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Research Article

Optimising Click and 500 Hz Tone-burst ABR Averaging Using Signal to Noise Ratio Criterion in Adults with and without Hearing Loss

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Abstract

Introduction: Optimising the recording of Auditory Brainstem responses is critical for the clinic because of its widespread utility. Objective determination of minimum number of sweeps using computationally less intensive methods required is a step in this direction.

Objective: To estimate the number of sweeps required to reach a good SNR for click and 500 Hz tone burst ABRs across intensities in normal hearing young adults, to check for inter-rater agreement and to check for the validity of this model in the clinical population.

Methods: ABRs were recorded in 30 young adults with normal hearing sensitivity using clicks and 500 Hz tone bursts at 90, 70 and 40 dB nHL. The variation of SNR with the number of sweeps was modeled with linear regression to estimate the optimal sweeps required for each stimulus condition. This model was checked for inter-rater reliability, and validated in 30 individuals with a diverse degree and type of hearing loss.

Results: In normal hearing young adults, SNR of 1 could be obtained with just 500 sweeps even at 40 dB nHL for clicks, but needed at least 2000 sweeps for 500 Hz tone burst. Recordings done based on this estimate required lesser time than the traditionally fixed sweep numbers. Further, peaks marked based on this criterion had a good inter-rater reliability, and was largely valid in different degrees of hearing loss.

Conclusions: The optimized sweep number could be used to guide relatively inexperienced clinicians on the minimum sweep number required for each stimulus condition.

Keywords: Auditory Brainstem Response; Objective Determination; Signal-to-Noise Ratio; BERA; Tone Brust, Clicks, Optimizing and Hearing Loss

Abbreviations

SNR: Signal to Noise Ratio; ABR: Auditory Brainstem Response; IHS: Intelligent Hearing Systems; SD: Standard Deviation; dBnHL: Decibel Normal Hearing Level; Hz: Hertz

Introduction

The Auditory brainstem responses (ABR) represent synchronous neural firing in the auditory nerve and brainstem in response to acoustic stimuli [1]. One of the most important applications of ABR is the objective estimation of auditory function [2-5]. ABRs can reliably yield information on the degree, type, and the pattern of hearing loss even in newborns [6,7], and critically, is robust to the effects of the state of arousal, sedation, or drugs [8,9].

ABR, recorded as a far-field neural potential, has a rather small amplitude (typically within 1 μV). The background noise electrical activity can reach up to 20 μV with the typical recording settings used to elicit ABR [10]. So, visualization of ABR is heavily dependent on the process of averaging to improve the signal to noise ratio. By repeatedly presenting the stimulus, and averaging the response recorded, the relatively constant and time-locked neural response is preserved, and the largely random noise is attenuated [11]. The number of sweeps to be averaged is not fixed, but varies depending on the signal to noise ratio of the recording [12,13]. The averaging is stopped when a response is obvious or when it is deemed that there is no response after a particular number of trials. This process of visual response identification is common, but is largely subjective. Previous studies have amply demonstrated that while peak identification by experts remains the gold standard, marking by relatively inexperienced clinicians depend on the signal to noise ratio of the response as well as the residual noise in the waveform [14,15]. Noisier recordings with atypical responses are more prone to subjectivity and has a low inter-judge reliability [16]. Supplementing visual peak-picking with objective analysis of the waveform is thus recommended [17-19].

One of the most used objective parameters that determines the quality of the response is the Signal to Noise Ratio (SNR) of the averaged response [12,20]. Some of the approaches to estimate the SNR include Standard deviation ratio [11], Fsp [12], and Point optimized variance ratio [21] to name a few. One way of approaching the problem is to determine the minimum number of sweeps required to reach a reliable SNR thus optimsing the sweep number. This methodology can potentially reduce the number of false positives and save valuable clinical time [20,22]. While data about SNR variation with sweep number is readily available for clicks, more data is needed for tone-burst ABRs [22,23]. To maximize the efficiency of ABR recording, we need more studies that optimize the sweep number for different stimuli across intensities. Further, the SNR determination methodology must have a low computational load so that it can be implemented easily in clinical setups. In this study, we investigated the SNR variation for Clicks and 500 Hz tone burst ABRs across intensities using a variation of standard deviation ratio technique that is used by the IHS systems (the SNR derived is numerically half the standard deviation ratio value) [24], and show that the model saves time, and has excellent inter-rater reliability.

Materials and Methods

Participants (primary)

Thirty participants with hearing sensitivity within normal limits and age ranging from 18 to 30 (mean age = 21.7 years, SD = 1.6 years, 17 females and 13 males) were recruited for the study as part of control group. These participants had air conduction thresholds (500 Hz and 8000 Hz) and bone conduction thresholds (500-4000 Hz) below 15 dB at each octave frequency. All the participants had type "A" tympanogram and present acoustic stapedius reflexes (ipsilateral and contralateral ears) at 500 Hz, 1000 Hz, and 2000 Hz at 90 dB HL. Participants who had any history of head injury, neurological disorders, tinnitus, or taking ototoxic medications were excluded from the study. Ethical clearance was obtained by the Institutional review board before conducting the study (JSSISH-RC-2023–101).

ABR recording

The ABRs were recorded using the Intelligent Hearing Systems (IHS) Duet instrument (Miami, USA). To minimize the impact of artifacts on recording ABR, each participant was instructed to sit comfortably and to refrain from eye and body movements as much as possible. The electrode locations were scrubbed with Nu-prep gel. Three disc-shaped gold-plated electrodes were placed at the designated sites [Active: Fz, Reference electrode: A1/A2, Ground: Fpz]. To ensure the electrodes are at the site, a surgical tape was employed. The ER-3A insert receiver was inserted into the participant's ear to deliver the stimulus for recording ABR. The stimulus & recording parameters used are shown in Table 1.

Table 1: Test protocol to record Clicks and 500 Hz Tone-burst ABR.

Stimulus parameters	
Type of stimulus	Clicks, 500 Hz Tone burst
Duration of stimulus	Clicks: 0.1 ms; 500 Hz tone burst: 2-0-2 configuration (Blackman window)- 8 ms
Polarity	Rarefaction
Repetition rate	30.1/sec
Stimulus intensity	90 dB nHL, 70 dB nHL and 40 dB nHL
Recording parameters	
Gain	100,000
Filter setting	30 Hz to 1500 Hz
Electrode impedance	Absolute impedance<5kΩ; Inter-electrode impedance<2kΩ
Artifact rejection	Threshold: 25 µV; number of rejected sweeps<5% of total number of sweeps

Number of sweeps	500, 750, 1000, 1250, 1500
Notch filter	None
Time window	Clicks: -1 to 15 ms; 500 Hz TB: -1 to 20 ms
Display gain	0.5 to 1 µV

Estimation of time window to calculate the SNR

A pilot study was conducted to determine the time window of SNR to record ABR for clicks and 500 Hz. The ABR was recorded from 10 normal hearing subjects with the protocol specified in Table 1. The mean and standard deviation (SD) of wave V latency of ABR at 90 dB nHL were used to estimate the lower limit of the SNR time window, by subtracting the 2 SD from the mean latency. Similarly, the mean and SD of wave V latency of ABR at 40 dB nHL was used to calculate the upper limit by adding the 2 SD to the mean latency. Thus, the range of time window to calculate the SNR was derived for clicks (4.34 ms-8.45 ms) as well as 500 Hz Tone bursts (7.65 ms-16.55 ms).

Measuring SNR across Sweeps at different intensities for the two stimuli

Starting from the 500th sweep, the recording of ABR was paused every 250 sweeps to note down the signal-to-noise ratio. A screenshot of the response at various sweeps was taken for further analysis of inter-rater reliability. This procedure was followed for clicks and 500 Hz tone bursts for three intensities: 90 dB nHL, 70 dB nHL and 40 dB nHL. Previous studies [20,24] using the Intelligent Hearing Systems instrument have identified that a signal to noise ratio equal to 1 is efficient at separating a present and absent response. Thus, the optimum number of sweeps required to achieve a signal to noise ratio of 1 was determined for each stimulus condition (2 stimuli, 3 intensities).

Determination of recording duration and inter-rater reliability across the stimulus conditions for the determined optimum number of sweeps

The recording duration for each stimulus condition was estimated as the product of repetition rate and number of sweeps. The presence of wave V recorded for optimum number of sweeps was rated by two experienced audiologists. Using a 5-point Likert rating scale (5: Definite response, 4: Possible response, 3: Probable response, 2: Probable No response, and 1: No response), the degree of agreement between the two audiologists on the presence of the V peak of ABR at the optimized sweeps was assessed. When rating the ABR waveforms, both the audiologists were blinded to the stimulus, intensity as well as the number of sweeps used to record the ABR.

Determining the applicability of the determined optimal number of sweeps in the clinical group

The model was checked for validity in a sample of clinical group. The clinical group consisted of those with conductive, sensorineural, and mixed hearing loss of varying degrees (Table 2). Experts identified and marked the responses at 500, 1500 and 2000 sweeps. The recording was run till the residual noise levels was at or below 0.08 µV before the response was declared absent [20,25]. Validity was assessed by checking if a response that was absent for the optimal number of sweeps was present for a greater number of sweeps for any stimulus condition across participants.

Table 2: Distribution of participants in the clinical group across types and degrees of hearing loss.

Degree of loss/ Type of loss	Mild	Moderate	Moderately Severe	Severe
Conductive	-	5	5	-
Sensorineural	5	10	10	5
Mixed	-	5	5	-

Results

The study measured the signal to noise ratio across sweeps at different intensities for clicks as well as 500 Hz tone bursts in individuals with normal hearing. Further, to validate the model, responses were assessed in different degrees of conductive and sensorineural hearing loss.

Clicks

The SNR, in general improved with the number of sweeps and with intensity (Figure 1). Shapiro-Wilk test indicated that the data distribution did not deviate significantly from normal distribution ($p > 0.05$). Repeated Measures ANOVA revealed that the main effect of number of sweeps ($F_{(4,26)} = 23.78$, $p < 0.001$, $\eta_p^2 = 0.86$) as well as Intensity was significant ($F_{(4,26)} = 23.78$, $p < 0.001$, $\eta_p^2 = 0.86$). The effect of intensity, however was not statistically significant ($F_{(2,28)} = 12.1$, $p < 0.001$, $\eta_p^2 = 0.57$). However, the interaction between number of sweeps and intensity was not significant ($F_{(8,22)} = 2.6$, $p = 0.066$) suggesting that the SNR variation across sweeps was similar at low, mid and high intensities. Pairwise analysis with Bonferroni correction revealed that the SNR (at all the three intensities tested) was significantly better with each of the increasing SNR intervals (Figure 1) ($p < 0.05$). The SNR was significantly better at 90 dB nHL than 70 and 30 dB nHL (90 Vs. 70: $p = 0.005$; 90 Vs 30: $p < 0.001$). The difference between SNR at the latter two intensities was not statistically significant (70 Vs. 30: $p = 0.057$).

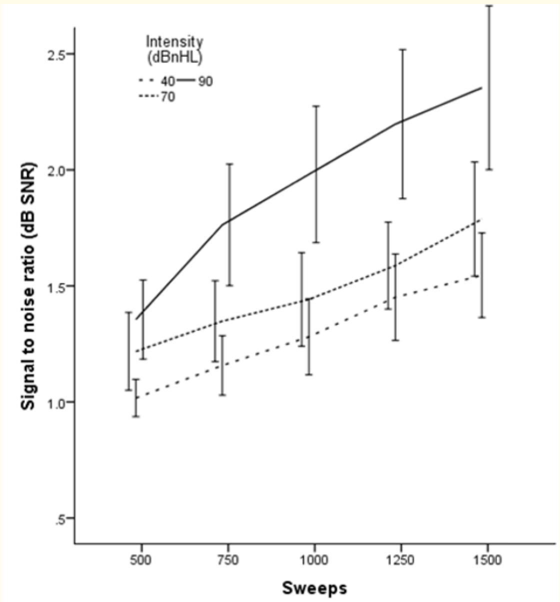

Figure 1: Variation of SNR across sweeps for clicks at 40, 70 and 90 dB nHL. Error bars represent ±2 SE.

500 Hz tone bursts

The variation of SNR across number of Sweeps and intensities was less clear-cut (Figure 2). The SNRs of 90 and 70 dB nHL largely overlapped across conditions. Also, though SNR tended to increase with number of sweeps, this jump was clear only in the earlier sweep interval of 500 to 750 sweeps. After this, the SNR was non-monotonic- especially at 70 and 90 dB nHL.

Like the click evoked ABRs, the data distribution of SNRs for tone burst ABR resembled a normal distribution based on Shapiro-Wilk test ($p > 0.05$). Repeated Measures ANOVA for 500 Hz tone burst evoked responses revealed that the main effect of number of sweeps ($F_{(4,26)} = 20.47$, $p < 0.001$, $\eta_p^2 = 0.84$) and that of intensity ($F_{(2,28)} = 27.4$, $p < 0.001$, $\eta_p^2 = 0.75$). The interaction between number of sweeps and intensity was not significant ($F_{(8, 22)} = 2.25$, $p = 0.1$).

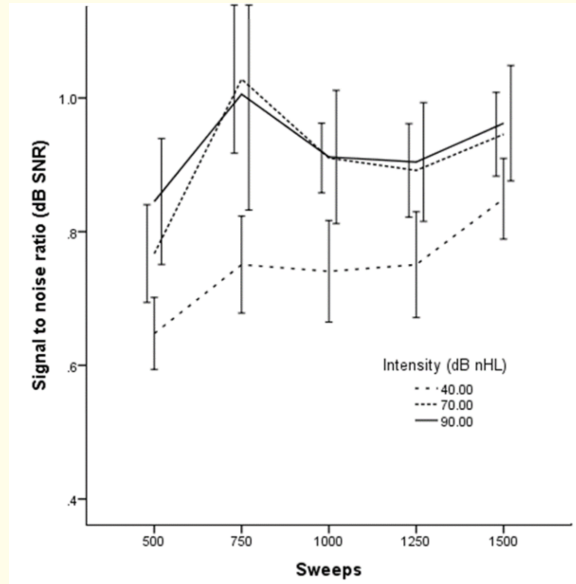

Figure 2: Variation of SNR across sweeps for 500 Hz tone bursts at 40, 70 and 90 dB nHL. Error bars represent ±2 SE.

Pairwise comparison across sweep conditions (with Bonferroni correction for multiple comparisons) - indicated that the SNR was significantly poorer at 500 sweeps than at any other higher sweep interval ($p < 0.05$). After this however, the differences between sweep conditions were not significantly different from one another ($p > 0.05$). Across Intensities, SNR at 40 dB nHL was significantly smaller than 70 and 90 dB nHL ($p > 0.05$), and the SNR between the latter two conditions were not significantly different ($p > 0.05$).

Predicting the number of sweeps required to achieve an SNR = 1

Polynomial regression was done to predict the best fit which determined that linear regression offered the most parsimonious model (higher order fits did not result in statistically significant ($p > 0.05$) increases in adjusted R^2). Linear regression was used to model SNR across sweeps at the three intensities (90, 70 and 40 dB nHL) for both the stimuli (Table 3). Based on these equations, the number of sweeps required to reach an SNR of 1 was predicted (Table 4). As it can be seen from Table 4, within 500 sweeps, the required SNR was achieved for all intensities for clicks. For the 500 Hz tone burst, at least 2000 sweeps were required to achieve the required SNR at the lowest intensity used in the study. So, the optimal number of sweeps that cover the entire intensity range was

Table 3: Linear Regression to predicting SNR change with number of sweeps for clicks and 500 Hz tone burst.

Stimulus/Intensity (dBnHL)	Clicks				500 Hz Tone burst			
	Constant	Slope	F	P value	Constant	Slope	F	P value
90	0.74	0.001	29.31	<0.001	0.78	0.00015	6.81	0.03
70	0.71	0.001	20.07	<0.001	0.72	0.00015	6.75	0.04
40	0.53	0.001	32.06	<0.001	0.64	0.00018	13.56	<0.001

Table 4: Estimated number of sweeps required to achieve an SNR of 1.

Stimulus/Intensity (dB nHL)	Clicks	500Hz tone burst
90	262	1467
70	295	1474
40	470	2000

found to be 500 sweeps for clicks and 2000 sweeps for 500 Hz tone burst.

Applicability of the model in clinical scenarios

The model was checked for validity in a sample of clinical group also. Experts identified and marked the responses at 500, 1500 and 2000 sweeps. The clinical group consisted of those with conductive, sensorineural, and mixed hearing loss of varying degrees (Table 2). The response was reliably present at 500 sweeps for clicks and at 2000 sweeps for tone bursts across different degrees of conductive and sensorineural hearing loss for clicks. The response typically remained absent at higher number of sweeps (1500 sweeps for clicks, and 3000 sweeps for 500 Hz tone burst) if the response was perceived to be absent at the recommended lower number of the sweeps (500 sweeps for clicks and 2000 sweeps for 500 Hz tone burst). Only in two cases (out of 20) with moderate sensorineural hearing loss, the response was absent for click stimulus at 70dB nHL for 500 sweeps, but present at 1000 sweeps. There were no discrepant results with 500 Hz tone burst ABR recordings.

Inter-rater reliability of the picked responses

Cohen's Kappa coefficient was administered to determine the magnitude of agreement between the two audiologist's judgment for the presence of V peak using the optimum number of sweeps (i.e., 500 sweeps for clicks and 2000 sweeps for 500 tone bursts) in 20 randomly chosen cases from the clinical group. The results revealed that there was an excellent agreement at each of the intensities i.e., 90 dB nHL ($\kappa = 0.893$, $p < .001$), 70 dB nHL ($\kappa = 0.871$, $p < .001$), and 40 dB nHL ($\kappa = 0.804$, $p < .001$).

Duration of ABR recording

The typical click ABR involves using 1500 sweeps presented at a rate of 30.1/sec, and takes around 50 seconds to complete. Using 500 sweeps as the default brings down this time to around 17 seconds. Similarly, around 100 seconds are required for the typical 3000 sweeps used for 500 Hz tone burst ABR. Limiting it to 2000 sweeps can reduce this time to 67 seconds. For threshold estimation, the best practice is to record the response two times to check for replications. The time gains made with lower number of sweeps double with replication, and further increase with the number of levels recorded.

Discussion

Effect of sweep number and intensity on the SNR of click and 500 Hz tone burst elicited ABRs

The general finding of the study was that the SNR improved with the number of sweeps at higher intensities for clicks as well as 500 Hz tone bursts. This has been a well-documented finding-especially for clicks [10,11,22]. Increasing the number of averages leads to attenuation of random aspects of the recorded response, the latter characteristic being primarily a characteristic of noise. The ABR, on the other hand has been shown to be largely constant across sweeps [22]. This combination of noise reduction and ABR preservation leads to a net improvement in signal to noise ratio. The effect of intensity on ABR amplitude is also well documented. At higher intensities, the ABR amplitude increases due to greater spread of excitation on the basilar membrane, and the consequent increase in neural activity [26].

Interestingly, we did not find an interaction between SNR variation across the number of sweeps and intensity- essentially meaning that the effect of increased number of sweeps on the SNR of ABR was independent of intensity. Elberling., *et al*. [12,22], on the other hand has shown that SNR improvement with increased sweeps is more appreciable at low intensities relative to high intensities. The difference in findings could be attributed to the differences in the SNR measurement procedure. The latter study used Fsp while in the current study, a version of standard deviation ratio procedure [24] was used to arrive at the SNR value. Relative to Fsp, this procedure is simpler to calculate and less computationally intensive. However, it is possible that the method is susceptible to increased variance as evidenced in this study. More research is necessary on which could be a preferable measure of SNR measurement.

Determination of optimal sweep number

Polynomial regression suggested that the fit beyond linear regression did not add significant value. So, linear regression was used to predict the sweep number at which SNR approached a value of 1 (Table 3). The required SNR was achieved for clicks, down to 40 dB HL at 500 sweeps. For 500 Hz tone bursts, 2000 sweeps were required to achieve the target SNR at 40 dB nHL. The traditional protocol, however, suggests around 1500 sweeps for clicks and anywhere between 2000-8000 sweeps for low frequency tone-bursts [27]. The traditional recommendation, based on clinical experience works well, but may ends up taking more time relative to the objectively determined required sweep number in this study (50 seconds relative to 17 seconds for clicks and more than 90 seconds relative to 67 seconds for 500 Hz tone burst). This is especially the case if more replications are necessary to confirm the response. Further, we found excellent inter-rater reliability for peak detection at the determined optimal number of sweeps.

Validation in the clinical group

The sweep number determined was also validated with a heterogenous clinical group, and was determined to be suitable. There were just two cases (out of 50) in which ABR was marked as absent at the optimized sweep number, but was marked present at a higher sweep number.

Limitations of the study

The model is based on ABR recording in co-operative young adults with normal hearing sensitivity. The recording conditions were controlled and ideal, with good impedances, negligible subject movement, and low electrical noise. However, the actual clinical conditions can be less ideal. For example, it can be a case of a partially awake and moving infant with relatively poor electrode impedance and high electrical interference. It is possible that when noise is higher, the model would need to be re-adjusted to reflect the greater time required. More research is also needed in different population (infants and children) to update the model to reflect the more commonly encountered clinical scenarios.

Conclusion

The optimized sweep number could be used to guide relatively inexperienced clinicians on the minimum sweep number required for each stimulus condition. Once this threshold sweep number is reached, visual detection as well as SNR could be used as a guide to predict response presence. If an obvious response is present, and a good SNR is present, averaging can be terminated. However, if the response is not obvious, recording can be continued till the residual noise falls below a set level like 0.08 μV [20,24].

Conflict of Interest

Authors have no financial conflict of interest.

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