Auditory Electrophysiological Thresholds With Different Chirps and Their Correlation With Behavioral Thresholds in Hearing-Impaired Children

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Objectives: Research focusing on changes in the clinical practice of audiological diagnosis has become increasingly necessary, particularly in pediatric audiology. The pursuit of accurate and reliable examinations has intensified given the importance of early detection and intervention in cases of childhood hearing loss. Thus, this study aims to investigate the correlation between electrophysiological auditory thresholds, as obtained through frequency-specific auditory brainstem responses with two distinct chirp stimuli (narrow-band CE-Chirp Level Specific and narrow-band iChirp), in children with hearing impairments. In addition, this research set out to correlate these thresholds with behavioral responses while simultaneously comparing the examination durations relative to the type of stimuli and the degree of hearing loss.

Design: A cohort of 20 children (aged 6 months to 12 years) with varying degrees of hearing impairment (ranging from mild to profound) were recruited. The participants underwent bilateral measurement of their electrophysiological thresholds via auditory brainstem responses across different frequencies (500, 1000, 2000, and 4000 Hz), and the timeframe for determining these thresholds was carefully recorded. Subsequently, behavioral thresholds were ascertained using pure-tone audiometry or visual reinforcement audiometry based on the child's age. The data collected was subsequently analyzed using Pearson and Spearman correlation coefficients. To compare examination times, the Student *t* test and the Kruskal–Wallis test were used.

Results: There was a pronounced correlation between the thresholds obtained through both narrow-band chirp stimuli. Moreover, a substantial correlation was found between electrophysiological and behavioral thresholds at 1000, 2000, and 4000 Hz, especially when compared with pure-tone audiometry. The mean differences between the electrophysiological and behavioral thresholds were below 6 dB nHL, and the exam duration was relatively consistent across both devices, averaging 47.63 (±19.41) min for the narrow-band CE-Chirp Level Specific and 52.42 (±26) min for the narrow-band iChirp. Notably, variations in exam duration did not relate to varying degrees of hearing loss when using the narrow-band CE-Chirp Level Specific. Nevertheless, the narrow-band iChirp indicated significantly shorter durations in instances of profound degree measurements, demonstrating a statistically significant difference.

Conclusions: The narrow-band CE-Chirp Level Specific and narrow-band iChirp stimuli provided similar estimates of electrophysiological auditory thresholds in children with hearing impairments, giving accurate estimations of behavioral thresholds. The time it took to complete the assessment is comparable between both stimuli. For the narrow-band iChirp, the degree of hearing loss was shown to impact the testing time, and children with profound hearing loss underwent faster exams. Ultimately, this study exhibits significant clinical implications as it reveals that the narrow-band CE-Chirp Level Specific and narrow-band iChirp stimuli could be remarkably promising for clinically exploring electrophysiological thresholds in children with hearing impairments.

Key words: Audiometry, Auditory brainstem response, Child, Electrophysiology, Hearing loss.

(Ear & Hearing 2024;XX;00–00)

INTRODUCTION

Accurately determining frequency-specific auditory thresholds is critical for pediatric audiologists, enabling the appropriate programming of hearing devices (McCreery et al. 2015; Norrix & Velenovsky 2017). Early intervention with this demographic is crucial, serving as the most effective approach to facilitating optimal linguistic development (Joint Committee on Infant Hearing 2019). According to the latest guidelines from the Joint Committee on Infant Hearing (2019), auditory diagnoses are recommended to occur within a child's first 2 months of life, with intervention initiated by the third month.

Widely recognized as the gold-standard method for identifying auditory thresholds in infants, auditory brainstem response (ABR) tests—which incorporate frequency specificity—are recommended by a number of established bodies and researchers (British Society of Audiology 2013; Joint Committee on Infant Hearing 2019; Eder et al. 2020; Sininger et al. 2020; Hatton et al. 2022). Nonetheless, in pediatric audiological diagnosis, cross-verification of results from both electrophysiological and behavioral processes remains a highly recommended practice (American Speech-Language-Hearing Association 2013; Norrix & Velenovsky 2017; Joint Committee on Infant Hearing 2019; Hatton et al. 2022). At present, the tone burst stimulus is typically the recommended stimulus applied in most protocols for determining electrophysiological thresholds (Joint Committee on Infant Hearing 2019; Hatton et al. 2022).

However, there is an emergent need for more reliable and accurate methods to ascertain hearing thresholds in the pediatric population (Norrix & Velenovsky 2017). This necessity arises from the potential risk that incorrect estimates could result in sub-optimal or excessive amplification, thereby adversely impacting the hearing-impaired child's auditory rehabilitation process (McCreery et al. 2015). The challenges in utilizing the tone burst stimuli for identifying wave V, particularly at low frequencies, align with the difficulties previously described in the literature (Rodrigues et al. 2013). In fact, the Joint Committee on Infant Hearing (2019) acknowledged the importance of further research on the efficacy of alternative protocols aside from tone burst stimuli to accurately and efficiently assess auditory thresholds across varied age demographics and different types and severities of hearing loss (HL). Given this context, there is

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<zdoi; 10.1097/AUD.0000000000001511>

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an evident gap in the literature regarding integrating alternative stimuli into pediatric assessment protocols, particularly chirp stimuli, thus highlighting the need for research that includes different age ranges and types and degrees of HL.

In recent years, the chirp stimulus has attracted considerable interest from researchers. Despite being studied for over 25 years (Don et al. 1994; Dau et al. 2000; Fobel & Dau 2004; Elberling et al. 2007), its potential for estimating electrically evoked auditory thresholds—those that closely match behavioral thresholds—due to its unique stimulation characteristics, is still a subject of research (Bargen 2015; Pinto et al. 2022). The chirp stimulus was engineered to compensate for the temporal delay of sound waves across different frequency regions of the basilar membrane. It considers the slower propagation of low frequencies to their respective receptive regions within the cochlea, followed by higher frequencies (Don et al. 2009; Elberling et al. 2010).

This innovative design allows for simultaneous depolarization of nerve endings, amplifying the electrophysiological responses recorded during auditory evoked potential measurements (Don et al. 2009; Elberling et al. 2010). Improvements in amplitudes, signal to noise ratios, and wave morphologies significantly contribute to acquiring responses at diminished intensities, thereby resulting in more accurate behavioral thresholds (Maloff & Hood 2014; Bargen 2015; Pinto et al. 2022).

Chirp stimuli can be classified into two principal categories: broadband chirps, which act as an alternative to conventional clicks, and narrow-band (NB) chirps, which are used to isolate frequency-specific responses as alternatives to tone bursts (Joint Committee on Infant Hearing 2019). Moreover, several companies have developed proprietary variations of chirp stimuli, subsequently branding these variations uniquely (Keesling et al. 2017). In this context, this study sought to investigate two distinct types of NB chirp stimuli: the NB CE-Chirp Level Specific (NB CE-Chirp LS) and the NB iChirp.

The CE-Chirp technology was originally patented by Elberling et al. (2007) in mid-2007; it is available in the Eclipse equipment, which is currently manufactured by Interacoustics. The NB CE-Chirp LS, a variant of the CE-Chirp, incorporates a filtering mechanism and is differentiated by specific central frequencies at 500, 1000, 2000, and 4000 Hz (Elberling et al. 2007). Furthermore, this variation features stimulus durations that adjust based on the stimulation level, as indicated by the “LS” (i.e., level specific). The NB iChirp is manufactured by Intelligent Hearing Systems and is used on the SmartEP platform (Delgado & Savio 2014). Inspired by the Boer model (Boer 1991), which achieves remarkable frequency selectivity in the cochlea, the NB iChirp encompasses an audible frequency range spanning more than nine octaves.

Understanding the unique characteristics of different chirp designs and their potential interference with cochlear stimulation is imperative. This understanding is essential for audiologists striving to improve their comprehension of response acquisition (Keesling et al. 2017; Rosa et al. 2018). Through such knowledge, audiologists can effectively interpret and apply auditory stimuli in their practice, enhancing the accuracy of auditory diagnostics and interventions.

Studies have shown a positive correlation between tone ABRs and behavioral thresholds (Gorga et al. 2006; Vander Werff et al. 2009; McCreery et al. 2015). Nonetheless, there is a notable lack of research on applying frequency-specific chirp stimuli in hearing-impaired children (Norrix & Velenovsky 2017; Pinto et al. 2022). This study is significant as it aims to enhance diagnostic methods for pediatric populations by examining the correlations between frequency-specific chirp stimuli and behavioral thresholds, thus potentially enabling the identification of more precise response patterns.

Reducing test duration when implementing protocols that utilize chirp stimuli is pivotal to providing a clearer clinical advantage over the tone burst stimulus (Joint Committee on Infant Hearing 2019), since shortening the diagnostic process could provide significant benefits, especially since these tests often take place during natural sleep and thus, demand brevity.

Given the earlier, this study sought to evaluate the correlation between chirp-evoked electrophysiological thresholds and behavioral thresholds in children with hearing impairment. Furthermore, it aimed to compare the duration of examinations according to the type of stimulus used and the degree of HL.

MATERIALS AND METHODS

Ethical Precepts

This observational, cross-sectional, and quantitative study was approved by the Research Ethics Committee of the originating institution (CAAE no. 04889018.1.0000.5346), adhering to all ethical standards regarding research with human subjects. Informed consent was obtained in writing from the caregivers of all participating children.

Participants

Twenty children (aged 6 months to 12 years) diagnosed with HL were recruited from two auditory rehabilitation centers of the Brazilian Unified Health System located in several cities of Rio Grande do Sul State (roughly 269.6 km apart). As components of the Unified Health System, these services adhere to uniform operational guidelines and follow an identical protocol for child audiological assessment (Brasil 2020; Secretaria Estadual da Saúde do Rio Grande do Sul 2020). This ensures that children can be combined into a cohesive sample despite receiving audiological diagnoses at different facilities.

All participants received auditory rehabilitation services from two providers and were selected through convenience sampling. The reduction in the number of child participants can be attributed to the onset of data collection in 2020, which coincided with the Corona Virus Disease (COVID-19) pandemic. As a result, several families withdrew from the study. Despite not being major centers, the centers catered to a limited number of children with HL, especially within this study’s age range of interest.

The sample comprised 12 female and 8 male participants (mean age 7.38 [±4.98] years). Notably, 10 participants (47.62%) presented with one or more risk indicators for HL. The most common risk indicator was a family history of permanent HL, followed by admission to neonatal intensive care for >5 days, the use of ototoxic medication, and extracorporeal membrane oxygenation treatment.

Each child had been previously diagnosed with mild to profound bilateral sensorineural HL (Clark 1981), and those with auditory neuropathy spectrum disorder or conductive HL were excluded. Additional tests to exclude these conditions were not conducted as all participants had a confirmed diagnosis of sensorineural HL. Similarly, children with neurological disorders and/or associated comorbidities were not included. The mean

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thresholds (±SD) for frequencies of 500, 1000, 2000, and 4000 Hz were 74.30 dBHL (±24.57) in the right ear and 75.67 dBHL (±24.33) in the left ear.

Figure 1 provides a detailed description of the participants' audiometric profiles, including the auditory thresholds for both ears at the selected frequencies. Notably, 500 and 2000 Hz were analyzed for participants 1, 4, 7, 8, 9, 11, 13, 14, 17, and 19, whereas 1000 and 4000 Hz were assessed for participants 2, 3, 5, 6, 10, 12, 15, 16, and 18.

The degree of HL was determined using the normative data proposed by Clark (1981), and data analyses revealed that two children (10%) exhibited mild HL, two children (10%) exhibited moderate HL, five children (25%) had moderately-severe HL, six children (30%) had severe HL, and five children (25%) were identified as having profound HL.

Procedures

Procedures Before Auditory Threshold Research • The electrophysiological and behavioral auditory thresholds were evaluated after inspecting the external acoustic meatus and obtaining tympanometric curves. These procedures were performed in every session and exclusively on children without abnormalities in the meatoscopy and showing type A tympanometric curves in both ears.

Electrophysiological Hearing Thresholds • In older children, electrophysiological thresholds were estimated using frequency-specific ABR with two chirp stimuli evaluated individually for each ear. The children were then randomly assigned to a group of 10 by drawing lots; 1 group was tested at 500 and 2000 Hz and the other at 1000 and 4000 Hz. This approach was taken as a methodological precaution, particularly since all responses were obtained during natural sleep with no sedation. Moreover, due to the length of the procedure, it was deemed necessary to limit the assessment to two frequencies per subject to ensure optimal recording conditions.

Electrophysiological thresholds were measured using NB CE-Chirp LS stimuli with the Eclipse EP25 ABR system (Interacoustics, Denmark), while thresholds with NB iChirp stimuli were recorded using the SmartEP device (Intelligent Hearing Systems, USA). The protocol for both stimuli included consistent parameters across equipment setups for polarity, number of stimuli, transducer type, and acceptable rejection levels. Specifically, an alternate polarity and 2048 sweeps were used, with each assessment conducted at least twice. ER-3A insert earphones served as the transducer, and a stimulus input rejection rate of up to 10% of the presented stimuli was permitted—equating to an acceptance of up to 204 rejected sweeps from the total of 2048.

For measurements with the Eclipse EP25 (i.e., NB CE-Chirp LS), a presentation rate of 39.1 stimuli per second was utilized with an analysis window of 20 msec, filter of 33 to 1500 Hz, and an artifact rejection threshold of up to ±40 nV. In addition, residual noise levels were kept below 25 nV, and the signal to noise ratio was estimated using the Fmp technique, deemed adequate at values above 2.5 (Sininger 1993). The specific configurations for frequencies and stimulus durations for the NB CE-Chirp LS were as follows: 500 Hz (360 to 720 Hz; 6 msec), 1000 Hz (720 to 1440 Hz; 4.9 msec), 2000 Hz (1440 to 2880 Hz; 3.8 msec), and 4000 Hz (2880 to 5760 Hz; 2.4 msec).

As for measurements using the SmartEP device (i.e., NB iChirp), a presentation rate of 27.7/sec was used with an analysis window spanning 24 msec and a 30 to 3000 Hz filter. The threshold for acceptable residual noise was set at 0.08 μV or lower, with the signal to noise ratio near 1.0 (Hatton et al. 2022). Stimulus parameters included frequency compositions of 500 Hz (275 to 1000 Hz; 5 msec), 1000 Hz (750 to 1750 Hz; 5 msec), 2000 Hz (1750 to 3250 Hz; 3 msec), and 4000 Hz (3250 to 5750 Hz; 2 msec).

The quantity of stimuli used remained consistent despite maintaining an adequate signal to noise ratio and appropriate Fmp and residual noise levels. Moreover, the evaluation of waveform presence or absence relied on visual inspection rather than adding smoothing filters to the recorded waveforms. Table 1 summarizes the parameters for each chirp utilized in the experimental procedures.

Two different stimulus presentation rates, 39.1/sec and 27.7/sec, were utilized according to the manufacturer's instructions for the equipment. These rates were selected for their efficiency and compatibility with rapid testing processes, which are particularly crucial in electrophysiological threshold research. The selection was also based on their potential to

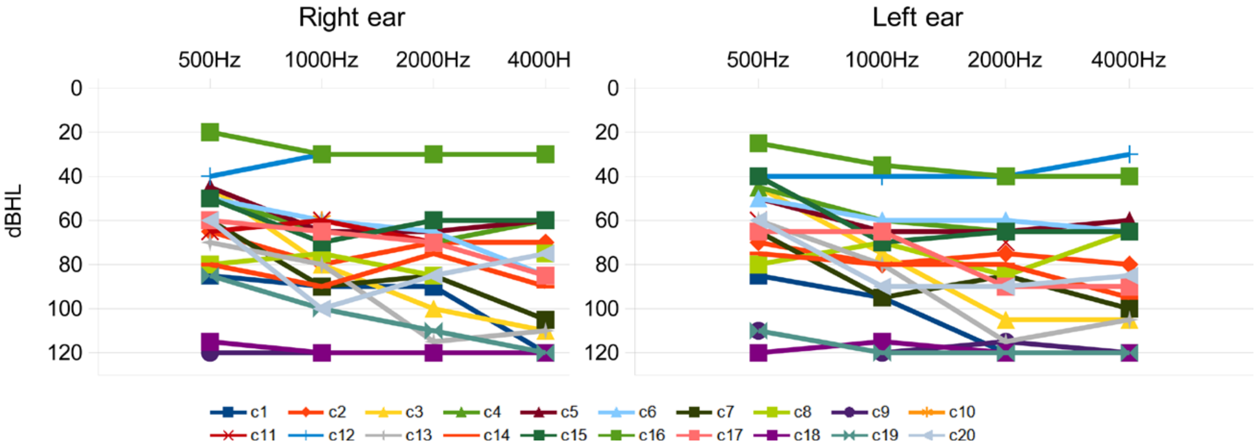

Fig. 1. Auditory thresholds of 500, 1000, 2000, and 4000 Hz of all children from the sample (n = 20). c indicates children; dBHL, decibel normalized hearing level; Hz, hertz.

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TABLE 1. Parameters for capturing electrophysiological thresholds with NB CE-Chirp LS and NB iChirp ABR

Stimuli	NB CE-Chirp LS	NB iChirp
Polarity	Alternate	Alternate
Number of stimuli	2048	2048
Presentation rate	39.1/sec	27.7/sec
Acquisition window	20 msec	24 msec
Filters	33–1500 Hz	30–3000 Hz
Percentage of declined stimuli	Up to 10% of the total presented stimuli	Up to 10% of the total presented stimuli
Residual noise	≤25 nV	≤0.08 μV
Signal to noise ratio	Fmp ≥2.5	≥1.0
Frequency composition	500 Hz: 360–720 Hz 1000 Hz: 720–1440 Hz 2000 Hz: 1440–2880 Hz 4000 Hz: 2880–5760 Hz	500 Hz: 275–1000 Hz 1000 Hz: 750–1750 Hz 2000 Hz: 1750–3250 Hz 4000 Hz: 3250–5750 Hz
Stimulus time	500 Hz: 6.0 msec 1000 Hz: 4.9 msec 2000 Hz: 3.8 msec 4000 Hz: 2.4 msec	500 Hz: 5.0 msec 1000 Hz: 5.0 msec 2000 Hz: 3.0 msec 4000 Hz: 2.0 msec

μV, microVolt; Fmp, F statistic using multiple points; Hz, hertz; msec, milliseconds; NB, narrow band; nV, nanoVolt; sec, seconds.

yield consistent results across various samples. Furthermore, filters were applied as per the established protocols. Notably, the application of a 3000 Hz filter in the iChirp resulted in a distinctly serrated visual pattern in the recordings, highlighting the significant impact of filter choice on data presentation. Hence, the authors acknowledge the possibility of research bias.

Regarding dB nHL calibration, it is important to note that, unlike pure tones—which have an established standard for hearing level (American National Standards Institute (ANSI) 2010)—there is no universally accepted benchmark for normalized hearing level (nHL). This lack of a standardized definition for audiometric zero makes calibration challenging (Norrix & Velenovsky 2017). Consequently, this study relied on the calibration approaches recommended by the manufacturers of the ABR systems used. The calibration values of dB pSPL required to establish the 0 dB nHL reference level for NB CE-Chirp LS were identified as −26.5 at 500 Hz, −24.5 at 1000 Hz, −30.5 at 2000 Hz, and −35 at 4000 Hz. For NB iChirp, the recorded values were −24 dB at 500 Hz, −27 dB at 1000 Hz, −27 dB at 2000 Hz, and −24 dB at 4000 Hz. These values were obtained directly from the equipment software.

Participant assessment protocols also merit mention. Infants were evaluated during natural sleep, comfortably positioned on their caregiver's lap in a tranquil room. Conversely, older children were assessed in a relaxed, semi-reclined position in a comfortable armchair, with instructions to keep their eyes closed throughout the process. Given the extended nature of the evaluation, thresholds were examined over multiple sessions. Nevertheless, the method was designed to allow one to assess identical frequencies using both equipment on the same day, wherever possible.

Preparation for recording the ABR included cleaning the participants' skin with abrasive gel (NuPrep) and gauze. Disposable electrodes (3M) were strategically placed on the right (A2) and left (A1) mastoids, with the active electrode situated at Fz and the ground electrode at Fpz on the forehead. The impedance was kept below 3 kΩ across both channels, ensuring no significant variation was observed between them.

The electrophysiological thresholds of the children were analyzed using the descending-ascending method, which involves progressively decreasing the stimuli in 10 dB steps until wave V was no longer discernible. Subsequently, the stimuli were increased in 5 dB increments until the minimum intensity required to identify wave V was achieved. The initial intensity for this study varied across participants, with a maximum intensity of 100 dB nHL (maximum output of the equipment).

Each recording was duplicated at least twice to confirm the presence of the wave and ensure response reliability. In addition, the time taken to determine the thresholds was measured using a digital stopwatch. Timing commenced immediately upon the placement of the electrodes on the child's skin and the onset of wave acquisition by the examiner. Should a participant necessitate a break, the stopwatch was temporarily halted and promptly restarted as the assessment continued.

Behavioral Auditory Thresholds

Behavioral thresholds were determined using pure-tone audiometry (PTA) in 13 (65%) of the children, while visual reinforcement audiometry (VRA) was used for 7 (35%). The choice between PTA and VRA depended on each child's age and their ability to participate in the testing process. The assessment involved the presentation of either pure tones or warbles through TDH 39 supra-aural headphones in a soundproof booth utilizing an AD226 audiometer (Interacoustics, Denmark) and Fonix FA-12 audiometer (Frye Electronics, USA). Testing was conducted for each ear individually. Thresholds were established using the descending-ascending technique, and in some cases, multiple sessions were required to complete the behavioral assessment, depending on the child's attentiveness.

Exam Analyses and Responses

Before the data were subjected to statistical analyses, the waveforms were evaluated by four expert judges, each with at least 10 years of experience in ABR assessments. To mitigate potential conflicts of interest, the practice of engaging judges for response evaluation was adopted. These judges were meticulously selected based on their expertise; two evaluated the exams conducted using the Eclipse EP25 apparatus, while the other two assessed those conducted on the SmartEP device, aligning with each judge's clinical expertise.

The judges were provided with anonymized copies of the exams to evaluate latency and amplitude values. To quantify the degree of agreement among the judges, their scores were statistically analyzed using the intraclass correlation coefficient (ICC) test. This test is a widely recognized method for evaluating the consistency of quantitative measurements made by two or more raters (Miot 2016). A threshold of ICC ≥0.50 was accepted as "markings with mutual agreement," and *p* values below 0.05 were considered statistically significant (Koo & Li 2016).

Consequently, the mean of the judges' scores was adopted when the ICC was equal to or exceeded 0.50 and the *p* value was below 0.05. In contrast, if the ICC fell below 0.50 or if the *p* value exceeded 0.05, an additional experienced ABR judge was sought. After a comprehensive review of all variables, only eight required further analysis by a fifth judge.

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Statistical Analyses

Upon analyzing the judges' agreement, the data were organized in spreadsheets. To enhance data reliability, values obtained from both the right and left ears were combined, effectively doubling the sample size. Moreover, children who exhibited no response to either electrophysiological or behavioral procedures were excluded from the analysis. Consequently, data from five children were excluded in the comparison between electrophysiological and behavioral thresholds, all of whom presented with profound HL. One child showed a lack of thresholds at 500 Hz in both ABR and behavioral assessments, while the other four children exhibited a lack of electrophysiological thresholds and the presence of behavioral thresholds. This difference is likely due to the inherent limitation of the ABR equipment, as opposed to audiometers, which have a higher maximum output capacity.

As a result, the sample size varied depending on the frequency studied and the analysis performed; thus, the sample size (n) is indicated in each table or figure. An initial descriptive statistical analysis was conducted. To examine the correlation between electrophysiological thresholds with the two chirp stimuli and between the behavioral and electrophysiological thresholds, Pearson correlation coefficient was utilized for data with a normal distribution, while Spearman correlation was used for data without a normal distribution.

The correlation between electrophysiological and behavioral thresholds was analyzed using the same statistical tests, which varied according to the type of behavioral assessment. The Student *t* test was applied to compare the examination times of the stimuli, whereas the Kruskal–Wallis test was used to assess the examination times based on the degree of HL. A 5% level of significance was adopted for all statistical tests.

RESULTS

The correlation between electrophysiological thresholds obtained from frequency-specific ABR using NB CE-Chirp LS and NB iChirp stimuli at 500, 1000, 2000, and 4000 Hz are shown in Table 2. A strong and statistically significant correlation was observed between the electrophysiological thresholds with both stimuli at all tested frequencies. These findings underscore the consistency of electrophysiological threshold measurements despite the implementation of distinct chirp stimuli using different devices.

Dispersion diagrams were created to demonstrate the relationship between the electrophysiological thresholds, ascertained through the NB CE-Chirp LS, and the behavioral thresholds at 500, 1000, 2000, and 4000 Hz (Fig. 2).

As shown in Figure 2, there were strong and statistically significant correlations at 1000, 2000, and 4000 Hz, suggesting the possibility of estimating behavioral thresholds based on electrophysiological thresholds at these frequencies. However, at 500 Hz, the correlation between electrophysiological and behavioral thresholds did not reach statistical significance.

Further analysis revealed that NB iChirp and behavioral thresholds exhibited correlation at 1000, 2000, and 4000 Hz, mirroring the findings with NB CE-Chirp LS. Notably, a moderate correlation was observed at 2000 Hz, diverging from the strong correlations noted at 1000 and 4000 Hz with the behavioral values. Once again, no statistical significance was observed between the electrophysiological and behavioral thresholds at 500 Hz. These findings are detailed in the dispersion diagrams presenting the correlation between behavioral thresholds and NB iChirps at the four analyzed frequencies (Fig. 3).

Figure 4 presents a comparison between behavioral thresholds determined using VRA in an acoustically treated cabin with headphones and electrophysiological thresholds obtained using NB CE-Chirp LS and NB iChirp stimuli at 500 and 2000 Hz for both ears. The data shown here were derived from the evaluation of a 9-month-old female infant diagnosed with moderate bilateral sensorineural HL who underwent the described procedures (Clark 1981). The electrophysiological assessment depicted in Figure 4 was conducted during natural sleep. This comparison highlights the closeness of the thresholds identified through electrophysiological and behavioral assessments, reinforcing that it is feasible to predict behavioral thresholds through electrophysiological evaluations using frequency-specific ABR. Minor discrepancies between the methods are expected, given their inherent differences and particularities.

Table 3 lists the results of the correlation analyses between electrophysiological and behavioral thresholds according to the type of behavioral assessment performed—namely, VRA and PTA. A strong correlation was observed between the behavioral thresholds measured using PTA and the electrophysiological thresholds elicited using both stimuli (i.e., NB CE-Chirp LS and NB iChirp) at the four frequencies evaluated. In contrast, with VRA, a strong correlation was only observed at 1000 and 4000 Hz, and again, this was consistent for both stimuli. This highlights a stronger correlation between electrophysiological and behavioral thresholds when the latter are acquired using PTA.

The mean differences between the electrophysiological and behavioral thresholds for each frequency and stimulus are presented in Table 4. These differences illustrate that

TABLE 2. Electrophysiological threshold correlations between NB CE-Chirp LS and NB iChirp stimuli at 500, 1000, 2000, and 4000 Hz in hearing-impaired children (n = 30)

	NB iChirp							
	n	500 Hz r* (p)	n	1000 Hz r* (p)	n	2000 Hz r† (p)	n	4000 Hz r† (p)
NB CE-Chirp LS	14	0.87 (<0.001)‡	15	0.94 (<0.001)‡	12	0.82 (0.004)‡	16	0.97 (<0.001)‡

*Pearson correlation.
†Spearman correlation.
‡Statistical significance.
Hz, hertz; NB, narrow band.

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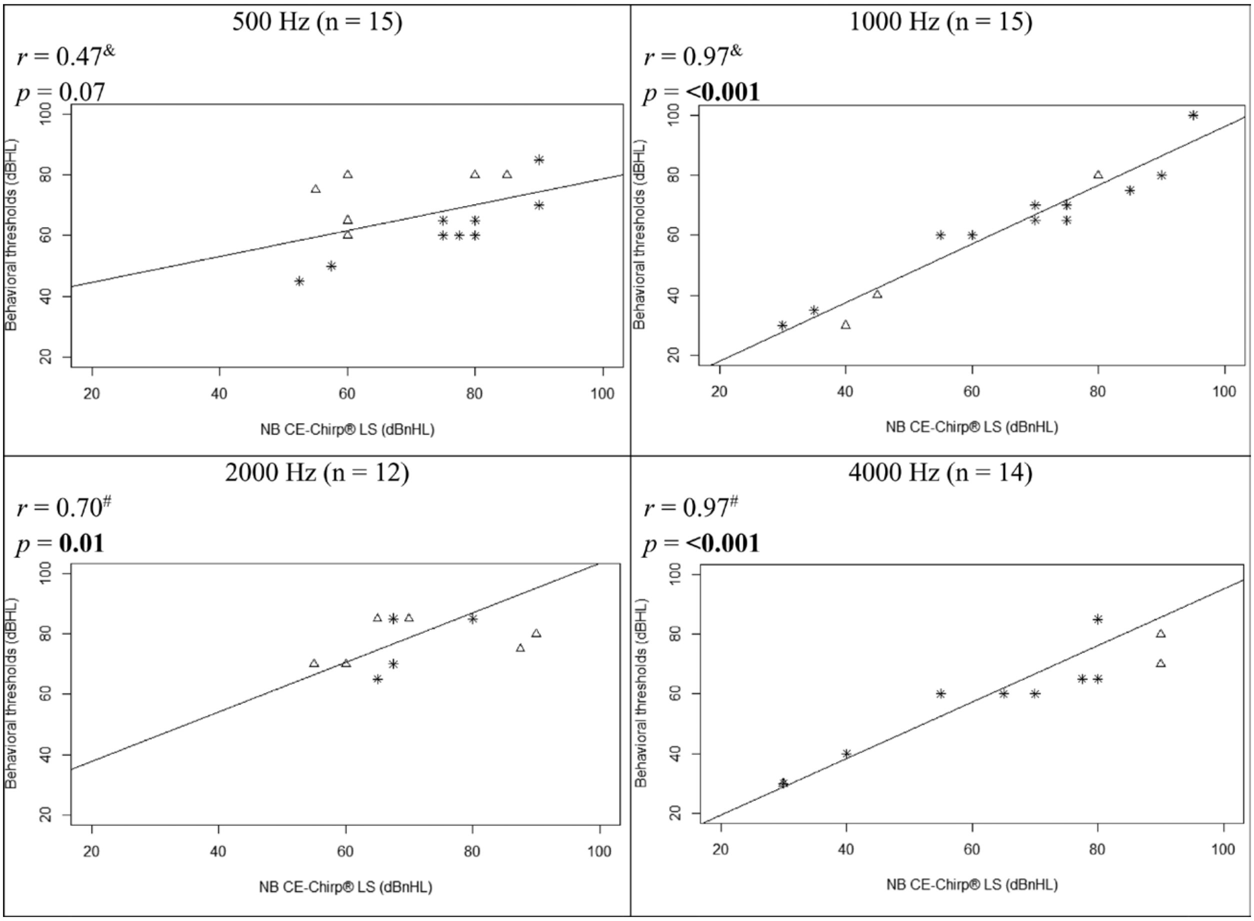

Fig. 2. Correlation between the electrophysiological thresholds with the NB CE-Chirp LS and behavioral thresholds at 500, 1000, 2000, and 4000 Hz in hearing-impaired children (n = 30). # indicates Spearman correlation coefficient; number of overlapping data points: 1000 Hz: one; 2000 Hz: two; 4000 Hz: four. Line of best fit considering all values; &, Pearson correlation coefficient; *, behavioral thresholds with PTA; values in bold show statistical significance; ▲, behavioral thresholds with VRA; Hz, hertz; NB, narrow band; PTA, pure-tone audiometry; VRA, visual reinforcement audiometry.

electrophysiological thresholds tend to be closely aligned with behavioral ones, with the largest mean difference not exceeding 6 dB nHL at 500, 1000, and 4000 Hz for the NB CE-Chirp LS and at 500 and 1000 Hz for the NB iChirp. Notably, electrophysiological thresholds were consistently lower than behavioral ones, with the maximum mean difference being less than 8 dB nHL.

The duration required to complete the examination was found to be similar across the stimuli, as indicated by a statistical analysis ($p = 0.52$). The mean time required to assess thresholds at two frequencies for both ears was 47.63 (±19.41) min using NB CE-Chirp LS and ~52.42 (±26) min with NB iChirp.

Figure 5 provides an analysis of the examination time needed to determine the electrophysiological thresholds using the NB CE-Chirp LS and NB iChirp stimuli, categorized by the degree of HL. The time is calculated in minutes required to determine the thresholds at two frequencies for both ears.

Statistical analysis via the Kruskal–Wallis test revealed no significant difference in exam duration based on the degree of HL for the NB CE-Chirp LS ($p = 0.55$). However, the NB iChirp stimulus demonstrated a significantly shorter exam duration for individuals with profound HL, as determined by the Kruskal–Wallis test ($p = 0.037$). This difference is likely due to the absence of responses linked to absent thresholds, which results in more rapid testing.

DISCUSSION

This study demonstrates that both chirp stimuli (NB CE-Chirp LS and NB iChirp) accurately estimate the electrophysiological thresholds in children with hearing impairment. Moreover, we established that these electrophysiological thresholds strongly correlate with behavioral thresholds at 1000, 2000, and 4000 Hz. The thresholds measured using chirp stimuli showed minimal deviations compared with behavioral thresholds while enabling practical exam durations.

These findings corroborate the inclusion of both the NB CE-Chirp LS and NB iChirp stimuli in the audiological diagnostic protocols for infants. As a result, this can enhance the practices of audiologists who utilize one of the two pieces of equipment and possibly even revolutionize the audiological clinical landscape. The stimuli used in this study demonstrate the capability to provide accurate and faster exams. Such advancements can facilitate early diagnosis and the programming of hearing aids for children with HL, thereby positively impacting these individuals' auditory rehabilitation process.

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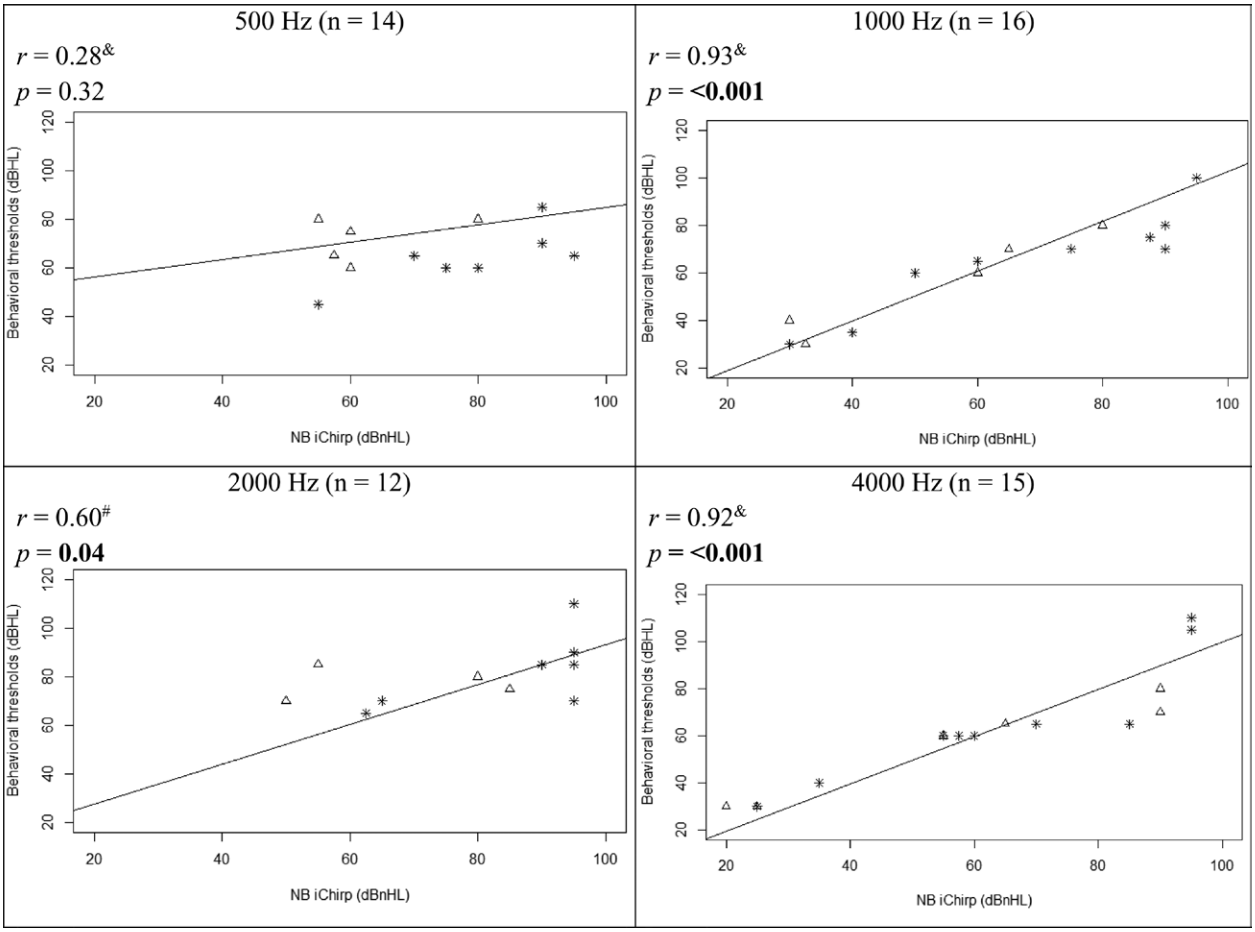

Fig. 3. Correlation between the electrophysiological thresholds with the NB iChirp and behavioral thresholds at 500, 1000, 2000, and 4000 Hz in hearing-impaired children (n = 30). # indicates Spearman correlation coefficient; number of overlapping data points: 1000 Hz: one; 2000 Hz: two; 4000 Hz: four. Line of best fit considering all values; &, Pearson correlation coefficient; *, behavioral thresholds with PTA; values in bold show statistical significance; ▲, behavioral thresholds with VRA; Hz, hertz; NB, narrow band; PTA, pure-tone audiometry; VRA, visual reinforcement audiometry.

Correlations Between NB CE-Chirp LS and NB iChirp

This study conducted the first known comparison between two chirp stimuli to estimate electrophysiological auditory thresholds at specific frequencies (500, 1000, 2000, and 4000 Hz) within a single session among a cohort of hearing-impaired children. As previously demonstrated in Table 2, our analyses revealed a strong correlation between both stimuli, lending support to their clinical utility. This outcome aligns with expectations, given that both stimuli share a similar mechanism for cochlear stimulation (Rosa et al. 2018). Chirp stimuli are designed to incorporate a delay compensation feature, allowing these stimuli to precede the recording time to accommodate the delay induced by the sound wave's passage through different frequency regions on the basilar membrane (Don et al. 2009; Elberling et al. 2010). This unique characteristic facilitates the simultaneous depolarization of a greater number of nerve endings (Don et al. 2005; Don et al. 2009; Elberling et al. 2010), manifesting in waves with increased amplitudes and an improved signal to noise ratio (Ferm et al. 2013; Bargen 2015).

Correlations Between Electrophysiological and Behavioral Thresholds

The existing literature and internationally recognized guidelines have highlighted the necessity for an in-depth exploration of chirp stimulus effects in HL-impaired cochleas (Rogrigues et al. 2013; Bargen 2015; Joint Committee on Infant Hearing 2019; Hatton et al. 2022). Hence, our study sought to correlate the thresholds derived from both chirp stimuli and behavioral thresholds and found that both stimuli (i.e., NB CE-Chirp LS and the NB iChirp) produced responses closely mirroring behavioral thresholds. Hence, examiners can estimate behavioral thresholds by utilizing these chirp stimuli for frequency-specific ABR, as illustrated in Figures 2 and 3. Notably, a significant correlation was found between behavioral and electrophysiological thresholds for both stimuli at 1000, 2000, and 4000 Hz.

Increased amplitude responses, enhanced neural synchrony, and a more favorable signal to noise ratio with chirp stimuli help in viewing wave V at lower intensities (Bargen 2015; Sininger et al. 2018), consequently improving the correlation between electrophysiological and behavioral thresholds (Ferm et al. 2013; Maloff & Hood 2014; Ferm & Lightfoot 2015). Moreover, research on frequency-specific chirp stimuli in hearing-impaired children is limited, and only a handful of studies have sought to correlate this type of assessment and behavioral thresholds. Xu et al. (2014) utilized the broadband LS-chirp stimulus to investigate the correlation between ABR and VRA estimates in infants aged 6 to 12 months with varying

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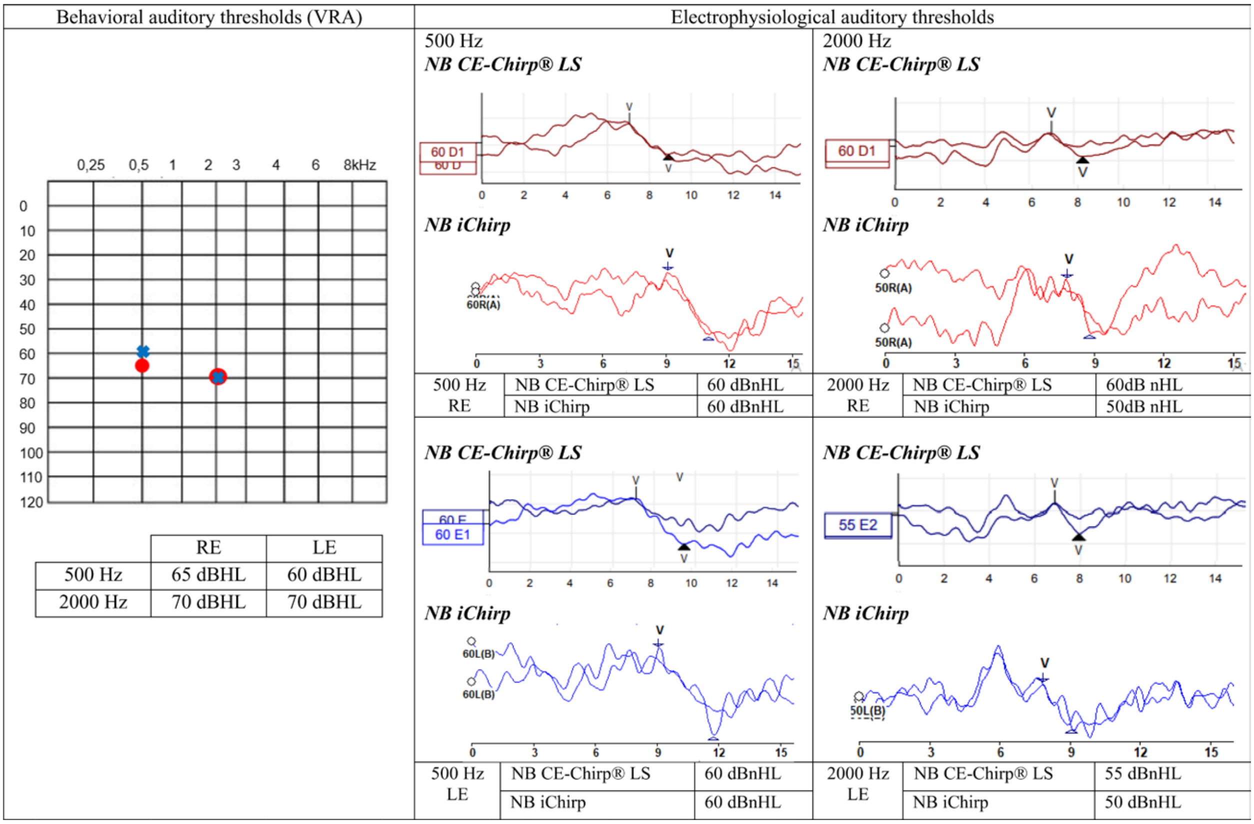

Fig. 4. Visual comparison of the behavioral thresholds (left image) and electrophysiological thresholds (right images) with NB CE-Chirp LS and NB iChirp stimuli at 500 and 2000 Hz in an infant with bilateral moderate sensorineural hearing loss (Clark 1981). dB nHL indicates decibel normalized hearing level; dBHL, decibel hearing level; Hz, hertz; LE, left ear; NB, narrow band; RE, right ear; VRA, visual reinforcement audiometry; wave amplitude—right ear, 500 Hz: 167nV with NB CE-Chirp LS and 260 nV with NB iChirp, 2000 Hz: 125nV with NB CE-Chirp LS and 150 nV with NB iChirp—left ear, 500 Hz: 235 nV with NB CE-Chirp LS and 290 nV with NB iChirp, 2000 Hz: 138 nV with NB CE-Chirp LS and 290 nV with NB iChirp.

degrees of HL; the authors reported a strong correlation, with a correlation coefficient of 0.97. Similarly, Wang et al. (2009) used broadband chirp stimuli to study their relationship with mean behavioral thresholds from 500 to 4000 Hz in children aged 3 to 6 years with HL, also finding a strong positive correlation ($r = 0.93$).

Given that chirp stimuli are designed to stimulate the entire cochlea uniformly, these stimuli were expected to provide a better predictive value of auditory thresholds, even at 500 Hz. Contrary to the initial expectations, we did not find any statistical significance when examining the correlation between electrophysiological and behavioral thresholds at this frequency (Figs. 2 and 3). There is evidence of reduced association at the 500 Hz with behavioral thresholds, and this trend remains even when alternative techniques (e.g., auditory steady state response), stimuli (e.g., broadband LS CE-Chirp), and tone burst stimuli are used to measure electrophysiological thresholds (Lee et al. 2008; Vander Werff et al. 2009; Cho et al. 2015; Biagio-de Jager et al. 2020; Eder et al. 2020). One hypothesis that may explain this is the presence of reduced neural

TABLE 3. Electrophysiological threshold correlations with NB CE-Chirp LS and NB iChirp stimuli and behavioral thresholds according to the type of behavioral assessment performed (PTA or VRA) in hearing-impaired children (n = 32)

	Frequency							
		500 Hz		1000 Hz		2000 Hz		4000 Hz
	n	r (p)	n	r (p)	n	r (p)	n	r (p)
NB CE-Chirp LS								
VRA	6	0.55* (0.26)	5	0.99* (**0.002**)	6	0.31* (0.54)	5	0.94† (**0.05**)
PTA	9	0.90* (**0.001**)	11	0.96* (**<0.001**)	6	0.96* (**0.002**)	10	0.93* (**<0.001**)
NB iChirp								
VRA	6	0.28† (0.60)	6	0.98* (**<0.001**)	5	0.29* (0.63)	6	0.97* (**0.001**)
PTA	8	0.75* (**0.03**)	10	0.91* (**<0.001**)	7	0.70† (**0.05**)	9	0.92* (**<0.001**)

Bold values mean statistical significance.
**Pearson correlation.*
†Spearman correlation.
Hz, hertz; NB, narrow band; PTA, pure-tone audiometry; VRA, visual reinforcement audiometry.

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TABLE 4. Mean difference (±SD) in dBnHL between the electrophysiological and behavioral thresholds for each frequency and stimuli studied in hearing-impaired children

dBnHL	n	500 Hz	n	1000 Hz	n	2000 Hz	n	4000 Hz
NB CE-Chirp LS	15		15		12		14	
Difference		5.16 ± 12.66		3.00 ± 5.28		−7.71 ± 10.79		3.04 ± 9.31
NB iChirp	14		16		12		15	
Difference		5.54 ± 15.07		0.94 ± 8.16		−3.13 ± 15.71		−0.50 ± 10.27

dBnHL, decibel normalized hearing level; Hz, hertz; NB, narrow band.

synchrony at frequencies below 1000 Hz (Sininger & Abdala 1996), combined with increased noise contamination (Ramos et al. 2013). This scenario could lead to higher electrophysiological thresholds compared with behavioral ones, thus affecting the correlation analysis between both measures.

Achieving optimal alignment between behavioral and electrophysiological thresholds presents a significant challenge, as illustrated in Figure 4. This difficulty arises from inherent variations among the methods utilized, including differences in stimulus duration, the involvement of central mechanisms within the auditory pathway during behavioral tests, and the influence of both auditory pathway maturation and the ear's physiological integrity (Norrix & Velenovsky 2017). Despite these obstacles, ABR testing remains invaluable in the audiological assessment of children. It is imperative to use established protocols to minimize variations in test outcomes. Several practices have been identified as beneficial in the field. For instance, professionals must have an in-depth understanding of the equipment, stimuli, and parameters used, as accurate identification of wave V is crucial. Moreover, maintaining low residual noise levels throughout the examination is another crucial factor (Sininger et al. 2020). In addition, using clinical protocols based on empirical evidence has also proven to enhance the reliability of assessments (Norrix & Velenovsky 2017).

Correlation Between Electrophysiological Thresholds and Type of Behavioral Assessment

Regarding the correlation between electrophysiological thresholds and the type of behavioral assessment conducted, Table 3 shows a stronger correlation when behavioral thresholds were determined using PTA. We posit that the behavioral responses obtained via VRA may lack accuracy due to the age of the children tested and the infants' developing response capabilities, which mature over time (Han et al. 2006). Given that behavioral threshold responses tend to improve with age (Parry et al. 2003), a heightened correlation between behavioral and electrophysiological thresholds is observed in older children who can respond more precisely to PTA assessments.

Analysis of the Mean Differences Between Electrophysiological and Behavioral Thresholds

Table 4 demonstrates the mean differences observed between electrophysiological and behavioral thresholds and shows that the chirp-evoked ABR closely predicts behavioral thresholds, with mean differences below 5.54 dB at all tested frequencies. This suggests that ABR using these stimuli can be reliably incorporated into clinical practice. Nonetheless, it is important to recognize that variations in estimated behavioral thresholds are inevitable, with discrepancies typically ranging from 10 to 15 dB (Stapells 2011).

The largest discrepancies between the thresholds were found at 500 Hz, whereas the thresholds revealed negative disparities at 2000 Hz. These results underline the influence of the tested frequency on the correlation between electrophysiological and behavioral thresholds. In fact, the behavioral thresholds for 500, 1000, and 4000 Hz, when elicited using the NB CE-Chirp LS stimulus, were consistently lower than the electrophysiological thresholds. These observations corroborate the literature, which could be partly attributed to variations in the stimulus durations used in different types of procedures (i.e., electrophysiological and behavioral) (Stapells 2000; McCreery et al. 2015).

Auditory stimuli such as pure tones or warbles, characterized by their gradual onset and longer duration, tend to facilitate sound detection. In contrast, electrophysiological stimuli are designed for rapid onset and brief duration, optimizing the elicitation of neural activity (Norrix & Velenovsky 2017). Notably, electrophysiological thresholds were lower than behavioral thresholds at 2000 and 4000 Hz with NB iChirp stimuli. This discrepancy can be attributed to the stimulus design, which aims to achieve synchronized and robust firing of many auditory nerve fibers while minimizing recording noise (Don et al. 2005; Don et al. 2009; Elberling et al. 2010). In addition, the denser distribution of nerve fibers at the cochlea's base supports the effective detection of wave V at low intensities (Gorga et al. 1988; Werner et al. 1994).

Some studies have proposed correction values for predicting behavioral thresholds using ABR with the tone burst (Stapells 2000; Bagatto et al. 2010; McCreery et al. 2015) and the NB chirp (British Society of Audiology 2013). While some studies have applied constant correction values (Bagatto et al. 2010), others have adjusted these values based on the degree of HL (McCreery et al. 2015) or even the age of the children (Stapells 2000; Marcoux 2011; British Society of Audiology 2013).

The correction factors derived from constants serve as essential benchmarks for audiologists. More explicitly, for the frequencies of 500, 1000, 2000, and 4000 Hz, the correction factors are determined to be 15, 10, 5, and 0 dB, respectively (Hatton et al. 2022). Moreover, for children older than 24 weeks, the correction factors when utilizing NB chirp stimuli are observed to be 15, 10, 5, and 5 dB at the same frequencies (British Society of Audiology 2013). Upon comparing the results from our study with previously reported values for all frequencies except 4000 Hz using NB CE-Chirp LS stimuli with the tone burst correction, it is evident that our findings were consistently lower (Hatton et al. 2022). This discrepancy may be attributed to the inherent characteristic of chirp stimuli that generate higher amplitudes at lower intensities, thereby fostering a closer approximation between electrophysiological and behavioral measures (Elberling & Don 2010; Ferm et al. 2013; Maloff & Hood 2014; Ferm & Lightfoot 2015).

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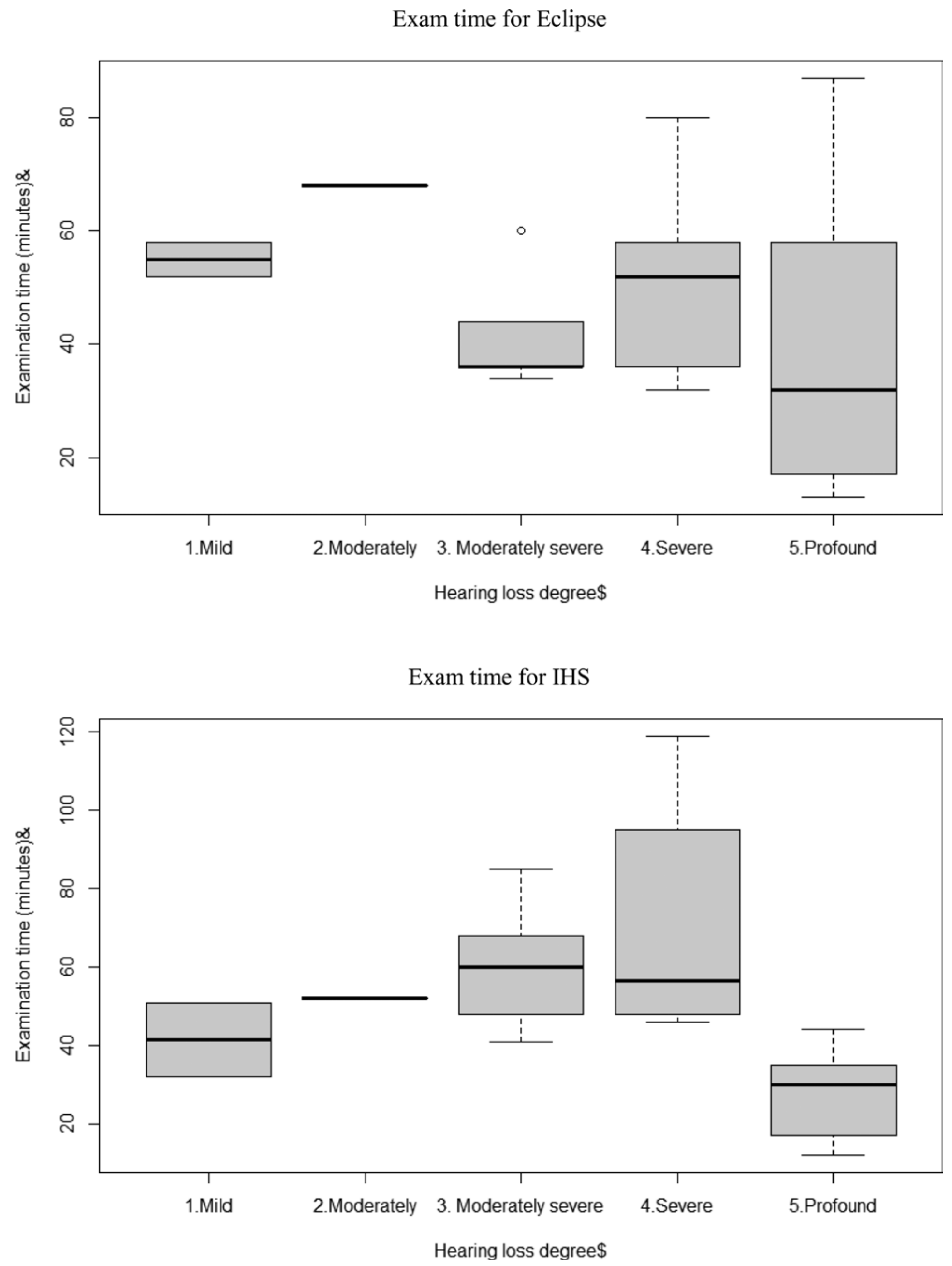
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Fig. 5. Examination time (in minutes) to obtain the electrophysiological thresholds with NB CE-Chirp LS and NB iChirp stimuli at two frequencies in both ears and according to the degree of hearing loss (Clark 1981). $ indicates Clark (1981); &, time in minutes considering the median ± interquartile range; *, absolute value of one particular child, not considered in the statistical test; p, Kruskal–Wallis test.

Despite the absence of a correlation between electrophysiological and behavioral thresholds at 500 Hz (Figs. 2 and 3), our analysis indicates a lesser disparity between these thresholds when applying tone bursts (Hatton et al. 2022). This suggests that chirp stimuli can be a valuable asset in enabling audiologists to obtain electrophysiological thresholds that more accurately reflect behavioral thresholds.

Examination Time Analysis

The investigation of examination times within ABR protocols represents a relatively unexplored area of research (Janssen et al. 2010). In our study, the mean time required by the examiner to assess thresholds at two frequencies for both ears was similar in both devices. Specifically, the mean duration for NB CE-Chirp LS was 47.63 (±19.41) min, in contrast with 52.42 (±26) min for NB iChirp.

The lack of research on applying frequency-specific ABR with chirp stimuli in children with hearing impairments limits the potential for comprehensive comparisons with existing studies. Sininger et al. (2018) evaluated the duration required to investigate electrophysiological thresholds in 102 children using frequency-specific ABR and NB CE-Chirp stimuli. This protocol harnessed automated response detection by analyzing the Fmp, a statistical measure linked to the record’s signal to

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noise ratio, thereby obviating the need for duplicating recordings to confirm responses. The authors reported a mean test duration of 32.15 min to assess eight thresholds (Sininger et al. 2018). Nevertheless, it is important to note that 35 children were tested under anesthesia, and 51% of the participants had normal-hearing, factors that are likely to have contributed to curbing frequency-specific ABR duration.

In another study, Janssen et al. (2010) implemented a similar protocol and reported a mean examination time of 54.6 min across 188 infants, of whom 116 were sedated and 51% exhibited normal auditory thresholds. Ceylan et al. (2020) examined the duration required to assess electrophysiological thresholds using four frequencies and frequency-specific ABR with NB CE-Chirp stimuli in adults with normal hearing; the authors found that the mean time was 23.6 min for one ear.

Comparing studies presents challenges due to methodological and protocol variations (Janssen et al. 2010; Sininger et al. 2018; Ceylan et al. 2020; Eder et al. 2020). However, incorporating NB CE-Chirp stimuli has been noted to reduce examination times under optimal testing conditions, attributed to the stimulus' design that enhances the detectability of wave V at intensities near the auditory threshold (Ferm et al. 2013; Sininger et al. 2018).

By comparing our findings with previous research using frequency-specific tone burst ABR, we noted a marked reduction in examination duration in our study. Almeida et al. (2011) also conducted a study in Brazil and reported a mean examination time of 90 min for infants with normal hearing and at four frequencies in one ear.

With regard to the examination duration and degree of HL observed in our research, as depicted in Figure 5, no statistically significant difference was observed across varying degrees of HL for NB CE-Chirp LS stimuli. Conversely, NB iChirp stimuli had notably shorter examination durations in cases of profound HL, a statistically significant difference. This outcome aligns with expectations that children with profound HL exhibit minimal responses at commonly tested intensities, thereby shortening the examination process. Sininger et al. (2018) also reported an influence of the degree of HL on examination durations, with quicker assessments observed in more severe cases of HL—approximately 50 min for children with thresholds of 26 to 60 dB nHL and 40 min for those with thresholds exceeding 61 dB nHL. Nonetheless, it is important to highlight that the researchers did not perform statistical analyses to determine the significance of their observed differences.

Study Limitations

Despite our promising findings, several factors must be considered when analyzing the data reported herein. A key limitation is the sample size. Despite implementing rigorous biosafety protocols due to the ongoing COVID-19 pandemic, a number of participants chose to withdraw from the study. Furthermore, electrophysiological threshold research during natural sleep made collecting data across all four frequencies from the entire sample challenging, affecting the overall sample size.

In addition, while the parameters used in both instruments for assessing electrophysiological thresholds were largely similar, there were notable differences, particularly in the use of different filters. This discrepancy likely had a significant impact on the recording of responses. The measurement of behavioral thresholds was also subject to research bias due to the utilization of different evaluation methods (i.e., VRA and PTA), as each method's use was determined by the neuropsychomotor development of the subjects, as per guideline recommendations.

CONCLUSIONS

Using chirp stimuli, specifically NB CE-Chirp LS and NB iChirp, proved a practical approach for assessing electrophysiological thresholds in hearing-impaired children through frequency-specific ABRes. Both stimuli showed comparable effectiveness in estimating these thresholds, providing a safe and reliable method for investigation. Moreover, using NB chirp stimuli enhanced the accuracy of auditory threshold estimation in hearing-impaired children, especially at the frequencies of 1000, 2000, and 4000 Hz. An added advantage is that electrophysiological thresholds obtained using NB chirp stimuli are closer to behavioral thresholds, significantly improving auditory threshold determination accuracy.

The duration required to complete assessments was similar for both stimuli, with the degree of HL influencing the duration of the examination. Tests were completed more quickly for children with profound HL, as they tend to produce fewer responses. This study has significant clinical implications; through the data presented and discussed, we can collaborate with professional guidelines to incorporate the NB chirp in assessing electrophysiological thresholds by specific frequency and using the corrections for more precise estimates of behavioral auditory thresholds in children with HL.

ACKNOWLEDGMENTS

The authors have no conflicts of interest to disclose.

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Received April 27, 2022; accepted March 20, 2024

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