Validation of Simultaneous Acquisition of Click and 0.5 kHz Tone burst (SiCT) ABR for its Accuracy of Hearing Threshold Estimation

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CERTIFICATE

This is to certify that this dissertation titled **"Validation of Simultaneous Acquisition of Click and 0.5kHz Tone burst (SiCT) ABR for its Accuracy of Hearing Threshold Estimation" is** the bonafide work submitted as part fulfilment for the Degree of Master of Science in Audiology of the student with Registration No. P01II21S0057. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other diploma or degree.

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CERTIFICATE

This is to certify that this dissertation titled **"Validation of Simultaneous Acquisition of Click and 0.5kHz Tone burst (SiCT) ABR for its Accuracy of Hearing Threshold Estimation''** has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier to any other University for the award of any other diploma or degree.

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DECLARATION

This dissertation titled **"Validation of Simultaneous Acquisition of Click and 0.5kHz Tone burst (SiCT) ABR for its Accuracy of Hearing Threshold Estimation"** is the result of my own study under the guidance of Dr. Sandeep M., Professor of Audiology, Department of Audiology, All India Institute of Speech and Hearing, and has not been submitted earlier to any other University for the award of any other diploma or degree.

Mysuru

September 2023

Registration No: **P01II21S0057**

Dedicated to

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&

My guide Dr. Sandeep M.

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Chapter 1

INTRODUCTION

Auditory brainstem responses (ABRs) evaluate peripheral auditory system and the lower brainstem. There are numerous clinical applications of ABRs, including hearing threshold estimation, screening for retrocochlear pathologies, newborn hearing screening and intraoperative monitoring. Clinically, ABR is the most preferred objective tool to estimate hearing thresholds, if the behavioural thresholds are not reliable, as that in infants and malingering adults.

Tone-burst evoked ABR (TB ABR) is the gold-standard method to estimate frequency-specific hearing thresholds. Conventionally, TBABRs to multiple frequencies are recorded serially and separately for the two ears. But it takes 1 to 3 hours to complete the test in such a case Eggermont, (2019) Gorga et al., (2006). Most often, completing the test requires multiple sessions. Therefore, scientists have attempted to modify the stimulus and acquisition paradigms of ABR in order to estimate hearing sensitivity in the audiometric frequency in a quick time. (Polonenko & Maddox, 2019) invented parallel ABR, which uses randomly timed tone burst stimuli to simultaneously acquire ABRs to 5 frequencies, in both ears. ABRs recorded were found to be similar to the ABRs recorded serially. This technique estimates frequency specific hearing reliably in quick time. But it requires complex algorithms in the stimulus presentation as well as response acquisition, and therefore is not feasible in the existing clinical AEP equipments.

Mamatha & Maruthy, (2017) recorded ABRs for tone bursts using a chained stimulus. They showed that ABRs of 4 frequencies could be recorded simultaneously without compromising on the quality of TBABRs recorded. However, owing to longer epoch required in this paradigm, stimulus repetition gets restricted to less than 10 per second which in turn extends the testing duration.

In order to reduce the testing time, majority of the audiologists use click-evoked ABR to estimate the hearing sensitivity as it gives a reliable estimate of the hearing sensitivity in 1 to 4 kHz region. Further, in order to estimate the hearing sensitivity at low frequencies, an additional TBABR for tone burst of 0.5 kHz is used. In the standard method, click evoked ABR and the 0.5 kHz TBABR are recorded serially. To estimate thresholds in these two ABRs, in the two ears of the subject, it takes approximately 30 minutes. In order to improve the time efficiency,(S. Maruthy, 2018) devised a new paradigm in which one can simultaneously record click-evoked and TB-evoked ABRs (SiCT ABR). They estimated ABR thresholds using SiCT paradigm in adult participants with normal hearing and demonstrated that the paradigm can cut down the recording time by half. Based on their finding they recommended the paradigm for clinical use in infants and young children.

1.1 Justification for the Study

Most often, Audiologists choose to record click ABRs instead of TBABR to estimate the hearing thresholds, owing to prolonged testing time in TBABRs. Clinicians typically record click ABRs and 0.5 kHz TBABRs in order to shorten testing times and to confirm the hearing sensitivity in the audiometric frequencies. Click ABR and 0.5 kHz TBABRs recorded serially in the conventional paradigm requires up to 40 minutes in order to track the threshold.

The SiCT paradigm appears theoretically feasible to be used in all commercially available clinical AEP equipments, provided there is a facility to load the external stimulus. (S. Maruthy et al. 2020.) demonstrated that the thresholds estimated by this paradigm is same as that by the click-alone and toneburst-alone paradigms. However, the paradigm is not validated in persons with hearing loss. Although at the outset it appears that the agreement between conventional paradigm and the SiCT paradigm in ears with hearing loss will be as good as that found in ears with normal hearing by (S. Maruthy, 2020), the premise needs to be scientifically supported. Only after validating in a group of persons with hearing loss, it will be appropriate to advice its feasibility for clinical use. If found valid in persons with hearing loss, in terms of latency and the thresholds estimated, it will be a potential tool for quick estimation of the hearing sensitivity. Importantly, it will not require any changes to the existing hardware or software of most of the commercially available clinical AEP equipments. Therefore, the paradigm will be available for immediate implementation with no additional cost.

1.2 Aim of the Study

To improve the time efficiency of ABR by modifying the stimuli paradigm by using click and tone burst stimuli simultaneously.

1.3 Objective of the Study

There were two objectives of the study:

1. To compare latency, amplitude and thresholds of SiCT ABR with that of click-alone and TB-alone ABRs (0.5 kHz) in persons with hearing loss.
2. To compare the two paradigms for their duration of recording ABR.

Chapter 2

REVIEW OF LITERATURE

Estimating hearing thresholds is crucial for accurate diagnosis and treatment. Conventionally, puretone audiometry, behavioral audiometry, and visual reinforcement audiometry are used to determine hearing thresholds, depending on the patient's age. Frequency-specific threshold estimation is essential in young children and other difficult-to-test population to enable early identification, precise hearing aid fitting, and rehabilitation (Hoke et al., 1991). Due to inconsistent behavioral thresholds, employing objective techniques to determine frequency-specific auditory thresholds is vital.

Audiologists now have a far greater likelihood of estimating auditory thresholds in individuals who cannot provide accurate behavioral thresholds by the advent of auditory brainstem responses (ABRs). Click-elicited ABRs are frequently utilized in threshold estimation because of their faster acquisition than other methods. However, as a broadband stimulus, clicks do not precisely estimate hearing thresholds for any given frequency and may totally miss or drastically underestimate hearing loss in specific frequency regions (Eggermont & Don, 1980; Mackersie & Stapells, 1994). Therefore, to obtain frequency-specific auditory thresholds in a quick time, various attempts have been made to modify stimulus and acquisition paradigms.

Literature suggests three general methods to obtain frequency-specific information from ABR: the conventional tonal method, masking method, and derived band technique (Mackersie & Stapells, 1994).

2.1 Auditory Brainstem Responses for Tone Bursts

Gorga et al. (1988) used tone-burst stimuli that were gated with cosine-squared functions to record ABR from 20 people with normal hearing. A wide range of frequencies and intensities elicited responses. The findings suggested that behavioral puretone thresholds were lower than ABR thresholds for all frequencies, more so for lower frequencies such as 250Hz and 500Hz. Also, the inter-subject variability was likewise greater at lower frequencies. As frequency and intensity increased, Wave-V latencies decreased. The rapid rise time of tone burst was associated with better responses at higher frequencies. The shorter rise time leads to greater discharge synchrony at higher frequencies, which in turn causes a larger amplitude of the response in comparison to the background noise. In addition,(Spoendlin, 1972) noted that the cochlea's basal end has a higher density of nerve fibers per unit area than its apical turns, which also would have contributed to higher discharge synchrony in response to high-frequency stimuli.

A similar study was done by(Dündar, 2014). The authors compared thresholds obtained from tone burst ABR to behavioral puretone threshold. They included 80 patients with sensorineural hearing loss in their investigation. ABR thresholds for tone bursts were estimated at 500Hz, 2000Hz, and 4000Hz, and the difference between them and pure-tone thresholds was calculated. At 500Hz, 2000Hz, and 4000Hz, the mean differences obtained were 4.75dB, 6.25dB, and 4.87dB, respectively.

Suzuki, Kodera, and Kaga (1982) compared ABR and behavioral thresholds at 500Hz and 1000Hz and reported that ABR thresholds were greater than behavioral thresholds. Using tone-burst ABRs to predict behavioral thresholds may be constrained by the increased variability in the discrepancies between ABR and behavioral thresholds for lower frequencies. However, due to its highly long test period of almost two hours, tone burst ABR's efficacy in obtaining frequency-specific responses for all frequencies is constrained (Karzon & Lieu, 2006; Stueve & O'Rourke, 2003).

Furthermore, ABR obtained using tone burst with rapid rise time may cause spectral splatter due to the contribution from adjacent frequencies, which, in turn, reduces the frequency specificity of the response (Orsini, 2004), Therefore, it was suggested to use notched noise along with tone bursts to reduce spectral splatter and improve frequency specificity.

2.2 Masking Methods in ABR

To obtain frequency specific ABR, ipsilateral masking noise of a characteristic frequency is presented along with the ABR eliciting stimuli to the test ear. The noise helps reduce spectral splatter, thus improving the frequency specificity of the ABR. The literature suggests the notched-noise, pure-tone, and high-pass masking noise methods.

Orsini, (2004) recorded standard tone burst ABR and notched noise ABR in individuals with normal hearing (n=25) and bilateral sensorineural hearing loss (n=16).

The results revealed no significant difference between Wave V latencies obtained from unmasked tone burst ABR and notched-noise tone burst. Hence, the authors did not recommend use of notch noise masking to improve the frequency specificity of ABR.

Beattie & Spence, (1991) also used the notch noise method to improve frequency specificity. Notch noise was used in conjuncture with clicks to elicit ABR. However, it was reported that a very high masking noise level (up to 95dBSPL) is required to mask a 65dBnHL click stimulus, which would almost reach the UCL level of the patient. Also, using the notch noise method higher ABR thresholds were obtained. Therefore, the authors suggested the use of tone burst ABR for improved frequency sensitivity.

Folsom, (1984) used pure-tones as masking stimuli. They presented simultaneous pure tone maskers at half octave intervals at the stimulus centre frequency. The masking profiles were obtained at 60 and 40dBSL. The results revealed that the masking profiles at 40dBSL were narrow and centered around the stimulus frequency. Whereas, masking profiles at 60dBSL showed high frequency spread of cochlear excitation.

Literature also suggests the use of high pass masking noise to improve frequency specificity in ABRs on(Don & Eggermont, 1978; Kileny, 1981; Laukli, 1983; Stapells et al., 1985). High pass masking noise method is preferred over notched noise method since it provides larger response amplitudes leading to greater response identifiability. Also, the presentation of high pass masking noise requires less cumbersome instrumentation than notch noise. However, there are limitations to the use of high pass masking noise. Tone bursts in the presence of masking noise includes all frequencies below the cutoff, which in turn reduces frequency specificity in comparison to the tone bursts in notched noise. However, frequencies below 1000Hz can still serve as a good tool to elicit frequency specific responses.

Don & Eggermont, (1978); Eggermont & Don, (1980) suggested another novel technique called derived band technique to obtain frequency specific ABRs. The ABR is recorded for clicks alone and in conjunction with high pass masking noise of different frequencies. Subsequently, offline subtraction of the two ABRs elicited with high pass masking noise of adjacent cut-off frequencies will give the derived band response. The underlying assumption is that these responses differ only in the contribution from the frequency region between the cut off frequencies of the maskers. Although the technique was experimentally validated, several limitations were observed. The derived band subtraction method was complex wherein the subtraction of the two waveforms lead to reduction in the signal to noise ratio. Also, instead of reducing the time of ABR acquisition, derived band technique was time consuming. Furthermore, the click elicited ABR has minimal contribution from frequency regions below 500Hz (Don et al., 1979; Don & Eggermont, 1978; Laukli et al., 1988) and therefore may not elicit an identifiable response in the 500Hz band.

2.3 Auditory Brainstem Responses for Chirps

Reddy et al., (2018) compared stacked tone ABR and ABR chirp in individuals with normal hearing and sensorineural hearing loss. The study involved two group of subjects. Group 1 included 20 ears with normal hearing (14 males and 6 females) and Group 2 consisted of 20 ears with mild to moderate cochlear hearing loss. Tone burst and two types of chirp (standard and modified) stimuli were used to record ABR. Tone burst of 0.25, 0.5, 1,2,4 and 8kHz with 2-0-2 cycles were used. The chirp stimuli were generated in MATLAB using the method described by Dau et al. (2000). The frequency range of the standard and modified chirp was 0.1kHz to 10kHz and 250Hz to 8kHz respectively. The duration of modified chirp (6msec) was less than the standard chirp (10msec). The findings suggested that the amplitude of Wave V for stacked tone was higher than chirp stimuli in both group of participants. Also, the amplitudes obtained with standard chirp ABR were greater than the modified chirp ABR. Further, the latency of Wave V obtained using standard chirps was longer compared to modified chirp stimulus, in both the groups.

2.4 The Parallel Auditory Brainstem Response

Polonenko & Maddox, (2019) introduces a new technique called the parallel ABR (pABR) as a potential improvement over the traditional ABR. The conventional ABR testing method involves presenting tone burst stimuli serially to one ear at a time. This approach has limitations, including the extended time required to measure multiple frequencies and intensities and the risk of incomplete data collection if the patient wakes up prematurely during the test. Therefore, instead of presenting tone bursts sequentially, the pABR uses randomly timed tone burst stimuli to simultaneously acquire ABR waveforms at five different frequencies in both ears. The pABR is reported to provide better place specificity, particularly for low frequencies at high intensities, due to the masking effect provided by the simultaneous tone burst sequences.

The pABR stimuli were constructed from windowed tone bursts centered at octave frequencies from 0.5kHz to 8kHz. For each frequency a tone burst train was created and tone bursts were randomly placed within 1s epoch time. This was repeated for all frequencies and the tone burts train were summed. The findings suggested that the pABR have faster acquisition times than conventional serial ABR measurement.

The pABR method offers several advantages over traditional serial ABR testing. The method has the potential to facilitate faster accumulation of diagnostic information. This could be especially valuable for the timely identification and treatment of hearing loss in individuals of all ages.

2.5 ABR for Multi Frequency Chain of Tone Bursts

Maruthy and H. R. Mamatha Maruthy, (2016) proposed a novel technique called the Multifrequency ABR (MFABR) for simultaneous acquisition of frequency specific ABRs utilising tone bursts of multiple frequencies. The study involved 30 adults with normal hearing and 11 individuals with sensorineural hearing loss. The latency and amplitude of Wave I, III and V were compared between the standard single frequency tone burst ABR and MFABR at 0.5, 1, 2 and 4kHz. Also, the behavioural audiometric thresholds were correlated with MFABR thresholds at the aforementioned frequencies. The results showed that MFABRs did not differ significantly from single frequency tone burst ABR to affect clinical diagnosis. Furthermore, the total time estimated to complete the testing at the four frequencies was one-fourth of the time taken by single frequency tone burst. Hence, the authors suggested that MFABR is a time efficient tool for assessing behavioural thresholds, particularly in difficult to test population.

A similar study was done by (Swathy, 2017) in infants. The study aimed to investigate the feasibility of MFABR in estimating frequency specific hearing thresholds in time efficient manner. A total of 21 infants participated in the study. The age range varied from one month to one year. Behavioral Observation Audiometry (BOA) was used to estimate the minimum response levels, and standard single frequency tone burst ABR and MFABR were performed at 0.5, 1, 2 and 4kHz. The findings suggested no significant difference between MFABR thresholds and the minimal response levels at 1,2 and 4kHz. At 0.5kHz, the median difference of agreement was less than 15dB. The MFABR thresholds were lower than the BOA levels, with an agreement of less than 10dB.

Overall, the studies suggest that MFABR have similar thresholds as standard frequency tone burst ABR. Also, the MFABR thresholds are in close agreement with the behavioral thresholds. Further, the time taken by MFABR significantly less than the time taken by standard frequency tone burst ABR.

Chapter 3

METHODS

The study aimed to assess the utility of SiCT paradigm in estimating hearing sensitivity of persons with sensorineural hearing loss (SNHL), in a quick time. Considering that Maruthy et al. (2020) had already validated it in normal hearing persons, the current study confined to persons with SNHL. The ABRs recorded in the SiCT paradigm were compared with that of the conventional paradigm for their latency, amplitude and ABR thresholds. The method adopted in this study conformed to the ethical guidelines prescribed for bio-behavioural research at the institute (Venkatesan & Basavaraj,2009). The specific details of the method used are given in the following sections.

3.1 Participants

Three groups of adults (3 females & 13 males) participated in the study; persons with mild SNHL, moderate SNHL and moderately severe SNHL. They either had unilateral or bilateral hearing loss. There were 8 ears with mild SNHL (5 participants), 10 ears with moderate SNHL (6 participants) and 10 ears with moderately severe SNHL (5 participants). All the participants were in the age range of 18 to 76 years (mean age: 65.1).

The test ears had either flat or gradually sloping SNHL. The tympanometry showed type A or As tympanogram with acoustic reflexes either present or absent depending the degree of hearing loss. The other audiological findings were suggestive of cochlear hearing loss and were not indicative of retrocochlear pathology. Otoacoustic emissions were absent in the test ear and click-evoked auditory brainstem responses were present, with no evidence of deviant absolute latency of Jewett waves or the inter-wave intervals. Those with conductive hearing loss were not considered for the study. Also, there was no relevant history of neurological or psychological abnormalities in any of the participants. The participants willingly participated in the study and gave a written informed consent, prior to their participation.

3.2 Test Stimuli

ABRs were recorded for click and 0.5 kHz TB, presented in two stimulus paradigms: the conventional paradigm and the SiCT paradigm. ABRs in the SiCT paradigm were elicited for a chained stimulus that included a click starting at 0ms and a 0.5 kHz tone burst starting at the 21^{st} ms. The onset to onset interval was 20 ms. ABRs in the conventional paradigm involved eliciting ABRs for the same click and 0.5kHz tone burst, but individually.

The test stimuli used in the study were generated using Praat software (version 5.3.36). The duration of 0.5 kHz tone burst was 8 ms (2-0-2 envelope and Hanning window), while the duration of click was 100 µs. In the chained stimulus used for SiCT paradigm, click and 0.5 kHz tone burst were sequentially concatenated with onset to onset interval of 20 ms, leading to a total duration of 28 ms. Waveform of the chained stimulus is given in Figure 3.1.

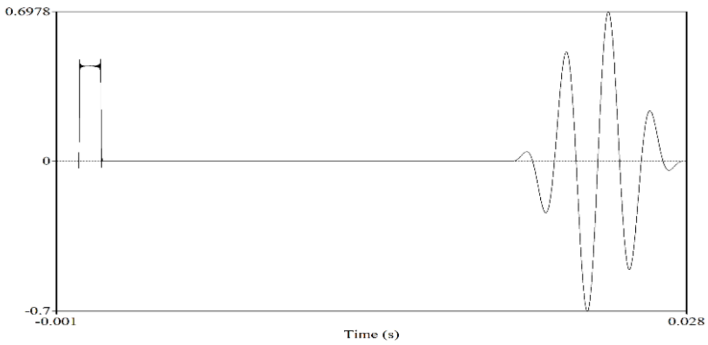

Figure 3.1: Waveform of the chained stimulus used to record SiCT ABR in the study.

3.3 Test Environment

All the tests (puretone audiometry, tympanometry, OAEs and ABRs) were administered in electrically shielded and acoustically treated rooms, wherein the noise levels were within the permissible limits (Frank, 2000). Pure tone audiometry was conducted in a double room suite and the three tests were conducted in single room suite.

3.4 Test Procedure

After obtaining the informed consent from the participants, they were tested for pure tone hearing thresholds, OAEs, and the ABRs using the two paradigms (standard & SiCT). The pure tone thresholds of the test ear was estimated using the modified Hughson-Westlake procedure (Durrant et al., 2021). Two pure tone averages was estimated: PTA1-average of hearing thresholds at 0.5kHz, 1kHz and 2 kHz, and PTA2-average of hearing thresholds at 1kHz, 2kHz and 4kHz.

The stimulus and acquisition parameters used to record ABRs are given in Table 3.1. The Biologic Navigator Pro AEP system with impedance-matched ER3C insert receivers was used to record the ABRs. The participants were seated in a comfortable reclining chair. They were instructed to relax and refrain from extraneous movements of head and neck. The electrode sites were cleaned using Nuprep cleaning gel and the disc electrodes were placed along with the ten-20 conductive paste. The electrodes were held firm in their place with the help of an adhesive tape.

In each participant, ABRs were recorded for two paradigms: the SiCT and the standard. The standard paradigm involved recording ABR for 0.5 kHz TB and ABRs for clicks individually, whereas the SiCT paradigm involved recording ABRs for the chained stimulus. The order of the paradigms was counterbalanced across participants. In case of both the paradigms, threshold of ABR was estimated. The procedure started by recording ABR at 90 dBnHL, followed by tracking ABR thresholds adaptively in 10 dB step size. In case of SiCT paradigm, thresholds were tracked for click as well as 500Hz TB.

Table 3.1: Stimulus and acquisition parameters to be used to record ABRs in the study

Stimulus Parameters	
Stimulus	Click, 0.5kHz TB and the chain of the two
Polarity	Rarefaction
Transducer	Insert ear phone
Repetition rate	11.1/sec
Intensity	90dBnHL and lowers intensity till threshold
Type of stimulation	Monaural
Acquisition Parameters	
Montage	Vertical
Electrode sites	Inverting: test ear mastoid Non-inverting-vertex (Fpz) Ground: non-test ear mastoid
Filters setting	30Hz - 3000Hz
Amplification	1,00,000 times
Artifact rejection	25µV
Analysis window	43ms
Total no. averages	2000
Data points	1024

3.5 Response Analysis

The averaged responses were visually inspected to identify the presence of wave I, III and V. Two audiologists experienced in the ABR waveform analysis inspected the waveforms. If the waves were present, the peak latency and amplitude of the wave was noted down. The latency of 0.5 kHz TB ABR recorded in SiCT paradigm was derived by reducing a fixed 20 ms from the observed latency. The ABR threshold was noted down in each case.

3.6 Data Analysis

The data was subjected to Shapiro-Wilk test of normality. Based on whether it meets the assumptions of normal distribution, appropriate statistical tests for within group comparison was chosen. Further, the PTA1 and PTA2 were tested for their correlation with the ABR thresholds estimated for clicks in the two paradigms. Pure tone hearing threshold at 0.5 kHz was tested for its correlation with the ABR threshold estimated for 0.5 kHz TB in the two paradigms.

Chapter 4

RESULTS

The present study aimed to test whether SiCT ABR is a valid method to objectively estimate hearing thresholds in individuals with sensorineural hearing loss. The ABRs were elicited using two different stimulus paradigm; standard and SiCT paradigm. Results obtained in the study are reported under the following headings:

1) Comparison between standard ABR and SiCT ABR paradigms for their latency, amplitude and thresholds
2) Agreement between puretone thresholds and ABR thresholds
3) Comparison of time taken for recording ABRs in the two paradigms

The group data was initially tested for its distribution using Shapiro-wilk test of normality. There were a total of 60 parameters tested for normality in each group which included latency, amplitude and threshold of ABR. The results of normality test showed normal distribution of the data. Accordingly, parametric test was used for further statistical analysis.

4.1 Comparison between Standard ABR and SiCT ABR Paradigms for their Latency, Amplitude and Thresholds

The ABR was elicited by two paradigms and the responses were compared in terms of their latency, amplitude and thresholds. This was done for click evoked ABR as well as 500Hz TBABR. The results are reported separately for latency, amplitude and thresholds.

4.1.1 Results of Click-evoked ABR

In click ABR it is important to note that when a particular wave was recordable in the standard paradigm, it could also be recorded in SiCT paradigm and viceversa. Wave I was recordable only in participants with mild SNHL, while the wave III and V were recordable in all three groups of participants.

Comparison of latency of click-evoked ABR: Table 4.1 gives the mean and standard deviation of the latency of wave I, III, and V recorded in the two paradigms at 90dBnHL in mild, moderate, and moderately severe SNHL groups. The latency of wave I, III and V recorded in the two paradigms (standard & SiCT) at 90dBnHL were compared on paired t-test. This was done separately for mild, moderate and moderately severe SNHL groups. The results of paired t-test showed that there is no significant diffierence in the latency of the waves recorded in the two paradigms. This was true for all the three waves, and in all the three groups.

Table 4.1: Mean and standard deviation of the latency wave I, III, and V at 90dBnHL clicks obtained in the standard and SiCT paradigms in the three groups of participants. The table also shows the results of paired t-test comparing the two paradigms

Group	Wave	Paradigm	Mean	SD	t	df	p
Mild	I	Standard	1.59	0.21	-2.19	7	0.06
		SiCT	1.60	0.20			
	III	Standard	3.72	0.18	-1.52	7	0.17
		SiCT	3.72	0.18			
	V	Standard	5.65	0.22	-2.49	7	0.04
		SiCT	5.66	0.22			
Moderate	III	Standard	3.81	0.09	1.06	9	0.31
		SiCT	3.75	0.17			
	V	Standard	5.78	0.14	-1.79	9	0.10
		SiCT	5.90	0.18			
Moderately severe	III	Standard	4.18	0.10	1.00	9	0.34
		SiCT	3.88	0.97			
	V	Standard	6.16	0.07	1.00	9	0.34
		SiCT	6.15	0.08			

Comparison of Amplitude of Click-evoked ABRs: Table 4.2 gives the mean and standard deviation of the amplitude of wave I, III, and V recorded in the two paradigms at 90dBnHL in mild, moderate, and moderately severe SNHL groups. The amplitude of wave I, III and V recorded in the two paradigms (standard & SiCT) at 90dBnHL were compared on paired t-test. This was done separately for mild, moderate and moderately severe SNHL groups. The results of paired t-test showed that there is no significant difference in the amplitude of the waves recorded in the two paradigms. This was true for all the three waves, and in all the three groups.

Table 4.2: Mean and standard deviation of the amplitude wave I, III, and V at 90dBnHL clicks obtained in the standard and SiCT paradigms in the three groups of participants. The table also shows the results of paired t-test comparing the two paradigms

Group	Wave	Paradigm	Mean	SD	t	df	p
Mild	I	Standard	0.24	0.91	0.42	9	0.67
		SiCT	0.24	0.81			
	III	Standard	0.26	0.09	1.30	9	0.22
		SiCT	0.25	0.09			
	V	Standard	0.24	0.13	1.33	9	0.21
		SiCT	0.18	0.05			
Moderate	III	Standard	0.20	0.05	-1.43	9	0.18
		SiCT	0.24	0.11			
	V	Standard	0.19	0.08	0.56	9	0.58
		SiCT	0.17	0.04			
Moderately severe	III	Standard	0.20	0.01	-1.36	9	0.20
		SiCT	0.24	0.09			
	V	Standard	0.21	0.01	1.6	9	0.14
		SiCT	0.17	0.07			

Comparison of Threshold of Click-evoked ABRs: In all the participants, in both the paradigms, wave V was the most robust peak. Accordingly, the threshold of ABR was tracked based on the presence of wave V. The mean and standard deviation of the ABR threshold obtained in standard and SiCT paradigm in the three groups of participants is given in Table 4.3. The results showed that the ABR thresholds obtained in the two groups is exactly same, leading to same mean and standard deviation of ABR thresholds.

Table 4.3: Mean and standard deviation of the ABR thresholds obtained for clicks in standard and SiCT paradigms in the three groups of participants

Group	Paradigm	Mean (dBnHL)	SD
Mild SNHL	Standard	36.25	5.1
	SiCT	36.25	5.1
Moderate SNHL	Standard	48	4.2
	SiCT	48	4.2
Moderately Severe SNHL	Standard	66	70
	SiCT	66	70

4.1.2 Results of 500Hz Tone burst-evoked ABR

In tone burst ABR again, when a particular wave was recordable in the standard paradigm, it could also be recorded in SiCT paradigm and vice versa. At 90dBnHL wave I was absent in all three groups; wave III was present only in mild and moderate SNHL groups, and wave V was present in all the three groups. The results are reported separately for latency, amplitude and ABR threshold.

Comparison of latency of tone burst-evoked ABR: Table 4.4 gives the mean and standard deviation of the latency of wave I, III, and V recorded for 500 Hz TB in the two paradigms at 90dBnHL in mild, moderate, and moderately severe SNHL groups. The latency of wave I, III and V recorded in the two paradigms (standard & SiCT) at 90dBnHL were compared on paired t-test. This was done separately for mild, moderate and moderately severe SNHL groups. The results of paired t-test showed significant prolongation of waves recorded in the SiCT paradigm compared to the standard paradigm. However, the difference was significant only in wave III of moderate SNHL group after correcting for multiple comparisons (the target p was 0.01 after correction).

Table 4.4: Mean and standard deviation of the latency wave I, III, and V at 90dBnHL 500Hz TB obtained in the standard and SiCT paradigms in the three groups of participants. The table also shows the results of paired t-test comparing the two paradigms

Group	Wave	Paradigm	Mean	SD	t	df	p
Mild	III	Standard	3.77	0.11	-2.6	9	0.02
		SiCT	3.95	0.13			
	V	Standard	5.81	0.08	-2.93	9	0.01
		SiCT	5.93	0.17			
Moderate	III	Standard	3.70	0.11	-6.83	9	0.00
		SiCT	4.06	0.90			
	V	Standard	5.72	0.17	-1.00	9	0.34
		SiCT	5.75	0.16			
Moderately severe	V	Standard	7.02	0.10	-2.4	9	0.03
		SiCT	7.13	0.12			

Comparison of amplitude of tone burst-evoked ABR: Table 4.5 gives the mean and standard deviation of the amplitude of wave I, III, and V recorded for 500 Hz TB in the two paradigms at 90dBnHL for 500Hz TB in mild, moderate, and moderately severe SNHL groups. The amplitude of wave I, III and V recorded in the two paradigms (standard & SiCT) at 90dBnHL were compared on paired t-test. This was done separately for mild, moderate and moderately severe SNHL groups. The results of paired t-test showed significant differences in the amplitude recorded in the two paradigms. However, the differences were not significant after correcting for multiple comparisons ($p < 0.01$).

Table 4.5: Mean and standard deviation of the amplitude wave I, III, and V at 90dBnHL clicks obtained in the standard and SiCT paradigms in the three groups of participants. The table also shows the results of paired t-test comparing the two paradigms

Group	Wave	Paradigm	Mean	SD	t	df	p
Mild	III	Standard	0.13	0.07	-2.46	9	0.03
		SiCT	0.25	0.15			
	V	Standard	0.18	0.05	2.51	9	0.03
		SiCT	0.12	0.07			
Moderate	III	Standard	0.16	0.04	0.335	9	0.74
		SiCT	0.15	0.07			
	V	Standard	0.17	0.04	-1.47	9	0.17
		SiCT	0.25	0.15			
Moderately severe	V	Standard	0.17	0.07	-0.387	9	0.70
		SiCT	0.18	0.05			

Comparison of threshold of 500Hz tone burst-evoked ABR: Similar to clicks, in all the participants, the ABRs elicited by 500Hz TB had robust wave V. This was true in both the paradigm. Accordingly, the threshold of ABR was tracked based on the presence of wave V. The mean and standard deviation of the ABR threshold obtained for 500Hz TB in standard and SiCT paradigms in the three groups of participants is given in Table 4.6. The results showed that the ABR thresholds obtained in the two groups is exactly same, leading to same mean and standard deviation of ABR thresholds.

Table 4.6: Mean and standard deviation of the ABR thresholds obtained for 500Hz TB in standard and SiCT paradigms in the three groups of participants

Group	Paradigm	Mean (dBnHL)	SD
Mild SNHL	Standard	35	5.3
	SiCT	35	5.3
Moderate SNHL	Standard	47	6.7
	SiCT	47	6.7
Moderately Severe SNHL	Standard	62	4.2
	SiCT	62	4.2

4.2 Agreement between Pure tone Thresholds and ABR Thresholds

The agreement between pure tone threshold and ABR threshold was assessed separately for click ABRs and 500Hz ABR. In click evoked ABRs, two pure tone averages (PTA 1 & PTA 2) were compared with the click ABR threshold. The mean PTA1, PTA2, click ABR threshold and the mean differences between the behavioural threshold and ABR threshold are given in Table 4.7. The data shows that the agreement between PTA and ABR threshold is within 5 dB. This is true for PTA 1 as well as PTA 2 and in all the three groups of participants. ABR threshold was higher than PTA 1 and lower that PTA 2.

Table 4.7: Mean PTA1, PTA2, click ABR threshold and the mean differences between the behavioural threshold and ABR threshold in the three groups of participants

Group	PTA 1	PTA 2	Click ABR Threshold	Mean difference	
				Click ABR Threshold- PTA 1	Click ABR Threshold- PTA 2
Mild SNHL	31.7	39.9	36.25	4.10	-3.65
Moderate SNHL	44.31	50.98	48	3.69	-2.98
Moderately Severe SNHL	60.45	65.13	66	4.68	0.87

In 500Hz TB ABRs, two hearing threshold for 500Hz puretone obtained in the puretone audiometry was compared with the 500Hz TB ABR threshold. The mean pure tone threshold at 500Hz, 500Hz TBABR threshold and the mean differences between the behavioural threshold and corresponding ABR threshold are given in Table 4.8. The data shows that the agreement between PTA and ABR threshold is within 10 dB. This is true in all the three groups of participants. ABR threshold was always higher than puretone threshold.

Table 4.8: Mean puretone thresholds at 500Hz, 500Hz TBABR thresholds and the mean differences between the behavioural threshold and ABR threshold in the three groups of participants

Group	PTT at 500Hz	500Hz TB ABR Threshold	Mean difference
			TB ABR Threshold-PTT
Mild SNHL	25.62	35	9.38
Moderate SNHL	39.5	47	7.5
Moderately Severe SNHL	56	62	6

4.3 Comparison of Time Taken for Recording ABRs in the Two Paradigms

Table 4.9 shows the mean and standard deviation of the recording time taken to estimate ABR threshold using standard and SiCT paradigm in the three groups of participants. Results of paired t-test showed a significant reduction in the recording time in the SiCT paradigm compared to the standard paradigm. Figure 4.1 shows a set of click alone, tone burst alone, and SiCT ABR recorded (at 90, 80, 70, 60, 50dBnHL) in a representative participant with mild SNHL.

Table 4.9: Mean standard deviation of the recording time taken to estimate ABR threshold using standard and SiCT paradigm in the three groups of participants

Group	Paradigm	Mean (seconds)	SD	t	df	p
Mild	Standard	58.52	2.36	-15.92	7	0.0
	SiCT	35.37	2.25			
Moderate	Standard	26.53	1.38	-2.45	9	0.03
	SiCT	24.57	2.36			
Moderately severe	Standard	21.08	0.64	-11.35	9	0.0
	SiCT	14.97	1.60			

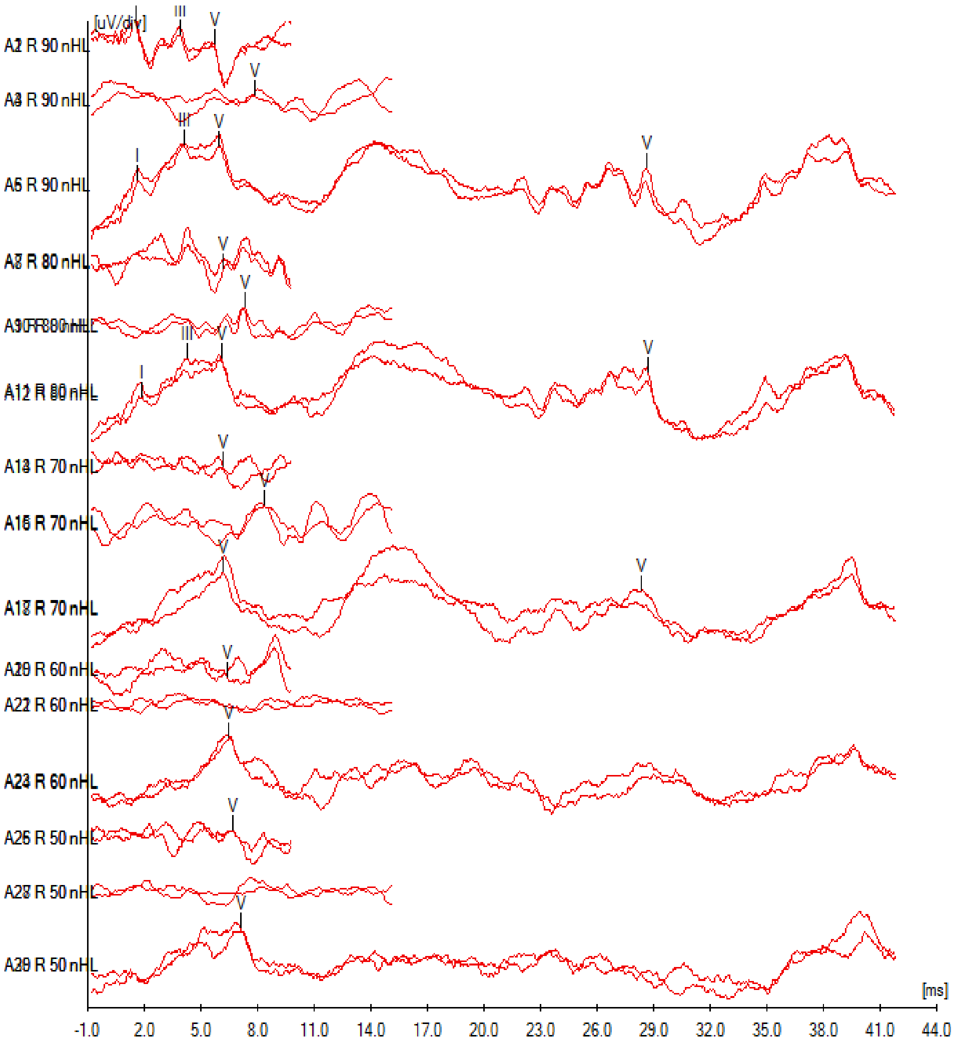

Figure 4.1: A set of click alone, tone burst alone, and SiCT ABR recorded (at 90, 80, 70, 60, 50dBnHL) in a representative participant with mild SNHL

Chapter 5

DISCUSSION

The study aimed to verify whether the SiCT paradigm can estimate hearing threshold as reliably as standard paradigm. Maruthy et al. (2020) had established it in the normal hearing individuals. Therefore, the primary aim of this study was to validate it in persons with the sensorineural hearing loss.

In the standard paradigm, a comprehensive hearing evaluation in a difficult to test individual takes more than an hour. If the hearing thresholds need a crosscheck through an objective measure such as ABR, the test time is extended at least by another half an hour. This is one of the most common criticisms in a busy audiological clinic and continuous efforts are on throughout the world to cut down the testing time Maruthe.et.al.,(2020) and Eggermont & Don, Stapells (1994).

In order to cut down the testing time involved in eliciting frequency-specific TBABRs, most often clinicians record click ABRs and 0.5 kHz TBABRs and verify the hearing sensitivity in the audiometric frequencies. As a standard method, click ABR and 0.5kHz TBABRs are recorded serially and the recording time may extend upto 40 minutes to track the threshold for the two ABRs. In the present study, SiCT paradigm was used to record ABRs for clicks and 0.5 kHz TB simultaneously using a chained stimulus. The paradigm aim at cutting down the testing time by half. However, it was important to ensure that the proposed method does not compromise the quality of the responses recorded and accuracy of the response measures in persons with hearing loss.

The findings support that the latency, amplitude as well as the threshold of ABRs elicited in the two paradigms are comparable in persons with different degrees of sensorineural hearing loss. This was true for click ABRs as well as 500TB ABRs. Therefore, the use of SiCT ABR for time efficiency is strongly supported as the thresholds determined by the SiCT paradigms is as accurate as that of standard ABRs.

The present study compared the latencies and thresholds obtained in the standard paradigm and the SiCT paradigm. This was done in order to assess if the waveforms elicited by the SiCT paradigm stand up to the standard ABRs that is already validated, but in much lesser testing duration. The results showed that the latency as well the thresholds obtained in the SiCT paradigm were same as that of the standard

ABRs. This suggests that the proposed paradigm does not compromise the quality of the responses recorded although cuts down the testing time.

Techniques to record ABR in a quick way, such as the maximum length sequence use a very high repetition rate and complex demodulation strategies to extract the ABR. However, the use of high rates to record the ABRs comes at a cost of affecting the morphology, peak amplitudes and latencies of ABR. This happens because the high rates results in neural fatigue, as the nerves do not get enough time to recover from their previous discharge and the subsequent discharge would be a less synchronous and low amplitude one Gorga, Kaminski(1988) and Spoendlin (1972). Using the current technique, we reduce the test time by simultaneously recording click and 0.5 kHz TBABRs using the same repetition rate as that in standard ABRs (11.1/s). Considering that the thresholds obtained in the two methods were comparable, it is promising tool for quick estimation of the hearing sensitivity in the audiometric frequencies.

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

The technique was implemented in a commercially available clinically equipment. Therefore, with minor changes in the stimulus and acquisition parameters, it is ready for immediate application in most of the commercially available equipments.

Though this technique was fast and useful, we need user-friendly algorithms to be developed such that the stimulus specific ABR separation, intensity roving across ears etc. can be done with ease. However, the data provides a strong empirical evidence and ensures that the new technique works as well as the gold standard technique. With subsequent research, if the new technique is further validated, it calls for collaborative efforts from academia and industry to join hands and develop a commercial product.

We believe that the outcome of the current research though is a breakthrough hearing diagnostics, the simplicity and efficacy of the technique will result a whole series of AEPs using the novel technique.

The thresholds of ABRs elicited for clicks was within 5 dB of the puretone average. The results showed that the click ABR threshold was about 5dB higher than PTA 1, but about 5dB lower than PTA 2. The ABR thresholds lower than PTA 2 suggests that lower frequencies have contributed for click evoked ABR, as the participants had sloping SNHL. ABR for 500Hz TB however had agreement with puretone threshold that was within 10dB. The larger deviation from puretone threshold in case of 500Hz TB may attributed to the poorer ABR elicited by low frequency TBs, owing to longer rise time. Taken together, the ABR thresholds elicited by SiCT paradigm is in close agreement with that of behavioural thresholds. Therefore, it can be used reliably to estimate hearing threshold objectively even in persons with sensorineural hearing loss.

The time taken by the SiCT paradigm is significantly lower than that in standard paradigm. But it is not half of that taken in the standard paradigm. This could be due to longer analysis window used in the SiCT paradigm. The epoch being longer, the probability of picking up post auricular muscle artifacts and some of the other artifacts, increases. This may results in more rejections in the SiCT paradigm, leading to longer recording time. However, the notion needs to be experimentally verified.

The thresholds obtained in the two paradigms in exactly same in all the participants, irrespective of the degree of hearing loss. Although this is positive finding in support of SiCT paradigm, it may be interpreted in light of the fact that the ABR threshold were tracked in 10dB steps. The study doesn’t rule out minor differences in the ABR thresholds. However, considering that ABR thresholds are generally tracked in 10dB steps in the audiology clinics, the finding may be read as no difference between the two paradigms.

Chapter 6

SUMMARY AND CONCLUSSIONS

Auditory brainstem response is known to be reliable technique for objective estimation of hearing thresholds and is extensively used in difficult to test population. Although the gold standard is tone-burst ABR (TBABR), most audiology clinics make use of click-evoked ABRs in view of the time efficiency. As the click ABR provides information primarily about the 1 to 4kHz region, an additional 500Hz TBABR is recorded for assessing the low frequency hearing sensitivity. In the standard paradigm, click ABR and 500Hz TBABR are sequentially recorded. Maruthy et al. (2020) proposed a new paradigm called SiCT paradigm in which a chain of click and 500Hz TB is used to simultaneously elicit click and 500Hz TBABR. They had even demonstrated on a group of normal hearing individuals that the ABR elicited using the SiCT paradigm is comparable to that of the standard paradigm. In the current study, it was attempted to validate the paradigm in a group of individuals with sensorineural hearing loss.

Adults with mild, moderate and moderately severe sensorineural hearing loss participated in the study. They were divided into three groups based on their degree of hearing loss. ABRs were recorded in them using the standard paradigm and the SiCT paradigm. To begin with, ABRs were recorded at 90dBnHL and the intensity was gradually reduced in 10 dB steps to track the ABR threshold. The latency and amplitude of ABRs recorded in the two paradigms at 90dBnHL, and the threshold of ABR obtained in the two paradigms were compared statistically. The agreement between puretone threshold and ABR threshold, as well as the recording time in the two paradigms were also analysed.

The results showed that there is no significant difference between the two paradigms in the latency as well as amplitude of ABRs obtained. The ABR thresholds obtained in the two paradigms were exactly same in all the participants. The mean threshold of click ABR was within 5 dB of the puretone average and the mean threshold of 500HzTBABR was within 10dB of the respective puretone threshold. The results were true for mild, moderate as well as moderately severe sensorineural hearing loss. The recording time in SiCT ABR was significantly lower than that of standard ABR.

The findings of the study provide strong evidence for the use of SiCT paradigm to estimate ABR thresholds in persons with sensorineural hearing loss. The paradigm provides information same as that of standard ABR, however in quick time. Therefore, SiCT paradigm is recommended as time-efficient hearing estimation tool for clinical set ups and it is feasible for immediate implementation in most of the clinical AEP equipment without any additional cost.

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