Complex auditory brainstem response in normal-hearing adults using binaural versus monaural speech stimuli

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Background
Binaural hearing refers to the ability of the auditory system to integrate sounds reaching both ears. The complex auditory brainstem response (cABR) to the /da/ synthetic syllable gives information about time-locked response that is either transient or sustained depending on the periodic or nonperiodic characteristics of the stimulus.

Objective
This is a preliminary research that was performed to study the binaural interaction component of cABR in normal-hearing adults.

Patients and methods
This study included 20 normal-hearing adults, whose age ranged from 15 to 60 years, with a mean age of 29.30±12.52 years. CABR was conducted for all patients. The stimulus used was the syllable [da] (40 ms), presented first monaurally (left and right) and then binaurally through TDH headphones, in alternating polarity at 80 dBnHL. The binaural interaction component (BIC) was then computed by subtracting the binaural waveform from the sum of the two monaural responses.

Results
The mean right amplitudes were smaller than binaural amplitudes for waves V, A, C, D, E, and F. However, this difference was statistically significant at D, E, and F waves only. The mean left amplitudes were smaller than binaural amplitudes for waves V, A, C, D, and E only. In addition, this difference was statistically significant. The mean binaural amplitudes were smaller than the summed right+left amplitudes for waves V, A, C, D, E, F, and O. There was no statistically significant difference among the mean latencies of responses recorded from right, left, or binaural for all cABR waves.

Conclusion
BICs reflecting binaural process can be obtained for ABR using speech stimuli comparing the binaural and summed monaural recorded responses. We recommend assessing the BIC on a large scale to obtain normative data, for comparison with patients with known auditory processing capabilities (shown by behavioural tests) to see how well the data can be used as an index of binaural process.

Keywords:
amplitude, binaural interaction component, complex auditory brainstem response, hearing

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Introduction

Binaural hearing refers to the ability of the auditory system to integrate sounds reaching both ears. It enables sound localization and improves speech perception in more adverse listening conditions [1]. Even without presence of peripheral hearing loss due to inner-ear deficiencies, elderly persons may have compromised ability to understand speech in a noisy environment [2] or localize sound sources, which may reflect more central processing deficits [3]. In addition, children who have experienced persistent conductive hearing loss because of common conditions such as otitis media with effusion, which is considered the number one cause of hearing loss in children [4], can show binaural and spatial hearing impairments even years after the cause of the hearing loss has passed and peripheral hearing has returned to normal [5,6].

Click-evoked auditory brainstem response (ABR) is the most commonly used auditory evoked potential to assess data processing in the auditory pathway in the first 10 ms after stimulus presentation [7–9]. The complex auditory brainstem response (cABR) to the /da/ synthetic syllable gives information about time-locked responses that are either transient or sustained depending on the periodic or nonperiodic characteristics of the stimulus [10,11].

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cABR is described in terms of an onset response and frequency following response (FFR). Both amplitude and latency deviances in onset response and FFR of cABR have been linked to abnormal perception and linguistic abilities [12]. Speech-evoked ABR response parameters were affected in children with learning disability, in the form of statistically significant delayed latencies and diminished amplitude of several waves, compared with their controls. This reflected abnormality in brainstem encoding of speech signals [13].

Binaural interaction is the process whereby detection of signals in background noise is improved with the detection and calculation at the brainstem of small timing differences between signals received at the two ears [14]. Several nuclei in the auditory brainstem are known to represent binaural acoustical cues based on the spectral and temporal characteristics of sounds arriving at the two ears [15].

The binaural interaction component (BIC) has proven to be an evoked response that can be identified in most, but interestingly not all, audiologically normal-hearing human patients [16–19]. A BIC can be derived from the ABR (ABR–BIC) by subtracting the response to binaural stimulation (B) from the sum of the monaural responses (L+R) [1]. The presence of an ABR–BIC is considered to be evidence for binaural interaction at the level of the auditory brainstem. The concept is based on the law of linear superposition of electric fields [20]. Uppunda *et al.* [21] demonstrated that BICs can be reliably recorded for speech stimuli. Because ABRs are not affected by sleep and mature early, this tool can be evaluated in identifying binaural interaction in younger and difficult-to-test populations.

Wrege and Starr [1] showed that the amplitude of the BIC attenuated when click intensity was reduced from 70 to 60 dB SL. The attenuation of BIC was greater than the attenuation of the sum of the monaurally evoked potentials. In addition, the latency of the BIC increased as the interaural time difference increased from 0 to 500 ms. The latency shift and the amount of interaural delay were proportionally related. Thus, BIC is affected by stimulus intensity and interaural time difference and is clearly affected by binaural neural processing.

Goksoy *et al.* [22] used the peaks naming of ABR as the following, the first vertex –positive peak stimulus onset is numbered P1, and successive positive peaks are numbered P2, P3 and so on and vertex –negative peaks are numbered N1, N2, and so on according. Similary, Dobie and Berlin [20], labeled the successive peaks in the BIC waveform as DP1, DN1, DP2 and DP3.

Rationale

The study of binaural interaction of speech stimuli at the level of the auditory brainstem using cABR can further add to the assessment of brainstem processing of complex signals, which would further allow the diagnosis of any abnormality in processing.

Aim

This is a preliminary research that was conducted to study the BIC of cABR in normal-hearing adults.

Patients and methods

This study is a cross-sectional study that was conducted on 20 normal-hearing adults, whose age ranged from 15 to 60 years, with a mean age of 29.30±12.52 years. They comprised eight (40%) female and 12 (60%) male participants. They were collected from Kasr Al-Ainy Hospital, Cairo University, from medical personnel and healthy volunteer relatives of patients. All patients were willing to participate in the study. The study took place during the period from April 2016 to July 2016.

Exclusion criteria included

Patients who had any otological or neurological disorder, history of ototoxic drugs use, or noise exposure were excluded from the study.

All patients who participated in this study were subjected to the following:

1. Full history taking.
2. Otological examination.
3. Audiological evaluation: tonal audiometry in the frequency range of 250–8000 Hz. Orbiter 922 was used in a sound-treated room with TDH 39 earphones. Speech audiometry including speech reception threshold (SRT) using arabic spondee words [23]. and word discrimination score (WDS), using, arabic phonetically balanced words [24].
4. Immittancemetry was done using Otometric Zodiac901 (Otometrics, Denmark) using single-component, single-frequency tympanometry with a probe tone of 226 Hz. The acoustic reflex threshold was tested, for ipsilateral and contralateral elicited reflexes, using pure tones at 500, 1000, 2000, and 4000 Hz.

(5) Speech-evoked ABR was conducted for all patients using Bio-logic Navigator Pro, Natus Medical Incorporated (San Carlos, California, USA). The parameters used to obtain cABR were as follows: the stimulus used consisted of the five first formants of the syllable [da] (40 ms), which were presented first monaurally (left and right) and then binaurally through TDH headphones, in alternating polarity at 80 dBnHL and at a presentation rate of 10.9 stimuli/s. The recording window was of 74.67, with 100 Hz low-pass and 1500-Hz high-pass filter. Recordings were repeated twice, and each run consisted of 2000 sweeps, to ensure the replicability of the waveforms. Ag/AgCl electrodes filled with conductive paste were fixed to the skin that was abraded with a skin prepping gel. Electrode impedances were less than 5 kΩ, and interelectrode impedances were less than 2 kΩ. The active electrode was placed on the forehead; the reference electrode was placed on the ipsilateral mastoid; and the ground electrode was placed on the contralateral mastoid.

Analysis of response

cABR was characterized by transient peaks, as well as sustained elements, that comprised the FFR. The response to the onset of the speech stimulus /da/ included a positive peak (wave V), likely analogous to the wave V elicited by click stimuli, followed immediately by a negative trough (wave A). Following the onset response, a series of peaks (C–F) represent FFR. Offset response was represented by wave O. Peak latency and baseline to peak amplitude of all waves were measured. Moreover, V–A slope was mathematically calculated. This component was calculated by dividing wave V–A amplitude by its duration [25]. The amplitude of the right-ear waveform was digitally added at every sampling point to the amplitude of the left-ear waveform to obtain an algebraic sum of the two monaural responses. The BIC was then obtained by digitally subtracting the binaural waveform from the sum of the two monaural responses. This was expressed as BIC=(R+L)–B, where R+L is the sum of the right- and left-evoked potentials obtained with monaural stimulation, and B is the response acquired from binaural stimulation.

Statistical methods

Data were coded and entered using the statistical package for the social sciences, version 23 (SPSS; SPSS Inc., Chicago, Illinois, USA). Data were summarized using mean, SD, median, minimum, and maximum in quantitative data and using frequency (count) and relative frequency (percentage) for categorical data. For comparison of serial measurements within each patient, the nonparametric Friedman test and Wilcoxon signed rank test were used [26]. *P* values less than 0.05 were considered statistically significant.

Results:

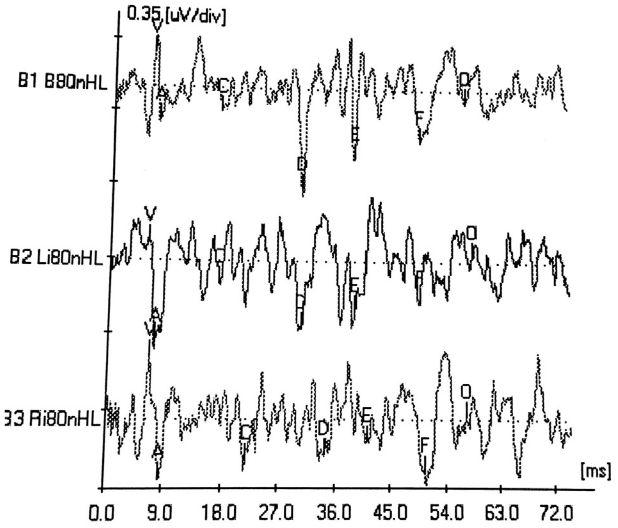
All patients had pure tone hearing sensitivity up to 20 dBHL at frequencies from 250 to 8000 Hz for air conduction and from 500 to 4000 Hz for bone conduction. All patients had a type A tympanogram with preserved acoustic reflexes at normal sensation levels in both ears.

Figure 1 shows cABR recorded from one of the patients in this study, as well as the response of binaural waves (B1), the left-ear response (B2), and the right-ear response (B3).

Table 1 shows that the mean right-ear amplitudes were smaller than the binaural amplitudes of waves V, A, C, D, E, and F. However, this difference was statistically significant for D, E, and F waves only (*P*<0.05).

Table 2 shows that mean the left-ear amplitudes were smaller than the binaural amplitudes of waves V, A, C, D, and E only. In addition, this difference was statistically significant (*P*<0.05).

Figure 1



Complex auditory brainstem response (ABR) recorded from one of the patients in this study showing the response of binaural waves (B1), the left-ear response (B2), and the right-ear response (B3).

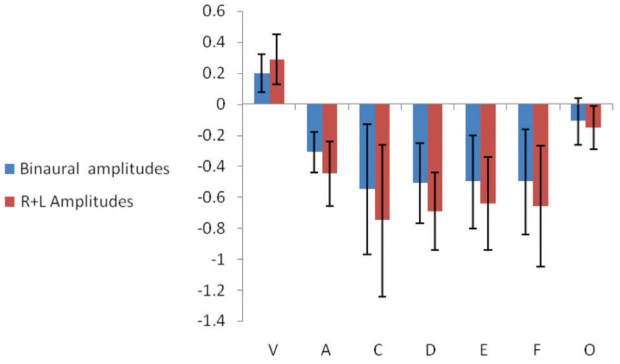
Table 3 shows that the mean binaural amplitudes were smaller than the summed right+left amplitudes of all waves V, A, C, D, E, F, and O. However, this difference was statistically significant ($P<0.05$) for all except waves F and O.

Table 4 shows the mean and SD of BIC [(right+left)–binaural amplitudes] of V, A, C, D, E, F, and O waves of cABR responses of the studied group.

Table 5 shows that there was no statistically significant difference among latencies of responses recorded from right, left, or binaural for all cABR waves.

Figure 2 showed that the mean binaural wave amplitudes were smaller than the summed right+left amplitudes for waves V, A, C, D, E, F, and O. It showed that there was a large SD of BIC amplitudes. This was more for C, A, E, and F BIC components than for other components.

Figure 2



The mean amplitudes along with one SD error bars for V, A, D, E, F, and O waves of complex auditory brainstem response (ABR) responses for the summed right+left and binaural amplitudes of the studied group.

Table 1 Comparison between the mean right-ear amplitudes and binaural amplitudes of complex auditory brainstem response of the studied group

	Right amplitudes					Binaural amplitudes					*P* value
	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	
V	0.14	0.11	0.12	−0.04	0.40	0.20	0.12	0.17	0.02	0.42	0.130
A	−0.24	0.16	−0.22	−0.53	−0.04	−0.31	0.13	−0.32	−0.58	−0.11	0.113
C	−0.40	0.27	−0.30	−1.01	−0.06	−0.55	0.42	−0.46	−1.45	−0.05	0.145
D	−0.34	0.14	−0.31	−0.62	−0.08	−0.51	0.26	−0.48	−1.44	−0.25	0.008
E	−0.31	0.18	−0.27	−0.61	−0.10	−0.50	0.30	−0.42	−1.46	−0.24	0.008
F	−0.26	0.19	−0.24	−0.56	0.00	−0.50	0.34	−0.38	−1.29	−0.18	0.002
O	−0.07	0.16	−0.04	−0.60	0.15	−0.11	0.15	−0.06	−0.54	0.06	0.125

Table 2 Comparison between the mean left-ear amplitudes and binaural amplitudes of complex auditory brainstem response of the studied group

	Left amplitudes					Binaural amplitudes					*P* value
	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	
V	0.14	0.09	0.15	−0.02	0.27	0.20	0.12	0.17	0.02	0.42	0.018
A	−0.21	0.12	−0.18	−0.51	−0.05	−0.31	0.13	−0.32	−0.58	−0.11	0.046
C	−0.34	0.37	−0.22	−1.58	0.00	−0.55	0.42	−0.46	−1.45	−0.05	0.014
D	−0.35	0.16	−0.33	−0.66	−0.07	−0.51	0.26	−0.48	−1.44	−0.25	0.008
E	−0.34	0.20	−0.28	−0.84	−0.09	−0.50	0.30	−0.42	−1.46	−0.24	0.025
F	−0.41	0.31	−0.27	−1.13	−0.08	−0.50	0.34	−0.38	−1.29	−0.18	0.563
O	−0.09	0.09	−0.08	−0.30	0.06	−0.11	0.15	−0.06	−0.54	0.06	0.896

Table 3 Comparison between the mean of binaural amplitudes and the mean of the summed right+left-ear amplitudes of complex auditory brainstem response of the studied group

	Binaural amplitudes					R+L amplitudes					*P* value
	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	
V	0.20	0.12	0.17	0.02	0.42	0.29	0.16	0.24	0.05	0.65	0.07
A	−0.31	0.13	−0.32	−0.58	−0.11	−0.45	0.21	−0.42	−0.82	−0.09	0.036
C	−0.55	0.42	−0.46	−1.45	−0.05	−0.75	0.49	−0.64	−1.77	−0.12	0.044
D	−0.51	0.26	−0.48	−1.44	−0.25	−0.69	0.25	−0.62	−1.21	−0.34	0.017
E	−0.50	0.30	−0.42	−1.46	−0.24	−0.64	0.30	−0.54	−1.33	−0.23	0.036
F	−0.50	0.34	−0.38	−1.29	−0.18	−0.66	0.39	−0.61	−1.37	−0.04	0.156
O	−0.11	0.15	−0.06	−0.54	0.06	−0.15	0.14	−0.15	−0.37	0.04	0.369

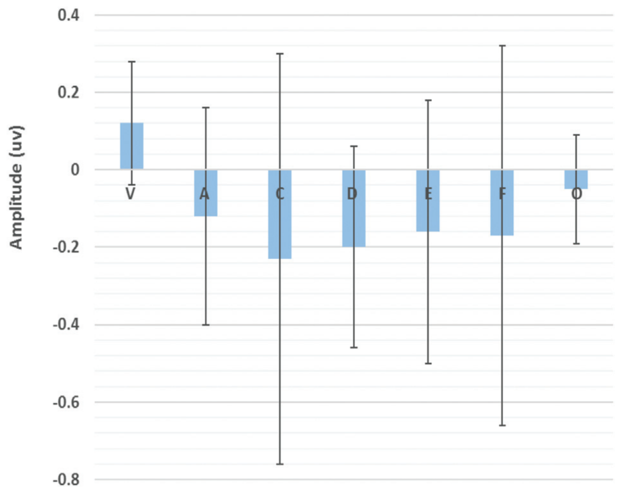
Figure 3 showed BIC values for the different cABR waves.

Discussion

The ABR represents the synchronized electrical activity of the neurons in the auditory pathway, which can be recorded noninvasively by electrodes placed on the skin. Because the different ABR waves broadly represent the activity of different parts of the auditory pathway, it is possible to draw conclusions about the functioning of distinct stages of the auditory pathway. This includes the binaural processing stages if the BIC of the ABR is investigated [27].

In the present study, we found that there were smaller right-ear amplitudes than binaural amplitudes of waves V, A, C, D, E, and F. However, this difference was statistically significant at waves D, E, and F only (Table 1). In addition, this was noticed in the

Figure 3



The binaural interaction component [(right+left)–binaural amplitudes] of V, A, C, D, E, F, and O waves of complex auditory brainstem responses of the studied group.

Table 4 The mean and SD of binaural interaction component [(right+left)–binaural amplitudes] of V, A, C, D, E, F, and O waves of complex auditory brainstem response of the studied group

	Mean	SD	Median	Minimum	Maximum
V (BIC)	0.12	0.16	0.11	−0.13	0.47
A (BIC)	−0.12	0.28	−0.06	−0.60	0.42
C (BIC)	−0.23	0.53	−0.22	−1.52	1.10
D (BIC)	−0.20	0.26	−0.14	−0.89	0.23
E (BIC)	−0.16	0.34	−0.18	−0.84	0.75
F (BIC)	−0.17	0.49	−0.14	−0.84	0.91
O (BIC)	−0.05	0.14	−0.04	−0.34	0.17

BIC, binaural interaction component.

Table 5 Comparison among the mean of right-ear latencies, the mean of left-ear latencies, and the mean of binaural latencies of complex auditory brainstem response of the studied group

	Right latencies					Left latencies					Binaural latencies					*P* value
	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	Mean	SD	Median	Minimum	Maximum	
V	6.06	0.40	5.98	5.40	7.00	6.02	0.29	5.98	5.69	6.85	6.09	0.41	6.12	5.40	7.00	0.754
A	7.31	0.54	7.15	6.56	8.46	7.18	0.40	7.08	6.56	8.31	7.23	0.47	7.29	6.56	8.31	0.563
C	19.95	1.61	20.06	17.06	22.02	19.65	2.51	19.69	15.31	24.65	19.17	2.16	18.74	15.02	22.02	0.247
D	30.34	1.25	30.19	28.29	34.42	29.85	1.01	30.26	26.54	30.77	30.00	0.79	30.14	27.86	31.06	0.554
E	39.37	2.02	38.79	36.90	46.23	38.84	1.67	38.72	36.61	45.06	38.96	1.58	38.79	36.90	44.92	0.650
F	44.77	10.61	46.89	0.00	50.61	47.03	1.85	46.89	44.77	52.79	47.43	1.89	47.18	43.75	53.67	0.169
O	56.99	2.39	56.36	54.25	61.84	56.89	2.58	56.08	52.79	60.82	57.07	2.41	56.00	53.81	61.54	0.521

left-ear amplitudes, which were smaller than binaural amplitudes for waves V, A, C, D, and E only. In addition, this difference was statistically significant (Table 2). As regards the summed right+left amplitudes of cABR waves, they were higher than the binaural amplitude waves. However, this difference was statistically significant for waves A, C, D, and E only ($P<0.05$) (Table 3 and Fig. 2).

Our results were in agreement with those of Uppuda *et al.* [20], who reported that the amplitudes of both the onset and frequency following components were larger in the right and left summed waveform than in the binaural waveform for peaks V, A, E, and F. Uppuda *et al.* [20] found that the first BIC (BIC-SP1) in the cABR occurred at around 6 ms in the region of peak V. The second BIC (BIC-SP2) was present around 8 ms in the latency region of peak A. The third and fourth BICs of cABR (BIC-SP3 and BIC-SP4) were observed at around 36 and 46 ms, respectively, in the latency regions of peaks E and F, respectively. BIC-SP1 and BIC-SP2 were present in all patients tested (100%), whereas BIC-SP3 and BIC-SP4 were present in 11 (73).

It is generally assumed that the BIC is generated by the activity of binaural neurons in the auditory pathway below the inferior colliculus. The most likely candidate structures providing sites of binaural interaction that produce the DN1 component of the BIC are two nuclei of the superior olivary complex – that is, the medial superior olive and the lateral superior olive (LSO) and their outputs [28–30]. The DN1 is a prominent negative peak of BIC, which has been interpreted as evidence that the excitation elicited by binaural stimulation is less than the sum of both the left and right monaural excitation. Because the LSO consists mainly of so-called EI neurons, which receive excitatory (E) input from the ipsilateral side and inhibitory (I) input from the contralateral side, the negative value of the DN1 amplitude could be interpreted to reflect the reduced output of the LSO when stimulated binaurally that is due to the inhibition [31].

In the present study, BIC amplitudes have been obtained in the studied group of normal-hearing adult individuals, by subtracting the binaural responses from the summed monaural recorded responses. There was a large SD for BIC amplitudes for C, E, and F BIC components than for other components (V, A, D, and O) (Table 4). This reflects less variation in the response to onset and offset of the speech stimulus than the onset of voicing and the transition from consonant to vowel and the periodic portion of the FFR. Uppuda *et al.* [20] stated less variation in the response occurring in the timing of the first and second BIC compared with the response occurring in the timing of the third and fourth BIC.

There was no statistically significant difference among the mean latencies of responses recorded from right, left, or binaural for all cABR waves (Table 5).

DN1 component of BIC is robustly evoked in nearly all normal-hearing patients [17,31–35], but it is altered in various disease states that affect binaural hearing. For example, altered BIC has been shown to reflect long-term behavioral binaural processing deficits [36,37].

Gopal and Pierel [38] showed that four out of nine children in the CAPD group exhibited different patterns of binaural responses. These children had binaural response amplitude greater than their summed amplitude, leading to a negative BIC value. They interpreted their results to suggest that the negative BIC reflected reduced inhibitory process at higher levels of the auditory brainstem. Gopal and Pierel [38] observed that the median BIC2 and BIC3 amplitude was significantly smaller in the specific language impairment group than in the control (normal) group.

The present study is in agreement with that of Dobie and Norton [32], who compared responses for the summed monaural and binaural speech stimulus conditions, and demonstrated that the BICs observed were indexing a reduction in amplitude of the binaural evoked response relative to the sum of the monaural responses [32].

Laumen *et al.* [39] stated that Stollman *et al.* [40] yields perhaps the most interesting investigation into the relationship between BIC and peripheral hearing loss. Stollman *et al.* [40] found a 97% detection of BIC in normal-hearing patients versus 20% in patients with hearing loss, effectively discriminating between the normal and hearing-impaired groups. They stated that the 20% detection in patients with hearing loss was likely a single false positive due to an artifact. Fowler and Swanson [41] reported that BICs were absent in patients with unilateral congenital profound sensorineural hearing loss and in patients with multiple sclerosis, because of pathological conditions of the binaural hearing system leading to the absence of binaural processing.

Conclusion

BICs reflecting binaural process can be obtained for ABR using speech stimuli comparing the binaural and summed monaural recorded responses. We recommend assessing the BIC on a large scale to obtain normative data, for comparison with patients with known auditory processing capabilities (shown by behavioural tests), to see how well the data can be used as an index of binaural process.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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