Absolute and Predicted Hearing Thresholds of Broadband Chirp-Auditory Brainstem Response in Adults with Sensorineural Hearing Loss

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Abstract

Background: : A CE-Chirp stimulus (named after Claus Elberling inventor) had been developed to compensate for the time delay associated with the cochlear traveling waves. The CE-Chirp evoked auditory brainstem responses (ABRs) are clearer and larger in amplitude than those obtained by click-evoked ABRs. Few or no data are available about the absolute and predicted hearing threshold using chirp evoked-ABR. **Aim:** This study aims to evaluate the absolute and predicted hearing thresholds using broad-band chirp (BBC) stimuli and to examine the relationship between the BBC-ABR and behavioral hearing thresholds in normal-hearing adults and those with different degrees and configurations of sensorineural hearing loss (SNHL).**Subjects and Methods:** The study involved a control group of 50 adults (18-50 years) with normal hearing and age- and gender-matched study group of 50 participants with variable degrees and configurations of SNHL. All participants were examined for basic audiological evaluation and BBC-ABR.**Results:** The BBC-ABR threshold showed the best correlation with the 0.5-4 kHz pure-tone average threshold. The mean difference of the BBC-ABR threshold versus the 0.5-4 kHz pure-tone average threshold showed a non-significant difference between normal hearing and different degrees and configurations of hearing loss except for a significantly lower difference at a severe hearing loss. There were moderate to strong correlations between the BBC-ABR and the 0.5-4 kHz pure-tone average threshold across different degrees and configurations of hearing loss. Uniquely, a regression equation y = -17.65 + (1*x) has been estimated to predict the 0.5-4 kHz pure-tone average threshold (y) from the BBC-ABR threshold (x). **Conclusion:** BBC-ABR provides an efficient method for estimating hearing thresholds in individuals with normal hearing and those with SNHL. Therefore, it can be suggested as an objective tool for hearing assessment in difficult-to-test subjects.

Keywords: Broadband-Chirp, SNHL, auditory brainstem response

DOI Number: 10.14704/nq.2022.20.8.NQ44725 NeuroQuantology 2022; 20(8):6993:7006

1.Introduction

The auditory brainstem responses (ABRs) are commonly recorded using click stimulus. The sudden start and broadband composition of the click activate a wide region of the cochlea synchronically **[1]**. However, it has been shown that the response to the click is not totally synchronized. When a click reaches the basilar membrane, the resulting sound wave spends an amount of time moving through the stimulated area of the basilar membrane, starting from the base to the apex. Hence, the lower frequency region responds a few milliseconds later than the higher one **[2]**. For this reason, the basilar membrane is not stimulated at the same time resulting in an asynchronous depolarization of neurons. More time is needed for the low-frequency region to attain maximum stimulation, a condition known as "the traveling wave delay" **[1;3;4]**.

This limitation in obtaining the ABR using a click stimulus required the elaboration of a new stimulus. An alternative stimulus known as CE-Chirp (named after Claus Elberling's inventor) had been developed to compensate for time delay associated with cochlear traveling waves **[5]**. This could be achieved through the adjustment of the temporal distribution of the stimulus components. The rising frequency sweeping of chirp stimuli repairs the temporal variations by delaying the higher frequency components of the stimulus until the lower frequency traveling waves are close to the apex of the cochlea. Therefore, the traveling waves of low and high frequencies concurrently arrive at their optimal response position on the basilar membrane, resulting in simultaneous neuronal activation and maximum neural synchrony **[6;7]**. The resulting CE-Chirp evoked ABRs are clearer and larger in amplitudes than those generated using the more conventional click stimulus, especially at lower intensities **[5;8;9]**.

Few data are available regarding the absolute electrophysiologic-behavioral hearing threshold difference. El Kousht et al. **[9]** studied BBC-ABR in 40 adults (80 ears; 20 with normal hearing sensitivity and 60 with different degrees of sensorineural hearing loss [SNHL]). They reported a mean broad-band chirp (BBC)-ABR threshold higher than the mean pure-tone threshold by 2 dB in ears with normal hearing and by 1.4 dB in ears with different degrees of SNHL. In addition, Maloff and Hood. **[10]** examined 25 normal-hearing adults and 25 adults with mild to severe SNHL. Participants with SNHL were separated into mild to moderate hearing loss and mild to severe hearing loss groups using click and BBC stimuli. They found that the behavioral thresholds were closer to chirp than click-evoked ABR in all groups. Moreover, BBC-ABR thresholds did not differ significantly from behavioral thresholds in the two hearing loss groups. In addition, no data about the predicted behavioral hearing threshold from the BBC-ABR are present in the literature.

Consequently, this study was conducted on adults with normal hearing and those with different degrees and configurations of SNHL to 1) estimate the absolute electrophysiologic hearing threshold as measured by BBC stimuli, 2) determine the mean difference between the electrophysiologic and behavioral hearing thresholds, 3) investigate the relationship between the electrophysiologic and behavioral hearing thresholds, and 4) calculate a predicted behavioral hearing threshold from the electrophysiologic one by applying regression analysis in normal hearing threshold and different degrees of SNHL. Identifying the absolute electrophysiologic hearing threshold, the mean difference between the electrophysiologic and behavioral hearing thresholds, and a predicted behavioral hearing threshold would be helpful in hearing assessment in difficult-to-test subjects with variable levels of hearing thresholds.

2. Methods

Subjects

This work involved control and study groups. The control group contained 50 participants (100 ears) with normal hearing sensitivity, an age range of 18 – 50 years, and both genders. The study group also consisted of 50 participants (100 ears), matching the control group in age and gender. They had bilateral SNHL, ranging from mild to profound across the hearing frequency range of 0.25 - 8 kHz. The degree of the hearing was determined according to the level of air conduction (AC) audiometry where the normal hearing was considered at AC of less than or equal to 25 dB HL, mild SNHL at 26-40 dB HL, moderate SNHL at 41-55 dB HL, moderately-severe SNHL at 56-70 dB HL, severe SNHL at 71-90 dB HL, and profound SNHL at a level greater than 90 dB HL **[11]**. Moreover, the hearing loss configuration was categorized based on the shape of the air conduction audiogram across the hearing frequency range of 0.25 – 8 kHz. Audiometric configurations in the study group included flat (< 5 dB difference per octave), sloping (15-20 dB increase per octave), and steeply sloping (> 20 dB increase per octave) **[12]**. Subjects with external ear, middle ear, or retro-cochlear lesions were excluded from the study.

Procedure

The study was done at the Audio-Vestibular Medicine unit, otorhinolaryngology department, Zagazig University Hospitals, Zagazig, Egypt, from which the participants were recruited. The examinations were established from May 2020 to September 2021. The nature and objectives of this study were clarified to participants prior to participation. They gave written consent before testing. Approval was obtained by the Institutional Review Board of Zagazig University with an ID of 6104-30-5-2020.

The procedure required one session of an hour to be completed. At the start, detailed history was obtained regarding hearing loss (side, onset, course, and duration), past history for medical conditions such as otological or neurological diseases, and family history. The otoscopic examination was followed to ensure intact external and middle ears. The basic audiological evaluation was then performed to determine the behavioral hearing threshold levels and configurations. Finally, BBC-ABR audiometry was applied to estimate the electrophysiologic hearing threshold.

Basic audiological evaluation

Behavioral audiometry was conducted in a sound isolated booth using a dual-channel audiometer, Madsen (Model Orbiter 902, version 2, Taastrup, Denmark). It involved AC pure-tone audiometry for octave frequencies 250 Hz through 8000 Hz, bone conduction pure-tone audiometry for octave frequencies 500 Hz through 4000 Hz, and speech audiometry that included speech reception threshold (SRT) test utilizing the Arabic bisyllabic words for adults and Word Recognition score (WRS) test utilizing the Arabic Phonetically Balanced Words for adults **[13]**. The air-conducted stimuli (including speech) were delivered through the supra-aural headphones, TDH-39. Furthermore, middle ear functions were assessed by a middle ear analyzer, Madsen (model Zodiac 901 v. 3.2, Taastrup, Denmark) through testing the tympanometry and the contralateral-acoustic reflex threshold over 500, 1000, 2000, and 4000 Hz frequencies.

Broad-Band Chirp-Evoked auditory brainstem response audiometry:

The BBC- ABR audiometry was performed in a sound-isolated room using an auditory evoked system Oto-Access (Eclipse 25; version 1.3; Assens, Denmark). The stimuli were delivered by insert-earphones (Etymotic Research-3) with alternating polarity and a rate of 19.3 stimuli/second. To measure the electrophysiologic threshold, the BBC stimuli were presented at a level of 90 dB nHL, then the level was reduced in 20 dB steps till wave V disappeared and increased in 10 dB steps till wave V reappear.

Disposable electrodes with a conductive gel were used to pick up the response. They were placed on the skin after scrubbing it with sandpaper to decrease the electrode impedance to less than 3 kΩ and to maintain interelectrode impedance at equilibrium. Four electrodes were placed after the 10-20 International System for electrode placement. The inverting electrodes were placed on the right and left mastoids, the non-inverting electrode on the Fz position (upper mid-frontal region), and the ground electrode on the Fpz position (lower mid-frontal region).

Participants were instructed to stay calm with their eyes closed during recording. Two thousand sweeps, a filter setting of 100 Hz to 3 kHz, an amplifier gain of 60-80 dB, and an artifact rejection of 40 µV were utilized to obtain an optimal recording. A time window of 20 ms was used to display the ABR traces. To ensure repeatability, we obtained two traces at each presentation level. The measures of BBC-ABR recording involved wave I, III, and V latency (in ms) and amplitude (in µV) at the 90 dB nHL and the threshold of wave V detection [14].

Statistical Analysis

The SPSS software (version 20.0, Armonk, New York: IBM Corporation) was used to collect data and perform analysis. The frequency (percentages) distribution was assessed by the Chi-square test. The normality of data distribution was estimated by the Shapiro-Wilk test. Quantitative data were presented as a range (minimum to maximum), mean, standard deviation (SD), and 95% confidence limits. For comparison between groups, the student's *t*-tests and the One-Way-ANOVA test were used. The Post-Hoc test was used when there was a statistically significant result to identify the actual differences that existed between groups and subgroups. In participants with profound SNHL, no wave V could be estimated during the BBC-ABR recording. Therefore, there was no data for this group to be involved in the comparison between groups.

The relationship between variables was determined by the Person's correlation coefficient. Regression analysis was then applied between the highest correlated dependent variable (the pure-tone average 0.5 – 4 kHz threshold) and the independent variable (BBC-ABR threshold). To obtain the predicted behavioral threshold (dependent variable) from the electrophysiologic one (independent variable), a regression equation was estimated from the regression analysis as follows:

$$y = a + b*x$$

where: "y" means the dependent variable, "a" represents the constant value (value of "y" when x equals zero), "b" indicates the slope of the regression line for the "x" variable (change of "y" with each unit change of x), and "x" represents the independent variable. The significance for all test results was set at a *p*-value less than 0.05.

3. Results

The two study groups in this work are matching in age and gender **(Table 1)**. Pure-tone audiometry reveals bilateral normal hearing sensitivity in all tested octave frequencies (0.25 – 8 kHz) in the control group **(Figure 1)**, whereas the study group has different degrees of SNHL with their mean values illustrated in **Figure 2**. **Figure 3** represents the distribution of hearing loss degrees in the right and left ears of the study group that appears to be homogenous [χ^2 (4, *N*=100) = 0.30, *p* = 0.99]. The audiometric configurations are shown in **Figure 4** with the predominance of the flat configuration (78% of right ears, 72% of left ears, and 75% of all ears). This is followed by sloping and then steeply-sloping configurations [χ^2 (2, N=100) =0.55, *p* = 0.76]. Both groups have an SRT that matches the average pure tone audiometric threshold and a WRS coinciding with the hearing threshold level in both ears. Additionally, immittancemetry reveals bilateral type A tympanograms in both groups with acoustic reflexes that match the mean audiometric thresholds.

To perform correlations between BBC-ABR and pure-tone thresholds and to predict the behavioral threshold from the electrophysiologic one, it was essential to combine data from both ears. This has been established by comparing BBC-ABR measures (latency, amplitude, and threshold) of both ears which reveals a statistically non-significant difference and excludes the ear effect **(Table 2)**.

Table 3 displays the mean and 95% CI of differences between BBC-ABR and pure-tone thresholds for individual frequencies (0.25, 0.5, 1, 2, 4, and 8 kHz) and different frequency averages (0.25-4, 0.5-4, 1-4, 2-4, 0.25-8, 0.5-8, 1-8, and 2-8 kHz) in 100 ears of the control group. Moreover, the relationships between the BBC-ABR and pure-tone thresholds are included in **Table 3** to find the best correlations that are for 0.5 kHz, 1 kHz, and average 0.5-4 kHz. The highest among these correlations is for the 0.5-4 kHz pure-tone hearing threshold average, hence it has been adopted throughout the rest of the calculations.

The effect of the degree of hearing is presented in **Table 4**. There is no significant difference in latency between normal hearing and mild SNHL while the higher degrees of hearing loss are significantly delayed. The amplitude measure is higher in normal hearing and earlier degrees of hearing loss then mostly significantly decreases at the higher degrees. Moreover, the BBC-ABR thresholds reveal a statistically significant increase as the level of hearing increases from normal up to a severe degree. The mean difference between BBC-ABR and the 0.5-4 kHz average (the highest correlate) thresholds exhibits a non-significant difference up to moderately-severe hearing loss while the difference in severe hearing loss is significantly lower than the better hearing levels. In studying the relationship between BBC-ABR and the 0.5-4 kHz average thresholds, moderate positive correlations have been found for normal hearing and different degrees of hearing loss.

Additionally, the effect of audiometric configuration has been evaluated **(Table 5)**. Wave V latency shows a significant delay in all hearing loss configurations as compared to normal hearing. However, the amplitude measure was nearly homogenous among the control group and different audiometric configurations of the study subgroups. The BBC-ABR threshold was significantly lower in the control group, but nearly comparable at different audiometric configurations of hearing loss with the sloping type having the highest threshold. Moreover, the difference between BBC-ABR and the average 0.5-4 kHz threshold reveals no statistically significant difference between the control group and the audiometric configurations in the study group. Strong correlations have been noticed between BBC-ABR and average 0.5-4 kHz pure-tone thresholds in different configurations of hearing loss.

To predict the value of pure-tone 0.5-4 kHz average threshold (y) from BBC-ABR threshold (x), a regression equation has been estimated from regression analysis of these two variables. **Table 6** shows a constant correction value of 17.65 as the BBC-ABR hearing threshold increases.

Table (1): Age and gender distribution of both groups.

Demographic Data	Study group (N=50)	Control group (N=50)	Test value	*p*
Age				
Mean±SD	34.54±8.69	32.22±8.39	*t*=1.36*	0.178
Range	18-49	19-48		
Sex				
Male	27(54.0%)	22(44.0%)	χ^2=1.00#	0.317
Female	23(46.0%)	28(56.0%)		

*Independent sample t-test; #Chi-square test.
Abbreviations: *p* = significance value

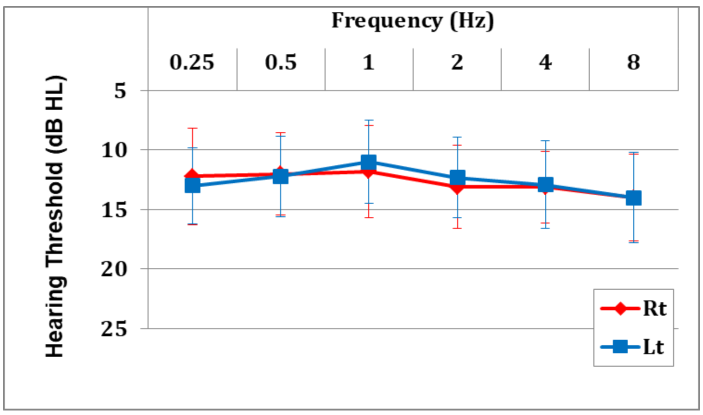

Figure (1): Pure-tone hearing threshold at different frequencies in both ears of the control group.

*e*ISSN 1303-5150

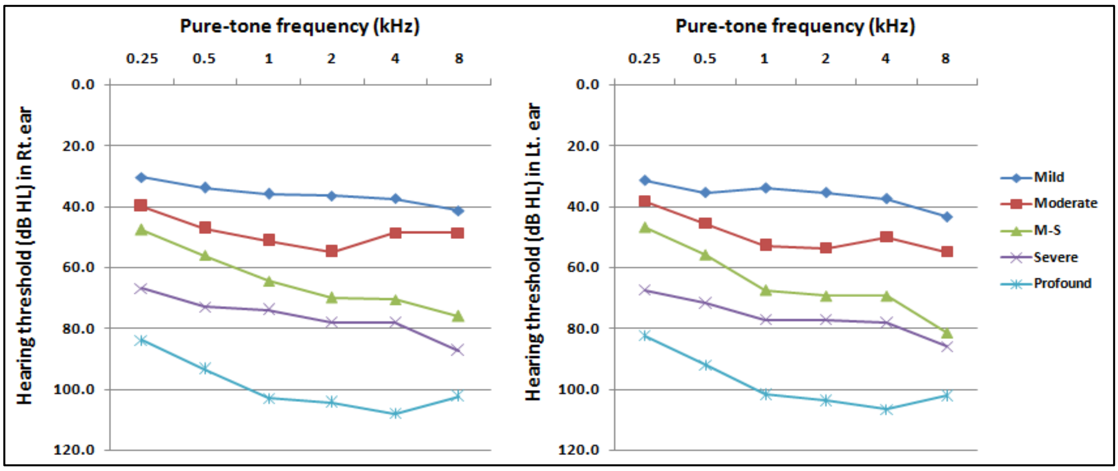

Figure (2): The mean pure-tone hearing thresholds at different degrees of hearing loss.
Abbreviations: Rt= Right; Lt= Left; M-S= Moderately- severe.

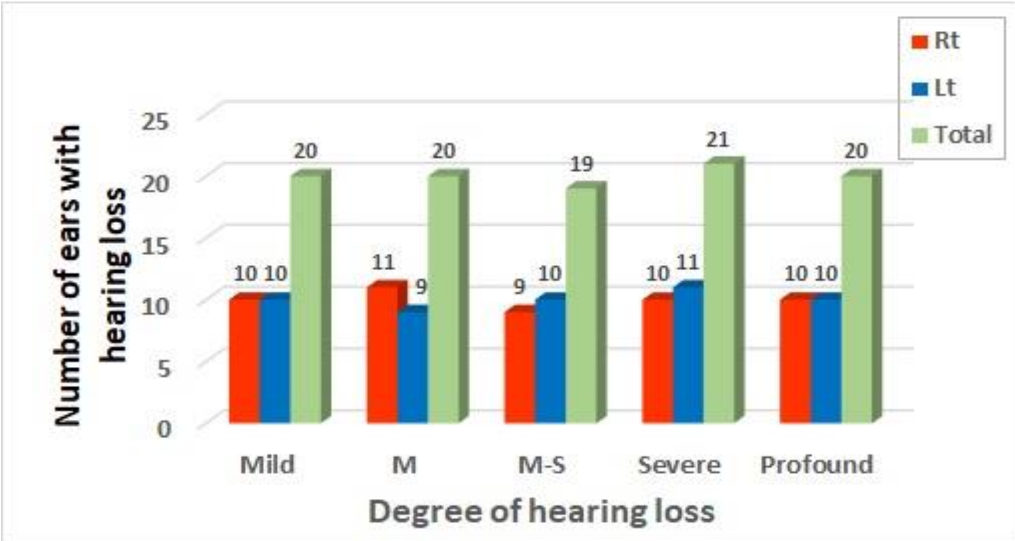

Figure (3): Distribution of hearing loss degrees in both ears of the study group.
Abbreviations: Rt = Right; Lt = Left; M = Moderate; M-S= Moderately-severe.

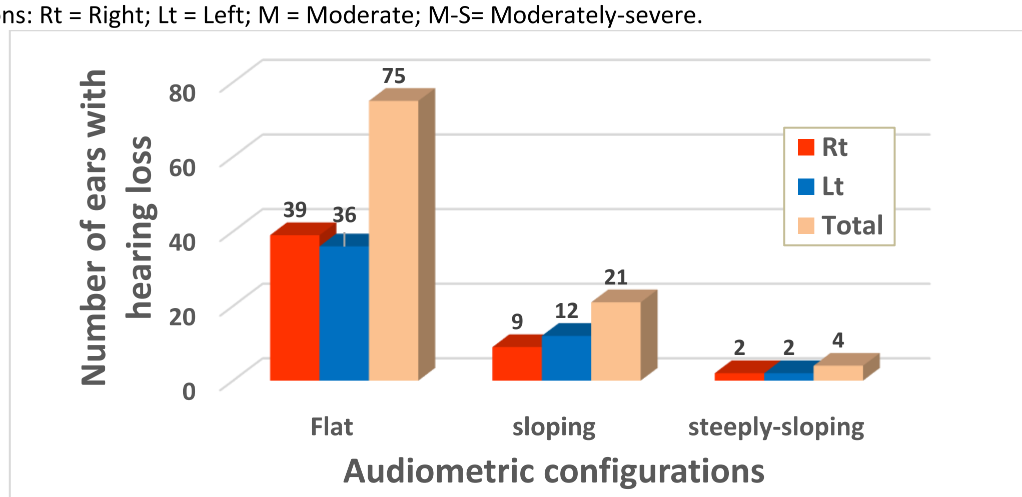

Figure (4): Distribution of audiometric configuration in both ears of the study group.
Abbreviations: Rt = Right; Lt = Left.

Table (2): Comparison between BBC-ABR measures of both ears in the control group (N= 50).

BBC-ABR measures	Rt. Ear		Lt. ear		*t*	*p*
	Mean±SD	**95%CI**	**Mean±SD**	**95%CI**		
Lat. of Wave V	5.14±0.21	5.08-5.20	5.17±0.11	5.11-5.22	1.29	0.20
Amp. of Wave V	0.51±0.15	0.48-0.56	0.51±0.15	0.46-0.55	0.57	0.57
BBC-ABR threshold (dB n HL)	30.00±1.75	29.50-30.50	29.80±0.99	29.52-30.08	1.00	0.32

Abbreviations: Lat. = Latency; Amp. = Amplitude; Rt. = Right; Lt. = Left; SD = Standard deviation; CI = Confidence interval; *t*= Paired sample t-test; *p* = significance value; BBC-ABR = Broad-band chirp-evoked auditory brainstem response.

Table (3): Mean difference (±SD) and correlation between BBC-ABR and pure-tone thresholds in dB for individual frequencies and different frequency averages (N=100 ears) in the control group.

Pure-tone frequency (kHz)	Mean difference (±SD) between BBC-ABR and pure-tone thresholds (dB)		Correlation between BBC-ABR and pure-tone thresholds	
	Mean ± SD	**95% CI**	***r***	***p***
0.25	17.30±3.53	16.30-18.30	0.061	0.67
0.5	17.80±2.97	16.96-18.64	0.548	<0.001*
1	18.50±3.03	17.64-19.36	0.591	<0.001*
2	17.20±2.93	16.37-18.03	0.081	0.58
4	16.90±2.88	16.08-17.72	0.467	0.001*
8	15.90±3.70	14.85-16.95	0.024	0.87
0.25-4	17.54±1.85	16.87-18.21	0.460	0.001*
0.5-4	17.60±1.81	16.92-18.28	0.602	<0.001*
1-4	17.54±1.90	16.84-18.23	0.503	<0.001*
2-4	17.06±2.27	16.32-17.78	0.329	0.02*
0.25-8	17.27±1.89	16.60-17.93	0.390	0.001
0.5-8	17.90±3.51	16.59-17.93	0.469	0.001*
1-8	17.13±1.85	16.44-17.81	0.391	0.005
2-8	16.67±2.34	15.95-17.38	0.215	0.13

Abbreviations: BBC-ABR = Broad-band chirp-evoked auditory brainstem response; SD = Standard deviation; CI = confidence interval; *r*= Correlation coefficient; *p* = significance value.

Table (4): BBC-ABR measures, mean difference, and correlation between BBC-ABR and 0.5-4 kHz pure-tone threshold average in the control group and different degrees of hearing loss in the study group.

BBC-ABR outcomes		**CG**	**Degree of HL in SG Mean ± SD**				**F**	***p***	**Ordering***
			Mild	**M**	**M-S**	**Severe**			
Lat. of wave V (ms)	**Rt.**	5.14 ± 0.21	5.30 ± 0.24	5.40 ± 0.53	5.70 ± 0.36	5.80 ± 0.19	16.93	<0.001	a, ab, bc, de, e
	Lt.	5.17 ± 0.20	5.27 ± 0.20	5.59 ± 0.46	5.80 ± 0.45	5.93 ± 0.37	21.51	<0.001	a, a, b, bc, c
Amp. of wave V (µV)	**Rt.**	0.52 ± 0.15	0.49 ± 0.13	0.46 ± 0.11	0.53 ± 0.34	0.24 ± 0.07	3.82	0.007	a, a, a, a, b
	Lt.	0.51 ± 0.15	0.44 ± 0.09	0.41 ± 0.16	0.32 ± 0.17	0.37 ± 0.26	3.88	0.006	a, ab, ab, b, b
BBC-ABR thresholds (dB nHL)	**Rt.**	30 ± 1.75	56 ± 5.16	67.27 ± 6.47	87.78 ± 4.41	86.67 ± 8.16	689.01	<0.001	a, b, c, d, de
	Lt.	29.80 ± 0.99	56 ± 5.16	70 ± 7.07	85 ± 8.50	85 ± 7.56	544.78	<0.001	a, b, c, de, e
BBC-ABR and average 0.5-4 kHz threshold difference (dB)	**Mean ±SD**	17.60 ± 1.81	18.36 ± 3.34	16.30 ± 5.59	17.62 ± 4.12	13.19 ± 5.34	4.76	0.001	a, a, a, a, b
	95% CI	16.92-18.28	16.80-19.92	13.68-18.91	15.64 -19.61	10.11-16.28			
	Range	11.25-22.50	11.20-23.70	5-23.70	7.50-23.70	0.00-18.70			
r		0.602	0.570	0.434	0.635	0.430	-		
p		<0.001	0.009	0.05	0.003	0.12			

*Ordering: Subgroups were given symbols (a, b, c, d, or e; according to the number of subgroups). When they shared the same symbol, this meant that there was no difference between them while different symbols meant a significant difference.

Abbreviations: BBC-ABR = Broad-band chirp-evoked auditory brainstem response; HL = Hearing loss; CG = Control group; SG = Study group; M = Moderate; M-S = Moderately-severe; SD = Standard deviation; CI = confidence interval; Lat. = Latency; Amp. = Amplitude; Rt = Right; Lt = Left; F = One-Way-ANOVA value; *r* = correlation coefficient; *p* = significance value.

Table (5): BBC-ABR measures, mean difference, and correlation between BBC-ABR and 0.5-4 kHz pure-tone threshold average in the control group and different audiometric configurations in the study group.

BBC-ABR outcomes		CG	Configuration of HL in the SG Mean ± SD			F	*p*	Ordering *
			Flat	Sloping	Steeply-sloping			
Lat. of wave V (ms)	Rt.	5.14 ± 0.21	5.52 ± 0.39	5.66 ± 0.78	5.67 ± 0.37	10.76	<0.001	a, b, b, b
	Lt.	5.17 ± 0.20	5.59 ± 0.41	5.69 ± 0.51	6.10 ± 0.71	16.91	<0.001	a, b, bc, c
Amp. of wave V (µV)	Rt.	0.52 ± 0.15	0.43 ± 0.21	0.56 ± 0.24	0.53 ± 0.07	2.08	0.11	-
	Lt.	0.51 ± 0.15	0.36 ± 0.13	0.46 ± 0.29	0.43 ± 0.27	4.81	0.004	a, b, ab, ab
BBC-ABR thresholds (dB n HL)	Rt.	30.00 ± 1.75	70.34 ± 14.10	82 ± 8.37	80 ± 14.14	151.94	<0.001	a, b, c, bc
	Lt.	29.80 ±0.99	71.07 ±14.99	81.43 ±8.10	80 ± 0.00	173.18	<0.001	a, b, c, bc
BBC-ABR and average 0.5-4 kHz threshold difference (dB)	Mean ± SD	17.60 ± 1.81	16.45 ± 4.92	16.57 ± 5.51	19.03 ± 2.14	1.19	0.32	-
	95% CI	16.92-18.28	15.15-17.76	13.07-20.07	15.62-22.43			
	Range	11.25-22.50	0.00-23.70	7.50-23.70	16.20-21.20			
r		0.602	0.954	0.789	0.997	-		
p		<0.001	<0.001	0.002	0.003			

*Ordering: Subgroups were given symbols (a, b, c, d, or e; according to the number of subgroups). When they shared the same symbol, this meant that there was no difference between them while different symbols meant a significant difference.

Abbreviations: BBC-ABR = Broad-band chirp-evoked auditory brainstem response; HL = Hearing loss; CG = Control group; SG = Study group; SD = Standard deviation; CI = Confidence interval; Lat. = Latency; Amp. = Amplitude; Rt = Right; Lt = Left; F = One-Way-ANOVA value; *r* = correlation coefficient; *p* = significance value.

Table (6): Predicted value of 0.5-4 kHz pure-tone average threshold (y) from BBC-ABR threshold (x) using the regression equation y = -17.65 + (1*x).

BBC-ABR threshold (x) (dB n HL)	Predicted 0.5-4 kHz pure-tone average threshold (y) (dB HL)	The correction value for y from x
In the control group		
20	2.35	-17.65
25	7.35	-17.65
30	12.35	-17.65
35	17.35	-17.65
40	22.35	-17.65
In the study group		
50	32.35	-17.65
60	42.35	-17.65
70	52.35	-17.65
80	62.35	-17.65
90	72.35	-17.65

Abbreviations: BBC-ABR = Broad-band chirp-evoked auditory brainstem response

4. Discussion

The ABR is an objective method that helps to evaluate the integrity of the auditory pathway up to the level of the brainstem and estimate the hearing threshold **[14]**. BBC-ABR has gained much interest in the field of hearing threshold assessment **[15]**. In the current study, the difference and relationship between the BBC-ABR hearing threshold and the hearing threshold at different pure-tones (0.25, 0.5, 1, 2, 4, and 8 kHz) and pure-tone averages (0.25-4, 0.5-4, 1-4, 2-4, 0.25-8, 0.5-8, 1-8, and 2-8 kHz) have been estimated in the control group. The highest correlation was found with the 0.5-4 kHz threshold average with an electrophysiologic-behavioral difference of 17.60 (SD = 1.81) dB.

Similarly, wang et al. **[16]** reported a strong positive correlation between the BBC-ABR hearing threshold and the 0.5-4 kHz average threshold in 35 ears with normal hearing and different degrees of hearing loss in children with an average age of 4.8 years. On the other hand, Baldwin and Watkin **[17]** have found a strong positive correlation between the click-evoked ABR and the pure-tone average thresholds at 2-4 kHz with an electrophysiologic-behavioral difference of 4.4 (SD = 19.29) dB in children with permanent childhood hearing impairment. It can be noticed that the behavioral representation of the BBC-ABR (0.5-4 kHz) extends to involve a broader frequency range including low frequencies as compared to that of the click-evoked ABR (2-4 kHz). This could be attributed to simultaneous displacement by canceling traveling-time differences along the cochlear partitions. Consequently, both low- and high-frequency cochlear parts are stimulated and reach maximum depolarization at the same time, causing a simultaneous neural response **[6]**.

The present study was designed to evaluate the potential role of BBC stimuli in identifying hearing thresholds and to estimate the effect of degree and audiometric configuration of hearing loss on the mean difference between the BBC-ABR and the behavioral thresholds in adults with normal hearing and those with SNHL. At 90 dB nHL stimulation level, wave V latency and amplitude were comparable in normal hearing and earlier degrees of SNHL, but became significantly different (longer latency and smaller amplitude) in higher degrees of hearing loss. In earlier degrees of SNHL, the cochlear damage is limited but becomes extensive in higher degrees of hearing loss with a resulting neural conduction delay and reduction in the magnitude of the potential **[18]**. Additionally, the BBC-ABR hearing threshold was determined by tracing down wave V and found to coincide with the behavioral threshold of the 0.5-4 kHz pure-tone average giving a moderate positive correlation at different hearing levels. This is in accordance with the accuracy of click-evoked ABR **[19]**.

The mean difference between BBC-ABR and the 0.5-4 kHz average thresholds was equivalent up to the moderately-severe degree of hearing loss [mean difference of 17.60, 18.36, 16.30, and 17.62 dB for normal hearing, mild, moderate, and moderately-severe hearing loss, respectively], whereas the severe hearing loss exhibited a significantly lower difference of 13.19 dB. These results agree with those of Ozdek et al. **[20]** which revealed a lower electrophysiologic-behavioral difference when the hearing loss degree increases as estimated by the auditory steady-state response in adults with normal hearing and different degrees of hearing loss. This could be based on the electrophysiological recruitment phenomenon where the increased damage of the outer hair cells, in severe degrees of hearing loss, leads to an increase in the magnitude of the potential near-threshold and better electrophysiological assessment at low **[21]**. Moreover, the present outcomes are higher than that of Elmously et al. **[22]** who estimated a mean BBC-ABR-behavioral difference of 12.6 dB in 50 infants. The lower difference in the previous study could be related to a younger age sample involving infants from 2 to 24 months old. In addition, El Kousht et al. **[9]** reported a mean ABR threshold for CE-chirp higher than the mean pure-tone threshold by 2 dB in 10 adults with normal hearing and 1.4 dB in 30 adults with different degrees of SNHL. This small difference could be explained by the nearly equal frequency of flat and sloping audiometric configurations but in the current study, there is a predominance of the flat configuration.

Furthermore, moderate positive correlations have been found between BBC-ABR and the 0.5-4 kHz average thresholds in normal hearing and different degrees of hearing loss. Maloff and Hood **[10]** exhibited the same results and found a positive correlation between the behavioral threshold and the chirp-ABR threshold for mild to severe hearing loss

The effect of audiometric configuration on BBC-ABR measures has been also studied. Wave V latency shows a statistically significant delay in all types of audiometric configurations in comparison to normal hearing. Nevertheless, the amplitude measure was nearly similar among the control group and different audiometric configurations of the study subgroups. Moreover, the BBC-ABR threshold was significantly lower in the control group, but nearly comparable at different hearing loss configurations with the sloping type having the highest threshold. Fowler and Durrant **[18]** and Musiek et al. **[23]** reported that the effect of audiometric configurations (flat, mildly sloping, and sharply sloping) of cochlear hearing loss on the ABR evoked by click stimulus can be quite variable. The extent of the latency shift is affected by the slope as well as the degree of hearing. In accordance with our results, they found that the effects of hearing loss on the ABR (at 80 dB nHL) in flat or mildly sloping hearing loss of mild to moderate severity were minimal or nonexistent with some reduction in amplitude may be found, presumably related to the reduction of neural units. However, in contrast to the current findings, patients with moderate to severe high-frequency SNHL exhibited wave V latency-intensity function that was steeper than normal. This could be related to the small number of ears with steeply-sloping hearing loss (n = 4) in the present study. On the other hand, the steeper latency-intensity function in the previous studies may be explained by the contribution of audiometric frequencies below 1000 Hz to the click-evoked ABR response at lower stimulus intensity levels. The response latency at this intensity is abnormally prolonged because ABR is generated from a more apical portion of the cochlea and requires greater travel time along the basilar membrane. Thereafter, as the stimulus intensity level exceeds hearing thresholds in the region of 1000-4000 Hz the latency of wave V decreases rapidly and falls within the normal region.

Additionally, the mean difference between the BBC-ABR and the 0.5-4 kHz average thresholds did not differ significantly with a strong positive correlation between the two measures among the control group and the different audiometric configurations study subgroups. Data regarding the effect of audiometric configurations on the mean difference between the electrophysiologic and behavioral thresholds are lacking. However, several researchers studied the correlation between these two measures at different configurations. Maloff and Hood **[10]** found a positive correlation between the behavioral threshold and the chirp-ABR threshold in flat and sloping configurations in adults with mild to severe hearing loss. El-Attar et al **[24]** found a strong positive correlation between CE-chirp ABR and 0.5-4 kHz average pure-tone threshold in normal children and those with the flat and steeping audiometric configurations of SNHL. Moreover, Hardman and Stapells **[25]** found a good agreement between ASSR threshold and behavioral thresholds in SNHL patients with different audiometric configurations.

A fundamental objective of this study was to perform a regression analysis in order to predict the behavioral hearing threshold from the electrophysiologic threshold. The testing outcomes of normal hearing adults were subjected to regression analysis to find a regression equation that could predict the value of y (pure-tone average threshold at 0.5- 4 kHz) from x (BBC-ABR threshold) in both study groups. The regression equation [y = -17.65 + (1*x)] provided a constant correction value even at high electrophysiologic thresholds. There are no previous studies that predicted the behavioral hearing threshold using BBC-ABR. Likewise, a linear regression model was estimated by Baldwin and Watkin **[17]** to predict the pure-tone threshold from the click-evoked ABR threshold in children with permanent hearing loss. These children were tested for ABR at an age below six months then the pure-tone audiometry was performed when they became 2.6 to 12.8 years old. A regression equation of $y = -1.32 + 0.94*x$ was estimated to predict the threshold of pure-tone average 2–4 kHz from the click-ABR threshold. Baldwin and Watkin **[17]** reported that this regression model may overestimate prospective hearing loss in infants who suffered perinatal complications or were prematurely born. This may be due to an associated temporary conductive hearing impairment or neural component during infancy that requires an adequate assessment.

The current outcomes showed that the BBC-ABR testing can be used effectively for hearing threshold estimation in adults with normal hearing and those having different degrees and configurations of SNHL. Consequently, this objective measure could be applied as an easy and rapid tool for threshold estimation in very young children and difficult-to-test subjects with considerable accuracy.

5. Conclusion:

The current study revealed that the BBC-ABR could provide an accurate objective estimation of the hearing threshold in normal hearing adults and those with different degrees and configurations of SNHL. The BBC-ABR threshold showed the highest correlation with the 0.5-4 kHz pure-tone average threshold as compared to the click-ABR threshold which was previously found to be correlated with the 2-4 kHz pure-tone average threshold. The mean difference between the BBC-ABR threshold and 0.5-4 kHz pure-tone average threshold was found to be comparable across normal hearing and different degrees and configurations of hearing loss except for a significantly lower difference at the severe degree of hearing loss. Additionally, there were moderate to strong correlations between the BBC-ABR and the 0.5-4 kHz pure-tone average threshold over different degrees and configurations of hearing loss. A novel outcome in this study is the estimation of a regression equation y = -17.65 + (1*x) to predict the 0.5-4 kHz pure-tone average threshold (y) from the BBC-ABR threshold (x) with a constant correction value of 17.65 throughout the electrophysiologic hearing thresholds. Consequently, BBC-ABR can provide an easy and reliable threshold estimation in adults with normal hearing and different degrees of SNHL and it can be suggested as an objective tool for threshold estimation in difficult-to-test subjects.

Conflict of Interest: None

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