited from both LS chirp and click stimuli. Fig. 3 shows the ABR waveforms using LS chirp (Fig. 3A, C, and E) and click (Fig. 3B, D, and F) stimuli in three test conditions from one of the study participants.

ABR amplitudes

Table 1 shows the mean amplitudes of ABR waves I, III, and V that were elicited by LS chirp and click stimuli under three different test conditions. Table 2 shows the RM ANOVA results to identify the main effect and interaction of stimuli and test conditions at each intensity level for the ABR amplitude. Two-way RM ANOVA showed a significant effect of stimulus types for ABR wave I (at 80 dBnHL) and wave V amplitudes (all intensity levels) [$F(1,11)$=16.97−47.90, p<0.01]. No significant effect for stimulus types for ABR wave III (80 dBnHL) was identified from the two-way RM ANOVA analysis [$F(1,11)$=0.47, p>0.05]. In addition, there was no significant effect on the test conditions for all ABR waves [$F(2,22)$=0.11−2.01, p>0.05]. There was also no significant interaction between the test conditions and stimulus types [$F(2,22)$=0.11−1.51, p>0.05] except for wave V amplitude at 30 dBnHL [$F(2,22)$=4.79, p<0.05].

Further analysis was conducted within each stimulus and test conditions following the significant interactions of ABR wave V amplitude at 30 dBnHL. Within each stimulus type, no significant difference in the mean amplitude of wave V across the test conditions was identified for ABR to click (p>0.05) and the result for ABR to LS chirp was borderline significant (p=0.05). However, Bonferroni adjusted pair-wise comparisons showed that none of the pairs in the ABR to LS chirp at different test conditions were significant (p>0.05). The p-value for the comparisons of ABR wave V amplitude elicited by LS chirp under white noise condition and the quiet condition at 30 dBnHL approached significant difference (p=0.08) with a smaller ABR wave V amplitude obtained in the white noise test conditions. For within the test conditions, the Bonferroni adjusted pair-wise comparisons revealed that wave V amplitudes were significantly larger from LS chirp than the click stimulus under all test conditions (p<0.05). Overall, the result from Table 1 shows that ABR wave I and wave V amplitudes were larger from LS chirp compared to the ABR elicited by click stimulus in all test conditions.

ABR absolute latencies

Table 3 shows the mean and standard deviations of absolute latencies of waves I, III, and V for all stimuli combinations, three intensities and three different test conditions. Table 2 shows the RM ANOVA results to identify the main effect and interaction of stimuli and test conditions at each intensity level for the ABR absolute latencies. There was no significant effect of stimulus types [$F(1,11)$=0.06−0.50, p>0.05], test conditions [$F(1,11)$=0.16−3.42, p>0.05] and interactions for absolute latencies III and V [$F(2,22)$=0.08−2.09, p>0.05] for all intensity levels. The exception was for wave V absolute latencies at 50 dBnHL, where there was a significant main effect in the stimulus type [$F(1,11)$=7.09, p<0.05]. In addition, there was a significant effect in the stimulus type for wave I at 80 dBnHL [$F(1,11)$=51.54, p<0.05]. The absolute latencies for wave I was significantly longer in LS chirp compared to the click ABR. For wave V at 50 dBnHL, the absolute latencies of ABR to click stimulus were significantly longer than the ABR to LS chirp stimulus.

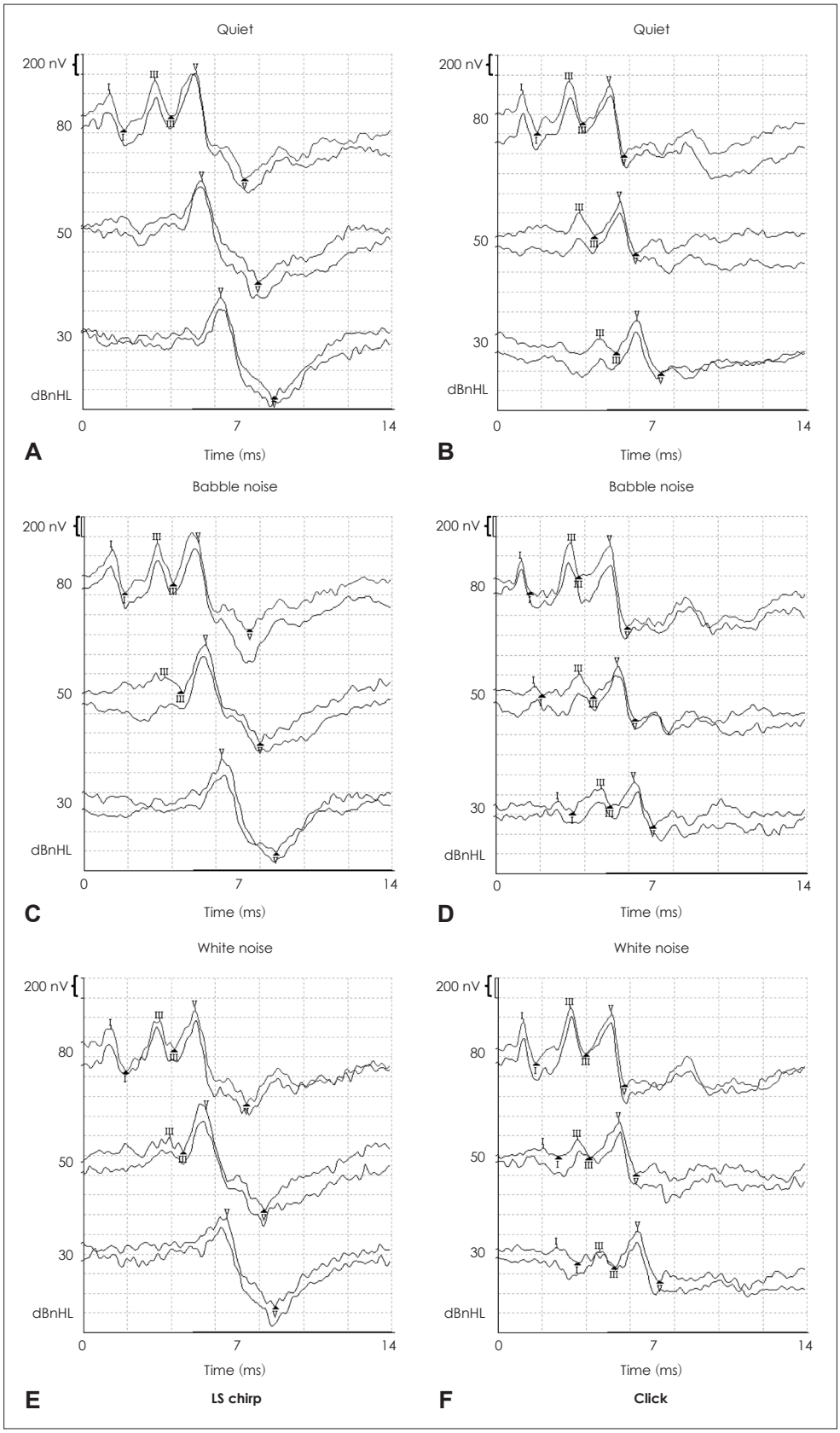

Fig. 3. Auditory brainstem response waveforms using level-specific (LS) chirp (left) and click (right) stimuli in three test conditions quiet (A and B), babble noise (C and D), and white noise (E and F) at intensities of 80, 50, and 30 dBnHL from one study participant.

Table 1. The amplitudes (μV) of ABR waves I, III, and V in three test conditions (quiet, babble noise, and white noise) and for two stimuli (click and LS chirp) at 80, 50, and 30 dBnHL

Intensity (dBnHL)	Waves	Click			LS chirp		
		Quiet	Babble noise	White noise	Quiet	Babble noise	White noise
80	I	0.32 (0.06)	0.32 (0.05)	0.34 (0.06)	0.36 (0.06)	0.37 (0.07)	0.37 (0.06)
	III	0.40 (0.17)	0.39 (0.14)	0.40 (0.16)	0.36 (0.11)	0.40 (0.15)	0.36 (0.14)
	V	0.63 (0.13)	0.62 (0.12)	0.61 (0.14)	0.87 (0.24)	0.82 (0.18)	0.81 (0.19)
50	V	0.41 (0.08)	0.42 (0.07)	0.43 (0.07)	0.78 (0.22)	0.80 (0.21)	0.77 (0.20)
30	V	0.36 (0.08)	0.38 (0.06)	0.40 (0.07)	0.72 (0.23)	0.68 (0.22)	0.67 (0.21)

Data are presented as mean (standard deviation). ABR, auditory brainstem response; LS, level-specific

Table 2. Results of two-way RM ANOVA for ABR absolute latencies and amplitudes at all intensities

Intensity (dBnHL)	Waves	Stimulus					Test condition				
		df	Type III sum of squares	Mean square	F-value	*p*-value	df	Type III sum of squares	Mean square	F-value	*p*-value
Absolute latencies											
80	I	1	0.23	0.23	51.54	<0.001	2	0.04	0.02	1.27	0.19
	III	1	5.5E-5	5.5E-5	0.06	0.81	2	0.02	0.01	3.42	0.51
	V	1	0.01	0.01	0.50	0.50	2	0.004	0.002	0.16	0.86
50	V	1	0.26	0.26	7.09	0.02	2	0.02	0.01	0.72	0.50
30	V	1	1.17	1.17	0.19	0.67	2	1.26	0.63	1.70	0.21
Amplitude											
80	I	1	0.03	0.03	17.52	<0.01	2	0.004	0.002	1.03	0.34
	III	1	0.01	0.01	0.47	0.51	2	0.03	0.001	0.71	0.50
	V	1	0.82	0.82	16.97	<0.01	2	0.02	0.01	2.01	0.16
50	V	1	2.39	2.39	47.90	<0.001	2	0.003	0.002	0.38	0.69
30	V	1	1.60	1.60	28.89	<0.001	2	0.001	0.000	0.11	0.90

RM ANOVA, repeated measures analysis of variance; ABR, auditory brainstem response; df, degrees of freedom

Table 3. The absolute latencies (ms) of ABR waves I, III, and V in three test conditions (quiet, babble noise, and white noise) and for two stimuli (click and LS chirp) at 80, 50 and 30 dBnHL

Intensity (dBnHL)	Waves	Click			LS chirp		
		Quiet	Babble noise	White noise	Quiet	Babble noise	White noise
80	I	1.29 (0.14)	1.23 (0.12)	1.27 (0.13)	1.40 (0.13)	1.36 (0.13)	1.37 (0.12)
	III	3.49 (0.17)	3.53 (0.14)	3.52 (0.16)	3.49 (0.16)	3.52 (0.23)	3.55 (0.15)
	V	5.30 (0.16)	5.29 (0.15)	5.31 (0.15)	5.28 (0.16)	5.26 (0.22)	5.26 (0.25)
50	V	5.88 (0.25)	5.86 (0.27)	5.86 (0.24)	5.67 (0.34)	5.77 (0.35)	5.73 (0.40)
30	V	6.63 (0.31)	6.65 (0.26)	6.63 (0.28)	6.61 (0.42)	6.71 (0.42)	6.69 (0.39)

Data are presented as mean (standard deviation). ABR, auditory brainstem response; LS, level-specific

Number of averages to the residual noise level of 0.04 μV

Fig. 4 shows the number of averages to reach 0.04 μV of residual noise level for each ABR elicited from click (Fig. 4A) and LS chirp (Fig. 4B) stimuli at different test conditions. The Friedman test found no significant difference ($p>0.05$) in the mean number averages among the ABR combinations from two different stimuli and three test conditions at all intensity levels [$\chi^2(5)=3.11-8.81$, $p>0.05$].

Discussion

The primary objective of the study was to systematically assess the influence of ambient acoustic noise on the ABR elicited from both LS chirp and click stimuli. In general, the present study found no significant influence of ambient acoustic noise on the ABR wave amplitudes and latencies at all intensity levels. This applies to the two types of noise used in this study—babble noise and white noise at 55 dBA. The present study coincides with a previous study by Richmond, et al. [5] where the authors found the ambient acoustic noise up to 60 dBA has a minimal effect on the ABR wave V latencies in their adult subjects.

However, the finding in this study was inconsistent with BinKhamis, et al. [8] and Kim, et al. [7] that evaluated the in-

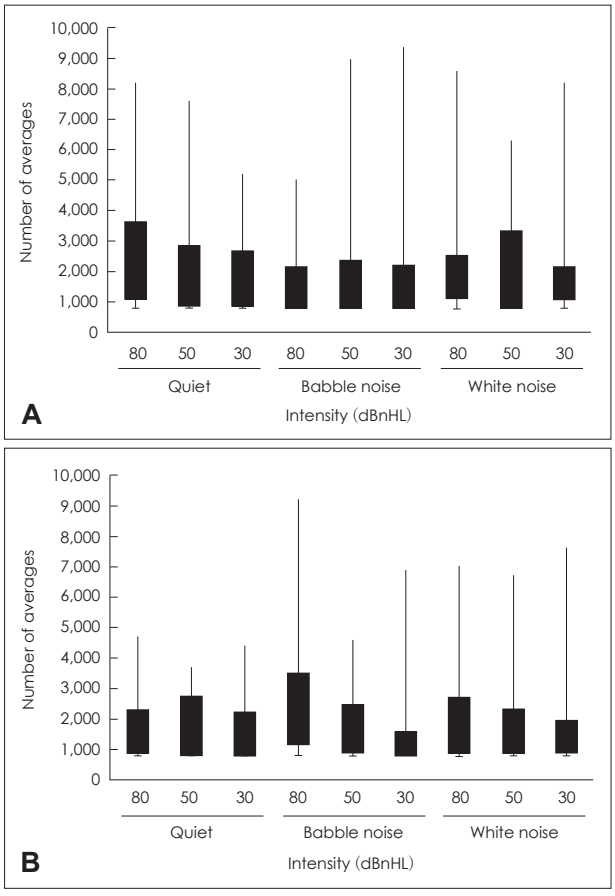

Fig. 4. Boxplot of number of averages to reach minimal residual noise level of 0.04 μV for the ABRs to clicks (A) and LS chirps (B) stimuli in three test conditions (quiet, babble noise, and white noise) at each intensity levels of 80, 50, and 30 dBnHL. The arrow bar indicates the minimum and maximum number of averages to achieve the minimal residual noise level. ABR, auditory brainstem response; LS, level-specific.

fluence of noise in ABR elicited from on-going speech stimuli and click stimuli, respectively. Both studies found an increase in absolute latencies and reduction in the ABR amplitudes in noise conditions compared to the quiet condition. One of the proposed reasons for the discrepancy in these studies could be due to the differences in the ambient acoustic noise levels. Kim, et al. [7] used white noise at 85 dBA where the level is considerably loud that may directly influence the ABR results. Previous studies involving ASSR and TEOAE have shown that both tests can be influenced by ambient acoustic noise, provided if the background noise levels exceed 70−75 dBA. Another plausible reason for the discrepancy between the present study and previous studies could also be due to the technique to stop the signal averaging applied in this study. In this study, the signal averaging was stopped only after the residual noise level relatively reached 0.04 μV. A study by Jamal, et al. [28] has shown that the ABR test-retest reliability for amplitudes and latencies were excellent if the recorded ABR signals were averaged until the remaining noise levels are low. This implied that the ABR amplitudes and latencies for all peaks in this study were not affected by the ambient acoustic noise due to the signal averaging processes that had overcome and minimized the ambient acoustic noise to an appropriate level to achieve an optimum SNR.

The present study found that no time savings can be obtained (from the number of averages) when using LS chirp stimulus to elicit an ABR compared to the ABR elicited by click stimulus in both quiet and noise conditions. Hypothetically, the ABR elicited from LS chirp could provide time savings due to its ability to enhance ABR waves I, III, and V amplitudes over the ABR to click stimulus [21,22,29]. Similar to the ABR amplitudes and latencies, the lack of differences in the time-savings provided could be caused by the signal averaging technique used in this study. A previous study investigated the time-savings provided by ABR elicited from LS chirp over click stimulus at multiple stimulus repetition rates and used the same signal averaging stopping criteria based on fixed residual noise level as in this study [22]. Similar to the current findings, the study observed no time-savings in the ABR using LS chirp or click stimuli or any of the stimulus repetition rates. The authors speculated that it could be due to the averaging based on fixed residual noise level that would not be able to reflect any time-savings if the ambient acoustic noise level were the same within all experimental conditions. Within the same test conditions (e.g., same noise types at same intensity level), both ABR to click and LS chirp stimuli could have a similar amount of noise, where there are translated to the same number of averages to overcome the same amount of noise in reaching the minimum fixed residual noise at 0.04 μV.

However, this explanation is not applicable for comparisons between different test conditions (e.g., in quiet vs. noise) for both ABR elicited from click and LS chirp stimuli. No significant difference was observed in the number of averages in ABRs elicited using both stimuli between quiet and the two noise test conditions. This implied that the ambient acoustic noise of up to 55 dBA used in this study does not influence the signal averaging process. Therefore, the number of averages would not make a difference in reaching the stopping criteria based on the remaining amount of noise compared to the quiet condition. One of the possible explanations could be because of the Bayesian signal averaging technique used in this study [14]. By using the Bayesian signal averaging technique, the ABR signals are averaged based on the quality of each recording. If the signal contains a substantial amount of noise, a lower weightage will be given, whereas, if the signal has a lesser noise, a higher weightage will be given. Therefore, the artefact rejection level can be raised to 40 μV instead of the

standard 10−20 μV, since the ABR signal will not be simply rejected, instead, different weightage will be given. In this study, no difference in the number of averages can be seen, which could be due to the weightage given to the acquired signal throughout the recording that did not reject the signals with a high amount of noise. The second possible explanation is on the intensity level of the ambient acoustic noise used in the present study. The present study used an ambient acoustic noise level at 55 dBA and there is a possibility that the ambient acoustic noise could affect the ABR recordings if the noise level exceeded 55 dBA, as shown in the previous ABR, ASSR, and TEOAE studies [1,5,9].

The present study also found larger waves I and V amplitudes in the ABR from LS chirp than the ABR from click stimulus, regardless of the test conditions and at all intensity levels tested. As highlighted in the introduction, several studies have reported similar findings [15,21,22]. This may be attributed to the abilities of the chirp, to stimulate the entire cochlear and the LS chirp, in general, and to minimize the upward spread of excitation at suprathreshold levels, specifically, as well as to enhance the slow discharge neurons of wave V by extending the duration of stimulus presentation at the lower intensity levels [17,19]. The LS chirp stimulus also has minimal influence on the ABR absolute latencies of waves III and V, similar to what has been reported previously in other studies [21,22]. It is anticipated that there will be no difference in latencies compared to the ABRs elicited from click and LS chirp stimuli due to the adjustment that has been done to the latency of the ABR from LS chirp. Specifically, the ABR to LS chirp has been adjusted in such a way that the reference 0 ms of the latencies is similar when all the entire LS chirp frequencies signals have been completely presented rather than at their true onset [30]. It is also noted that a statistically significant differences were identified in the absolute latencies between the ABR elicited from LS chirp and click for wave I at 80 dBnHL and wave V at 50 dBnHL. The respective mean differences of the absolute latencies between ABRs to LS chirp and click stimuli were only slightly above the test-retest repeatability of an ABR absolute latencies [25]. This suggests the differences found in those ABRs maybe cause by a normal variability when the ABR is repeated in the same subject and the variability may be greater when the recording was conducted in noisy conditions [7].

Future studies could further investigate the influence of ambient acoustic noise in the ABR from either click or LS chirp using the SNR as a stopping criterion. SNR is probably the best method to determine the influence of ambient acoustic noise, specifically to measure time-saving provided by the ABR to LS chirp as this technique will consider both the target ABR signal and the amount of ambient acoustic noise. In addition, future studies should also consider using different types of noise that can resemble the actual ambient acoustic noise, for example, in Universal Newborn Hearing Screening application and using different intensity levels of ambient acoustic noise.

In conclusion, this study demonstrated no influence of ambient acoustic noise on the ABR findings, regardless of the stimulus types. There was also no time-savings provided when the ABR was elicited using LS chirp over click stimuli, either in noise or quiet conditions. The results indicated that the ABR waves I and V amplitudes were larger with LS chirp than with click stimulus in all test conditions. The conclusion of this study applied only to the parameters used in the current study, including the ambient acoustic noise intensity level, the type of noise, and the ABR test protocols.

Acknowledgments

The authors wish to acknowledge the Transdisciplinary Research Grant Scheme (TRGS/1/2019/UIAM/02/4/2) from Ministry of Higher Education of Malaysia, for their financial support in conducting this study.

Conflicts of interest

The authors have no financial conflicts of interest.

Author Contributions

Conceptualization: Ahmad Aidil Arafat Dzulkarnain. Data curation: Balqis Aqilah Mat Rahed. Formal analysis: Ahmad Aidil Arafat Dzulkarnain, Balqis Aqilah Mat Rahed. Funding acquisition: Ahmad Aidil Arafat Dzulkarnain. Investigation: Ahmad Aidil Arafat Dzulkarnain, Balqis Aqilah Mat Rahed. Methodology: Ahmad Aidil Arafat Dzulkarnain, Balqis Aqilah Mat Rahed. Project administration: Fatin Amira Shahrudin, Fatin Nabilah Jamal. Resources: Mohd Normani Zakaria. Software: Ahmad Aidil Arafat Dzulkarnain, Balqis Aqilah Mat Rahed, Fatin Amira Shahrudin. Supervision: Ahmad Aidil Arafat Dzulkarnain. Validation: all authors. Visualization: Fatin Amira Shahrudin, Fatin Nabilah Jamal. Writing—original draft: Balqis Aqilah Mat Rahed. Writing—review & editing: Ahmad Aidil Arafat Dzulkarnain. Approval of final manuscript: all authors.

ORCID iDs

Ahmad Aidil Arafat Dzulkarnain https://orcid.org/0000-0003-4679-4910
Balqis Aqilah Mat Rahed https://orcid.org/0000-0002-3860-3216
Fatin Amira Shahrudin https://orcid.org/0000-0002-7494-7526
Fatin Nabilah Jamal https://orcid.org/0000-0002-9593-7132
Mohd Normani Zakaria https://orcid.org/0000-0002-3694-3460

REFERENCES

1) Kei J, Smith D, Joseph S, Stopa J, Kang S, Darnell R. Effects of ambient acoustic noise on the auditory steady-state response thresholds in normally hearing adults. Audiol Neurootol 2008;13:13-8.
2) Hall JW. eHandbook of auditory evoked responses: principles, procedures & protocols. Pretoria: Pearson;2015.
3) Stevens J, Sutton G, Wood S. Guidelines for the early audiological as-

sessment and management of babies referred from the Newborn Hearing Screening Programme. Version 3.1 [Internet]. [cited 2021 June 25]. Available from: URL: https://www.thebsa.org.uk/wp-content/uploads/2014/08/NHSP_NeonateAssess_2014.pdf.
4) Olusanya BO. Ambient noise levels and infant hearing screening programs in developing countries: an observational report. Int J Audiol 2010;49:535-41.
5) Richmond KH, Konkle DF, Potsic WP. ABR screening of high-risk infants: effects of ambient noise in the neonatal nursery. Otolaryngol Head Neck Surg 1986;94:552-60.
6) Burkard RF, Sims D. A comparison of the effects of broadband masking noise on the auditory brainstem response in young and older adults. Am J Audiol 2002;11:13-22.
7) Kim S, You S, Kim Y, Han W. Establishment of normative data for auditory brainstem responses in white noise condition. Korean J Otorhinolaryngol-Head Neck Surg 2019;63:14-20.
8) BinKhamis G, Léger A, Bell SL, Prendergast G, O'Driscoll M, Kluk K. Speech auditory brainstem responses: effects of background, stimulus duration, consonant−vowel, and number of epochs. Ear Hear 2019; 40:659-70.
9) Smith S, Kei J, McPherson B, Smyth V. Effects of speech babble on transient evoked otoacoustic emissions in normal-hearing adults. J Am Acad Audiol 2001;12:371-8.
10) Ananthanarayan AK, Gerken GM. Response enhancement and reduction of the auditory brain-stem response in a forward-masking paradigm. Electroencephalogr Clin Neurophysiol 1987;66:427-39.
11) Walton J, Orlando M, Burkard R. Auditory brainstem response forward-masking recovery functions in older humans with normal hearing. Hear Res 1999;127:86-94.
12) Don M, Elberling C. Evaluating residual background noise in human auditory brain-stem responses. J Acoust Soc Am 1994;96(5 Pt 1): 2746-57.
13) Elberling C, Don M. Quality estimation of averaged auditory brainstem responses. Scand Audiol 1984;13:187-97.
14) Elberling C, Wahlgreen O. Estimation of auditory brainstem response, ABR, by means of Bayesian inference. Scand Audiol 1985;14:89-96.
15) Kristensen SG, Elberling C. Auditory brainstem responses to level-specific chirps in normal-hearing adults. J Am Acad Audiol 2012;23: 712-21.
16) Dau T, Wegner O, Mellert V, Kollmeier B. Auditory brainstem responses with optimized chirp signals compensating basilar-membrane dispersion. J Acoust Soc Am 2000;107:1530-40.
17) Elberling C, Don M. Auditory brainstem responses to a chirp stimulus designed from derived-band latencies in normal-hearing subjects. J Acoust Soc Am 2008;124:3022-37.
18) Petoe MA, Bradley AP, Wilson WJ. On chirp stimuli and neural synchrony in the suprathreshold auditory brainstem response. J Acoust Soc Am 2010;128:235-46.
19) Elberling C, Callø J, Don M. Evaluating auditory brainstem responses to different chirp stimuli at three levels of stimulation. J Acoust Soc Am 2010;128:215-23.
20) Dzulkarnain AAA, Abdullah SA, Ruzai MAM, Ibrahim SHMN, Anuar NFA, Rahim EA. Effects of different electrode configurations on the narrow band level-specific CE-Chirp and tone-burst auditory brainstem response at multiple intensity levels and frequencies in subjects with normal hearing. Am J Audiol 2018;27:294-305.
21) Dzulkarnain AAA, Noor Ibrahim SHM, Anuar NFA, Abdullah SA, Tengku Zam Zam TZH, Rahmat S, et al. Influence of two-electrode montages on the level-specific (LS) CE-Chirp auditory brainstem response (ABR) at multiple intensity levels. Int J Audiol 2017;56:723-32.
22) Dzulkarnain AAA, Shahrudin FA, Jamal FN, Marzuki MN, Mazlan MNS. Effects of stimulus repetition rates on the auditory brainstem response to level-specific CE-Chirp in normal-hearing adults. Am J Audiol 2020;29:838-50.
23) Lopes BM, Bueno CD, Didoné DD, Sleifer P. Comparison between click and CE-Chirp® stimuli in neonatal hearing screening. J Hum Growth Dev 2020;30:260-5.
24) American National Standards Institute. American National Standard maximum permissible ambient noise levels for audiometric test rooms (ANSI S3.1-1999). New York: American National Standards Institute;1999.
25) American National Standards Institute. American National Standard specification for audiometers (ANSI S3.6-2004). New York: American National Standards Institute;2004.
26) Hatanaka T, Shuto H, Yasuhara A, Kobayashi Y. Ipsilateral and contralateral recordings of auditory brainstem responses to monaural stimulation. Pediatr Neurol 1988;4:354-7.
27) International Organization for Standardization. Acoustics—Reference zero fro the calibration of audiometric equipment—Part 6: reference threshold of hearing for test signals of short duration (ISO 389-6:2007). Geneva: International Organization for Standardization; 2007.
28) Jamal FN, Arafat Dzulkarnain AA, Shahrudin FA, Marzuki MN. Test-retest reliability of level-specific CE-Chirp auditory brainstem response in normal-hearing adults. J Audiol Otol 2021;25:14-21.
29) Cargnelutti M, Cóser PL, Biaggio EPV. LS CE-Chirp® vs. click in the neuroaudiological diagnosis by ABR. Braz J Otorhinolaryngol 2017;83:313-7.
30) Zakaria MN, Zainun Z, Cheu Lih A. Considerations when analyzing vestibular evoked myogenic potential (VEMP) outcomes elicited by chirp stimulus in healthy participants. J Int Adv Otol 2015;11: 271-2.