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Evaluating Stimulus Efficacy In Auditory Brainstem Response Testing For Threshold Estimation: A Systematic Review

Amna Awais[1], Nukhbat Ullah Awan[2]*, Rabia Zulfiqar[3], Uzma Malik[4]*, Ayesha Aslam[5], Anum Nasrullah[6], Syeda Hamda[7]

[1] King Edward Medical University/Mayo Hospital, Lahore, Pakistan
[2*]Associate Professor, ENT department, King Edward Medical University/Mayo Hospital, Lahore, Pakistan
[3]Oral & Maxillofacial Surgery Department, King Edward Medical University/Mayo Hospital, Lahore, Pakistan
[4*]Associate Professor, Medicine, King Edward Medical University/Mayo Hospital, Lahore, Pakistan
[5]Associate Professor, Department of Neurology, King Edward Medical University/Mayo Hospital, Lahore, Pakistan
[6]Clinical Audiologists, King Edward Medical University/Mayo Hospital, Lahore, Pakistan
[7] King Edward Medical University/Mayo Hospital, Lahore, Pakistan

***Corresponding Authors:** Nukhbat Ullah Awan, Uzma Malik
[*]Associate Professor, ENT department, King Edward Medical University/Mayo Hospital, Lahore, Pakistan
[*]Associate Professor, Medicine, King Edward Medical University/Mayo Hospital, Lahore, Pakistan

ABSTRACT
Accurate threshold estimation using Auditory Brainstem Response (ABR) is crucial in clinical audiology. This systematic review evaluates various stimulus types for their effectiveness in generating reliable ABR wave V amplitudes, focusing on Chirp stimuli compared to Click and Tone Burst stimuli. To determine which stimulus type—Chirp (Broadband CE Chirp, LS Chirp, Narrowband Chirp), Click, or Tone Burst—provides the most reliable threshold estimation for different intensity levels. A comprehensive review of studies comparing ABR results across different stimulus types was conducted. Emphasis was placed on wave V amplitude reliability, particularly at low intensities (below 60 dB nHL) and high intensities (80 dB nHL and above). Chirp stimuli consistently generated larger wave V amplitudes compared to Clicks, especially at lower intensities. The Broadband CE Chirp and Narrowband Chirp were notably effective in producing larger amplitudes and improving threshold estimation accuracy. Although Chirp stimuli showed reduced effectiveness at higher intensities, they still outperformed Clicks and Tone Bursts in overall amplitude and reliability. Narrowband Chirp was particularly effective for frequency-specific threshold estimation. Some studies indicated a decrease in Chirp amplitude at high intensities, potentially due to the upward spread of excitation. Chirp stimuli, including Broadband CE Chirp, LS Chirp, and Narrowband Chirp, are generally superior to Click stimuli for reliable ABR threshold estimation, particularly at lower intensities. While Chirp stimuli offer robust and consistent results, further research is needed to address their effectiveness at higher intensities and to establish normative data across various populations to refine clinical practices.

Keywords: Auditory brainstem response, threshold estimation, amplitude, wave V, intensity

INTRODUCTION

The World Health Organization (W.H.O) estimates that approximately 466 million people globally have disabling hearing loss, with 34 million of these being children (1). In developing countries, the prevalence of permanent hearing loss in newborns ranges from 3 to 6 per 1000, while in developed countries, it is between 1 and 3 per 1000 (2). Hearing is crucial for child development, as it facilitates integration into a society where oral communication is key. Hearing disorders can delay cognitive, intellectual, cultural, and social development (3). Regardless of severity, undiagnosed hearing loss can impede speech and language development in children (4). Therefore, early detection of hearing loss is essential to promote normal language and social development.

Auditory Brainstem Response (ABR) is a non-invasive method for hearing assessment that does not require behavioral responses from the individual. It is particularly useful for testing individuals who are challenging to assess through subjective methods. The primary goal of ABR is to enable early identification and intervention for hearing loss, especially within the critical period of language development. ABR measures electrical potentials generated in the brainstem in response to auditory stimuli (5). The resulting waveform includes seven distinct waves, each originating from different sites in the brainstem, with Waves I, III, and V being especially significant. Wave V is the most robust and reproducible, making it crucial for accurate hearing assessments (6). Each wave reflects the functionality of the specific brainstem site it originates from, and abnormalities in these waves can indicate pathologies (7). Accurate threshold estimation and clear Wave V morphology are essential for reliable ABR interpretation. However, determining the optimal stimulus parameters for achieving these objectives remains an area of ongoing research.

ABR testing involves setting various parameters, including stimulus type, stimulus polarity, filter settings, and stimulus rate. Different parameters can yield varying results, making the choice of stimulus type particularly important. Chirp, Click-evoked, and Tone Burst stimuli each produce different waveforms. In click-evoked ABR, the sound wave reaches its peak at the basal region of the cochlea later than at the high-frequency region, resulting in a delay in the emergence of the low-frequency response (8). Since the basal cells are not uniformly stimulated, nerve cells cannot depolarize simultaneously. This phenomenon is known as cochlear travel delay or cochlear delay, referring to the time it takes for sound waves to travel through the cochlea (8, 9).

Although the Joint Committee on Infant Hearing (JCIH) recommends using tone burst stimuli for ABR testing, suggesting that clinicians use air-conduction tone bursts to record ABR and, if thresholds are elevated, switch to bone-conduction tone bursts to differentiate between sensory, conductive, and mixed hearing losses and to assess the configuration of hearing loss in each ear (10), many clinicians remain reluctant to adopt tone burst stimuli. A common issue cited is the difficulty in identifying Wave V, especially when using low-frequency stimuli (11).

The Chirp stimulus is a relatively new addition to ABR evaluation methods (12). It comes in two main forms: the broad-band Click-stimulus derivative, CE-Chirp, and the frequency-specific narrow-band CE (NB-CE) Chirp. Recently, a Level Specific (LS) Chirp stimulus has also been developed (13). While Click and CE-Chirp stimuli share the same frequency spectrum, CE-Chirp is designed to provide synchronous stimulation across the cochlea by simultaneously delivering low, medium, and high-frequency components, allowing for simultaneous depolarization of all frequency regions (12, 13). This simultaneous stimulation with the CE-Chirp stimulus results in larger amplitude ABR waves than Click stimuli (14, 15).

Despite their significance, there is no consensus on the optimal stimulus type for ABR testing. A systematic review is necessary to synthesize evidence on different stimulus types' effectiveness for ABR testing. This review aims to compare the performance of various stimuli—such as Click, Tone Burst, and Chirp—in accurately determining hearing thresholds and producing clear Wave V morphology. It will identify gaps in current research and suggest areas for future investigation, providing evidence-based recommendations for clinicians and researchers. The review will use a comprehensive search strategy, strict inclusion/exclusion criteria, and a transparent analysis process to ensure a high-quality evidence synthesis.

METHODOLOGY:

This review adheres to PRISMA guidelines, which outline the preferred reporting items for systematic reviews and meta-analyses. We included peer-reviewed studies that used Auditory Brainstem Response (ABR) testing with various stimuli to estimate hearing thresholds across a broad population, from infants to early middle-aged individuals. Only full-text articles were considered to ensure comprehensive data collection on key parameters, including stimulus type, stimulus rate, stimulus polarity, and filter settings (high-pass and low-pass). Detailed inclusion and exclusion criteria based on the PICOS framework are provided in Table 1.

Search Strategy:

We searched PUBMED, GOOGLE SCHOLAR, and the Cochrane Library to find relevant studies. Keywords used were 'Auditory Brainstem Response,' 'Click,' 'Tone Burst,' and 'Chirp.' The search was performed on July 10, 2024. We screened titles and abstracts and then reviewed full-text articles to ensure they met the inclusion and exclusion criteria. Two reviewers independently searched the databases. The initial search yielded 4,983 studies. After removing duplicates, 3,801 articles were left. Title screening excluded 3,571 articles, and a further review of 230 abstracts resulted in 195 exclusions. Finally, 35 full-text articles were reviewed and assessed for eligibility by both reviewers, resulting in 13 articles that met the inclusion criteria (Figure 1).

Table 1: PICOS Framework to define inclusion and exclusion criteria of the study

Criteria	Inclusion Criteria	Exclusion Criteria
Population	Newborn to Adults (mid-forties) Normal-hearing individuals and those with mild to profound degree hearing loss	Populations outside newborn to Adults (mid-forties) range Populations with conditions significantly affecting ABR (Auditory neuropathy, neurological and developmental disorders, mental and physical disorders)
Intervention	Studies using Auditory Brainstem Response testing Studies exploring different stimuli in ABR	Studies not using ABR testing Studies not using or exploring different stimuli in ABR
Comparison	Studies comparing different stimuli for hearing threshold estimation Focus on wave V morphology or amplitude	Studies not comparing different stimuli in ABR Studies not reporting on wave V morphology or amplitude

Outcome	Morphology and amplitude response of wave V in ABR Accuracy of threshold estimation based on different stimuli	Studies not assessing or reporting wave V morphology or amplitude response Studies not providing any data on threshold estimation
Studies Design	Experimental, observational, or any design that allows for comparison of different stimuli in ABR testing	Non-original research (e.g., reviews, commentaries) Studies without sufficient methodological detail

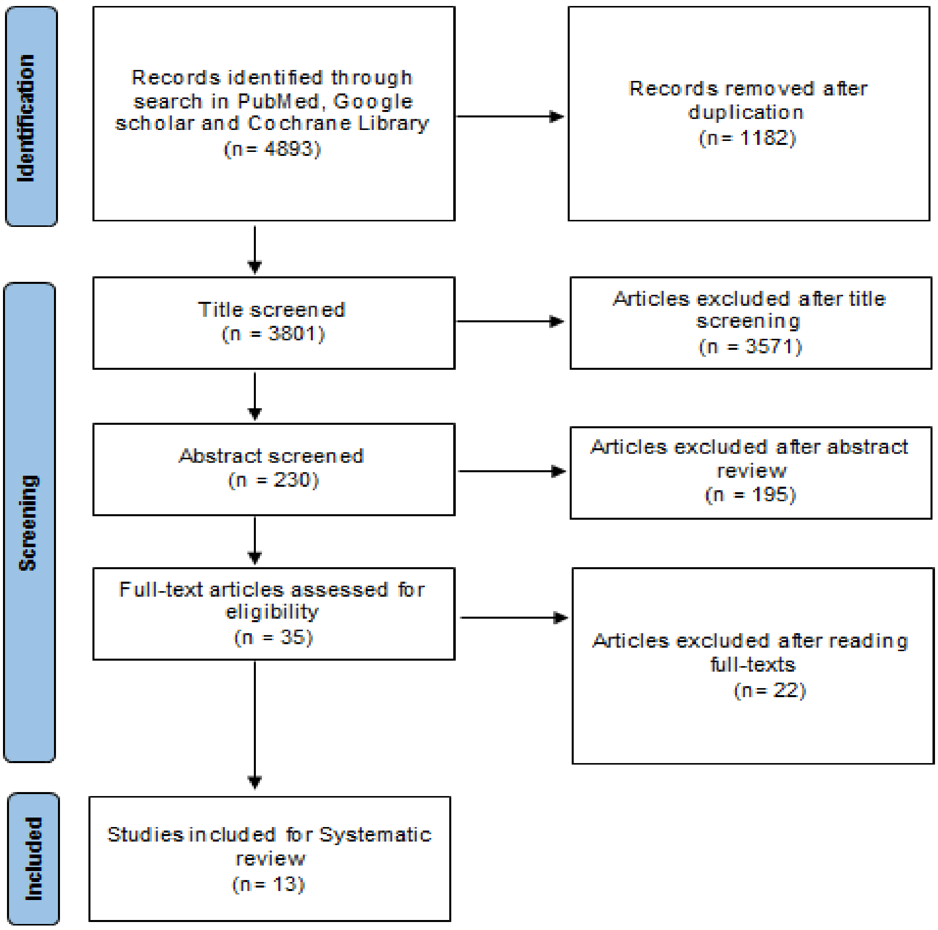

Figure 1: PRISMA flow diagram to summarize the selection procedure for this study

RESULTS:

The sample sizes across the studies in this review ranged from 10 to 100 participants. The parameters used in the studies are detailed in Table 2. Most studies employed alternating polarity and utilized the Interacoustics Eclipse system. The findings from these studies are summarized in Table 3. Most studies (12, 16-23) indicate that Chirp stimuli are more effective for threshold estimation than Click stimuli. Chirp stimuli reduce test duration and produce larger Wave V amplitudes. Specifically, Chirp stimuli are more effective in detecting Wave V in infants, children, and adults with normal hearing, sensorineural hearing loss (SNHL), and unilateral hearing loss, especially at lower intensities, yielding amplitudes that are approximately twice as large as those obtained with Click stimuli.

Chirp stimuli also provide more reliable detection of Wave V than Click stimuli. However, when comparing tone burst ABR with NB Chirp ABR in two of the studies, NB Chirp wave V responses were greater in amplitude (24, 25). However, some studies (18, 23, 26) suggest that click stimuli perform better at high-intensity levels when detecting ABR waves than chirp stimuli, as summarized in Table 4. For instance, NB Chirp generates shorter ABR latencies than tone burst (TB) ABR and produces higher ABR amplitudes except at high levels (80 dB nHL), where TB stimuli result in greater amplitudes (25). Additionally, NB Chirp has been identified as a more effective clinical tool for identifying damage at higher auditory system levels compared to tone bursts at 500 Hz (27).

Table 2: Auditory Brainstem Response Test Parameters used in the studies

Study	***ABR System***	***Stimulus Type***	***Rate***	***Polarity***	***Filter settings***
Attar et al. 2018	Interacoustics Eclipse EP 25	Click Chirp	Click = 21.1/sec Chirp = 44/sec, 35/sec	Alternating	150-3000 Hz
Cargnelutti et al. 2017	Interacoustics Eclipse EP 25	Click LS Chirp	17.1/sec	Alternating	100-3000 Hz
Ceylan et al. 2023	Interacoustics Eclipse EP 15	Click Chirp	20.1/sec	Alternating	100-3000 Hz
Dzulkarnain et al. 2022	Interacoustics Eclipse EP 25	Click LS Chirp	33.1/sec	Alternating	100-3000 Hz
Galhoum et al. 2022	Oto-Access (Eclipse 25)	Click Broadband Chirp	19.3/sec	Alternating	100-3000 Hz
Hoda et al. 2019	Interacoustics Eclipse EP 25	Click Chirp	Click = 21.1/sec Chirp = 44/sec, 35/sec	Alternating	150-3000 Hz
Megha et al. 2019	Interacoustics Eclipse EP 25	NB Chirp Tone Burst	11.1/sec	Not Reported	100-3000 Hz
Pani et al. 2020	Not Reported	Click Chirp	11.4/sec, 20/sec, 27.1/sec, 27.7/sec, 33.1/sec, 44.1/sec	Alternating	100-3000 Hz
Talaat et al. 2019	Interacoustics Eclipse EP 25	NB Chirp Tone Burst	19.1/sec	Alternating	Not Reported
Elberling et al. 2008	Interacoustics Eclipse EP 25	Click Chirp	27/sec	Rarefaction	100-3000 Hz
Keesling et al. 2017	Smart EP Platform	Click iChirp	19.3/sec	Rarefaction	100-3000 Hz
Rodrigues et al. 2013	Interacoustics Eclipse EP 25	NB Chirp Tone Burst	27.1/sec	Alternating	100-1500 Hz
Rodrigues et al. 2012	Interacoustics Eclipse EP 25	Click Chirp	27.1/sec	Alternating	100-3000 Hz

Table 3: Summary of the studies included in the systematic review

Study	***Sample Size***	***Age Group***	***Patient Characteristics***	***Hearing Assessments***	***Findings***
Attar et al. 2018	90 (C=30, E=60)	6-12 Years	C=Normal peripheral hearing B/L E= Moderate and Severe degree SNHL	Tympanometry, Pure Tone Audiometry, Speech Audiometry, ABR	Chirp is more effective for threshold estimation than Click. It reduces test time and gives a larger wave V amplitude. Click stimulus is better at high-intensity levels for detecting waves I and III and is a better indicator of brainstem transmission time.
Cargnelutti et al. 2017	30 (M=12, F=18)	12-42 Years	Normal hearing B/L	Pure Tone Audiometry, ABR	LS Chirp is as efficient as Click in obtaining waves I, III, and V at high stimulation levels. Wave V has a greater amplitude than that of Click ABR.
Ceylan et al. 2023	71 (M=71, F=0)	18-25 Years	Unilateral Hearing Loss (total hearing loss in one ear and normal hearing in the other)	Tympanometry, Stenger Test, Pure Tone Audiometry, ABR	Chirp ABR thresholds are closer to PTA thresholds than Click ABR in normal and unilateral hearing losses. It takes a shorter test time than a click. It is more appropriate than click stimuli for unilateral hearing loss cases.
Dzulkarnain et al. 2022	12	23-25 Years	Normal hearing B/L	Tympanometry, Pure Tone	In all conditions, no time-saving was observed when ABR with LS Chirp over

				Audiometry, ABR	Click stimuli was performed. LS Chirp produced higher amplitudes of waves I and V.
Galhoum et al. 2022	100 (C=50, E=50)	18-25 Years	C=Normal hearing B/L E=Mild to Profound degree SNHL	Tympanometry, Pure Tone Audiometry, Speech Audiometry, BBC-ABR	BB Chirp gives an accurate, objective estimation of the hearing threshold. It showed the highest correlation with a 0.5kH-4kHz pure tone average threshold compared to that of Click (2-4kHZ).
Hoda et al. 2019	90 (C=30, E=60)	6-12 Years	C=Normal hearing B/L E=Moderate to Severe degree SNHL	Tympanometry, Pure Tone Audiometry, ABR	Chirp stimuli are more effective in detecting wave V in children with SNHL than click stimuli, especially at lower intensities.
Megha et al. 2019	40 (M=40, F=0) (C=20, E=20)		C=Not exposed to occupational Noise E=Exposed to Noise 80dB(A) more than 8 hours/day for 3 years minimum	Tympanometry, DPOAEs, Pure Tone Audiometry, ABR	NB Chirp is a better clinical tool for identifying damage at a higher level of the auditory system than in a tone burst at 500 Hz.
Pani et al. 2020	30 (M=15, F=15)	18-25 Years	Normal hearing B/L	Tympanometry, Pure Tone Audiometry, Speech Audiometry, ABR	Chirp gives two times larger amplitude than click ABR. It reduces the test time and can detect wave V more confidently than Click ABR.
Talaat et al. 2019	100	8-12 Years	Normal middle ear function, Normal hearing B/L to Profound degree SNHL	Tympanometry, Pure Tone Audiometry, ABR	Chirp is more sensitive and accurate than TB ABR for frequency-specific thresholds in young children. It takes less time and has larger responses.
Elberling et al. 2008	10 (M=5, F=5)	24-42 Years	Normal hearing B/L	Pure Tone Audiometry, ABR	Chirp generates a higher response amplitude than click. The gain in amplitude is lower at 60 dB nHL than at 50 dB nHL.
Keesling et al. 2017	43 (M=8, F=35)	18-29 Years	Normal hearing B/L	Pure Tone Audiometry, DPOAE, ABR	Broadband click produces more reliable latencies and significantly larger amplitudes for all ABR waveforms than chirp at high-intensity levels. For retro cochlear evaluations of the auditory pathway, click stimuli should be continuously used as a standard for ABR neurodiagnostic testing.
Rodrigues et al. 2013	40	1-3 Months	Normal hearing B/L	TEOAE, ABR	NB Chirp generates shorter ABR latencies than TB ABR. It generates higher ABR amplitudes, except at high levels (80dBnHL), when TB stimuli amplitudes are greater.
Rodrigues et al. 2012	12 (M=6, F=6)	21-30 Years	Normal hearing B/L	Tympanometry, Pure Tone Audiometry, ABR	Chirp has shorter latencies than observed, with clicks at high-intensity levels. It showed larger amplitudes than with clicks, except at 80dBnHL.

DISCUSSION

The purpose of the systematic review was to determine which type of stimulus should be used for threshold estimation of individuals. The results from the present systematic review indicate that the Chirp stimulus in its various forms (i.e., Broadband CE Chirp, LS (level specific) Chirp, and Narrowband Chirp) works best for generating greater amplitudes of wave V for reliable threshold estimation, especially at low intensities (lower than 60 dB nHL). While Clicks offer broad-spectrum stimuli, they might be less specific in frequency analysis. In most of our included studies (10, 14-21), Chirp stimuli have dominated with larger amplitudes of wave V than those obtained using click stimuli. They all clearly state that a significant difference was seen in the magnitude of amplitudes of wave V obtained from both stimuli. Stuart and Cobb compared the results of ABR tests with CE-Chirp and Click stimuli in 23 newborns at 30 dB nHL, and their findings showed that larger wave V amplitudes were obtained with the CE-Chirp stimulus. Although the frequency spectrums of click and CE-Chirp stimuli are the same, CE-Chirp can provide synchronous stimulation in the cochlea (12, 13)(5, 6). The difference between the CE chirp stimulus from the click stimulus is the occurrence of delivery of low, medium, and high-

frequency components to stimulate all frequency regions in the cochlea simultaneously basal cells can achieve different frequency targets using CE-Chirp stimulus (23).
Larger amplitude ABR waves are obtained by simultaneous depolarization in all frequency regions of the cochlea by CE-Chirp stimulus (14, 15). This synchronous stimulation in the cochlea due to CE-Chirp usage reduces the overall time of ABR testing. Attar, Ceylan, Pani, and Talaat concluded in their studies that the test time using Chirp stimuli was significantly smaller than ABR testing done using Click stimuli (16, 18, 22, 24). Some studies from our SR have suggested that chirp amplitudes decrease at high intensity (i.e., 80 dB nHL) (12, 18, 23, 25, 26). Table 3 demonstrates the comparison of wave V amplitudes at lower intensities and higher intensities from our review. Keesling suggests that for high-intensity stimulation, the low-frequency component of the chirp interferes with basal cochlear regions and impedes afferent neural synchrony, resulting in compromised ABRS. Some authors speculate that the upward spread of excitation could be responsible for this observation because, at low levels, each frequency component of a chirp excites a restricted location in the cochlea, but for higher levels, the excitation broadens, resulting in reduced amplitude response (23, 28, 29). As far as Tone burst stimulation is concerned, it is a frequency-specific stimulus. A major problem that remains with the clinical use of tone burst today is the interpretation of the waveforms (25). Some studies have compared the ABR results obtained from tone burst stimuli and Narrow-band chirp stimuli. Studies have suggested that NB chirp stimulus generates higher ABR amplitudes than tone burst stimuli. The contrast in studies exists as Rodrigues suggest that at higher levels of intensity (i.e., 80 dB nHL), tone burst amplitudes dominate, while Talaat demonstrated that even at 90 dB nHL stimulation, NB Chirp amplitudes were greater than tone burst amplitudes (24, 25). For threshold estimation, a greater wave V amplitude that makes interpretation easier is required. Studies in the review suggest that Chirp stimuli are the recommended stimulus for ABR in different populations. Broadband CE Chirp outweighs click significantly with its greater amplitude; however, at high intensities, more studies are required for enough evidence to prove that click should be the preferred choice of stimulus at higher intensities. Moreover, for frequency specific threshold estimation, which is the most correlated to Pure tone behavioral thresholds, NB chirp is the preferred choice of stimulus that will provide easier interpretation of wave V across all frequencies tested. However, more studies are required for normative data using different types of chirp stimuli in normal-hearing individuals and those with different disorders.

Table 4: Literature comparison of Click, Chirp, and Tone Burst stimulation at different intensity levels for wave V amplitude of ABR

Study	*Wave V amplitude larger for low intensities (<60 dB nHL)*	*Wave V amplitude larger for high intensities (>=60 dB nHL)*
Attar et al. 2018	Chirp	Chirp
Cargnelutti et al. 2017	----	LS Chirp
Ceylan et al. 2023	Chirp	Click
Dzulkarnain et al. 2022	LS Chirp	LS Chirp
Galhoum et al. 2022	----	----
Hoda et al. 2019	Chirp	Chirp
Megha et al. 2019	----	TB/NB Chirp
Pani et al. 2020	----	Chirp
Talaat et al. 2019	----	Chirp
Elberling et al. 2008	Chirp	Click
Keesling et al. 2017	----	Click
Rodrigues et al. 2013	Chirp	Click
Rodrigues et al. 2012	NB Chirp	Tone Burst

CONCLUSION

This systematic review underscores that Chirp stimuli, including Broadband CE Chirp, LS Chirp, and Narrowband Chirp, are superior to Click stimuli for reliable ABR threshold estimation, particularly at lower intensities (below 60 dB nHL), due to their ability to stimulate multiple cochlear regions simultaneously and produce larger wave V amplitudes. Despite some evidence suggesting reduced effectiveness at higher intensities, Chirp stimuli generally offer more robust and consistent results compared to Clicks and tone bursts. Narrowband Chirp, in particular, is favored for frequency-specific threshold estimation. Further research is needed to refine using Chirp stimuli at high intensities and across different populations to optimize clinical practices.

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