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Original Article

Novel Paradigm to Record Bilateral Click-Evoked Auditory Brainstem Responses Simultaneously (BiSi-ABR)

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OBJECTIVES: The current study proposes a new and fast technique to record the auditory brainstem responses (ABRs) simultaneously (BiSi-ABR) from two ears. The BiSi-ABR technique can be used to record the ABRs two times faster than with a conventional ABR recording method. The objective of the study was to show the proof of concept and to compare the BiSi-ABR technique with that of a conventional ABRs recording method to test its clinical feasibility.

MATERIALS and METHODS: A repeated-measures design was used, wherein ABRs recorded in the BiSi-ABR were compared with that of conventional ABRs recordings. Twenty-five normal-hearing adults participated in the study. ABRs were recorded using the BiSi-ABR technique, as well as the conventional method. The peak latencies (in ms) of waves III and V between the new technique and conventional method were compared. The minimum intensity at which the wave V was present was tracked using both the methods.

RESULTS: The wave latencies and thresholds of ABR using the BiSi-ABR technique were remarkably similar to those recorded in the conventional ABR technique. The ABR wave latencies and thresholds did not differ significantly between the new technique and the conventional method.

CONCLUSION: ABRs recorded with the BiSi-ABR technique can be used to estimate ear-specific hearing thresholds with the same reliability as that of conventional ABRs, in half the recording time. The results of the study have strong implications for screening, diagnostic, and research purposes as they aid in cutting down the ABR testing time.

KEYWORDS: ABR, binaural ABR, ear-specific ABR, threshold estimation, testing time

INTRODUCTION

The auditory brainstem response (ABR) is an invaluable tool in the audiologist's test battery for screening and diagnosis of hearing sensitivity and hearing disorders. The objective nature of the ABR makes it a test of choice where reliable behavioral estimates cannot be obtained. Hecox and Galambos [1] showed that ABR could be used for threshold estimation in adults and infants. In the past four decades, ABR has been used in hearing threshold estimation for both screening and diagnostics in difficult-to-test population and as a cross-check metric. ABR is being used as a gold standard test, considering its higher sensitivity and specificity [2, 3]. Because of its high sensitivity, specificity, and reliability, it is being used as an important test in the hearing screening protocol of newborns [4]. It is imperative that the opportunity of administering the ABR be available for all the cases in which an accurate hearing threshold estimation is needed. One constraint to this is the limited availability of the clinical time because the test consumes considerable time for preparation, as well as for recording. This has led to its reduced use, especially for hearing screening, as the first round of neonatal hearing screening mandates [4] an otoacoustic emissions test *or* an automated ABR test, but not both. Such time constraint when using the ABR is also present in diagnostic hearing evaluations in a busy audiology clinic.

Conventionally, a comprehensive hearing evaluation in difficult-to-test individuals takes longer than an hour. If the hearing thresholds need a cross-check through an objective measure such as ABR, the test time is extended at least by another hour. However, in clinical use, there is a dire need to reduce the recording time in ABRs in an individual patient. This is particularly required in individuals with multiple disabilities and in the pediatric population for known reasons. This is one of the most common complaints in a busy audiological clinic, and there are global continuous efforts to cut down the testing time [5-7].

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In the past, several attempts have been made to cut down the recording time for ABRs during screening as well as diagnostic applications, such as Maximum Length Sequences [6, 7] and chained stimuli presentation [5]. These methods are promising, but they have not been very popular in clinical settings due to additional hardware and software requirements. Furthermore, these techniques are not readily available in most commercial ABR equipment.

The current study proposes a new technique termed *bilateral-simultaneous ABR* (BiSi-ABR) as a simple and intuitive technique to reduce the ABR testing time. Here, the ABR-eliciting stimulus is alternated between the ears, while each ear receives stimulus at the rate of 30.1/s. As the stimulus is alternated between the two ears, the effective repetition rate is 60.2/s, with each ear receiving the clicks at 30.1/s. Because of such a stimulus presentation strategy, the time taken for testing both the ears is the same as that taken for testing one ear. Due to this, the time taken for testing two ears using the BiSi-ABR technique can be reduced by half.

The current study was conducted to provide the proof of concept for the BiSi-ABR technique. Considering that the neural generators of ABR of each ear are different, one would expect that the responses would not be affected by the BiSi-ABR technique, as the stimulus is alternated between the two ears, and the ear-specific inter-stimulus interval is maintained similar to that in the conventional method. However, this needs to be experimentally validated. Thus, the ABRs recorded using the BiSi-ABR technique were compared with those recorded in the conventional paradigm to validate it against the conventional method of recording click ABRs.

MATERIALS and METHODS

Participants

Seventy-five normal-hearing individuals who were 18 to 25 years old participated in the study. Fifty of these participants were recruited for subjective calibration of the stimuli, while 25 participants were recruited for the ABRs recording. None of the participants had any history of otological or neurological dysfunction. The hearing sensitivity of the individuals was assessed by pure tone audiometry using the modified Hughson and Westlake procedure [8]. All the participants had pure tone thresholds within 15 dB HL in all octave frequencies from 250Hz to 8000 Hz in both ears. Normal middle ear functioning was ensured by immittance evaluation. All the participants had an A or As type tympanogram with acoustic stapedial reflexes present at normal intensity levels. Normal inner ear function was ensured using click-evoked otoacoustic emissions (CEOAE). All the participants had CEOAE amplitudes at least 6 dB above the noise floor in at least three mid-octave frequency bands, with reproducibility greater than 80%. All the procedures used in the study conformed to the institutional ethical guidelines and the Declaration of Helsinki. All the participants signed an informed consent form before participating in the study.

Instrumentation

For the preliminary audiological evaluations, a calibrated diagnostic audiometer was used for pure-tone audiometry (Inventis piano) with TDH-39 supra-aural headphones and Radio ear-B71 bone vibrator. A GSI-Tympstar middle ear analyzer was used for the immittance evaluation. The MATLAB version 2016b (Mathworks Inc., Natick USA) was used to generate the click stimuli. The intelligent hearing systems (IHS) smart EP acquisition system was used for stimulus presentation and ABR acquisition.

Stimuli

Broadband clicks (100µs) were used to elicit the ABRs. Clicks were used as they were efficient in eliciting good ABRs. Broadband clicks were generated in MATLAB (Mathworks Inc., Natick, Massachusetts, USA).

Clicks for the BiSi-ABR technique were generated in MATLAB and were loaded into the IHS advanced research module. The clicks in the two ears were presented with an interaural time delay of 16 ms. This click pair was presented at a repetition rate of 30.1/s, which resulted in a total repetition rate of 60.2 clicks/s. Thus, the effective inter-stimulus interval for each ear was 33.2 ms (See Figure 1). This BiSi-ABR technique of stimulus presentation ensured that the refractory period per ear remained the same as in the conventional ABR recording.

Procedure

Behavioral thresholds for detecting the click were obtained in 50 participants. The mean behavioral threshold was considered as the nHL correction factor and set at the 0 dB nHL level. The intensity levels were controlled by the IHS system. The nHL correction factor was then applied to the intensity levels of the clicks used to elicit the BiSi-ABRs.

Participants were seated in an acoustically treated room in a relaxed position. The Ag/AgCl electrodes were used for the ABR recording. The electrode sites were chosen according to the 10–20 classification system. Two channels (five electrodes) were used for the ABR recording. The inverting electrodes were placed on the left (A1) and right (A2) earlobes, non-inverting electrode on the vertex (Cz) (the same electrode was connected to the leads of both the channels using a jumper), and the ground electrode on the low forehead. Table 1 lists the stimulus and acquisition parameters used to record the ABRs.

The ABRs were recorded in three stimulus conditions (two BiSi-ABR and one monaural conventional). In the two BiSi-ABR conditions, both the ears were stimulated using clicks with an inter-aural interval of 16 ms between the clicks presented in the two ears. In the first BiSi-ABR condition, the click was presented to the right ear at the 0 ms onset and the left ear at 16 ms (RL stimulus). On the other hand, in the second BiSi-ABR condition, the click was presented to the left ear at the 0 ms onset and the right ear at 16 ms (LR stimulus). Comparison between the two binaural conditions would help in inferring the order effect, if any. Practically, when presented at a 30.1/s repetition rate, the stimulus alternated between the two ears with a total repetition rate of 60.2/s. Figure 1 depicts stimulus presentation in the RL stimulus condition and the corresponding ABRs. For the purpose of comparison, the ABRs of the two ears were also recorded under the conventional monaural conditions. The analysis window was 30 ms in all the recordings. In the right monaural condition, the click was presented at 0 ms, whereas, in the left monaural condition, the onset of the click was at 16 ms. This was done to control for all other extraneous variables, while comparing between the conventional and BiSi-ABR recordings.

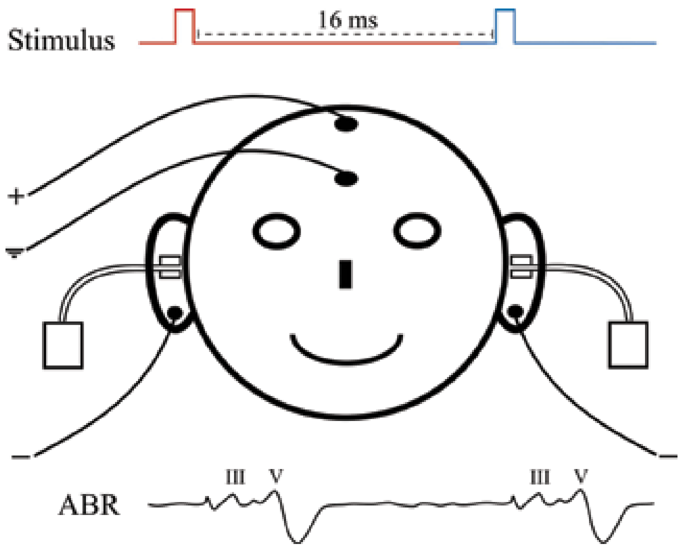

Figure 1. Illustration depicting the BiSi-ABR paradigm. This is the BiSi-ABR paradigm in which the left ear receives the click stimulus 16 ms after the right ear.

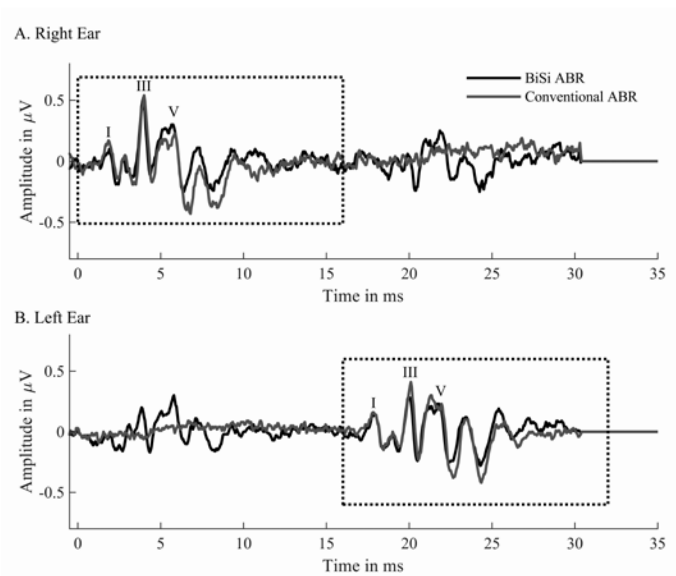

Figure 2. a, b. The ABR waveforms recorded from one representative participant using the BiSi-ABR technique and the conventional method. a) The waveforms of the right channel in the BiSi-ABR and the right channels (Cz-A2) in the conventional ABR overlaid. The click onsets in the right ear start at 0 ms in both the conventional and BiSi-ABRs. b) Similarly, the left channels (Cz-A1) in the BiSi-ABR and the conventional ABR are overlaid. The click onsets in the left ear start at 16 ms. It can also be seen that the BiSi-ABRs show waves even when there are none in the conventional ABRs. These correspond to the waves of the ABR in the contralateral channels to the right/left clicks in the BiSi-ABR. The corresponding ABRs of the BiSi-ABR and conventional ABRs are marked with a dotted rectangle.

The ABR thresholds were tracked in all the four stimulus conditions. Every session begun with a starting intensity level of 70 dB nHL, followed by 50 dB nHL, 30 dB nHL, 20 dB nHL, and 10 dB nHL. ABRs were recorded twice at each intensity in every condition to check for the replicability. The approximate total time of testing (including all the BiSi-ABR and conventional ABR conditions) in each participant was 1 hour and 15 minutes.

Table 1. Stimulus and acquisition parameters for the acquisition of auditory brainstem responses

Stimulus Parameters	
Stimulus	Broad band clicks
Polarity	Rarefaction
Transducer	Insert ear phone
Repetition rate	30.1/sec
Intensity	70 dBnHL
Type of stimulation	Binaural
Acquisition Parameters	
Montage	Vertical
Electrode sites	Inverting: Left (A1) & Right (A2)
	Non-inverting vertex (Cz)
Ground: Nasion	
Filters setting	100Hz–1500Hz
Amplification	1,00,000 times
Artifact rejection	20 µV
Analysis window	30 ms
Total no. averages	2000
Data points	1024

All the procedures used in the study were non-invasive and were approved by the institutional review board. All the procedures used conformed to the Declaration of Helsinki.

Response Analysis

The averaged responses were visually inspected by two experienced audiologists to identify the presence of waves III and V. The ipsilateral channel of each ear was used for marking their respective III and V waves. Wave latencies were analyzed only at 70 dB nHL. These wave latencies were corrected for the delay in the click onset times. The lowest intensity level at which wave V was present was considered as the ABR threshold. The latency of the waves and the ABR threshold were compared across the three stimulus conditions in the two ears.

Statistical Analysis

The wave latencies were statistically compared using a two-way (3×2) repeated measures analysis of variance with the condition and ear as within-subject factors, and wave III and wave V latencies as the dependent variables. The ABR thresholds were compared between the three conditions and for each ear using a non-parametric Friedman test.

RESULTS

Both the BiSi-ABR and conventional ABR recording techniques elicited replicable ABR waveforms with reliable waves at 70 dB nHL and lower intensities (Figures 2, 3). The ABRs in both ears were strikingly similar for both techniques. The latencies of the ABR waves for both techniques were corrected for delay in the click onset times for each ear. The mean wave latencies of the ABR waves III and V in all the conditions at 70 dB nHL are shown in Figure 4. Latencies of waves III and V in each ear were compared across the following three conditions:

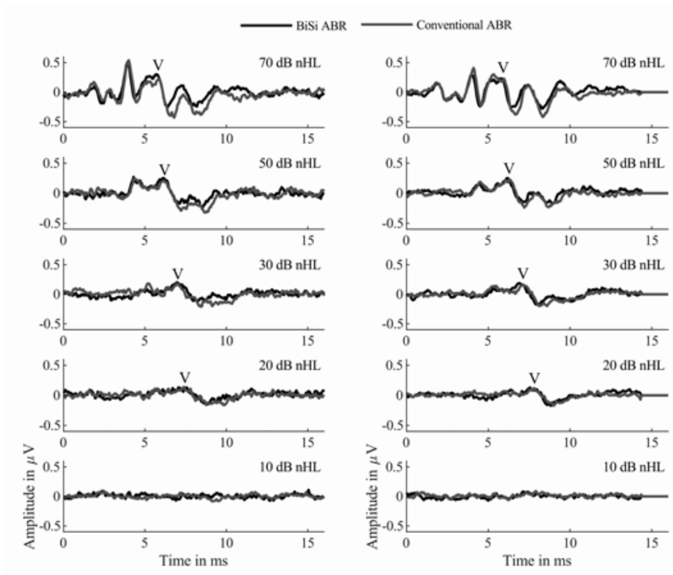

Figure 3. The ABR waveforms in a representative participant using the BiSi technique and the conventional technique at different intensities are shown. Waveforms on the right were for the right ear and those on the left were for the left ear. The wave latencies have been corrected for the click onset times. Wave V has been marked in the BiSi and conventional ABRs. It can be seen that wave V in both techniques overlaps at all the intensities tested.

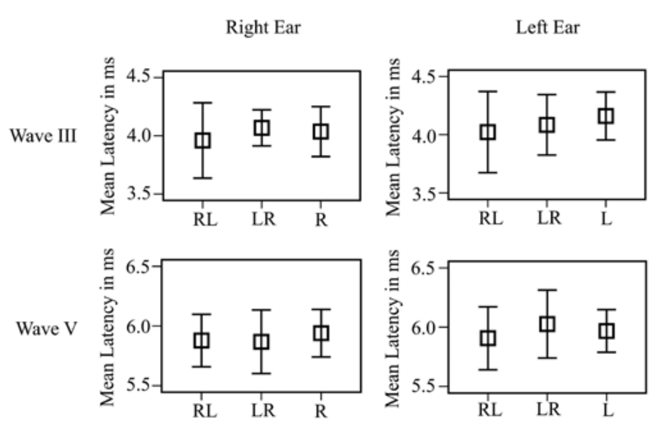

Figure 4. The mean and standard deviation of wave III and wave V latencies across the conditions in the two ears.
RL: BiSi-ABR with click presented to the right ear first, LR: BiSi-ABR with click presented to the right ear first. R: conventional method with click presented only to the right ear. L: conventional method with click presented only to the left ear.

(1) BiSi-ABR with right click followed by a left click (RL), (2) BiSi-ABR with left click followed by a right click (LR), and (3) conventional monaural ABRs (of the respective ear R & L). The mean ABR latencies in the three conditions did not differ across the two conditions for both waves III and V. The statistical analysis of the wave III and V latencies showed no significant main effect of the condition [$F(4,94)=2.115$, $p=0.085$, $\eta_p^2=0.083$] or ear [$F(2,23)=3.370$, $p=0.052$, $\eta_p^2=0.227$] on the wave III and wave V latencies. Additionally, there was no significant interaction between the condition and ear [$F(4,94)=1.884$, $p=0.120$, $\eta_p^2=0.072$].

The wave V in both the techniques followed the same pattern across the different intensities; thus, the thresholds were similar in both the intensities. The ABRs recorded using both the techniques at different intensities

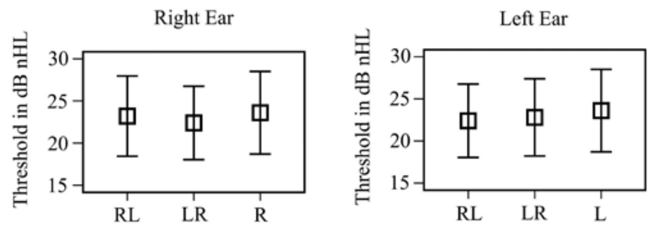

Figure 5. Hearing thresholds estimated using the BiSi-ABR technique and the conventional method. The threshold was estimated as the minimum intensity at which a replicable wave V could be obtained.
RL: BiSi-ABR with click presented to the right ear first. LR: BiSi-ABR with click presented to the right ear first. R: conventional method with click presented only to the right ear. L: conventional method with click presented only to the left ear.

in a representative participant are shown in Figure 3. Similar to the ABR wave latencies, the mean ABR thresholds too (based on wave V) did not differ across the conditions (Figure 5). Statistical analysis showed that there was no significant main effect of conditions on the ABR thresholds estimated in the right ($\chi^2=2.33$, $p=0.311$, Kendall's $W=0.047$) as well as left ears ($\chi^2=2.33$, $p=0.311$, Kendall's $W=0.047$).

DISCUSSION

The ABRs recorded using the BiSi-ABR technique were not different than those in the conventional method in terms of the peak latencies and thresholds. This provides the proof of concept that the BiSi-ABR technique can be used to record ABRs that are similar to those recorded using conventional ABR techniques.

Using the BiSi-ABR technique, the test time was reduced by maintaining the click repetition rate, and the repetition rate was maintained at 30.1/sec in each ear. However, the repetition rate for both ears combined was 60.2/sec, with the ear-specific repetition rate at 30.1/sec. Essentially, the time gap between the presentation of the two stimuli in the test ear is utilized by presenting the click in the other ear during the gap. This ensured that the ear-specific neurons had sufficient time, like the one used in the conventional method, to recover. This ear-specific recovery of the nerve fibers is possible because the neural generators of ABRs for the two ears are independent. These results were further strengthened by testing the order manipulation in the paradigm. To assess if there was an order effect, the stimulus presentation order between the two ears in the BiSi-ABR technique was counterbalanced (RL&LR). In this case, the order effect, if any, would suggest that the stimulus presented in one ear is affecting the ABR of the other ear by fatiguing the auditory nerve fibers. However, there was no such order effect in the BiSi-ABR, which strengthens the point we make: The ABR in the BiSi-ABR technique is not affected by the stimulation of one ear within 16 ms of the other.

An important step in the BiSi-ABR was the need to temporally alternate the stimuli in the two ears. If clicks in both the ears were presented simultaneously, they would result in a single binaural ABR, and it would be hard to differentiate if the response is from the right ear or the left ear. This happens because the scalp-recorded ABR signal is a volume-conducted electrical field. Because of the volume conduction, the electrical field generated by the compactly placed ear-specific neural generators mixes and results in a large ABR [9]. Thus, it was important to space the two stimuli in time (16 ms), such that the evoked ABRs did not temporally overlap. This ensured that the offset of the first ABR and the onset of the next ABR were separated by a minimum period of 10 ms.

Although we assumed that the generators of ABR are ear-specific and not fatigued by temporally alternating binaural stimuli, it was necessary to evaluate if this was essentially true. And this was the major objective of the study. We found that there was no latency difference between the BiSi-ABR and the conventional ABR. This was a very important finding, in favor of the new technique. If the ABR generators were not ear-specific, then they would experience a repetition rate of 60.2/sec instead of the ear-specific 30.1/sec. Such doubling of the repetition rate per neural generator would have resulted in an increased latency of the ABR peaks. However, this was not true. The ABR morphology and latencies in the two methods were strikingly similar. This suggests that the neural generators are actually experiencing the ear-specific repetition rate of 30.1/sec, which is in line with our assumption and is the proof of concept.

The next step, after we ensured that the ABRs in the BiSi-ABR were actually ear-specific ABRs, was to evaluate if it could be used for threshold estimation. The thresholds obtained in the BiSi–ABR paradigm did not differ from those in the conventional method, providing further strength to the idea that they can be used for threshold estimation.

The ABR is invariably used for hearing threshold estimation in neonates and infants according to the cross-check principle [10]. In the pediatric population, the sleep time is a major factor for comprehensive threshold estimation. So, cutting down test time by half for the ABR threshold estimation would cut down the time taken for comprehensive diagnostics and thus mean lesser worry and fewer visits for the family in terms of completion of the hearing diagnostics.

Apart from a threshold estimation in a clinical scenario, this technique will be useful for research purposes as well. Whenever someone is interested in employing new stimuli for the ABR estimation etc., they can follow the BiSi-ABR technique and record the ABRs from both the ears without spending any extra time. The remarkable similarity of the ABRs in the new and conventional technique also suggests that the new technique can be used for every purpose which the conventional ABR was earlier used for, and that includes the site of lesion testing.

An important point to be emphasized is that the new technique, due to its time efficiency and waveforms with remarkable similarity to those with the gold standard, finds a place in the screening as well as in the diagnostic test battery. Additionally, this binaural temporally alternating BiSi-ABR strategy should not be restricted to record the ABRs alone. Thus, future studies should also explore the utility of this technique to record various responses like ECochg, PAM, VEMP, etc., which would greatly impact the time and efficiency of the test battery. It must be noted that although the new technique cuts down the testing time by half, it does not reduce the patient preparation time.

In addition to the reduction in testing time, there are additional practical advantages to the BiSi-ABR technique. The clinician's interaction with the computer is reduced as one click accomplishes the task of recording from the two ears. This would reduce the risk of potential mistakes during the recording. Additionally, as the ABRs of the two ears are recorded almost simultaneously, the background noise in the ABRs of the two ears would be essentially stationary. This would aid in better interpretation of the bilateral hearing status of the patient being tested and at the same time while avoiding possible confounds of differences in the background levels of noise when testing each ear individually as in the conventional method.

The results obtained here are from the preliminary data of a larger project, and they serve as the proof of concept. The technique was implemented in the research module of a commercially available clinical equipment. Although this technique was fast and useful, there is a need for user-friendly algorithms to be developed such that the ear-specific ABR separation, intensity roving across ears, etc. can be done with ease.

The outcome of the current research is expected to be an important step in hearing diagnostics. The simplicity and efficacy of the technique are expected to result in a whole series of AEPs using the new technique. Taking into consideration the simplicity of the technique, it can be used in most commercial AEP equipment, and in others with very small modification in the stimulus presentation.

Limitations, Caveats, and Future Directions

Although we suggest that the technique can be applied to a wide range of AEPs, this application would be limited to transient responses. The same method would not be practical for recording sustained responses.

Another limitation to this technique is the inability to record masked ABRs. However, due to the wide utility of insert earphones for recording the click ABRs, the number of instances that one would use masking is much lower than earlier. Thus, this limitation would not be a major hindrance in the application of the technique for threshold estimation.

A major application of this technique is in the hearing screening of young children and babies. The current findings in adults provide the proof of concept for the technique. However, further studies have to be carried out in young babies to understand the feasibility and validity of the new technique.

In the current study, utility of the BiSi-ABR technique was assessed in normal-hearing individuals, but this cannot be generalized to individuals with hearing loss. Future studies can evaluate the utility of this technique in individuals with hearing loss.

In the current study, the BiSi-ABR technique was used to record click-evoked ABRs. However, clicks do not provide the frequency-specific information about the hearing status. Tone-burst-evoked ABRs are the current gold standard for obtaining frequency-specific objective hearing thresholds. The BiSi-ABR can easily be adapted to record the tone-burst-evoked ABRs. Efforts to validate the BiSi-ABR technique in recording tone-burst-evoked ABRs are underway.

CONCLUSION

The study findings suggest that the estimates of hearing sensitivity using the novel BiSi-ABR technique are as accurate as the conventional technique. This also supports the fact that the BiSi-ABR technique has the potential to serve as a promising clinical tool for threshold estimation and neuro-diagnostic applications. Accurate and high-quality ABR recordings can be obtained using the BiSi-ABR with twice the speed of a conventional ABR method.

Ethics Committee Approval: Ethics Committee approval was received for this study from the Ethics Committee of All India Institute of Speech and Hearing.

Informed Consent: Written informed consent was obtained from all the participants.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.M.; Design - S.M., G.N.G.; Supervision - S.M.; Resource - S.M.; Materials - G.N.G.; Data Collection and/or Processing - C.S., K.S. ; Analysis and/or Interpretation - S.M., G.N.G., S.S., K.S.; Literature Search - G.N.G., S.S., K.S.; Writing - S.M., G.N.G., S.S., K.S.; Critical Reviews - S.M.

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Conflict of Interest: The authors have no conflict of interest to declare.

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