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Editor-in-Chief

Prof. Henryk Skarzynski, M.D., Ph.D., Dr. h.c. multi

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Dear Colleagues,

This issue of the *Journal of Hearing Science* brings together papers on auditory science, clinical assessment, hearing screening, and cochlear implantation.

The issue opens with a hypothesis paper proposing middle ear muscle hyperactivity as a possible contributor to tinnitus and highlighting the potential role of middle ear mechanoreceptors. This conceptual contribution offers a fresh perspective on tinnitus mechanisms and may stimulate further experimental and clinical investigation.

The original articles span population-based and specialized clinical topics: booth-free audiometry in noisy environments, phonological influences on speech perception under multi-talker babble, and skill progression among novice auditory brainstem response (ABR) interpreters. The last of these touches on a problem the field has been slow to confront directly: hearing test results are not purely objective. ABR threshold estimation requires interpretive judgment, and that judgment is acquired unevenly, shaped by supervision quality, caseload exposure, and the presence or absence of structured feedback. Where training is informal or inconsistent, large diagnostic errors are to be expected rather than being exceptional. The deeper concern is inter-institutional variability: clinics differ substantially in how they train, supervise, and benchmark interpreters, yet these differences rarely surface in the literature or in accreditation standards. An erroneous estimate can misdirect a diagnostic pathway, delay intervention, or generate false reassurance. Reducing such errors requires not only better individual training but agreed-upon competency standards and external benchmarking. The field has yet to systematically develop such tools.

The issue closes with a comparative study of sacculo-collic function in children before and after cochlear implantation, adding to the literature on vestibular outcomes in pediatric implant recipients.

Together, these papers reflect the breadth of contemporary hearing science, connecting theory with advances in diagnosis, training, screening, and rehabilitations.

With kind regards and greetings,

Prof. Henryk Skarzynski, M.D., Ph.D., Dr. h.c. multi

Hypothesis papers

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MIDDLE EAR MUSCLE HYPERACTIVITY AS ONE CAUSE OF TINNITUS: A PUTATIVE ROLE FOR MIDDLE EAR MECHANORECEPTORS

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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Abstract

Subjective tinnitus is common yet poorly understood, and existing models do not fully explain its clinical diversity. This article presents a mechanistic hypothesis, based on existing literature, in which tinnitus may emerge not only from reduced auditory input due to inner ear injury but also from increased activity of the middle ear muscles, which may ultimately increase extracochlear, largely somatosensory, input to the cochlear nucleus. In this framework, auditory deafferentation is necessary but insufficient on its own.

We further hypothesise that, in some clinical contexts, somatosensory drive may be amplified by excessive stimulation of putative middle ear mechanoreceptors (MeRs). This stimulation may originate from muscle vibration (tremor) within the tympanic cavity, associated with heightened activity of the stapedius, tensor tympani, and tensor veli palatini muscles. Clinical situations such as loud-noise exposure, temporomandibular disorders, cervical dysfunction, and ear canal irritation may be interpreted within this framework as diverse triggers converging on enhanced middle ear muscle activity and mechanosensory overstimulation.

Although hypothetical, the model yields testable predictions. Functional neuroimaging could reveal abnormal activation of somatosensory cortical areas in tinnitus not directly related to acoustic trauma; middle ear muscle activity could be assessed in animal models using electromyography; and refined impedance-based measurements may help detect and characterise middle ear vibratory phenomena. Clinically, inter-individual variability in the stapedius reflex should modulate transient tinnitus and aural fullness after exposure to loud noise. By integrating auditory deafferentation, somatosensory modulation, and middle ear biomechanics, this hypothesis aims to guide future experimental work and therapeutic strategies.

Keywords: tinnitus • middle ear muscles • cochlear nucleus • mechanoreceptors

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NADAKTYWNOŚĆ MIĘŚNI UCHA ŚRODKOWEGO JAKO JEDNA Z PRZYCZYN SZUMÓW USZNYCH: HIPOTETYCZNA ROLA MECHANORECEPTORÓW UCHA ŚRODKOWEGO

Streszczenie

Subiektywne szumy uszne (*tinnitus*) są powszechnym, lecz wciąż słabo poznanym zjawiskiem, a istniejące modele patofizjologiczne nie wyjaśniają w pełni ich różnorodności klinicznej. W niniejszej pracy przedstawiono hipotezę dotyczącą mechanizmu powstawania szumów usznych, opartą na publikacjach naukowych, zgodnie z którymi szumy uszne mogą powstawać nie tylko jako skutek ograniczenia dopływu informacji słuchowych, spowodowanego uszkodzeniem ucha wewnętrznego, lecz również z powodu zwiększonej aktywności mięśni ucha środkowego. Ta ostatnia może prowadzić do nasilenia pozaślimakowego napływu bodźców do jądra ślimakowego, w szczególności somatosensorycznego. W ujęciu proponowanego modelu ograniczenie dopływu bodźców słuchowych do ośrodkowego układu nerwowego stanowi warunek konieczny, lecz niewystarczający do powstania szumów usznych.

Ponadto wysuwamy hipotezę, że w niektórych sytuacjach klinicznych wzmocnienie somatosensoryczne może się zwiększyć wskutek nadmiernej stymulacji mechanoreceptorów znajdujących się w uchu środkowym (MeRs). Źródłem tej stymulacji może być mimowolne drżenie mięśniowe (*tremor*) w jamie bębenkowej związane ze wzmożoną aktywnością mięśnia strzemiączkowego (*stapedius*), mięśnia napinacza błony bębenkowej (*tensor tympani*) oraz mięśnia napinacza podniebienia miękkiego (*tensor veli palatini*). W ramach tego modelu uwarunkowania kliniczne, takie jak: ekspozycja na hałas o dużym natężeniu, zaburzenia czynności stawu skroniowo-żuchwowego, dysfunkcje odcinka szyjnego kręgosłupa czy podrażnienie przewodu słuchowego zewnętrznego, mogą być interpretowane jako czynniki wyzwalające, które prowadzą do zwiększonej aktywności mięśni ucha środkowego i nadmiernej stymulacji układu somatosensorycznego.

Przedstawiony model ma charakter hipotetyczny, jednak pozwala na sformułowanie szeregu wniosków możliwych do zweryfikowania eksperymentalnie. Funkcjonalne badania neuroobrazowe mogłyby ujawnić nieprawidłową aktywację korowych obszarów somatosensorycznych u pacjentów z szumami usznymi niezwiązanymi bezpośrednio z urazem akustycznym. Aktywność mięśni ucha środkowego mogłaby być oceniana na podstawie modeli zwierzęcych z wykorzystaniem elektromiografii, natomiast udoskonalone metody pomiaru impedancji akustycznej mogłyby umożliwić wykrywanie i charakterystykę zjawisk wibracyjnych zachodzących w uchu środkowym. Z klinicznego punktu widzenia osobnicza zmienność odruchu mięśnia strzemiączkowego powinna wpływać na występowanie przemijających szumów usznych oraz uczucia pełności w uchu po ekspozycji na hałas o wysokim natężeniu.

Ujmując łącznie zjawiska ograniczenia dopływu bodźców słuchowych do wyższych pięter układu nerwowego, modulacji somatosensorycznej oraz biomechaniki ucha środkowego, przedstawiona hipoteza ma na celu wskazanie kierunków przyszłych badań eksperymentalnych i rozwoju nowych strategii terapeutycznych.

Słowa kluczowe: szumy uszne • mięśnie ucha środkowego • jądro ślimakowe • mechanoreceptory

Key to abbreviations	
BA	Brodmann area
CI	cochlear input
CN	cochlear nucleus
DCN	dorsal cochlear nucleus
ECI	extracochlear input
HRMEMS	Hyper-Reactive Middle Ear Muscle Syndrome
LTP	long-term potentiation
MeRs	middle ear mechanoreceptors
OHCs	outer hair cells
PCs	Pacinian corpuscles
SM	stapedius muscle
STDP	spike-timing-dependent plasticity
TMDs	temporomandibular disorders
TTM	tensor tympani muscle
TTTS	Tonic Tensor Tympani Syndrome
TVPM	tensor veli palatini muscle
VGLUT2	vesicular glutamate transporter 2

Introduction

Subjective tinnitus, defined as an auditory perception occurring in the absence of any acoustic stimulation, is a frequent complaint in clinical practice. Its high prevalence in the general population and its potential to markedly impair quality of life [1] underline the need for mechanistic models that can account for its clinical diversity.

Cochlear deafferentation is strongly associated with tinnitus [2,3], yet it appears to be necessary but insufficient. Hearing loss on standard audiometry does not invariably coincide with tinnitus [4], experimental cochlear lesions do not consistently generate tinnitus-like percepts in animal models [5], and tinnitus may occur despite a normal audiogram, consistent with subclinical cochlear damage [6]. Accordingly, although tinnitus secondary to acute or chronic acoustic trauma is the most common clinical presentation, cochlear injury alone does not fully explain why tinnitus develops in some cases and not in others.

Clinical observations suggest that additional, non-auditory factors may influence tinnitus emergence. Tinnitus may occur without obvious noise trauma, as in temporomandibular disorders (TMDs) [7], and may also resolve after removal of a cerumen plug [8]. These observations are difficult to reconcile with a purely cochlear account and instead suggest that clinically diverse triggers may converge on a common pathway. The proposed pathway is summarized in **Figure 1**.

Here, we propose an integrative mechanistic hypothesis, grounded in existing literature. In this framework, cochlear inputs (CIs) refer to auditory information conveyed from the cochlea to the cochlear nucleus (CN) through the auditory nerve. Tinnitus may emerge not only from a reduction in these inputs following inner ear injury, but also from increased activity of the middle ear muscles. More specifically, heightened activity of the stapedius (SM), tensor tympani (TTM), and tensor veli palatini (TVPM) may generate tremor-like vibrations within the tympanic cavity, overstimulating putative middle ear mechanoreceptors (MeRs) and thereby increasing extracochlear, largely somatosensory, inputs (ECIs) to the CN. Cochlear deafferentation, potentially subclinical, is therefore viewed as permissive but insufficient on its own, while abnormal middle ear muscle activity may provide the additional drive required to shift CN processing toward tinnitus-related activity.

The goal of this framework is not to provide confirmatory evidence, but to generate falsifiable predictions and identify experimental approaches to test whether this pathway contributes to subjective tinnitus across etiologies.

Linking middle ear afferents to extracochlear pathways

To assess how middle ear activity might increase ECIs, the key question is whether mechanosensory signals arising from the tympanic membrane, middle ear cavity, or middle ear muscles can reach pathways known to provide extracochlear input to the CN. The tympanic membrane receives a triple innervation [9,10], predominantly via the auriculotemporal nerve (branch of the mandibular division of the trigeminal nerve), with additional contributions from the auricular branch of the vagus nerve and the tympanic plexus, formed by anterior and posterior tympanic branches of the glossopharyngeal nerve, together with sympathetic fibers from the superior and inferior caroticotympanic nerves. Nociception from the tympanic membrane is mediated almost exclusively by the trigeminal nerve [11]. However, global tympanic membrane

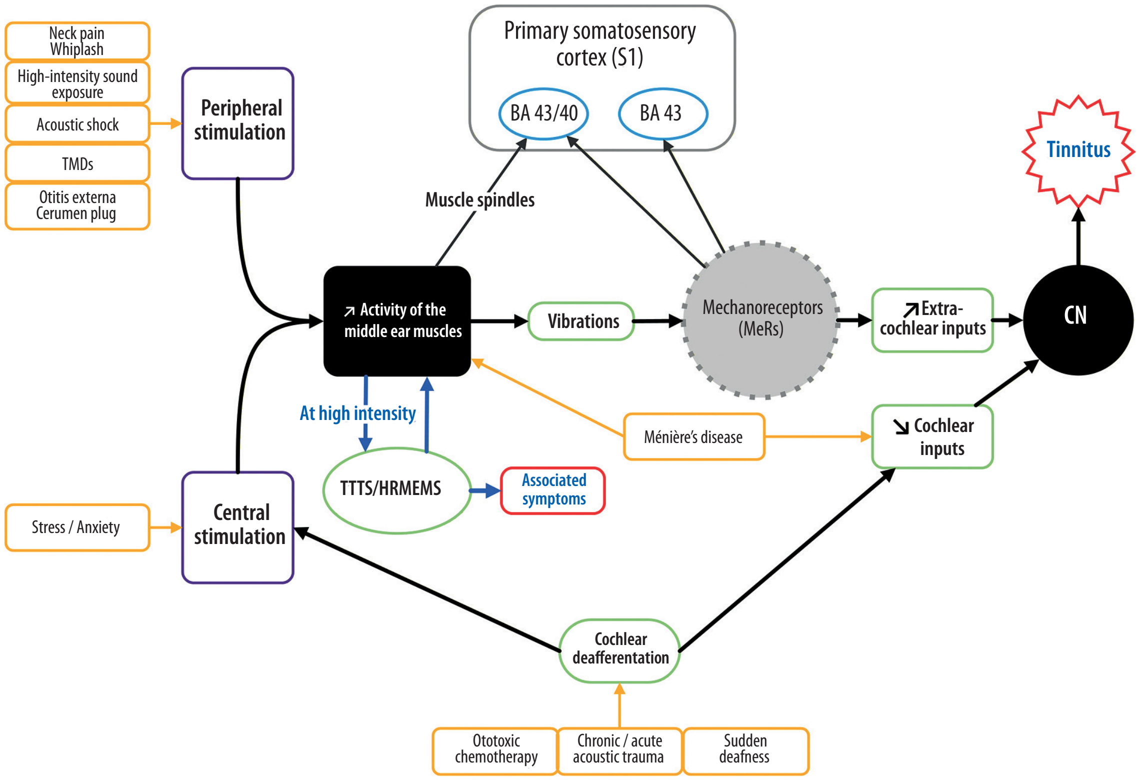

Figure 1. Proposed model linking middle ear muscle hyperactivity to tinnitus via the cochlear nucleus. The diagram summarizes the proposed pathway by which increased activity of the middle ear muscles may contribute to tinnitus. The black shapes indicate key components of the model, including the middle ear muscles and the cochlear nucleus (CN). Tremor-like activity of the stapedius, tensor tympani, and tensor veli palatini muscles may generate vibrations within the tympanic cavity and overstimulate putative middle ear mechanoreceptors (MeRs), shown in the grey circle. This mechanosensory drive may increase extracochlear inputs to the CN, where it may interact with reduced cochlear inputs resulting from cochlear deafferentation. Their convergence may contribute to abnormal CN activity and tinnitus. The same middle ear somatosensory drive may be associated with activation of the primary somatosensory cortex (S1; BA 43 and BA 43/40). At higher levels of middle ear muscle activation, this process may also contribute to Hyper-Reactive Middle Ear Muscle Syndrome (HRMEMS), including cases historically described as Tonic Tensor Tympani Syndrome (TTTS). Etiologies highlighted in yellow, such as acute or chronic acoustic trauma, temporomandibular disorders (TMDs), cervical dysfunction, otitis externa, or Ménière's disease, may act peripherally or centrally to increase middle ear muscle activity, either directly or through cochlear deafferentation, and thereby promote overstimulation of MeRs

displacement induced by moderate pressure changes is typically painless [12], suggesting that tympanic membrane displacement may generate a mechanosensory signal without necessarily engaging a nociceptive response. The mucosa of the middle ear cavity is likewise supplied by the tympanic plexus.

Afferent projections from the tympanic membrane and middle ear mucosa have been traced to trigeminal, facial, glossopharyngeal, vagal, and upper cervical ganglia [13,14]. Centrally, trigeminal thermonociceptive afferents relay through the spinal trigeminal nucleus, whereas discriminative touch is relayed to the principal sensory nucleus of V [15]. General somatic afferents from the facial, glossopharyngeal, and vagal nerves also converge on the spinal trigeminal nucleus. Upper cervical afferents relay through the dorsal column nuclei, including the cuneate nucleus, and can also influence trigeminal and vestibular nuclei [16,17]. Among these pathways, the spinal trigeminal nucleus appears particularly relevant for the present model because it is the only trigeminal nucleus known to contribute directly to ECIs. Upper cervical pathways may likewise be relevant through their convergence with trigeminal and vestibular systems. In light of currently identified sources of ECI to the CN, the most plausible routes by which middle ear signals could access known extracochlear pathways involve the spinal trigeminal nucleus, the C2 dorsal root ganglion, the cuneate nucleus, the trigeminal ganglion, and the vestibular nuclei [18–21].

The SM is innervated by the stapedius nerve, a branch of the facial nerve, whereas the TTM and TVPM are innervated by the medial pterygoid nerve, a branch of the mandibular division of the trigeminal nerve [22]. Muscle spindle afferents from the TTM and TVPM project to the mesencephalic trigeminal nucleus, and a similar pathway has been suggested for the SM [23,24]. No Golgi tendon organs have been identified in middle ear muscles. Because no direct connections have been identified between the CN and the mesencephalic or motor trigeminal nuclei, a dominant proprioceptive route from middle ear muscle spindles appears less likely, although indirect influences cannot be excluded. Thermal sensitivity is likewise unlikely to play a major role. Clinically, even severely painful acute otitis media does not necessarily produce tinnitus. Taken together, these observations support mechanosensory input arising from the tympanic membrane or middle ear cavity as a plausible route by which middle ear activity could access known ECI pathways and thereby increase ECI drive.

Which muscles respond to what, and why this matters

Somatic maneuvers capable of engaging middle ear muscles have been associated with changes in tinnitus loudness, typically in the direction of worsening [25]. In the present framework, this observation is important because it links tinnitus modulation to stimuli known to activate the middle ear muscles. The respective roles of these muscles in response to different stimuli remain incompletely understood, but several observations indicate that they can be activated by a wide range of acoustic and non-acoustic events. In humans, intense sound stimulation elicits the acoustic reflex, that is, a tonic bilateral contraction of the SM [26]. In contrast with common animal models of tinnitus, where both the SM and TTM may be involved, the human acoustic reflex is predominantly stapedius-mediated [27]. At very high sound intensities, however, both the TTM and SM may contract, and this response has been linked to the startle reflex, although this interpretation is not universally accepted [28–30]. The TTM generally requires higher sound intensities, is more exhaustible, and has a longer latency than the SM [28–31]. The TVPM may also participate in this broader response. Although it lies outside the tympanic cavity, it affects middle ear mechanics through Eustachian tube opening and has been proposed to function as a unit with the TTM [32–34]. Startle-related impedance changes can still be observed in patients lacking a functional TTM, likely reflecting contraction of the TVPM [28]. Because the startle reflex is influenced by vigilance and fatigue, the associated middle ear muscle response may be state-dependent [28].

Middle ear muscle activity can also be triggered by non-acoustic events. Contractions of the TTM and SM have been reported during vocalisation, coughing, yawning, swallowing, laughter, smiling, clenching the teeth, head flexion, and head rotation [25,30,31,35,36]. Cutaneous stimulation of the external auditory canal or adjacent skin can provoke a phasic SM contraction and, in some studies, TTM contraction as well, likely via startle-related mechanisms [30,37]. The external auditory canal and meatus appear to be among the most sensitive sites for this response [37,38], a point relevant to the later discussion of ear canal irritation and cerumen impaction. Electrical stimulation of the tongue and air puffs directed toward the orbital region can also activate the TTM [29,32,38]. In addition, some individuals are able to voluntarily contract the TTM, suggesting a degree of cortical control [38,39].

These observations support a key point of the present model: if putative MeRs contribute to tinnitus, the most likely endogenous source of the relevant mechanical stimulation is the middle ear muscles themselves. The precise nature of this stimulation is considered in the following sections.

Vibrations

In the present model, the relevant mechanical stimulus is not an isolated muscle contraction but tremor-like vibration of sufficient amplitude to increase ECI drive. If middle ear muscles are indeed the endogenous source of this stimulation, force instability during contraction is the most plausible mechanism. In striated muscle, sustained force depends on sequential and largely asynchronous recruitment of motor units, because the contraction of individual fibers is brief [40]. However, motor units are not fully independent and tend to exhibit partial synchronisation, such that two units fire nearly simultaneously more often than expected by chance [40–42]. This phenomenon is thought to arise centrally [41,43]. Partial synchronisation increases force variability and tremor amplitude, and this effect becomes more pronounced as contraction intensity rises [40,44–46]. Importantly, tremor can also occur during low to moderate contractions, for example during simple postural activity [44], and it tends to increase with aging [47].

Although these phenomena have been studied mainly in limb muscles, similar synchronisation has also been demonstrated in facial muscles, which, like middle ear muscles, are controlled by cranial motor nuclei [42]. Several factors can enhance this instability, including fatigue and training [48,49]. Repetitive intense contractions, even of short duration, can durably increase synchronisation, and this effect may persist after prolonged rest [46,48]. Marked inter-individual variability in synchronisation intensity has also been reported, suggesting that comparable levels of middle ear muscle activation may not produce the same degree of vibratory stimulation in all individuals [40,44,46]. Some authors have also suggested that smaller muscles may be particularly prone to synchronised activity, although this remains debated [42,43]. In this respect, the middle ear muscles, which are small striated muscles, may be particularly susceptible to developing tremor capable of overstimulating putative MeRs.

The effect of such vibration on putative MeRs nevertheless depends on two unresolved factors: the amplitude of muscle-generated vibration and the sensitivity of the receptors themselves. The second of these factors is particularly uncertain, because the functional properties of these putative receptors remain unknown. This distinction is central to the present model, because the pathological issue may not be pressure change per se, but rather the delivery of a sufficiently rapid and repeated mechanical stimulus to receptors that are likely to be phasic. The following section therefore examines the anatomical evidence supporting their presence in the middle ear and the limited basis for inferring how they might respond to vibration.

Mechanoreceptors

If vibration is indeed the relevant mechanical stimulus, the next question is whether the middle ear contains sensory structures capable of detecting it. Histological studies have identified encapsulated nerve endings within the middle ear, but their functional properties remain unknown.

Two distinct types of encapsulated formations have been described. The first is located within the tympanic membrane. Because of its encapsulated morphology, it was initially described by some authors as a *modified Pacinian corpuscle* [10], although its structure differs from that of canonical Pacinian corpuscles (PCs) [50]. The second type consists of encapsulated formations suspended by fine connective tissue strands anchored to the middle ear mucosa. These structures have been observed within the tympanic cavity, particularly near the ossicles, their suspensory ligaments, and the tendons of the TTM and SM [51]. Their onion-like lamellar capsule likewise prompted comparison with PCs, although their ultrastructure again differs from genuine PCs [52]. Notably, this second type has not been observed in children or young adults [52].

Although their function has not been directly characterised, their morphology suggests a mechanosensory role broadly analogous to that of PCs. PCs are rapidly adapting, phasic receptors that respond preferentially to dynamic deformation rather than sustained force and are therefore sensitive to vibration [53]. The structural differences between MeRs and canonical PCs likely alter these response characteristics, but by morphological analogy it remains plausible that MeRs also behave as phasic receptors [54]. If so, vibratory activity within the middle ear would represent a plausible stimulus. This point is central to the present model. If MeRs are indeed phasic receptors, slow or quasi-static pressure changes would be expected to remain within their normal operating range, whereas repetitive tremor-like deformation could recruit them repeatedly and, through temporal summation, generate a supra-physiological ECI drive. In this sense, the relevant variable may not be pressure itself, but the rate and repetition of the mechanical stimulus.

Several indirect observations are consistent with this interpretation. In a study involving 25 healthy volunteers, experimentally induced middle ear vibration produced transient phantom auditory percepts whose occurrence increased with stimulation frequency and became nearly universal at higher frequencies [55]. The fact that this percept became much more frequent as stimulation frequency increased is consistent with the present hypothesis, because it suggests that repeated vibratory stimulation, rather than pressure change alone, is the critical factor. We suggest that these subjects may have experienced a stimulus-induced tinnitus-like percept, potentially engaging mechanisms relevant to tinnitus. Similarly, intense low-frequency sound is known to trigger transient tinnitus [56]. Although a direct effect on cochlear structures cannot be excluded [57], such sounds plausibly generate large-amplitude oscillations within the middle ear.

A second line of evidence comes from the effects of local anesthetics. Agents such as lidocaine, procaine, dibucaine, and tetracaine have long been known to reduce, or even abolish, subjective tinnitus, despite significant adverse effects. This phenomenon has been observed after both intravenous administration [58] and transtympanic application into the middle ear cavity [59]. While traditionally attributed to suppression of cochlear hyperactivity [58], an alternative explanation is possible. Local anesthetics inhibit action potential generation in PCs [60], owing to the presence of unmyelinated neurites. Because MeRs also contain unmyelinated fibers [50], they might be similarly susceptible, which raises the possibility that at least part of the beneficial effect of local anesthetics could involve inhibition of MeRs.

Taken together, these observations are consistent with the hypothesis that the middle ear contains putative MeRs capable of responding to vibration. However, their functional characteristics remain unknown, and direct physiological validation will be required to determine whether they contribute to increased ECI drive in tinnitus.

Clinical correlates of middle-ear muscle hyperactivity

TTTS and HRMEMS

If the proposed pathway is relevant, heightened middle ear muscle activity should have recognisable clinical correlates. Such an association has long been described under the term *Tonic Tensor Tympani Syndrome* (TTTS) [61]. Originally attributed to sustained hyperactivity or hypertonia of the TTM, TTTS encompasses a broad spectrum of symptoms, including tinnitus, aural fullness, otalgia, facial or cervical pain, burning sensations in or around the ear, distorted hearing, vertigo, and nausea [62,63]. It is often described in the context of acoustic shock syndrome, in which a sudden, loud, and emotionally threatening sound triggers this constellation of symptoms [62]. Importantly, TTTS is not exclusively linked to acoustic shock and may occur in patients without such a history. An epidemiological study found that a large majority of patients consulting for tinnitus, with or without hyperacusis, reported at least one TTTS-related symptom, the most frequent being aural fullness, which may be the clinical manifestation most directly related to stimulation of MeRs [63].

More recently, Fournier and colleagues developed a technique that differentiates SM and TTM activity by combining tympanometry with direct recording of air-pressure changes in a sealed external auditory canal [39]. In the same configuration, Eustachian tube opening, primarily mediated by the TVPM, can also be detected. Using this approach, the authors reported involvement of the TTM, SM, and TVPM, alone or in combination, in patients presenting symptoms classically attributed to TTTS [64]. Because the syndrome appears to reflect excessive reactivity rather than purely tonic contraction, they proposed the broader term *Hyper-Reactive Middle Ear Muscle Syndrome* (HRMEMS). Notably, all participants in their study exhibited tinnitus, despite diverse triggering events including stress, sudden sensorineural hearing loss, acoustic shock, otologic surgery, and loud-noise exposure. These observations support the view that abnormal middle ear muscle activation may represent a common denominator across clinically heterogeneous but tinnitus-associated conditions.

Within this framework, isolated tinnitus and tinnitus accompanied by TTTS/HRMEMS symptoms may lie along a continuum, with symptom expression depending on the intensity and persistence of middle ear muscle activation.

Persistence and chronicity

Tinnitus is often transient, but its chronic form is the one that most significantly impairs quality of life. If middle ear muscle activity contributes to persistent tinnitus, the associated mechanical stimulation must itself persist over time. In healthy individuals, transient tinnitus is typically reported to resolve shortly after the putative overstimulation of MeRs ends [55]. As discussed above, muscle tremor may persist for several hours after exertion [65], but in the absence of renewed activation it eventually subsides.

A pathophysiological model proposed by Noreña et al. may help explain how such activity could become self-sustaining after acoustic shock [66]. In this model, excessive TTM contraction leads to local ischemia, metabolic stress, and neurogenic inflammation. This inflammatory milieu lowers activation thresholds in somatosensory afferents and amplifies peripheral input [67,68]. These afferents project to the trigeminocervical complex, a convergence hub for trigeminal and upper cervical inputs [69]. Because the trigeminocervical complex also exerts descending control over head and neck musculature, its sensitisation may increase efferent drive to the middle ear muscles, thereby reinforcing their hyperreactivity and facilitating reflex-related contractions [70,71]. In this way, peripheral inflammation and central sensitisation could establish a positive feedback loop capable of maintaining excessive muscle activation beyond the initial trigger.

At the same time, HRMEMS has not been described by its authors as a permanent state. Rather, it represents hyperreactivity to stimuli, and its apparent intermittence may partly reflect methodological limitations. The available pressure and impedance measures detect only sufficiently large changes in muscle tension. A near-perfectly stable tonic contraction may be poorly captured by such methods [72]. Consistent with this interpretation, in a particularly severe case of TTTS, continuous middle ear impedance monitoring revealed baseline instability in the more symptomatic ear [62]. Such instability could reflect subtle vibration-related changes in the mechanical state of the ossicles and tympanic membrane. This suggests that the hypertonia initially described in TTTS and the hyperreactivity reported in HRMEMS may represent two facets of the same phenomenon, namely an overall increase in neural drive to the middle ear muscular system.

The cochlear nucleus as a site of cochlear and extracochlear convergence

Plasticity in tinnitus models

Current evidence suggests that the earliest tinnitus-specific neural correlate emerges within the CN [73]. The CN is both the first central relay of auditory afferents and an early site of multisensory integration, combining CIs with numerous ECIs [74]. The mechanisms governing this integration remain incompletely understood. The present model proposes that tinnitus arises when reduced CI is accompanied by an abnormal increase in ECI drive.

This interpretation is supported by animal models of tinnitus. Following cochlear deafferentation, reduced auditory nerve activity is observed at several entry points to the CN. However, these changes are not sufficient to explain tinnitus, because they reflect cochlear injury in general and are not restricted to animals that develop tinnitus-like behavior. By contrast, only animals classified as having tinnitus show a marked increase in the spontaneous activity of fusiform cells, the principal output neurons of the dorsal cochlear nucleus (DCN).

Several facilitatory plastic changes affecting ECI pathways have likewise been reported specifically in tinnitus models [73]. These include increased glutamatergic transmission associated with upregulation of vesicular glutamate transporter 2 (VGLUT2) in CN regions receiving ECIs, and a shift in spike-timing-dependent plasticity (STDP) rules toward sustained facilitation and long-term potentiation (LTP) [5,75]. VGLUT2 is specifically associated with ECI terminals [76]. Collectively, these mechanisms increase the relative weighting of ECIs in CN processing.

Our interpretation of these findings is that the plastic changes are more likely to be a consequence of excessive ECI drive than its primary cause. In humans, tinnitus typically begins almost immediately after acute acoustic trauma [77], whereas at least some of the observed plastic changes, particularly VGLUT2-related remodeling, require time to develop. Although timing-dependent synaptic changes might emerge more rapidly [78], the most parsimonious explanation is that tinnitus onset depends on a supra-physiological increase in ECI drive superimposed on reduced CI. The same excessive ECI drive could then induce the plastic adaptations observed in tinnitus models. If this interpretation is correct, the presence of tinnitus-specific plastic changes itself implies that ECI activity must reach a supra-physiological level, since it is sufficient to induce pathway-specific remodeling rather than simple physiological modulation. It also implies that an isolated increase in ECI drive, even in the absence of established structural plasticity, may be sufficient to trigger tinnitus. These plastic changes may subsequently stabilise or maintain tinnitus-related hyperactivity once established.

Extracochlear inputs

In the present model, the middle ear is proposed as a plausible source of the increased ECI drive required for tinnitus. Several observations support this interpretation. First, in tinnitus models, VGLUT2 overexpression in the CN has been associated with increased projections from the spinal trigeminal nucleus, cuneate nucleus, and lateral vestibular nucleus to the CN [18,19]. This pattern is consistent with the anatomical links between the middle ear and the CN described above.

Further support comes from human imaging. In soldiers with tinnitus following acute acoustic trauma, Job et al. reported increased activation in Brodmann area 43 (BA 43) and BA 43/40 on functional MRI [79]. Both regions lie within the primary somatosensory cortex (S1). Notably, BA 43 had previously been activated by deformation of the tympanic membrane induced by pressure changes in the external auditory canal [12], whereas the deeper BA 43/40 region has been linked to somatosensory information arising from the middle ear. In addition, activation intensity in these regions correlated with tinnitus periodicity and subjective distress. These pressure variations produce a global deformation of the tympanic membrane, whose MeRs are likely to be the primary transducers.

In the present framework, stimulation of tympanic membrane MeRs may therefore plausibly contribute to activation of BA 43, while stimulation of MeRs within the tympanic cavity could, together with neuromuscular spindle afferents, contribute to activation of BA 43/40. In this interpretation, activation of BA 43 and BA 43/40 should be understood primarily as a marker of middle ear somatosensory activity in tinnitus subjects. Taken together, these observations support the middle ear as a plausible source of increased ECI drive in tinnitus.

Clinical contexts potentially associated with increased middle ear muscle activity

In the present framework, the following clinical contexts may be interpreted as situations in which middle ear muscle activity becomes abnormally elevated, thereby providing a possible route to tinnitus.

Loud-noise exposure and other deafferentation-related contexts

Noise exposure is the clearest clinical context in which the present model may operate, because it can combine the two key conditions summarised in Figure 1, namely reduced CI and increased middle ear muscle activity. Temporary tinnitus following loud-noise exposure is common both in individuals without chronic tinnitus and in patients who experience a transient worsening of pre-existing symptoms. Intense sounds elicit the acoustic reflex, that is, a sustained contraction of the SM whose strength increases with sound intensity [80]. Particularly intense, unexpected, or threatening sounds can also recruit the TTM and TVPM, likely through startle-related mechanisms [28,30]. Since tremor-like instability increases with contraction intensity and fatigue, and since repetitive intense contractions may act as a form of training that durably enhances synchronisation, prolonged or repeated loud-noise exposure could plausibly generate sufficient mechanical stimulation of MeRs to trigger transient tinnitus or exacerbate existing tinnitus [28,65].

Other deafferentation-related contexts may also fit the model, because cochlear injury may not only reduce CI but also secondarily increase middle ear muscle activity. A documented case of TTTS developing after sudden sensorineural hearing loss supports this possibility [64]. Moreover, aural fullness is experienced by the vast majority of patients during episodes of sudden hearing loss [81,82]. Two observations are particularly suggestive. In one study, perceived fullness correlated with the severity of the auditory deficit after auditory thresholds had stabilised [82]. In another, patients who initially reported fullness showed better long-term recovery of low frequencies [81], a pattern consistent with a reversible low-frequency threshold elevation caused by middle ear muscle contraction rather than permanent cochlear damage alone [83]. Although the available data are limited, these findings are consistent with the idea that cochlear deafferentation may, in some cases, trigger secondary activation of middle ear muscles. Taken together, acoustic trauma and related deafferentation contexts are especially relevant to the present model because they may combine reduced CI with increased middle ear muscle activity, either simultaneously or through secondary muscle activation following cochlear injury.

External auditory canal

External auditory canal disorders are relevant to the present model because they may precipitate tinnitus without themselves causing direct cochlear deafferentation, and tinnitus often resolves when the local cause is treated. External otitis and cerumen impaction have both been associated with tinnitus [8,84], and resolution commonly follows treatment or wax removal [8]. This observation is difficult to explain solely by reduced sound transmission, since occlusion of the auditory meatus does not itself produce cochlear injury; from the inner ear's perspective, there is no fundamental difference between reduced sound input caused by canal obstruction and a quieter acoustic environment.

Within the present framework, a more plausible explanation is that repeated stimulation of the external auditory canal increases middle ear muscle activity and, in the presence of pre-existing or subclinical cochlear deafferentation, may contribute to tinnitus. As discussed above, stimulation of the external auditory canal can induce changes in middle ear impedance, attributed mainly to SM contraction [30,37]. Recurrent canal irritation, whether from cerumen impaction or otitis externa, could therefore enhance middle ear muscle activation and, in susceptible individuals, promote tinnitus. When the local stimulation ceases, the disappearance of the triggering factor may account for tinnitus remission.

In addition, both external otitis and irritation from a cerumen plug are often accompanied by local inflammation. This may enhance tactile sensitivity [68], strengthen the afferent component of the reflex, and sensitise the trigeminocervical complex, thereby amplifying the efferent response. In this way, external auditory canal disorders can be understood as peripheral triggers of the pathway proposed in **Figure 1**.

Temporomandibular and cranio-cervical disorders

Temporomandibular and cranio-cervical disorders may fit the present model because both can engage trigeminal and upper cervical pathways linked to middle ear muscle activity. Clinically, these conditions are often accompanied by otological symptoms such as aural fullness, otalgia, vertigo, hearing loss, and tinnitus, with substantial overlap in their manifestations [85,86].

Several anatomical and functional links support the possibility that TMDs may contribute to tinnitus through increased middle ear muscle activity [87]. The temporomandibular system and the middle ear muscles share a common embryological origin in the first branchial arch, and phylogenetic analyses suggest a relationship between the masticatory muscles and the ossicular chain. The TTM and TVPM, like the masticatory muscles, are innervated by branches of the trigeminal nerve, particularly the medial pterygoid nerve. A functional association between the TTM and TVPM has been reported, especially during swallowing [32,36], and dental malocclusion has been linked to Eustachian tube dysfunction [88]. The auriculotemporal nerve, which innervates part of the temporomandibular joint, also supplies the tympanic membrane and external auditory canal, providing a plausible route for symptom overlap. Jaw movements can modulate tinnitus loudness and may even elicit tinnitus in susceptible individuals [25,89], suggesting that middle ear muscle activation could represent a shared contributing factor linking TMDs and tinnitus [87]. In addition, inflammation associated with TMDs may sensitise the trigeminocervical complex [68,90], potentially facilitating increased middle ear muscle activity.

A similar logic may apply to cranio-cervical disorders. Conditions affecting the cervical spine, neck muscles, or the broader cranio-cervical region have long been associated with tinnitus and related otological symptoms [85]. Levine, in a case series of patients with cranio-cervical dysfunction, proposed that somatic afferents from this region could modulate DCN activity and thereby contribute to tinnitus [91]. An additional interpretation is possible: middle ear muscles can contract in response to movements involving the cranio-cervical region, and sustained head flexion, for example, elicits prolonged contraction of both the SM and TTM [30]. Musculoskeletal disorders affecting this region might therefore provoke inappropriate activation of local mechanoreceptors, leading to increased middle ear muscle activity. As in TMDs, associated inflammation could further enhance this pathway by sensitising the trigeminocervical complex. A direct somatosensory influence on the DCN, as originally suggested by Levine, cannot be excluded. However, both TMDs and cranio-cervical disorders are consistent with the present model in that they may converge on increased middle ear muscle activity through trigeminal and upper cervical pathways.

Ménière's disease

Ménière's disease is characterised by episodic vertigo, fluctuating hearing loss, tinnitus, and aural fullness. Beyond the classical endolymphatic hydrops model [92], Bell [93] proposed an alternative hypothesis involving dysregulation and increased activity of the middle ear muscles, particularly the TTM, as a possible contributing mechanism. In this view, excessive contraction of the TTM could exert a mechanical effect on the ossicular chain, increase intra-labyrinthine pressure, and thereby influence outer hair cell (OHC) function and auditory gain, especially at low frequencies.

Several observations are compatible with a possible muscular contribution. First, no clearly established dedicated sensory pathway has yet been identified to detect pressure changes within the inner ear, whereas mechanosensory and proprioceptive feedback exists within the middle ear. Second, voluntary TTM contraction in healthy subjects induces a low-frequency threshold elevation that exceeds what would be expected from changes in middle ear admittance alone [83,94], with similar effects even under bone-conduction testing. Finally, symptomatic improvement, including tinnitus relief, has been reported following TTM tenotomy in selected cases [95], in contrast to the frequently limited efficacy of surgical interventions targeting endolymphatic hydrops [96].

Taken together, these findings suggest that abnormal middle ear muscle activity could contribute to at least some features of the syndrome, including tinnitus.

A possible role of middle ear input in acoustic gain integration

A natural question raised by the present hypothesis is what information putative MeRs could convey, and what functional role such input might play once it reaches the CN through extracochlear pathways. One possibility is that these receptors monitor changes in the mechanical state of the middle ear and therefore convey information about variations in middle ear admittance. MeR-related input could thus provide the CN with information about a precochlear component of acoustic gain. Tinnitus might then reflect, at least in part, a disturbance of mechanisms integrating information about acoustic gain. In this respect, the present hypothesis may be viewed as broadly compatible with central-gain accounts, while extending them by proposing a middle ear source of increased ECI drive. This interpretation is also consistent with Bell's proposal that middle ear muscle activity may influence cochlear sensitivity, thereby linking changes in middle ear mechanics to the regulation of acoustic gain at the cochlear level [97].

Several observations are compatible with this view. First, tinnitus is strongly associated with hyperacusis [63], a condition involving altered processing of sound intensity. Second, following significant acoustic trauma, many cochlear lesions involve the OHCs, a pattern also reported after certain chemotherapies [2,98]. Because OHCs contribute to active cochlear amplification, their dysfunction is also relevant to acoustic gain. It has therefore been proposed that type II auditory fibers, small unmyelinated fibers conveying signals from OHCs to the CN through the auditory nerve, may interact with extracochlear pathways in a process relevant to tinnitus generation [2,98].

Although the functional role of type II fibers remains uncertain [99,100], one may hypothesise that they provide the CN with information about cochlear amplification, whereas MeRs provide complementary information about the mechanical state and admittance of the middle ear. In this framework, the CN would integrate distinct signals related to acoustic gain at both the middle ear and cochlear levels. A disturbance of this integrative process could contribute not only to tinnitus, but also to its frequent association with hyperacusis.

Conclusions

This work proposes that subjective tinnitus may arise when reduced cochlear input is accompanied by abnormally increased extracochlear drive to the cochlear nucleus. In the present framework, heightened activity of the stapedius, tensor tympani, and tensor veli palatini may generate tremor-like vibrations within the tympanic cavity, overstimulating putative middle ear mechanoreceptors and thereby increasing somatosensory input to the cochlear nucleus (**Figure 1**).

A major limitation of this hypothesis is that the functional properties of these putative mechanoreceptors remain unknown. Progress is therefore most likely to come from direct physiological testing rather than further conceptual expansion. In animals, spontaneous or evoked activity of middle ear muscles could be assessed with electromyography and compared between tinnitus and non-tinnitus animals. In humans, refined admittance or impedance measurements with higher sampling rates could be used to search for rapid middle ear fluctuations consistent with tremor-like activity. Functional neuroimaging could test whether activation of BA 43 and BA 43/40 is also observed in tinnitus unrelated to acoustic trauma. A further prediction is that, among otherwise healthy subjects without clinically evident hearing impairment, individuals lacking a measurable stapedius reflex should show a different susceptibility to transient tinnitus or aural fullness after loud-noise exposure. Direct physiological validation will be required to determine whether this proposed pathway operates *in vivo*.

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COMPARISON OF A BOOTH-FREE AUDIOMETER WITH A CONVENTIONAL DEVICE IN TERMS OF IMMUNITY TO NOISE AND SUBJECTIVE COMFORT

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
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Abstract

Introduction: This study aimed to evaluate the noise immunity level (NIL) of the booth-free KUDUwave™ audiometer and compare the subjective comfort of its headphones against a conventional screening audiometer under simulated noise conditions, in order to determine its suitability for hearing screening in resource-limited settings.

Material and methods: 30 normal-hearing adults (aged 20–25 years) participated in a repeated-measures crossover study. Pure-tone air- and bone-conduction thresholds were obtained under quiet and background noise conditions using the KUDUwave audiometer and a conventional audiometer from Interacoustics. Three types of noise were presented: broadband noise (BBN), speech-shaped noise (SSN), and eight-talker babble (8-TB). In addition, the subjective comfort associated with each audiometer's headset was evaluated.

Results: Baseline air-conduction (AC) thresholds were comparable between the two audiometers, whereas bone-conduction (BC) thresholds were significantly lower with the KUDUwave, likely due to the occlusion effect. Across all noise conditions, the KUDUwave demonstrated higher NILs than the conventional audiometer, indicating greater resistance to ambient noise. In AC testing, NILs were lowest at low frequencies and highest at mid frequencies, with 8-TB producing greater masking effects than BBN and SSN. However, participants reported lower comfort with the KUDUwave headset compared to the conventional audiometer.

Conclusions: The KUDUwave audiometer demonstrated greater noise immunity than the conventional device, indicating enhanced resistance to ambient noise. These findings suggest its potential suitability for hearing screening in non–sound-treated, community-based environments. However, its real-world utility and practical advantages in such settings need to be further validated through field-based studies.

Keywords: pure-tone audiometry • ambient noise • noise immunity • hearing screening • user comfort

PORÓWNANIE DZIAŁANIA AUDIOMETRU NIEWYMAGAJĄCEGO KABINY AUDIOMETRYCZNEJ I AUDIOMETRU KONWENCJONALNEGO POD WZGLĘDEM ODPORNOŚCI NA HAŁAS OTOCZENIA ORAZ SUBIEKTYWNEGO KOMFORTU UŻYTKOWANIA

Streszczenie

Wprowadzenie: Celem badania była ocena odporności na hałas otoczenia (NIL) bezkabinowego audiometru KUDUwave™ oraz porównanie subiektywnego komfortu użytkowania jego słuchawek z komfortem zapewnianym przez konwencjonalny audiometr przesiewowy w warunkach symulowanego hałasu. Badanie miało na celu określenie przydatności tego urządzenia do prowadzenia badań przesiewowych słuchu w warunkach pozbawionych specjalistycznego zaplecza diagnostycznego.

Materiał i metody: W badaniu typu *crossover* z powtarzanymi pomiarami uczestniczyło 30 dorosłych osób z prawidłowym słuchem (w wieku 20–25 lat). Progi słyszenia dla przewodnictwa powietrznego (AC) i przewodnictwa kostnego (BC) wyznaczano w warunkach ciszy oraz w warunkach szumu tła z wykorzystaniem audiometru KUDUwave i konwencjonalnego audiometru firmy Interacoustics. Zastosowano trzy rodzaje szumu: 1) szerokopasmowy (BBN); 2) o widmie mowy (SSN) oraz 3) gwar ośmiu rozmówców (8-TB). Dodatkowo oceniono subiektywny komfort użytkowania zestawów słuchawkowych obu audiometrów.

Wyniki: Wyjściowe progi słyszenia dla przewodnictwa powietrznego były porównywalne w przypadku obu audiometrów, natomiast progi dla przewodnictwa kostnego były istotnie niższe w przypadku audiometru KUDUwave, co prawdopodobnie wynikało z efektu okluzji. W badaniach uwzględniających trzy rodzaje szumu audiometr KUDUwave wykazywał wyższy poziom odporności na hałas (NIL) niż audiometr konwencjonalny, co wskazuje na jego większą odporność na zakłócenia pochodzące z otoczenia. W badaniach przewodnictwa powietrznego wartości NIL były najniższe dla niskich częstotliwości, a najwyższe – dla średnich. Spośród zastosowanych rodzajów szumu największy efekt maskowania powodował gwar ośmiu rozmówców (8-TB) w porównaniu z hałasem szerokopasmowym (BBN) i hałasem o widmie mowy (SSN). Jednak uczestnicy badania ocenili komfort użytkowania zestawu słuchawkowego KUDUwave jako niższy niż komfort związany z używaniem słuchawek audiometru konwencjonalnego.

Wnioski: Audiometr KUDUwave wykazał większą odporność na hałas otoczenia niż urządzenie konwencjonalne, co wskazuje na jego większą skuteczność w ograniczaniu wpływu zakłóceń akustycznych podczas badania słuchu. Wyniki sugerują, że urządzenie to może być przydatne do prowadzenia przesiewowych badań słuchu poza kabiną audiometryczną – w warunkach terenowych, niespełniających standardów wyciszenia akustycznego. Konieczne są jednak dalsze badania terenowe w celu potwierdzenia jego użyteczności klinicznej oraz przewag praktycznych w rzeczywistych warunkach użytkowania.

Słowa kluczowe: audiometria tonalna • hałas otoczenia • odporność na hałas • przesiewowe badania słuchu • komfort użytkownika

Key to abbreviations	
8-TB	eight-talker babble
AC	air-conduction
BBN	broadband noise
BC	bone-conduction
NIL	noise immunity level
PTA	pure tone averages
SSN	speech-shaped noise

Introduction

Hearing loss is a global health concern that impairs communication, social interactions, and quality of life for millions worldwide. According to the World Health Organization, over 5% of the world's population (approximately 466 million people) suffer from disabling hearing loss, with projections indicating this number could rise to over 900 million by 2050 [1]. Early detection and intervention are critical to minimize the adverse effects of hearing loss and to improve the quality of life for those affected [2]. Given the demand for early identification and intervention, technologies that facilitate accurate detection of hearing loss by reducing false positives and retaining high specificity are critical. Booth-free audiometers are gaining traction as a cost-effective strategy to minimize referral rates and reduce the overall burden on healthcare systems [3].

Traditional hearing assessments typically use audiometric booths to minimize background noise and provide a controlled environment for accurate hearing threshold measurements. These booths, however, are expensive, bulky, and require significant space, making them impractical for use in low-resource settings, remote areas, or mobile hearing screening programs [4]. Additionally, the setup and maintenance of these booths can be challenging [5].

Innovative solutions such as booth-free audiometers have been developed to address these challenges. These systems are compact and portable, enabling audiometric testing in diverse settings, including remote areas and in patients' homes [6]. Advanced noise-cancellation technologies allow them to be used in environments with higher ambient noise, permitting reliable hearing assessment outside controlled clinical settings [7–9]. In addition, booth-free audiometers reduce the cost and complexity of sound-treated rooms, making hearing assessments more feasible for clinics with limited resources. Their quick and simple setup also promotes efficient workflows in busy clinics [5,8].

Several booth-free audiometry systems are currently available, including the KUDUwave™ boothless audiometer (GeoAxon Technologies, South Africa), PC-based audiometers (MedRx Inc., USA), mobile or tablet-based audiometers (HearX Group, USA), and virtual booth technologies such as the Wireless Automated Hearing Test System (Edare Inc., Lebanon). Previous studies have demonstrated the reliability of the KUDUwave for hearing assessment. For instance, Storey et al. [10] compared automated hearing assessments obtained using the KUDUwave and the GSI 61 clinical audiometer under different noise conditions. Their results showed that 89% of thresholds obtained using the KUDUwave in quiet and 92% obtained in background noise were within ±5 dB of those measured using a clinical audiometer. Similarly, Swanepoel et al. [11] reported that air- and bone-conduction thresholds obtained remotely using the KUDUwave closely matched in-person measurements within a quiet sound booth, with 96% of thresholds falling within a 10 dB range. Maclennan-Smith et al. [12] further demonstrated that KUDUwave's manual mode produced accurate hearing thresholds in background noise (47–54 dBA), with 95% of air-conduction (AC) and 86% of bone-conduction (BC) thresholds falling within ±5 dB of those obtained in a sound booth.

While previous studies have investigated the effectiveness of booth-free audiometers in continuous noise environments, a direct comparison of noise immunity level between conventional audiometers and the KUDUwave is lacking. Furthermore, validation of this technology is necessary to address challenges posed by multi-talker babble noise, which more closely resembles the auditory conditions encountered in community screening settings. Unlike continuous or steady-state noise, speech babble shares cognitive and linguistic characteristics with the target speech, making it more representative of real-world listening environments. This results in greater informational masking, as listeners must distinguish between acoustically and linguistically similar signals. Research has consistently shown that, due to this linguistic similarity, speech perception is more adversely affected by speech maskers than by non-speech noise [13–16]. Eight-talker babble, in particular, closely resembles the auditory conditions found in community screening camps, where multiple simultaneous conversations generate a highly dynamic and cognitively demanding background [17].

To the best of our knowledge, this study is perhaps the first to systematically compare noise immunity level between a booth-free audiometer and a conventional audiometer across multiple ecologically relevant noise conditions, including both steady-state and speech-based maskers.

Additionally, technological advancements in audiometry have primarily emphasized improvements in diagnostic accuracy and portability; however, user comfort and experience remain important but frequently underreported factors affecting clinical adoption and long-term usability. Discomfort or poor headset fit during audiometric testing can affect participant cooperation, concentration, and the reliability of threshold measurements [18]. Therefore, as well as assessing the diagnostic efficacy of booth-free audiometers it is equally important to evaluate user comfort.

Therefore, the current study compared the efficacy of the KUDUwave and a conventional audiometer in mitigating the adverse effects of ambient noise during audiometric testing. This was achieved by comparing the NIL obtained from both audiometers in the presence of three different types of noise: broadband noise (BBN), speech-shaped noise (SSN), and eight-talker babble (8-TB). Additionally, the study assessed participants' subjective perceptions of the comfort of both devices, focusing on attributes such as headset comfort, noise attenuation, pain, isolation, and ear blockage.

Material and methods

Participants

For this single-group repeated measures study, we randomly selected 30 normal-hearing individuals (14 males and 16 females, aged 20–25 years) with PTAs less than 15 dB HL and interaural asymmetry of less than 10 dB. All volunteered for the study, and written informed consent was obtained. The subjects had no present or past complaints of ear pain, ear discharge, recent change in hearing or balance, outer ear blockage as determined by otoscopic examination, or middle-ear dysfunction as determined by tympanometry. All experimental procedures adhered to the guidelines of the Institutional Ethical Committee for Bio-Behavioural Research Involving Human Subjects at the All India Institute of Speech and Hearing, Mysuru, India (approval SH/IRB/M.1/14//2024-25, dated 27.07.2024).

Young adults present an ideal study cohort because they typically exhibit a relatively homogeneous profile in terms of auditory function and overall health, which minimizes the presence of age-related hearing loss, degenerative changes, and chronic conditions that could otherwise confound audiometric measurements. This homogeneity enabled us to establish a reliable baseline of hearing thresholds and NIL. In addition, individuals in this age range are less likely to have experienced significant cumulative noise exposure, ototoxic medication use, or metabolic changes, thereby reducing potential confounding factors and making it more likely that any observed differences in NIL of KUDUwave were attributable to the device itself rather than underlying variations in hearing status [19,20].

Procedure

Each run began by estimating the baseline threshold at the test frequency for both AC and BC. We employed the modified Hughson–Westlake procedure [22] to determine thresholds. Once the baseline threshold was established, the respective pure tone was delivered continuously at baseline while a masking noise (broadband, SSN, or 8-TB) was turned on and presented continuously, starting at a level 5 dB below the baseline. After a 5-second acclimatization period, the modified Hughson–Westlake procedure was repeated to estimate the masked threshold. In preliminary data, it was seen that this threshold was the same as the baseline threshold in all participants. The noise level was then increased in 5 dB steps, re-estimating threshold at each noise level.

The NIL was defined as the lowest noise level at which the masked threshold showed a consistent >5 dB elevation from baseline (i.e., two of three ascending–descending trials). NILs were obtained separately for BBN, SSN, and 8-TB across both AC and BC modalities using both audiometers.

Each participant completed all tests in a single session lasting approximately 140–160 minutes, including short breaks. The order of testing conditions comprising audiometer type (conventional, KUDUwave), transducer modality (AC, BC), and noise type (BBN, SSN, 8-TB) was fully counterbalanced across participants to minimize order effects. For each condition, testing duration was approximately 8–10 minutes.

To control for fatigue, participants were provided a 1-minute rest after every five noise-level increments, along with additional short breaks (2–3 minutes) between major test blocks (e.g., between AC and BC testing or between audiometers). Fatigue was monitored informally through participant feedback and observation of response consistency, and testing was paused if participants reported discomfort or showed reduced concentration.

For BC testing with the KUDUwave, the bone vibrator was placed on the forehead while circumaural earcups remained in position, as per device configuration. To minimize response bias, participants were not informed about the study hypotheses or expected device differences. The flow chart of the procedures is shown in **Figure 1**.

Measurement of noise immunity level

Stimuli and equipment

Hearing thresholds were measured at octave frequencies from 250 to 8000 Hz using pure tones presented by air and bone conduction. Testing was performed under quiet conditions and in the presence of three noise types: BBN, SSN, and 8-TB. BBN (white noise with a flat power spectral density from 250–8000 Hz) was presented using a diagnostic audiometer (Inventis Piano, Inventis Inc., Italy). SSN simulates the long-term average spectrum of speech

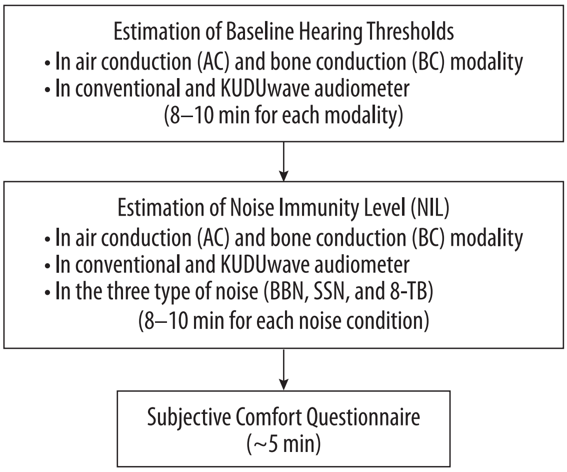

Figure 1. Flowchart illustrating the test procedure followed in the study

without linguistic content, whereas 8-TB consists of simultaneous recordings of multiple speakers. The 8-TB used in the study was in Kannada, as all participants were native Kannada speakers. Both SSN and 8-TB were the same as those generated by Kumar and Sandeep [21]. The KUDUwave 5000 (GeoAxon, Pretoria) Type-2 clinical audiometer (IEC 60645-1/2) was used to obtain hearing thresholds in the booth-free setup. The system was operated via eMoyo, a PC-based software platform supporting manual, automated screening, diagnostic pure-tone, and speech audiometry. For AC testing, the KUDUwave utilizes ER-3A insert earphones coupled with circumaural noise-attenuating earcups, while BC testing is performed using a forehead-placed bone vibrator integrated within the headset configuration.

To reduce ambient noise across a broad frequency range the device employs a dual-layer passive noise attenuation system, combining insert earphones with circumaural earcups. Additionally, built-in probe microphones continuously monitor real-time environmental noise levels within the ear canal, allowing the system to pause or flag testing when ambient noise exceeds permissible limits, thereby minimizing contamination of threshold measurements. This integrated approach enhances signal-to-noise ratio and reduces the likelihood of false-positive responses during testing in non-sound-treated environments.

Audiometric hearing thresholds using the conventional setup were obtained with the Interacoustics AD222 Type-2 clinical audiometer (IEC 60645-1), using TDH-39 supra-aural headphones for AC and a B71 bone vibrator for BC. All testing was conducted in a double-walled, sound-treated audiometric room to ensure accurate threshold and noise immunity level measurements. Noise stimuli (BBN, SSN, and 8-TB) were routed through a calibrated sound-field speaker using a separate diagnostic audiometer (Inventis Piano, Inventis Inc., Italy). The sound field speaker was positioned at 0-degree azimuth relative to the participant's ear and 1-m away. The loudspeaker output at ear level was monitored through a sound level meter (B&K 2270).

Subjective comfort of headsets

After completing audiometric testing with both audiometers, participants rated their subjective experiences. Discomfort associated with audiometric testing can affect the accuracy of test outcomes and overall compliance (IEC 60645-1: 2017). From the existing standardized 24 attributes of headsets reported in the literature, five attributes were selected that specifically focused on assessing headphone comfort [23]. They were; comfort, pain caused by the headphones, noise attenuation, sense of acoustic isolation, and sensation of ears being blocked or full – selected as they directly relate to the physical and perceptual experience associated with audiometric headset use. Other attributes in the original framework (e.g., design, brand perception, and sound quality) were not included, as they were not relevant to the objectives of the present study. Each participant rated these attributes on a 5-point Likert-type scale, where 1 indicated the least favourable experience (i.e., very uncomfortable, severe pain, very poor noise attenuation, no sense of acoustic isolation, very strong sensation of ear blockage or fullness) and 5 indicated the most favourable experience (i.e., very comfortable, no pain, excellent noise attenuation, complete sense of isolation, no sense of blockage or fullness).

Statistical analysis

The noise immunity level with NIL obtained in AC and BC modalities were analyzed across noise conditions and audiometers. A $2 \times 3 \times 6$ factorial repeated-measures ANOVA was conducted for the AC modality, with the factors being audiometer type (conventional, KUDUwave), noise type (BBN, SSN, 8-TB), and frequency (250, 500, 1000, 2000, 4000, and 8000 Hz). Similarly, for the BC modality, a $2 \times 3 \times 5$ repeated-measures ANOVA was performed across 250, 500, 1000, 2000, and 4000 Hz. Post hoc pairwise comparisons were conducted where appropriate, and significance was set at $p < 0.05$.

Table 1. Paired *t*-tests at each test frequency comparing baseline air conduction and bone conduction thresholds between the conventional audiometer and the KUDUwave audiometer

Modality	Test frequency	*df*	Mean difference	SE	*t*-values	*p*-values	Cohen's *d*
Air conduction (AC)	250	29	–0.333	4.722	–0.387	0.702	–
	500	29	–0.667	4.686	–0.779	0.442	–
	1000	29	0.000	4.913	0.001	> 0.999	–
	2000	29	0.000	4.913	0.001	> 0.999	–
	4000	29	–0.166	4.639	–0.197	0.845	–
	8000	29	0.166	4.639	0.197	0.845	–
Bone conduction (BC)	250	29	3.500	4.939	3.881	0.001	0.71
	500	29	4.666	5.241	4.877	< 0.001	0.89
	1000	29	5.000	5.085	5.385	< 0.001	0.98
	2000	29	1.833	3.591	2.796	0.009	0.51
	4000	29	2.000	2.816	3.890	0.001	0.71

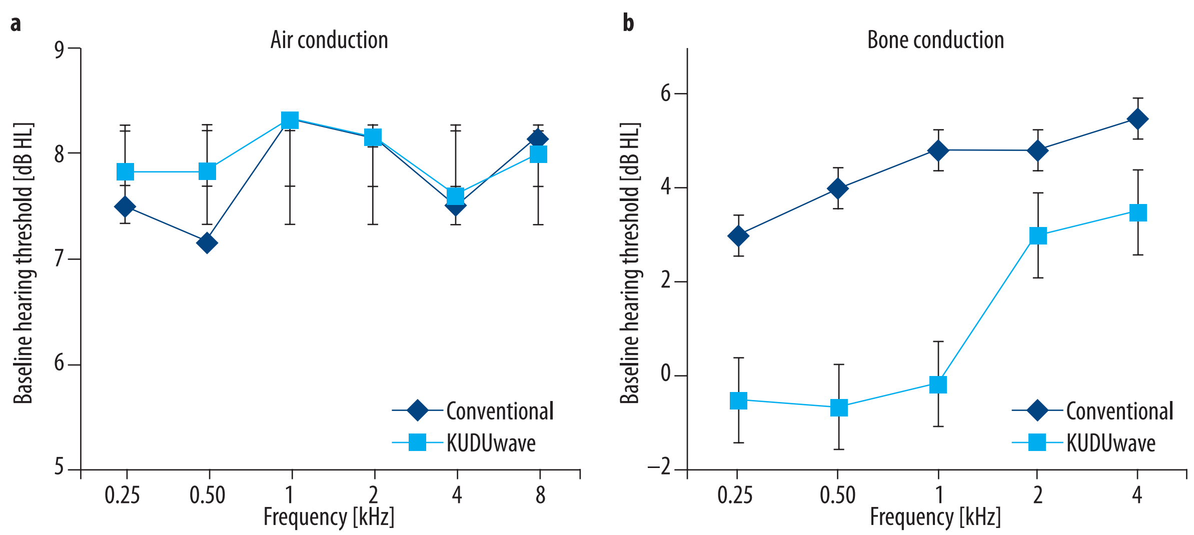

Figure 2. Baseline hearing thresholds (mean and standard deviation) for air conduction (**a**) and bone conduction (**b**) obtained using both the conventional and KUDUwave audiometers

Results

Noise immunity level

The KUDUwave audiometer consistently yielded lower (better) thresholds than the conventional audiometer. Paired *t*-tests (**Table 1**) showed no significant differences in baseline AC thresholds across all frequencies. However, BC thresholds were significantly lower with the KUDUwave audiometer ($p < 0.001$) at all frequencies, with moderate to large effect sizes (Cohen's $d = 0.51–0.98$). **Figure 2** presents the mean and standard deviation of the thresholds. Mean AC differences were within 5 dB HL across frequencies, whereas BC thresholds showed larger differences, particularly at lower frequencies.

A 2 × 3 × 6 factorial repeated measures ANOVA was conducted for the AC modality across six frequencies, and a similar analysis was performed for the BC modality across five frequencies. **Table 2** presents the main and interaction effects of the repeated-measures ANOVA for AC and BC modalities. In the AC modality, NILs were higher for the KUDUwave audiometer than the conventional audiometer across all noise types (**Figure 3**), with mean differences ranging from 20 to 28 dB HL for AC and standard deviations within 5.6 dB HL at all test frequencies across the three noise conditions.

Across the noise conditions, mean NILs were slightly higher for BBN and SSN compared to 8-TB, with similar values between BBN and SSN. Across frequencies, NILs were highest at mid frequencies (1000–4000 Hz), lower at low

Table 2. Results of repeated measures ANOVA for factors audiometer type, noise type, and frequency, and their interaction in AC and BC; the *F*-values, *p*-values, and effect sizes are shown

Modality	Condition	*F*-values	*p*-values	ηp^2
Air conduction (AC)	Audiometer type	1192.427	< 0.001	0.976
	Noise type	31.559	< 0.001	0.521
	Frequency	47.803	< 0.001	0.622
	Audiometer type / Noise type	1.031	0.363	–
	Audiometer type / Frequency	44.108	< 0.001	0.603
	Noise type / Frequency	3.536	< 0.001	0.109
	Audiometer type / Noise type / Frequency	0.868	0.564	–
Bone conduction (BC)	Audiometer type	12537.467	< 0.001	0.998
	Noise type	0.352	0.705	–
	Frequency	21.945	< 0.001	0.413
	Audiometer type / Noise type	0.114	0.893	–
	Audiometer type / Frequency	51.050	< 0.001	0.638
	Noise type / Frequency	0.824	0.582	–
	Audiometer type / Noise type / Frequency	0.447	0.892	–

frequencies (250–500 Hz), and lowest at 8000 Hz, irrespective of noise type. A significant main effect of audiometer type, noise type, and frequency was observed, along with a significant audiometer × frequency interaction. However, the audiometer × noise type and three-way interactions were not significant.

In the BC modality and for all three noise types, the mean NILs (**Figure 3**) were higher for the KUDUwave audiometer than for the conventional audiometer, with mean differences ranging from 35 to 42 dB and standard deviations within 4.42 dB for all test frequencies and noise type.

Across noise type and all tested frequencies, mean NILs were consistent across BBN, SSN, and 8-TB. Additionally, in BC mode, NILs decreased as frequency increased, regardless of the noise types. A significant interaction was found between audiometer type and frequency, suggesting that the difference in NILs between audiometers varied across frequencies.

Pairwise comparisons (**Table 3**) showed that in the AC modality, significant differences were observed between SSN and 8-TB, as well as between BBN and 8-TB. However, no significant difference was found between SSN and BBN. The pairwise comparisons across the frequency in AC modality, indicated that the NIL was sigificantly higher at mid frequencies compared to the low (250 Hz) and high (8000 Hz) frequencies. Mean differences in NIL ranged from 1.167 to 4.639. In contrast, in the BC modality, the low frequencies (250 and 500 Hz) exhibited higher NILs with mean differences ranging from 0.833 to 1.861 (detailed statistics are available with the authors and will be published on request).

Subjective comfort

Figure 4 depicts the ratings for the five target attributes (comfort, headphone-induced pain, noise attenuation, feeling of complete isolation, and sensation of the ears feeling blocked/full) obtained on the 5-point scale for the two headsets. For the attributes of comfort and headphone-induced pain, most participants rated the conventional audiometer headphones between 4 and 5 (representing comfortable to very comfortable and minimal to no pain, respectively), whereas the KUDUwave headset was commonly rated between 1 and 3 (representing very uncomfortable to neutral and very painful to neutral, respectively). On the contrary, the opposite was obtained for the other three attributes. The Wilcoxon signed-rank test showed a significant difference in all five measured attributes: comfort ($z = 4.767$, $p < 0.001$, $r = 0.870$), pain ($z = 4.627$, $p < 0.001$, $r = 0.844$), noise attenuation ($z = 4.594$, $p < 0.001$, $r = 0.839$), feeling of complete isolation ($z = 4.543$, $p < 0.001$, $r = 0.830$), and sensation of ears feeling blocked/full ($z = 4.780$, $p < 0.001$, $r = 0.873$), showing that participants rated the two audiometers quite differently.

Discussion

The present study evaluated hearing threshold estimation using a conventional and the KUDUwave audiometer under quiet and noisy conditions involving three noise types: BBN, SSN, and 8-TB, across various frequencies. Baseline AC thresholds obtained using both audiometers were comparable, indicating stable and reliable measurements under quiet conditions.

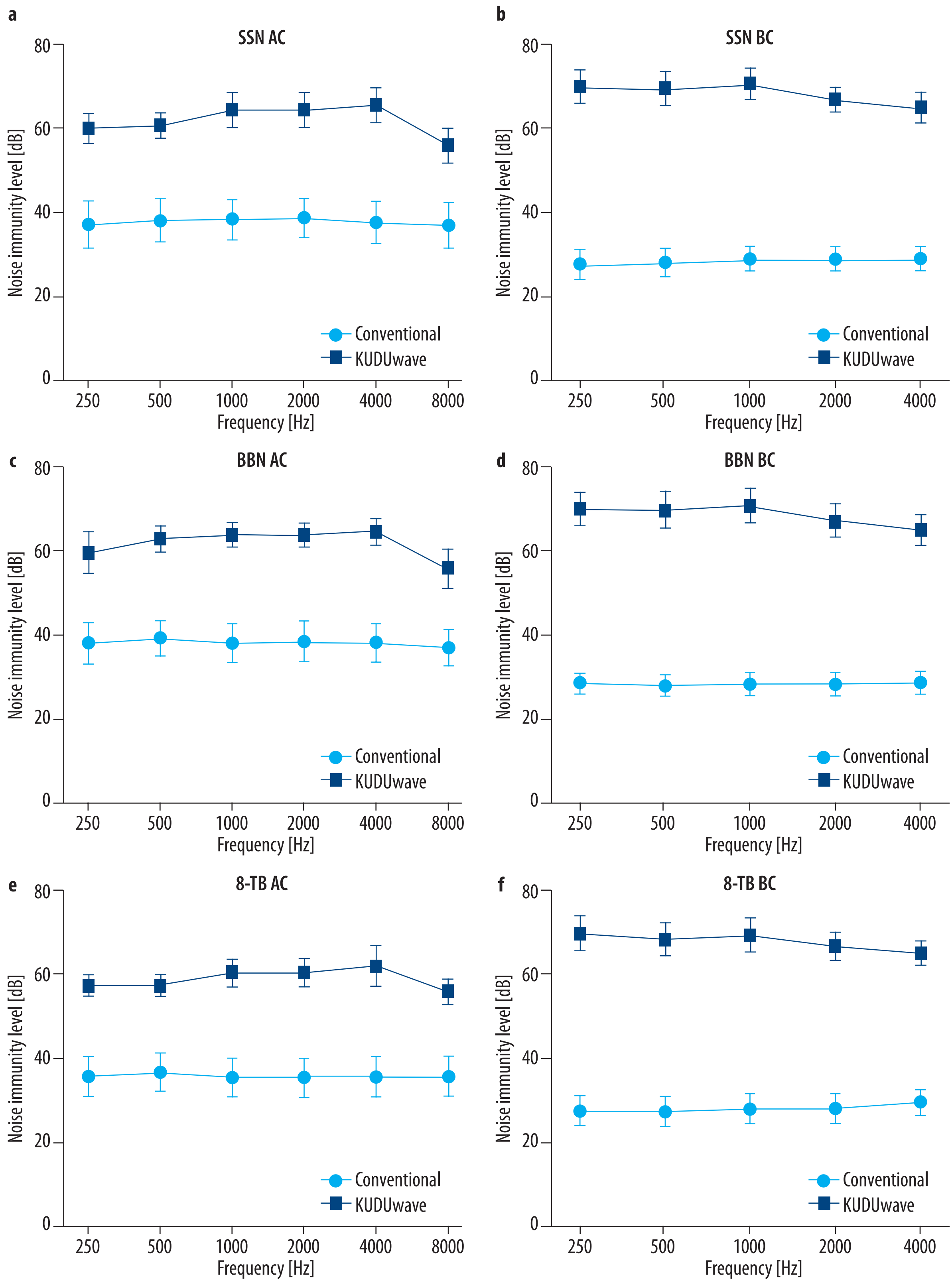

Figure 3. Noise immunity level (mean and standard deviation) obtained using the conventional and KUDUwave™ audiometer in air conduction (AC) and bone conduction (BC) modalities across three noise conditions: (**a, b**) speech-shaped noise, SSN; (**c, d**) broad-band noise, BBN; and (**e, f**) eight-talker babble, 8-TB

Table 3. Pairwise comparison of noise immunity level (NIL) across frequencies in air conduction and bone conduction; S = significant; NS = not significant

Modality	Frequency [Hz]	250	500	1000	2000	4000	8000
Air conduction	250		S	S	S	S	S
	500			NS	NS	S	S
	1000				NS	NS	S
	2000					NS	S
	4000						S
Bone conduction	250		NS	NS	S	S	
	500			S	S	S	
	1000				S	S	
	2000					NS	

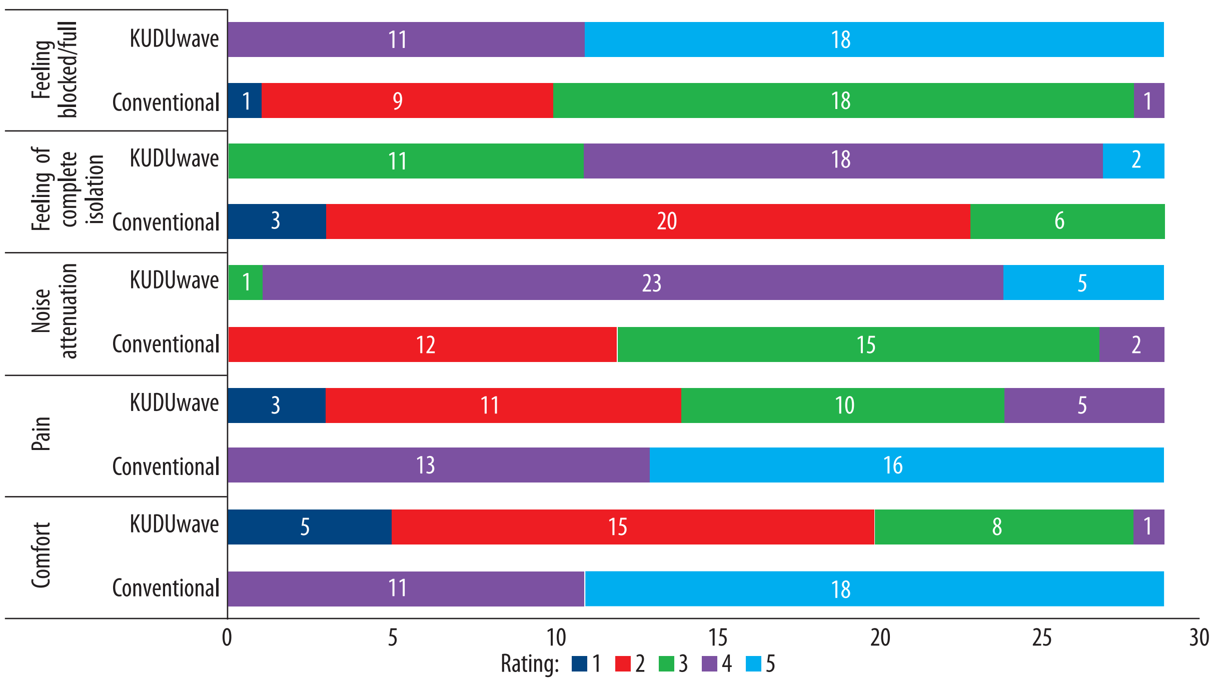

Figure 4. Subjective ratings (colour coded 1 to 5) given by 30 participants (the number giving each rating provided on bars) for their experience with the audiometer headphones (conventional and KUDUwave) during hearing threshold estimation. The ratings are for comfort (very uncomfortable to very comfortable), pain caused by the headphones (severe to none), effectiveness of noise attenuation (very poor to excellent), sense of isolation from the environment (none to complete), and sensation of ear blockage or fullness (very strong to none)

BC thresholds measured using the KUDUwave were consistently lower (i.e., better) than those obtained using a conventional audiometer. This difference can be attributed to the occlusion effect introduced by the circumaural headphones of the KUDUwave, which tightly cover both ears (while its bone vibrator is placed on the forehead). The occlusion effect enhances the perception of bone-conducted sound, especially at low frequencies, by trapping vibratory energy within the occluded ear canal. Goldstein and Hayes [24] reported the occlusion effect to be approximately +24 dB at 250 Hz, +20 dB at 500 Hz, and +10 dB at 1000 Hz, diminishing to near 0 dB at 2000 Hz and higher. These frequency-specific differences in occlusion explain the pronounced BC threshold improvements at lower frequencies. Direct comparison of BC thresholds between the two systems should be interpreted cautiously, because the KUDUwave introduces an occlusion effect due to its circumaural earcups, which is absent in conventional BC measurements. Thus, the observed differences are probably attributable to an occlusion effect.

The KUDUwave demonstrated superior performance in noisy environments compared to conventional audiometers, maintaining threshold accuracy even as ambient noise levels increased. It reliably estimated AC thresholds in environments with noise levels up to 50–65 dB SPL and BC thresholds up to 60–75 dB SPL. This enhanced noise immunity is primarily due to the combination of insert earphones and circumaural earcups, which together provide substantial passive attenuation across the frequency range.

Such capability is particularly beneficial for community-based hearing screening programs, where sound-treated environments are unavailable and ambient noise levels are typically high. For instance, Abraham et al. [25] reported ambient noise levels of 58.3 dB SPL in a meditation center, 60.1 dB SPL in a household, and 64.8 dB SPL in a rural panchayat office, levels that exceed the operating threshold of standard audiometers (20–40 dB SPL). In these contexts, the KUDUwave can reduce the rate of false-positive referrals that often arise when testing in noisy environments at the standard 25 dB HL cut-off. Even in such conditions the KUDUwave is capable of reliably detecting hearing losses up to a moderately severe degree [26]. Given that ambient noise poses greater interference for individuals with milder hearing losses [27], the KUDUwave's resistance to noise assists in estimating more accurate thresholds.

Across all noise types and frequencies, inter-subject variability in NILs was minimal, with standard deviations consistently below 6 dB. This indicates a good degree of test–retest reliability.

The significant interaction between noise and frequency in the AC modality indicates that masking effects varied with the spectral characteristics of the stimuli (BBN, SSN, and 8-TB). NILs were lower at low frequencies (250–500 Hz), likely due to stronger energetic masking from dominant low-frequency ambient noise, and highest at mid frequencies (1000–4000 Hz), indicating greater resistance to masking. Slightly reduced noise immunity at 8000 Hz may reflect limitations in transducer attenuation and residual masking effects. These findings align with those of Storey et al. [10], who reported reduced accuracy at 250 and 8000 Hz. Despite this variation, NIL differences across frequencies were within 10 dB, and performance remained robust at the key screening frequencies of 0.5, 1, 2, and 4 kHz recommended by WHO [1].

When comparing noise types, the KUDUwave exhibited greater immunity to BBN and SSN than to 8-TB. The 8-TB condition produced lower NILs, indicating a higher masking effect, likely due to both energetic and informational masking. As speech babble simulates more realistic and cognitively demanding listening environments, it poses greater challenges for threshold determination. Thus, NILs obtained under 8-TB conditions may serve as the most conservative and realistic reference values for noise immunity in field applications. In contrast, BC thresholds remained stable across noise types, likely because bone-conducted signals bypass the outer and middle ear and are less affected by environmental noise. This highlights the device's relative advantage in BC testing in adverse conditions. However, a limitation of this study is the inclusion of only young adults with normal hearing, limiting generalization of the findings to children and older adults with normal hearing and to individuals with hearing loss. We do not expect that the other participant groups will have different levels of immunity to ambient noise. However, it needs to be scientifically validated.

Despite its technical advantages, user feedback highlighted notable discomfort with the KUDUwave headset, particularly the weight and pressure of its circumaural earcups. Participants reported sensations of ear fullness and pressure, possibly exacerbated by extended testing durations. Similar observations have been made by Liu et al. [28], who noted that increased attenuation from circumaural configurations may lead to physical discomfort during prolonged use.

In this study, both AC and BC thresholds were measured, resulting in longer test sessions. However, in typical screening camps where only AC thresholds are assessed, the duration will be considerably shorter, perhaps mitigating the reported discomfort issue. To maintain user comfort, future research should explore preferred session durations for different age groups, particularly pediatric and geriatric populations.

The findings point to the suitability of the KUDUwave audiometer for use in community screening settings, particularly where the acoustic environment is uncontrolled. Its ability to maintain accurate thresholds in ambient noise up to 65 dB SPL and its robustness against noise-induced variability make it a promising tool for large-scale outreach initiatives. However, the trade-off between comfort and attenuation must be carefully considered, noting that community screenings will prioritize short test sessions.

It is important to note that the present study did not directly evaluate screening outcomes (e.g., referral rates or diagnostic accuracy) in real-world contexts. Therefore, while the findings indicate robustness to ambient noise, their applicability to actual community screening settings warrants further validation.

Conclusions

We found that the KUDUwave boothless audiometer demonstrated reliable noise immunity up to 65 dB HL, supporting its suitability for community-based hearing screening in acoustically uncontrolled environments. Accurate thresholds were maintained even in the presence of challenging speech babble noise, an advantage for hearing assessment in community-based settings. However, concerns about user comfort particularly headset weight and pressure during prolonged testing highlight the need for an improved ergonomic design. However, in general, the KUDUwave audiometer is a promising solution for expanding access to reliable hearing screening in resource-limited and noisy settings.

Limitations and future work

The present study has some limitations. First, the sample consisted exclusively of young adults with normal hearing, which limits the generalizability of the results to pediatric, geriatric, and hearing-impaired populations, who may exhibit different susceptibility to ambient noise and variability in threshold estimation. Second, the study did not directly evaluate real-world screening outcomes such as referral rates, sensitivity, specificity, or diagnostic accuracy in community settings; therefore, the implications for large-scale screening programs remain uncertain. Third, discrepancies in bone conduction thresholds between the audiometer were affected by the occlusion effect inherent to the KUDUwave headset, limiting comparisons with conventional audiometer. Additionally, user-reported discomfort related to the weight and pressure of the circumaural earcups is an ergonomic limitation, particularly for prolonged testing. Future research should include diverse age groups and individuals with varying degrees and types of hearing loss, assess performance in real-world community screening environments, and examine clinical outcomes such as false-positive and false-negative rates. Further studies should also explore optimization of test duration and ergonomic improvements in headset design to enhance user comfort, especially for pediatric and older populations.

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Supplementary material

Supplement 1. Mean noise immunity level [dB HL] across frequencies and noise types in air conduction (AC) and bone conduction (BC) modality

Modality	Frequency [Hz]	Conventional audiometer			KUDUwave audiometer		
		BBN	SSN	8-TB	BBN	SSN	8-TB
Air conduction (AC)	250	37.83	37	35.5	59.5	59.83	57.17
	500	39.00	38	36.5	62.67	60.5	57.17
	1000	37.83	38.17	35.33	63.67	64.17	60.17
	2000	38.16	38.5	35.33	63.66	64.16	60.16
	4000	38	37.5	35.5	64.5	65.33	61.83
	8000	36.83	36.83	35.5	55.66	55.83	55.66
Bone conduction (BC)	250	28.16	27.33	27.33	69.66	69.83	69.66
	500	27.66	27.83	27.16	69.5	69.33	68.33
	1000	28	28.66	27.83	70.5	70.5	69.33
	2000	28	28.66	27.83	67	66.66	66.66
	4000	28.33	28.66	29.83	64.66	64.83	65

Supplement 2. Pairwise comparisons of noise immunity level (NIL) across frequencies in air conduction (AC) modality

Compared frequency pairs [Hz]	Mean difference	*p*
250 vs 500	–1.167	< 0.001
250 vs 1000	–2.083	0.002
250 vs 2000	–2.194	0.001
250 vs 4000	–2.639	< 0.001
250 vs 8000	2.0	> 0.001
500 vs 1000	–0.917	0.409
500 vs 2000	–1.028	0.259
500 vs 4000	–1.472	< 0.001
500 vs 8000	3.167	< 0.001
1000 vs 2000	–0.111	> 0.999
1000 vs 4000	–0.556	0.824
1000 vs 8000	4.083	< 0.001
2000 vs 4000	–0.444	> 0.999
2000 vs 8000	4.194	< 0.001
4000 vs 8000	4.639	< 0.001

Supplement 3. Pairwise comparisons of noise immunity level (NIL) across frequencies in bone conduction (BC) modality

Compared frequency pairs [Hz]	Mean difference	*p*
250 vs 500	0.361	> 0.999
250 vs 1000	–0.472	0.269
250 vs 2000	1.194	0.001
250 vs 4000	1.861	< 0.001
500 vs 1000	–0.833	0.012
500 vs 2000	0.833	0.023
500 vs 4000	1.500	0.002
1000 vs 2000	1.667	< 0.001
1000 vs 4000	2.333	< 0.001
2000 vs 4000	0.667	0.194

Supplement 4. Questionnaire for Subjective Comfort with Headphones of Audiometer

Participant's Demographic Details

Name:

Age:

Gender:

Occupation:

Informed consent

'I have been informed about the purpose and procedure of the questionnaire. I declare that my participation in this study is entirely voluntary and that I may withdraw at any time without incurring a penalty or without being obligated to provide a reason. I understand that my participation in the study will not adversely affect me in any way and that confidentiality will be maintained about my identity at all times. I also understand that the information given by me will be used only for the purpose of the study. I do not have any financial or non-financial benefits from this study. I hereby give my consent to participate.'

Date: Name:

Place: Signature:

Instructions to Participants

The questionnaire consists of five items assessing headset experience on a 5-point scale across the following attributes: overall comfort, pain caused by the headphones, effectiveness of noise attenuation, sense of complete isolation from the environment, and sensation of ear blockage or fullness.

You will be asked to rate your experience with the two audiometer headsets used during testing (KUDUwave™ and the conventional headphones). Please read each item carefully and indicate your response based on your personal experience with each headset. There are no right or wrong answers; kindly select the option that best reflects your perception.

No.	Attributes	1	2	3	4	5
1.	Overall comfort while wearing the headphones	very uncomfortable	uncomfortable	neutral	comfortable	very comfortable
2.	Pain caused by the headphones	severe pain	moderate pain	mild pain	minimal pain	no pain
3.	Effectiveness of noise attenuation	very poor	poor	moderate	good	excellent
4.	Sense of acoustic isolation from the environment	none	slight	moderate	good	complete
5.	Sensation of ear blockage or fullness	very strong	strong	moderate	slight	none

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MONOSYLLABIC SPEECH PERCEPTION UNDER MULTI-TALKER BABBLE FOR NORMAL ADULTS: A PHONOLOGICAL PERSPECTIVE

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
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Abstract

Introduction: Speech perception in noisy environments is a crucial skill that often declines with age and varies across languages. Considering the need for a language-specific assessment tool, the present study aimed to develop the Speech-in-Noise Test–Hindi (SiNT-H) and to evaluate speech recognition performance and phonetic error patterns between younger and middle-aged adults at varying signal-to-noise ratios (SNRs).

Material and methods: The study included 27 young and 27 middle-aged native Hindi speakers with hearing thresholds ≤ 25 dB HL. The study was conducted in two phases. Phase I involved the development of the SiNT-H, its administration to young adults, analysis of performance across SNRs, and assessment of test–retest reliability. Phase II compared SiNT-H scores between young and middle-aged adults at different SNRs using four-talker babble noise. Additionally, a detailed phonetic error analysis was carried out across SNR conditions.

Results: The SiNT-H demonstrated no significant ear-wise or list-wise differences. Females outperformed males, with younger females showing better performance than middle-aged females, indicating a gender–age interaction. Performance significantly declined with decreasing SNRs, confirming the test's sensitivity to noise. Phonetic analysis revealed increased errors at lower SNRs, particularly in voicing, manner, place, and aspiration features. At 0 dB SNR, voicing, manner, and aspiration errors were more prevalent among middle-aged adults, reflecting declines in age-related processing.

Conclusions: The findings highlight the importance of incorporating language-specific acoustic-phonetic features in speech-in-noise assessment and underscore the influence of age on speech perception in noisy environments. The SiNT-H appears to be a sensitive tool for evaluating age-related changes in speech recognition in noise among Hindi speakers.

Keywords: Hindi • speech-in-noise test • monosyllabic words • speech babble • phonetic error analysis

ROZUMIENIE SŁÓW JEDNOSYLABOWYCH NA TLE GWARU PRZEZ DOROSŁYCH ZE SŁUCHEM W NORMIE: PERSPEKTYWA FONOLOGICZNA

Streszczenie

Wprowadzenie: Percepcja mowy w warunkach szumu stanowi podstawową zdolność komunikacyjną, która często ulega pogorszeniu wraz z wiekiem i wykazuje zróżnicowanie w zależności od języka. W rezultacie istnieje konieczność dostosowania narzędzi diagnostycznych do specyfiki danego języka. Celem niniejszego badania było opracowanie Hindi Speech-in-Noise Test (SiNT-H), dokonanie oceny wyników rozumienia mowy oraz zidentyfikowanie wzorców błędów fonetycznych u osób młodych i w średnim wieku przy różnych wartościach stosunku sygnału do szumu (SNR).

Materiał i metody: Badaniem objęto 27 młodych oraz 27 osób w średnim wieku, będących rodzimymi użytkownikami języka hindi, z progami słyszenia ≤ 25 dB HL. Badanie przeprowadzono w dwóch etapach. Etap I obejmował opracowanie testu SiNT-H, jego zastosowanie w grupie młodych dorosłych, analizę uzyskanych wyników dla różnych wartości SNR oraz ocenę rzetelności testu metodą test–retest. Etap II polegał na porównaniu wyników uzyskanych w teście SiNT-H przez osoby młode i osoby w wieku średnim dla różnych wartości SNR z wykorzystaniem gwaru. Ponadto przeprowadzono szczegółową analizę błędów fonetycznych w poszczególnych warunkach SNR.

Wyniki: W teście SiNT-H nie stwierdzono istotnych różnic związanych ani z badanym uchem, ani z zastosowaną listą materiału słownego. Kobiety uzyskiwały wyższe wyniki niż mężczyźni, przy czym młodsze kobiety osiągały wyższe wyniki niż kobiety w średnim wieku, co wskazuje na korelację między płcią a wiekiem. Wyniki obniżały się istotnie wraz ze zmniejszaniem wartości SNR, co stanowi potwierdzenie czułości testu na obecność szumu. Analiza fonetyczna wykazała wzrost liczby błędów przy niższych wartościach SNR, zwłaszcza w zakresie cech takich jak:

dźwięczność, sposób artykulacji, miejsce artykulacji oraz aspiracja. Przy SNR równym 0 dB błędy dotyczące dźwięczności, sposobu artykulacji i aspiracji występowały częściej u osób w średnim wieku, odzwierciedlając związane z wiekiem obniżenie sprawności przetwarzania mowy.

Wnioski: Uzyskane wyniki świadczą o tym, że w ocenie rozumienia mowy w warunkach szumu ważną rolę odgrywa uwzględnienie cech akustyczno-fonetycznych specyficznych dla danego języka, oraz wskazują na istotny wpływ wieku na percepcję mowy w hałaśliwym otoczeniu. Test SiNT-H wydaje się czułym narzędziem, właściwym do oceny zmian związanych z wiekiem w rozpoznawaniu mowy w warunkach szumu u użytkowników języka hindi.

Słowa kluczowe: hindi • test rozumienia mowy w szumie • słowa jednosylabowe • szum wielogłosowy • analiza błędów fonetycznych

Key to abbreviations	
AI	articulation index
F0	fundamental frequency
IEEE	Institute of Electrical and Electronics Engineers
IQR	interquartile range
MOC	medial olivocochlear
PTA	pure-tone average
RMS	root mean square
SiN	speech in noise
SiNT-H	Speech-in-Noise Test–Hindi
SNR	signal-to-noise ratio
SRT	speech reception threshold
WRS	word recognition score

Introduction

Effective speech communication depends critically on the listener's ability to perceive and comprehend spoken language at the word level. While pure-tone audiometry remains the gold standard for assessing auditory sensitivity, it provides limited insight into functional speech understanding. In contrast, speech perception testing offers a more ecologically valid perspective by evaluating how individuals process spoken language in real-world contexts [1].

Among the conventional tools, Speech Reception Threshold (SRT) and Word Recognition Score (WRS) are commonly employed to assess speech perception in quiet environments [2,3]. However, these measures inadequately represent the challenges listeners face in everyday noisy situations [4]. Understanding speech in noise (SiN) remains challenging even for individuals with normal audiometric thresholds [5–8]. Effective SiN perception requires the suppression of competing background noise and the selective attention to target speech – abilities that rely on an intricate interplay between auditory processing and higher-order cognitive functions [4,9]. Listener-related factors such as age, cognitive capacity, and peripheral hearing status further modulate performance in noisy environments [10].

Speech-in-noise tests provide critical information beyond what is available from traditional audiometric evaluations. These assessments capture complex auditory mechanisms, including temporal resolution, binaural integration, and the interface between linguistic and cognitive processing [1]. Various SiN measures differ in linguistic structure and cognitive demands. Sentence-based tests leverage contextual cues, engaging top-down processing mechanisms [11], whereas monosyllabic word tests emphasise bottom-up auditory perception by minimising linguistic redundancy [8]. This distinction holds clinical relevance as it aids in differentiating peripheral from central auditory impairments and is particularly valuable in evaluating the benefit of hearing aid features such as noise reduction algorithms [12,13]. Importantly, SiN testing is instrumental in identifying "hidden hearing loss", a phenomenon where individuals experience listening difficulties in noise despite normal pure-tone thresholds [14]. Over the decades, SiN testing has been extended to the diagnosis of auditory processing disorders, hearing aid candidacy, and post-intervention outcome monitoring [15,16]. However, a critical limitation remains: speech-in-noise perception is highly language-specific [17], necessitating the development of linguistically and culturally appropriate assessment tools [18].

In a multilingual country like India, Hindi is the most widely spoken language [19,20]. Yet, there is a conspicuous lack of standardised SiN tests in Hindi, especially those employing monosyllabic stimuli, which are essential for evaluating phoneme-level auditory deficits. This gap is particularly pertinent given the known age-related variations in SiN perception [21]. Research has shown that individuals across age groups employ distinct processing strategies and are differently influenced by both energetic and informational masking [21,22]. Additionally, performance in SiN tasks is known to vary at the phoneme level. Research has demonstrated that vowels are generally more robust against masking than consonants. For instance, Weber and Smits [23] reported vowel recognition accuracy at 78%, compared to 69% for consonants in multitalker babble. Similarly, Moreno-Torres et al. [24] observed enhanced vowel recognition in Spanish-speaking populations, with frontal consonants being particularly vulnerable to masking. Such differences are largely attributed to acoustic features such as frequency content, intensity, and temporal structure, where high-frequency consonants like /ʧ/, /s/, and /j/ tend to be recognised more reliably than mid- and low-frequency sounds like /r/, /m/, /n/, /p/, /t/, and /k/. The complexity of Hindi phonology further amplifies these challenges. Hindi comprises a rich array of phonemic distinctions – such as aspiration, retroflexion, and vowel length – that may influence susceptibility to noise-induced distortion [25]. Aspirated and retroflex consonants, for instance, carry unique acoustic markers that may degrade more readily in noisy environments.

Wang and Bilger [26] found that fricatives like /f/ and /h/ are particularly vulnerable to masking, while Cutler et al. [27] noted that consonant recognition improves with increasing signal-to-noise ratio (SNR), albeit with non-native listeners experiencing greater difficulty.

Given this context, the present study was undertaken to develop and evaluate the Speech-in-Noise Test in Hindi (SiNT-H) using monosyllabic word stimuli embedded in ecologically valid multitalker babble. By assessing both age-wise performance and phoneme-specific error patterns, this study aims to provide normative benchmarks and contribute to a deeper phonological understanding of speech perception in Hindi.

Material and methods

Participants

A total of 54 native Hindi-speaking adults participated in the study. The sample size was determined with reference to the findings of Vaidyanath and Yathiraj [28], who reported mean speech-in-noise scores of 22.74 ± 2.09 for young adults ($n = 34$) and 13.83 ± 3.93 for older adults ($n = 49$) with hearing thresholds ≤ 15 dB HL. Based on these values, an effect size (d) of 2.5 was considered. With a significance level (α) of 5% corresponding to a 95% confidence interval ($Z = 1.96$) and a test power of 80%, the required sample size was calculated to be 27 participants per group. Thus, the total sample size comprised 54 participants. Hence, the participants were equally divided into two age groups: young adults aged 20–39 years and middle-aged adults aged 40–59 years, with 27 individuals in each group. The young adult group consisted of 10 males and 17 females, whereas the middle-aged group included 16 males and 11 females.

All participants demonstrated normal hearing sensitivity, with pure-tone thresholds ≤ 25 dB HL across octave frequencies from 0.25 to 4 kHz in both ears. Middle ear function was confirmed using tympanometry, and individuals exhibiting any signs of middle ear pathology, otological complaints, tinnitus, speech-language or neurological disorders, or cognitive impairments were excluded. Ethical approval for the study was obtained from the Institutional Ethics Committee of Bharati Vidyapeeth (Deemed to be University) Medical College, Pune (Ref: BVDUMC/IEC/141). Written informed consent was obtained from all participants before initiating the procedure.

Study design and procedure

This cross-sectional study utilised purposive sampling and was carried out in two phases. In Phase I, the Speech-in-Noise Test in Hindi (SiNT-H) was developed. Phase II involved administering the SiNT-H to participants in two different age groups to assess their speech-in-noise performance.

Phase I: Development of the monosyllabic SiNT-H

Stimulus selection and familiarity ratings. A pool of 300 monosyllabic Hindi words was initially extracted from the standard word lists of De [29] and evenly distributed across six word lists. Five native Hindi-speaking adults independently rated each word on a 5-point familiarity scale (1 = "unknown" to 5 = "most familiar"), as adapted from Chinnaraj et al. [30]. Based on the mean familiarity scores, 177 words were identified as sufficiently familiar and were retained for subsequent steps. To minimise inter-item and inter-list variability, all test stimuli underwent a structured equalisation procedure. Familiar monosyllabic words with comparable phonological structure were selected as speech materials. Using Praat software, each recorded word token was individually amplitude-normalised to achieve a consistent RMS level. Noise samples were also normalised separately prior to mixing. Speech and noise were then combined at the required SNR conditions, after which the final mixed stimuli were re-equalised to ensure a uniform overall presentation level across all items and lists. In addition, spectral characteristics of the stimuli were reviewed to maintain broad acoustic comparability across lists.

Recording protocol. The total of 177 selected words were recorded in a sound-treated room by a 23-year-old native Hindi-speaking female. Recordings were made using Audacity (v3.6.3) on a Hewlett-Packard KTMP99C system, with a studio-quality microphone placed 15 cm from the speaker's mouth at 45°. Speech samples were digitised at a sampling rate of 44.1 kHz using a 16-bit analog-to--digital converter.

Recording speaker selection. From the pool of available speakers, one 23-year-old female speaker was selected based on perceptual evaluation of voice clarity, articulatory precision, consistency of vocal quality, and absence of noticeable accent or dialectal variation relative to the target language variety. This screening was conducted to ensure that the recorded stimuli would be linguistically neutral and easily intelligible for the intended participant population. During the recording process, multiple takes of each stimulus item were obtained. The recordings were then reviewed, and the most natural and consistent token for each item was selected based on clarity of pronunciation, stable intensity, appropriate speaking rate, and uniform prosodic characteristics (including stress pattern and intonation contour). Tokens containing hesitations, misarticulations, irregular pauses, or unintended prosodic emphasis were excluded. In addition, efforts were made to minimise acoustic variability across the final stimulus set. Recordings were monitored to maintain consistency in fundamental frequency (F0), overall speaking rate, and vocal intensity as far as practically feasible within natural speech production constraints. These procedures were undertaken to ensure that differences in participant performance were attributable to the experimental conditions rather than unwanted speaker-related acoustic variability.

Intelligibility ratings and refinement. To ensure perceptual clarity, five native Hindi speakers rated the intelligibility of the recorded words on a 5-point Likert scale (1 = "bad" to 5 = "excellent") based on IEEE (1969) guidelines. Words rated below a mean of 4 were re-recorded. This process led to the refinement of 16 items to enhance clarity and naturalness.

Table 1. Construction of two monosyllabic word lists based on the distribution of the acoustic energy across critical bandwidths in the selected words

Frequency band [Hz]	Total words in the band	Proportional distribution [%]	Number of words allocated to List 1	Number of words allocated to List 2
0–150	102	57.62	14	14
151–250	34	19.20	5	5
251–350	16	9.03	2	2
351–450	15	8.47	2	2
451–570	2	1.69	1	1
571–700	8	3.95	1	1
Total	177	100.00	25	25

Acoustic analysis and list construction. Acoustic analyses were conducted using PRAAT (v6.4.01). Formant frequencies (F0, F1, F2) and bandwidths (F1, F2, F3) were measured. Words were then categorised according to critical band centre frequencies as described by Zwicker [31], and articulation index (AI) values were calculated. Based on these parameters, two final test lists of 25 monosyllabic words each were created (**Table 1**). All items were RMS-normalised to −18.0 dB using Audacity to ensure uniform intensity across stimuli. Analysis of list performance revealed no statistically significant differences across word lists, suggesting functional equivalence and absence of measurable list bias under the present test conditions.

Background noise construction. To generate multitalker babble noise, four native Hindi speakers (two male, two female) recorded two standardised Hindi paragraphs titled /ˈmeːɾeː ˈd͡ʒiːʋən kɑː ˈləkʂjə/ and /ˈɦoːliː/ in cold running speech style, following the methodology of Gundmi et al. [32]. The individual recordings were merged to produce a 41-second, four-talker babble, which was RMS-matched to −18.0 dB to align with the target word stimuli.

Signal-to-noise ratios (SNRs). The final test material was created by mixing the normalised word lists with the multitalker babble at three SNRs (0, +5, and +10 dB, reflecting progressively easier speech-in-noise conditions. Additionally, five practice items were constructed at various SNR levels (+20 dB, +10 dB, +5 dB, and two at 0 dB) to familiarise participants with the testing format.

Phase II: Administration of the Speech-in-Noise Test in Hindi (SiNT-H)

In the second phase of the study, the finalised SiNT-H was administered to the 54 participants, comprising 27 young adults (20–39 years) and 27 middle-aged adults (40–59 years). All participants were native Hindi speakers with normal hearing sensitivity and no reported otological, neurological, or speech-language disorders.

Test environment and preliminary screening. The assessments were conducted in a sound-treated and acoustically calibrated room. Stimuli were presented binaurally at 60 dB SPL through Boat Bassheads 225 insert earphones connected to a Hewlett-Packard KTMP99C laptop. Prior to testing, a comprehensive case history was obtained, followed by otoscopic examination to screen for external or middle ear anomalies. Hearing screening was performed using the Hearing Test mobile application (e-audiologia.pl; version 2.7) [33] – a validated Android-based tool for estimating pure-tone hearing thresholds across standard audiometric frequencies. Testing was conducted in a quiet environment following standardised instructions. Pure-tone averages (PTAs) were calculated using thresholds at 0.5, 1, 2, and 4 kHz. The mean PTA across participants was 17.9 dB HL, indicating hearing sensitivity within normal limits. All participants met the study inclusion criteria based on this screening procedure.

Test procedure. Each participant was administered two word lists – List 1 and List 2 – each comprising 25 monosyllabic words (Supplement 1). The lists were presented under three signal-to-noise ratio (SNR) conditions: +10, +5, and 0 dB. The order of list presentation and ear dominance was randomised across participants to mitigate order and lateralisation effects. To ensure participants understood the test paradigm, practice trials were conducted prior to each SNR condition using five words presented at various SNRs. Participants were instructed to listen carefully to the target words embedded in multitalker babble and ignore the background noise. Responses were recorded manually by the examiner. A brief rest interval of 10 minutes was provided between the two lists to minimise listening fatigue and maintain performance consistency.

Scoring and reliability. Scoring for the SiNT-H was conducted at two levels: word-level accuracy and phoneme-level error analysis. For word-level scoring, each correctly identified monosyllabic word was awarded 4%, resulting in a maximum possible score of 100% per list. This scoring scheme allowed for straightforward quantification of speech recognition performance across different SNR conditions. In addition to overall accuracy, a detailed phoneme-level error analysis was performed to identify specific patterns of misperception and to gain deeper insight into the acoustic-phonetic challenges encountered by participants during speech-in-noise recognition.

To ensure the reliability of the SiNT-H, test–retest consistency was evaluated in a subset of participants. Approximately 10% of the total sample ($n = 12$) was reassessed after an interval of 1 month using the same stimulus lists and identical testing procedures. This re-administration allowed for the examination of the stability and temporal reliability of the test scores, thereby contributing to the validation of SiNT-H as a dependable tool for assessing speech-in-noise perception in Hindi-speaking populations.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 23.0. The normality of the SiNT-H scores across different SNR conditions was initially assessed using a Shapiro–Wilk test. The results indicated a significant deviation from a normal distribution ($p < 0.05$), necessitating the use of non-parametric statistical methods for all subsequent analyses. To examine ear-wise differences in performance, a Wilcoxon signed-rank test was applied separately to List 1 and List 2 for male and female participants. In order to assess potential list-related effects and gender differences within Group I (young adults), a Mann–Whitney *U*-test was employed using combined scores from both ears. The impact of varying SNR conditions (+10, +5, and 0 dB) on speech-in-noise performance was analysed using Friedman's test for repeated measures, allowing for within-group comparison of performance across noise levels.

Furthermore, between-group differences in SiNT-H performance were analysed using a Mann–Whitney *U*-test to compare the young adult group (Group I) with the middle-aged adult group (Group II). This comprehensive statistical framework enabled a detailed evaluation of test performance across demographic variables, test conditions, and linguistic complexity, contributing to the validation of SiNT-H as a reliable and clinically relevant assessment tool.

Results

The findings are presented in several parts: (1) Comparison of SiNT-H scores between ears; (2) Gender-wise performance analysis; (3) Assessment of list equivalency across genders; (4) Performance across different SNRs (0, +5, +10 dB) to determine the test's responsiveness to changes in listening difficulty; (5) Age-related performance differences across genders; (6) Evaluation of test–retest reliability; (7) Phonemic error analysis to identify perceptual confusions. Additionally, the performance was examined across different SNRs to determine the test's responsiveness to changes in listening difficulty.

1) Comparison of SiNT-H scores between ears

To compare the ear-specific performance in the SiNT-H test between ears, both male and female participants were compared (Supplement 2). The analysis was conducted separately for each list (List 1 and List 2) under three signal-to-noise ratio (SNR) conditions (0, +5, and +10 dB) and shown in **Figure 1**.

Figure 1 shows median and interquartile ranges for List 1 and List 2 scores between ears across genders at three different SNRs. Among males, List 1 showed marginally superior scores in the left ear compared to the right, whereas List 2 yielded nearly symmetrical distributions across ears for three conditions. Conversely, females exhibited a consistent pattern of better right ear performance, with higher median scores and broader IQRs noted in both lists at 0, +5, and +10 dB SNRs. Although certain patterns were observable, the Wilcoxon signed-rank test (Supplement 3) revealed no statistically significant differences across either list for male participants at any condition. Specifically, no significant differences were found for males at baseline for List 1 ($Z = 0.72$, $p = 0.473$) and List 2 ($Z = 0.69$, $p = 0.491$). Female participants also showed non-significant results at baseline (List 1: $Z = 2.09$, $p = 0.071$; List 2: $Z = 1.94$, $p = 0.052$). A similar trend was observed at +5 dB SNR, with male participants showing no significant differences (List 1: $Z = 0.21$, $p = 0.831$; List 2: $Z = 0.61$, $p = 0.542$). Female participants at this SNR also did not reach statistical significance (List 1: $Z = 1.92$, $p = 0.062$; List 2: $Z = 0.71$, $p = 0.473$). At +10 dB SNR as well, the results remained non-significant for males (List 1: $Z = 1.59$, $p = 0.112$; List 2: $Z = 0.82$, $p = 0.414$) and females (List 1: $Z = 1.11$, $p = 0.273$; List 2: $Z = 0.83$, $p = 0.414$). These findings support the ear-wise equivalence of the SiNT-H test. Consequently, data from both ears were pooled for subsequent analyses.

2) Gender-wise performance analysis

To assess the difference in performance between gender on the SiNT-H performance, a comparison of scores between male and female participants was conducted using the Mann–Whitney *U*-test (Supplement 4). Female participants were found to consistently achieve higher median scores than their male counterparts across both List 1 and List 2 under all SNR conditions. At 0 dB SNR, females performed significantly better than males on both lists [List 1 ($U = 506$, $p = 0.012$); List 2 ($U = 519.5$, $p = 0.011$)]. This gender-based performance difference remained statistically significant at +5 dB SNR [List 1 ($U = 450$, $p = 0.043$); List 2 ($U = 454$, $p = 0.042$)], and a similar trend was observed at +10 dB SNR [List 1 ($U = 497$, $p = 0.043$); List 2 ($U = 458$, $p = 0.026$)].

3) Assessment of list equivalency across genders

Further, the present study examined the psychometric equivalency of two monosyllabic word lists of the SiNT-H test at three SNR levels using a Wilcoxon Signed-Rank test. At 0 dB SNR, no significant differences were observed between the lists for males ($Z = 1.23$, $p = 0.212$) or females ($Z = 1.87$, $p = 0.074$). Similarly, at +5 dB SNR, comparisons revealed no significant difference for males ($Z = 0.95$, $p = 0.341$) or females ($Z = 1.40$, $p = 0.162$). At +10 dB SNR, performance improved further, but the lists remained equivalent with no significant differences for males ($Z = 0.65$, $p = 0.524$) or females ($Z = 1.10$, $p = 0.275$).

4) Performance across different SNRs

The performance on the SiNT-H test was compared across SNRs which revealed a decline in median test scores with decreasing SNRs as depicted in **Figure 1**.

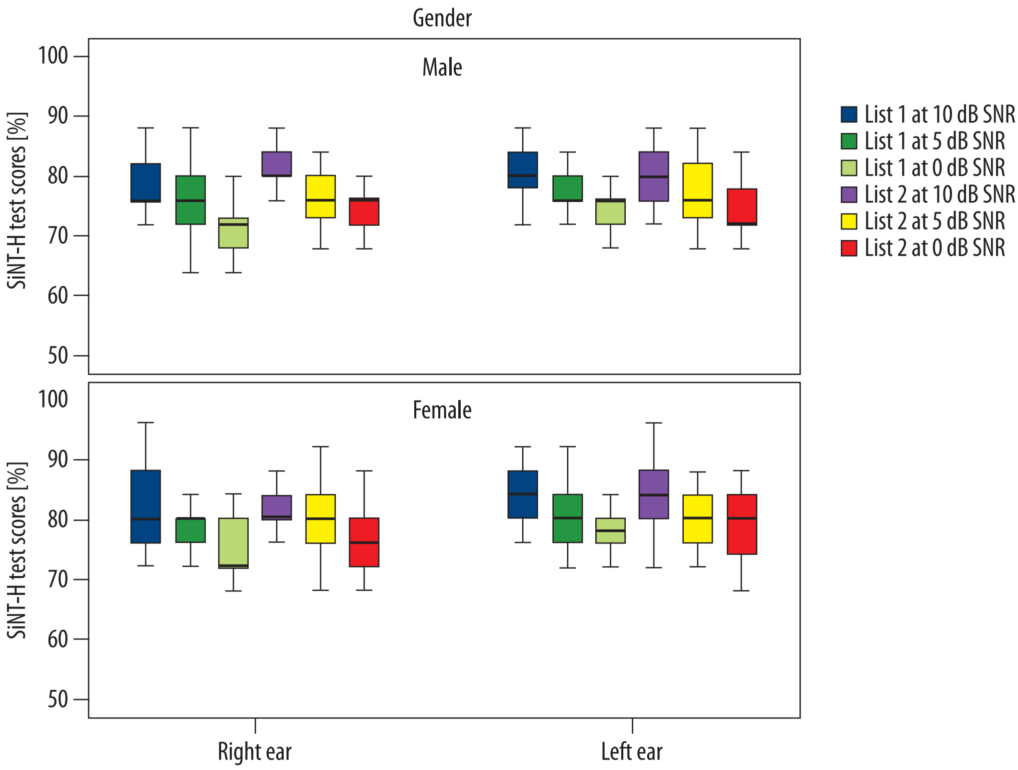

Figure 1. Scores in the SiNT-H test for both List 1 and List 2. The data is divided into that for males (top) and females (bottom); for right ears (left) and left ears (right); and for 0 dB, +5 dB, and +10 dB SNR (colour coding)

A Friedman test revealed a significant main effect of SNR on speech recognition scores, with performance declining notably at 0 dB SNR compared to +5 and +10 dB. Specifically, the test was applied to assess the impact of varying SNR levels on List 1 performance in the right ear. A statistically significant difference was observed across the three SNR conditions. To determine the specific contrasts, post hoc pairwise comparisons were conducted using the Bonferroni correction. For Group 1, the speech recognition scores at 0 dB SNR were significantly lower than those at +5 dB ($\chi^2 = 0.593$, $p < 0.001$) and +10 dB ($\chi^2 = 1.255$, $p < 0.001$). Additionally, the scores at +5 dB SNR were significantly lower than those at +10 dB ($\chi^2 = 0.662$, $p < 0.001$). Similarly, in Group 2, the performance at 0 dB SNR was significantly reduced in comparison to both +5 dB SNR ($\chi^2 = 0.620$, $p < 0.001$) and +10 dB SNR ($\chi^2 = 1.532$, $p < 0.001$), with +5 dB SNR scores also significantly lower than +10 dB SNR ($\chi^2 = 0.912$, $p < 0.001$).

5) Age-related performance differences across genders

An analysis of the performance in the SiNT-H test was done between young and middle-aged adults across genders (Supplement 5). It was found that the young female adults had significantly superior test scores than middle-aged females at 0 dB SNR ($U = 130$, $p = 0.025$) and +5 dB SNR ($U = 1347$, $p = 0.026$). However, the difference was not statistically significant at +10 dB SNR ($U = 1295$, $p = 0.107$). In contrast, male participants exhibited no significant age-related differences across any of the SNR levels [0 dB ($U = 1176$, $p = 0.373$); +5 dB ($U = 958$, $p = 0.404$); +10 dB ($U = 1005$, $p = 0.477$)]. These results indicate a statistically significant age-related decline in the SiNT-H performance among females, particularly under more challenging SNR conditions, whereas male participants showed stable performance across age groups.

6) Evaluation of test–retest reliability

To determine the consistency in the performance between tests and retest scores of SiNT-H, a test–retest reliability analysis was performed (Supplement 6). A subset of participants ($n = 12$; 6 males and 6 females) was reassessed after an interval of 15 days. The Wilcoxon signed-rank test was employed to compare paired performance scores between the initial and follow-up sessions. The results indicated no statistically significant differences across ears, lists, and SNRs. At 10 dB SNR, both List 1 and List 2 showed stable scores across ears – List 1: right ear ($Z = 0.45$, $p = 0.661$), left ear ($Z = 0.81$, $p = 0.412$); List 2: right ear ($Z = 1.00$, $p = 0.313$), left ear ($Z = 1.00$, $p = 0.317$). A similar stability was observed at +5 dB SNR – List 1: right ear ($Z = -0.707$, $p = 0.480$), left ear ($Z = 0.707$, $p = 0.480$); List 2: right ear ($Z = 2.449$, $p = 0.143$), left ear ($Z < 0.01$, $p = 0.999$). At 0 dB SNR, List 1 scores were: right ear ($Z = 1.933$, $p = 0.053$), left ear ($Z = 1.342$, $p = 0.180$), while List 2 scores were: right ear ($Z = 0.447$, $p = 0.655$), left ear ($Z = 0.378$, $p = 0.705$). Further, Spearman's rank-order correlation coefficient was calculated to examine the strength of association between test and retest scores across the different SNRs. At 0 dB SNR, strong positive correlations were

Table 2. Percentage of word recognition errors at different SNRs for List 1 and List 2 of the SiNT-H

No.	List 1 words	Total error [%]			List 2 words	Total error [%]		
		at 0 dB SNR	at 5 dB SNR	at 10 dB SNR		at 0 dB SNR	at 5 dB SNR	at 10 dB SNR
1	/tʃʰət/	10.60	10.61	5.30	/paːs/	31.82	31.82	15.91
2	/kʊtʃʰ/	2.43	3.03	0.76	/neːk/	11.36	11.36	3.03
3	/tiːn/	6.81	10.61	9.85	/pəl/	15.15	15.15	3.79
4	/pʰɪr/	42.42	53.79	45.45	/leːkʰ/	16.67	16.67	14.39
5	/gʊʈ/	71.97	58.33	28.79	/peːʃ/	57.58	57.58	31.82
6	/buːʈ/	38.64	33.33	23.48	/teːdʒ/	3.03	3.03	5.30
7	/ʈoːp/	21.21	25.00	22.73	/sɪkʰ/	24.24	24.24	26.52
8	/dʒʱiːl/	6.06	6.06	0.00	/poːʂ/	42.42	42.42	25.76
9	/bəl/	48.48	50.00	53.79	/sətʃ/	25.00	25.00	22.73
10	/bɛːl/	30.30	36.36	31.06	/dʒəj/	6.82	6.82	9.85
11	/eːk/	9.09	6.82	3.03	/mɛːl/	27.27	27.27	12.88
12	/ʈʰiːk/	0.00	0.76	3.79	/məʈʰ/	16.67	16.67	5.30
13	/tiːs/	0.76	3.03	7.58	/seːb/	58.33	58.33	49.24
14	/d̪eːʋ/	50.00	46.21	26.52	/rəs/	21.21	21.21	15.15
15	/aːm/	12.88	13.64	9.85	/aːg/	42.42	42.42	17.42
16	/kʰaːd̪/	40.91	37.12	27.27	/ɦəʈʰ/	7.58	7.58	6.06
17	/raːdʒ/	8.33	6.06	9.85	/tʃaːr/	43.94	43.94	28.79
18	/kəʈ/	16.67	12.12	6.06	/dʒaːn/	0	0	0
19	/nəl/	13.64	13.64	7.58	/loːbʰ/	43.18	43.18	17.42
20	/saːg/	93.18	92.42	86.36	/mən/	7.58	7.58	6.82
21	/baːt̪/	41.67	38.64	18.94	/dɪn/	22.73	22.73	3.79
22	/paːʈʰ/	30.30	26.52	13.64	/kaːm/	21.21	21.21	12.88
23	/kaːn/	4.55	6.82	2.27	/gaːʋ/	6.82	6.82	7.58
24	/gəm/	3.79	3.79	4.55	/tʃaːp/	42.42	42.42	31.82
25	/taːʃ/	0	0	0	/ɦoːʈʰ/	0.76	0.76	4.55

observed for the right ear in List 1 ($\rho = 0.84$, $p < 0.011$) and List 2 ($\rho = 0.86$, $p < 0.011$), as well as for left ear in List 2 ($\rho = 0.90$, $p < 0.012$), while a moderately strong yet significant correlation was found for List 1 ($\rho = 0.66$, $p = 0.022$). At +5 dB SNR, the correlations remained robust across all test conditions. For the right ear, strong associations were observed for List 1 ($\rho = 0.90$, $p < 0.012$) and List 2 ($\rho = 0.85$, $p < 0.013$). For the left ear, similarly strong correlations were noted for List 1 ($\rho = 0.88$, $p < 0.011$) and List 2 ($\rho = 0.87$, $p < 0.012$). At +10 dB SNR, test–retest associations continued to be strong across all conditions. For the right ear, high correlations were observed for List 1 ($\rho = 0.94$, $p < 0.013$) and List 2 ($\rho = 0.89$, $p < 0.014$). For the left ear, strong correlations were also noted for List 1 ($\rho = 0.80$, $p < 0.012$) and List 2 ($\rho = 0.72$, $p < 0.011$).

7) Phonemic error analysis

To elucidate the influence of background noise on speech perception, a comprehensive phonemic error analysis was conducted at three SNR conditions (0, +5, and +10 dB) (Supplement 7). This analysis encompassed both young and middle-aged adult participants. Therefore, each participant's response to the monosyllabic word stimuli was evaluated at the phoneme level to detect substitution patterns. Phonemic classification was guided by the articulatory taxonomy proposed by Shipra and Chandra [25], which organises phonemes based on place of articulation (e.g., bilabial, dental, retroflex, palatal), manner of articulation (e.g., stops, nasals, fricatives, affricates, liquids), as well as features such as voicing and aspiration. Word-wise

Table 3a. Phoneme substitution patterns in List 1 across three SNR conditions (0 dB, +5 dB, +10 dB)

Correct phoneme in List 1	Phoneme class	Incorrect phoneme in List 1	Phoneme class	0 dB SNR (no of ears)	+5 dB SNR (no of ears)	+10 dB SNR (no of ears)
/t̪/	voiceless unaspirated stop	/l/	dental liquids	9	9	3
/t̪/	voiceless unaspirated stop	/p/	bilabial voiceless unaspirated stop	2	5	3
/pʰ/	bilabial voiceless aspirated stop	/p/	bilabial voiceless unaspirated stop	5	5	9
/g/	voiced unaspirated velar stop	/k/	voiceless unaspirated velar stop	6	1	4
/b/	bilabial voiced unaspirated stop	/uː/	back vowel	19	18	12
/ʈ/	voiceless unaspirated retroflex stop	/ɖ/	voiced unaspirated retroflex stop	3	3	0
/b/	bilabial voiced unaspirated stop	/p/	bilabial voiceless unaspirated stop	53	52	45
		/pʰ/	bilabial voiceless aspirated stop	3	2	9
/b/	bilabial voiced unaspirated stop	/m/	bilabial nasal	15	12	11
/e/	front mid-short vowel	/i/	front short vowel	3	3	5
/ʈʰ/	retroflex voiceless aspirated stop	/pʰ/	bilabial voiceless aspirated stop	1	3	3
/s/	dental fricative	/n/	dental nasal	3	4	3
/m/	bilabial nasal	/d͡ʒ/	palatal voiced unaspirated affricate	8	8	6
/d̪/	dental voiced unaspirated stop	/n/	dental nasal	12	10	5
/ɾ/	retroflex liquid	/l/	dental liquid	4	3	0
/s/	dental fricative	/p/	bilabial voiceless unaspirated 7 stop	43	41	22
/b/	bilabial voiced unaspirated stop	/p/	bilabial voiceless unaspirated stop	14	12	7
/ʈʰ/	retroflex voiceless aspirated stop	/t͡ʃ/	palatal voiceless unaspirated affricate	5	5	0

error percentages were computed for each stimulus in Lists 1 and 2 by dividing the number of incorrect responses by the total number of ears tested ($n = 116$) and multiplying by 100. This allowed for the identification of lexemes most vulnerable to noise-induced perceptual degradation across SNR conditions (**Table 2**). Further, the substitution errors were examined cumulatively across 116 ears for each word. Each erroneous phoneme was classified as per its articulatory features. The total number of phoneme-level errors was calculated separately for each SNR condition, providing a granular view of error patterns for both Lists 1 and 2 as given in **Tables 3a** and **3b**. The findings revealed that phoneme confusions were the most prevalent at 0 dB SNR and showed a progressive decline as the SNR improved to +5 and +10 dB. Notably, phonemes that shared articulatory properties – such as common place or manner of articulation, or similar voicing and aspiration characteristics, were seen to be more frequently misperceived. Additionally, middle-aged adults demonstrated a higher incidence of such confusions compared to their younger counterparts, suggesting an age-related decline in fine-grained phonological processing under acoustically challenging conditions.

Discussion

The present study developed the Speech-in-Noise Test in Hindi (SiNT-H) to assess monosyllabic word recognition using multi-talker babble among normal-hearing Hindi-speaking adults. By integrating linguistically relevant stimuli within a multi-talker babble context, the SiNT-H effectively mirrors real-world communication demands while maintaining diagnostic precision. This approach adheres to best practices recommended by Pichora-Fuller et al. [34], reinforcing the test's clinical and ecological validity.

Table 3b. Phoneme substitution patterns in List 2 across three SNR conditions (0 dB, +5 dB, +10 dB)

Correct phoneme in List 2	Phoneme class	Incorrect phoneme in List 2	Phoneme class	0 dB SNR (no of ears)	+5 dB SNR (no of ears)	+10 dB SNR (no of ears)
/s/	dental fricative	/n/	dental nasal palatal voiceless	14	11	9
		/t͡ʃ/	unaspirated affricate	6	5	4
/n/	dental nasal	/e/	front mid-short vowel	4	7	3
/l/	dental liquid	/e/	front mid-short vowel	2	10	5
/p/	bilabial voiceless unaspirated stop	/t̪/	voiceless unaspirated stop	8	11	3
		/d̪/	dental voiced unaspirated stop	6	7	7
		/ʋ/	bilabial glide	12	11	8
/s/	dental fricative	|/t̪/	voiceless unaspirated stop	10	9	3
		/p/	bilabial voiceless unaspirated stop	15	17	8
/p/	bilabial voiceless unaspirated stop	/ɦ/	glottal fricative	13	26	0
/s/	dental fricative	/t̪/	dental voiceless unaspirated stop	12	13	11
		/k/	velar voiceless unaspirated stop	5	4	2
/b/	bilabial voiced unaspirated stop	/m/	bilabial nasal	11	5	3
/m/	bilabial nasal	/ɦ/	glottal fricative	3	2	0
/ɾ/	retroflex liquid	/d̪/	dental voiced unaspirated stop	33	29	11
/d͡ʒ/	palatal voiced unaspirated affricate	/g/	voiced unaspirated velar stop	8	5	4
/bʰ/	bilabial voiced aspirated stop	/g/	voiced unaspirated velar stop	12	9	13
/m/	bilabial nasal	/n/	dental nasal	11	7	0
/p/	bilabial voiceless unaspirated stop	/ɾ/	retroflex liquid	22	23	13
		/j/	palatal glide	10	9	8

In the study, participants exhibited the highest speech recognition accuracy at +10 dB SNR, with performance declining progressively as the SNR decreased – demonstrating the expected SNR-dependent gradient in speech perception. This pattern reflects listeners' enhanced ability to extract phonetic and lexical cues under favorable listening conditions, with reduced performance in more challenging noise environments, particularly at 0 dB SNR. Such a decline is likely attributable to the increased impact of both energetic and informational masking, resulting in heightened cognitive listening demands. These findings align with the established literature which has consistently reported robust speech-in-noise performance among normal-hearing individuals under higher SNRs [35–39], as well as studies emphasising the cognitive load imposed by masking effects in degraded auditory environments [40,41]. Furthermore, the use of familiar, high-frequency monosyllabic words in SiNT-H likely facilitated word recognition by reducing lexical processing complexity and minimising intersubject variability – an approach supported by psycholinguistic evidence [42,43]. The exclusive use of monosyllables also minimised linguistic redundancy, thereby enabling a more focused evaluation of auditory processing.

In the study, no significant ear differences were observed in the test scores, reflecting bilateral symmetry in auditory processing among young, normal-hearing adults. These findings corroborate earlier studies [44–46] that attributed symmetrical performance to intact peripheral function and balanced cortical processing across hemispheres. Although some researchers have reported right-ear advantages associated with hemispheric language dominance and stronger medial olivocochlear (MOC) reflexes [47–50], such asymmetries are more likely to manifest in older adults or clinical populations. The present findings affirm the suitability of the SiNT-H for bilateral testing in young adults without necessitating ear-specific norms. Additionally, the absence of ceiling or floor effects, and the comparable performance across Lists 1 and 2, provide empirical support for their equivalence and validate their interchangeable use.

A notable finding in the study was the presence of superior performance of female participants, particularly at lower SNRs. This observation aligns with prior research [38,46,51] and may be explained by a confluence of anatomical, hormonal, and cognitive factors. Females have been shown to possess shorter and more numerous outer hair cells [46], potentially contributing to enhanced cochlear amplifier function. Cortically, they may exhibit greater gray matter density in language-associated regions [52,53], along with more bilateral activation during linguistic tasks [54], which may confer advantages under degraded listening conditions. Given emerging evidence of earlier cognitive decline in women post-menopause, the reduced SiN performance in middle-aged females may reflect subtle, hormone-mediated auditory–cognitive interactions, which have yet to be fully understood [5]. Furthermore, the ability to engage top-down processing strategies more effectively [55] could enhance signal extraction from noise. Although some studies [56,57] have reported inconsistent gender effects, the present data support the inclusion of gender-specific normative values, particularly when testing at challenging SNRs.

The SiNT-H demonstrated high test–retest reliability, affirming its potential for repeated clinical use. Psychometric analysis confirmed that the two test lists were statistically equivalent across genders, supporting their interchangeability. This is critical for ensuring internal validity and avoiding vocabulary bias, as emphasised by Braza et al. [42] and Banks et al. [58]. Randomised test presentation further reduced the potential for order effects and preserved the cognitive consistency of the listening task.

Age-related comparisons revealed that younger females outperformed their middle-aged counterparts, whereas male participants did not exhibit significant age-related differences. These findings partly mirror the literature, where minimal decline is typically observed in individuals under 60 years [45,59]. However, the reduced performance in middle-aged females may indicate early signs of age--related auditory decline, even in the absence of audiometric hearing loss. Studies have linked age-related SiN deficits to reduced temporal resolution, decreased cortical inhibition, and weakened benefit from temporal dips in noise [10,60]. Neurocognitive factors such as slower processing speed and diminished working memory may contribute to these changes [5,6]. The absence of significant decline among males may reflect differential aging trajectories or compensatory neuroplastic mechanisms [61], but further research is needed to elucidate gender-specific auditory aging patterns.

Detailed phoneme-level error analysis revealed specific patterns consistent with the phonological characteristics of Hindi. Consonantal errors were markedly more frequent at lower SNRs, where masking effects were strongest. Voicing confusions (e.g., /b/ ↔ /p/, /k/ ↔ /g/, /ʈ/ ↔ /ɖ/) were prominent, underscoring the vulnerability of periodicity and voice-onset cues in noisy conditions, findings that align with Weber et al. [23] and Moreno-Torres et al. [24]. Errors in manner of articulation, such as /b/ ↔ /m/ and /d̪/ ↔ /n/, may reflect the degradation of nasal murmur and articulatory transitions.

The place of articulation errors, including retroflex–dental and palatal confusions (e.g., /ʈʰ/ ↔ /t͡ʃ/, /s/ ↔ /k/), suggest a loss of spectral localisation cues in multitalker babble. Aspiration, a phonemic feature in Hindi, was also significantly affected, with substitutions such as /pʰ/ ↔ /p/ and /bʱ/ ↔ /g/ pointing to the masking of low-intensity aspiration bursts. In contrast, vowel perception remained stable across SNRs, likely due to vowels' higher intensity, longer duration, and distinctive formant structure. This robustness is well-documented [24] and further supports the inclusion of consonant-heavy stimuli in SiN testing to maximise diagnostic sensitivity.

Conclusions

The present study developed the Speech-in-Noise Test in Hindi (SiNT-H) as a linguistically and culturally appropriate tool for assessing speech perception in noise among Hindi-speaking adults. Constructed using monosyllabic words and multitalker babble across various SNR levels, the SiNT-H demonstrated high test–retest reliability. The absence of significant ear-wise differences and the superior performance observed among females align with established gender-related auditory processing patterns. However, the decline in performance among middle-aged females may suggest early signs of auditory aging. It is important to note that the gender-related differences in the SiNT-H performance could also be influenced by factors such as sociolinguistic exposure, task familiarity, and cognitive engagement, which were not controlled in the present study. A detailed phonological error analysis revealed increased susceptibility to voicing, manner, place, and aspiration contrasts at lower SNRs (particularly among older participants), underscoring the test's sensitivity to language-specific phonetic demands. These findings collectively support the SiNT-H as a reliable and ecologically valid tool for clinical and research use in Hindi-speaking populations. Nonetheless, the inclusion of a broader sample of older adults could have further enhanced the study's value and should be considered in future investigations.

Limitations and future direction

The present findings should be interpreted in light of certain methodological considerations. Test–retest reliability was established on a relatively small subsample ($n = 12$), which, although adequate for preliminary estimation, may limit the precision and generalisability. Further, the interpretation of age- and gender-related effects warrants caution. Speech-in-noise performance is known to be sensitive to subtle auditory changes – such as cochlear synaptopathy, reduced temporal resolution, and suprathreshold processing deficits – that are not captured by conventional pure tone audiometry. In addition, the unequal gender distribution across age groups may have contributed to variability in group comparisons. Future investigations incorporating demographically balanced samples along with extended audiological profiling would help delineate these effects more clearly.

Although acoustic normalisation and empirical list-equivalence procedures were implemented, formal psychometric equalisation at the item level was not undertaken. Consequently, a small degree of residual lexical or acoustic variability across test items cannot be entirely ruled out. Subsequent work employing item-level calibration using larger normative datasets would further enhance the standardisation, as well as the overall reliability and validity, of SiNT-H.

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Supplementary material

The supplementary materials are available at https://www.journalofhearingscience.com/

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SKILL PROGRESSION AND ERROR REDUCTION IN NOVICE INTERPRETERS OF AUDITORY BRAINSTEM RESPONSES (ABR)

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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Abstract

Introduction: Auditory brainstem response (ABR) is a key objective diagnostic method in audiology; however, the interpretation of recordings – especially estimating hearing thresholds – is challenging for novices. The aim of this preliminary descriptive study was to document the learning process of novices in ABR threshold interpretation in preparation for the ABR.AI project.

Material and methods: Seven students with varying levels of baseline theoretical knowledge participated in the training. The program consisted of a multi-stage cycle including theoretical lectures, individual analysis of ABR recordings, independent practice with available expert consultation, and case-based discussions. The students' hearing threshold estimations were compared with expert assessments across three clinical datasets (115–122 cases each). Results were presented as the percentage of full agreement (0 dB difference), minor discrepancies (≤ 10 dB), and large discrepancies (> 10 dB) relative to the expert's assessment.

Results: Across the three training stages, mean full agreement with the expert increased from 55% (Set 1) to 60% (Set 3), while major discrepancies decreased from 9% to 6%. Despite individual differences in learning dynamics, the majority of participants demonstrated a consolidation of interpretive skills and a reduction in large diagnostic errors. Most deviations were ≤ 10 dB, indicating that discrepancies were generally small and clinically acceptable.

Conclusions: This preliminary descriptive study demonstrated that multi-stage, expert-guided training was associated with an improvement in ABR threshold estimation accuracy, and most importantly, with a clinically meaningful reduction in large discrepancies (>10 dB) from the expert's assessment. These findings highlight the importance of structured, feedback-based learning in the education of audiology professionals.

Keywords: medical education • auditory brainstem response • hearing threshold • ABR interpretation • speech therapy students

POSTĘPY W NABYWANIU UMIEJĘTNOŚCI I ZMNIEJSZENIE LICZBY BŁĘDÓW U POCZĄTKUJĄCYCH OSÓB INTERPRETUJĄCYCH WYNIKI BADANIA SŁUCHOWYCH POTENCJAŁÓW WYWOŁANYCH (ABR)

Streszczenie

Wprowadzenie: Słuchowe potencjały wywołane pnia mózgu (ABR) stanowią podstawową metodę diagnostyki obiektywnej w audiologii, jednak interpretacja zapisów – szczególnie przy szacowaniu progów słyszenia – jest trudna dla osób początkujących. Celem tego wstępnego badania opisowego było udokumentowanie procesu uczenia się nowicjuszy w zakresie interpretacji progów ABR w ramach przygotowań do projektu ABR.AI.

Materiał i metody: W szkoleniu wzięło udział 7 studentów o zróżnicowanym poziomie początkowej wiedzy teoretycznej. Program obejmował wieloetapowy cykl z wykładami teoretycznymi, indywidualną analizą zapisów ABR, pracą własną z możliwą konsultacją ekspercką oraz omawianiem przypadków. Oceny progów słyszenia wykonane przez studentów porównano z ocenami eksperta w trzech zestawach danych klinicznych (każdy po 115–122 przypadki). Wyniki przedstawiono jako odsetki pełnej zgodności (0 dB) oraz rozbieżności względem oceny eksperta: niewielkie (≤ 10 dB) i znaczne (> 10 dB).

Wyniki: Średni poziom pełnej zgodności z ocenami eksperta wynosił 55,4% w zestawie 1. i wzrósł do 60,0% w zestawie 3., a odsetek znacznych rozbieżności (> 10 dB) spadł z 8,7% do 5,8%. Mimo indywidualnych różnic w dynamice nauki, u większości uczestników zaobserwowano konsolidację umiejętności interpretacyjnych i zmniejszenie liczby istotnych błędów diagnostycznych.

Wnioski: Niniejsze wstępne badanie obserwacyjne wykazało, że rezultatem wieloetapowego szkolenia prowadzonego przez ekspertów była poprawa dokładności szacowania progów ABR, a przede wszystkim istotna klinicznie redukcja znacznych rozbieżności w porównaniu z oceną eksperta (>10 dB). Wyniki te podkreślają znaczenie ustrukturyzowanej nauki z informacją zwrotną w procesie kształcenia kadr audiologicznych.

Słowa kluczowe: edukacja medyczna • słuchowe potencjały wywołane pnia mózgu • próg słyszenia • interpretacja wyników ABR • studenci logopedii

Introduction

The auditory brainstem response (ABR) is a key method in objective audiological diagnostics, used to assess neural conduction latencies along the auditory pathway [1] and to estimate frequency-specific hearing thresholds [2], making it particularly useful when behavioral testing is unreliable or infeasible. ABR recordings display a characteristic sequence of waves (typically labelled I–VII), each reflecting synchronous neural activity at different levels of the auditory pathway. For example, wave I arises from the distal portion of the cochlear nerve, wave III from the cochlear nucleus, wave V from the inferior colliculus, and waves VI–VII likely originate from still higher auditory centers [3]. Among these, wave V is generally considered the most robust and clinically relevant component [4], therefore becoming the primary indicator for estimating hearing threshold [5]. Threshold assessment in ABR testing involves recording responses to stimuli presented at progressively lower intensities and determining the lowest sound level at which wave V remains detectable. The stimuli most commonly used are clicks and tone bursts at 500, 1000, 2000, and 4000 Hz, allowing evaluation of hearing sensitivity across different frequency regions.

Accurate identification of wave V plays a crucial role in the threshold determination. However, interpretation of ABR waveforms remains particularly challenging [6] due to variability in morphology [7] and recording conditions [8]. The morphology of ABR waves is affected by stimulus parameters such as frequency and intensity [9], as well as by subject-related factors including age, hearing status, and neural synchrony [10]. In contrast, variability in recording conditions arises primarily from technical and environmental factors [11], including electrode placement [12] and background noise [13]. Given the interplay between these sources of variability, reliable threshold estimation requires both technical proficiency and clinical experience in waveform interpretation. Nevertheless, variability can persist even with substantial expertise.

Even among experienced clinicians, inter-rater variability in threshold estimation can be substantial [14]. Differences in individual judgment may lead to threshold discrepancies of up to 10–20 dB, particularly in recordings with low signal-to-noise ratio or atypical wave morphology [15]. This variability illustrates the subjective nature of ABR interpretation and the importance of clear, standardised evaluation criteria. To address these challenges, recent research has increasingly turned toward machine learning (ML) as a potential solution [16]. The use of ML algorithms is being explored to enable objective, consistent, and rapid analysis of ABR recordings, supporting or even in some extent replacing human evaluation in threshold determination. Various ML approaches have been explored for this purpose [17], ranging from classical classifiers [18,19] to advanced deep learning architectures [20–22].

Despite the broad use of ABR in clinical practice and ongoing research on automated detection methods, relatively little attention has been paid to the learning process of novice interpreters. In particular, there is limited evidence on how quickly students can acquire the skills needed for ABR threshold estimation, how closely their judgments align with expert evaluations, and what types of errors are most frequent during training. Previous studies have shown that direct, face-to-face training tends to be more effective [23] than computer- or simulator-based instruction in developing interpretive accuracy. Understanding these aspects is important for improving educational strategies and preparing future clinicians for diagnostic challenges in audiology.

This educational study was conducted as part of the ABR. AI project, which was initiated to develop an AI-based application for the automated assessment of ABR waveforms [24]. Building and validating such an algorithm requires a large, high-quality, human-annotated database of recordings. To achieve this, a group of novice trainees was engaged to support the expert team in dataset preparation. It is critical to clarify that while the overarching project is AI-focused, the educational process described in this paper was entirely traditional (human-to-human). No AI tools, automated feedback, or machine learning algorithms were utilised during the training or evaluation of the students. This dual purpose – supporting dataset development while providing supervised training – created a unique opportunity to document the learning curve of novice interpreters.

The present paper reports on this educational component of the project. It describes the multi-stage training workflow, the methods used to assess student performance, and the progression of their interpretive accuracy on the following tasks. By documenting both the learning curve and the challenges encountered, this study seeks to illustrate how novice interpreters develop their skills in ABR threshold estimation under expert supervision. The main objectives of this preliminary descriptive study were to document students' learning progress across successive training stages, observe changes in their performance over time, and compare their ABR interpretation accuracy with expert judgements. While the instructional sequence itself follows a standard clinical teaching model, the novelty of this study lies in providing objective, empirical data on the actual learning trajectory of novices. By quantifying how quickly interpretation skills consolidate and identifying the specific types of errors that persist – particularly the clinically significant >10 dB deviations – this research addresses a notable gap in the audiological literature regarding the evidence-based training of electrophysiology interpreters.

Material and methods

This study was conducted with the approval of the Bioethics Committee of the Institute of Physiology and Pathology of Hearing in Warsaw (approval no. KB.IFPS 6/2025, 27 March 2025). It was carried out under a grant to ABR.AI (no. 2024/ABM/03/KPO/KPOD.07.07-IW.07-0222/24-00 – An AI-based system for estimating hearing thresholds from intensity series of wave V responses) funded by the Polish Medical Research Agency (Agencja Badań Medycznych, ABM).

Participants

Within the ABR.AI project, 7 students (2 from medicine and 5 from the speech therapy with audiology program) participated as trainees. The selection of these specific disciplines reflects the organisational structure of audiological care in Poland. In the Polish healthcare system, objective hearing assessments, including ABR, are a shared clinical competency. They are routinely performed and interpreted not only by dedicated audiophonologists but also extensively by medical doctors specialising in otolaryngology or audiology, as well as professionals graduating from speech therapy with audiology programs. Because these students will be directly responsible for performing and interpreting such examinations in their future clinical practice, they were specifically included in this training project. The trainees entered the project with varying levels of baseline theoretical knowledge regarding auditory brainstem responses (ABRs), ranging from no prior exposure to basic coursework-level familiarity. The expert panel included experienced audiologists and electrophysiologists, among them a pioneer of ABR threshold evaluation methods in Poland (co-author K.K.), who has had longstanding clinical and research experience in auditory evoked potentials since the 1980s.

Procedures

Data

All ABR recordings used for the training datasets were obtained from consecutive patients undergoing routine audiological diagnosis. The clinical material was not pre-selected or stratified based on specific auditory pathologies. This approach ensured that the datasets reflected the natural variability, technical artifacts, and typical diagnostic challenges encountered in everyday clinical practice, rather than being an artificially designed progression of difficulty. All stages of the education process are shown in **Figure 1**.

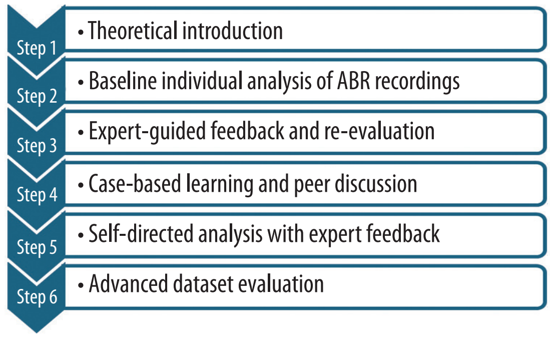

Figure 1. Six-step training process for students in ABR interpretation

Step 1 – Theoretical introduction

First introductory expert-led lecture included theoretical section which addressed the physiological and physical foundations of the ABR, including the generation mechanisms of waves I–V, the basilar membrane response to changes in stimulus intensity, neural firing rate adaptation, and the application of averaging techniques in signal processing. Based on this framework, practical strategies for the detection of wave V were presented, with particular focus on its clinical significance for threshold estimation. After an hour the session ended with a guided analysis of representative recordings, during which thresholds were determined collectively under expert supervision and alternative interpretations were discussed.

Step 2 – Baseline analysis of ABR recordings

Following this theoretical introduction, participants received their first dataset comprising ABR recordings from 30 patients (117 ear-specific cases using both click and tone-burst stimuli at 500, 1000, 2000, and 4000 Hz). Students were instructed to estimate auditory thresholds based on the presence of wave V. Their results were compared with expert evaluations, and discrepancies were quantified as the percentage of instances of complete agreement with expert judgments, the percentage of estimates within 10 dB of the expert thresholds, and the percentage of estimates deviating by more than 10 dB.

Step 3 – Expert-guided feedback and re-evaluation

In subsequent sessions, participants received structured feedback on their performance. Each meeting began with a presentation of summary statistics, including the proportion of responses in complete agreement with expert thresholds and the distribution of deviations. The most challenging cases for students were then selected for detailed discussion. An expert prepared a number of case-based presentations and explained the rationale for the correct threshold determination, highlighting key features important for reliable wave V identification. Alternative interpretations were discussed collectively, and potential

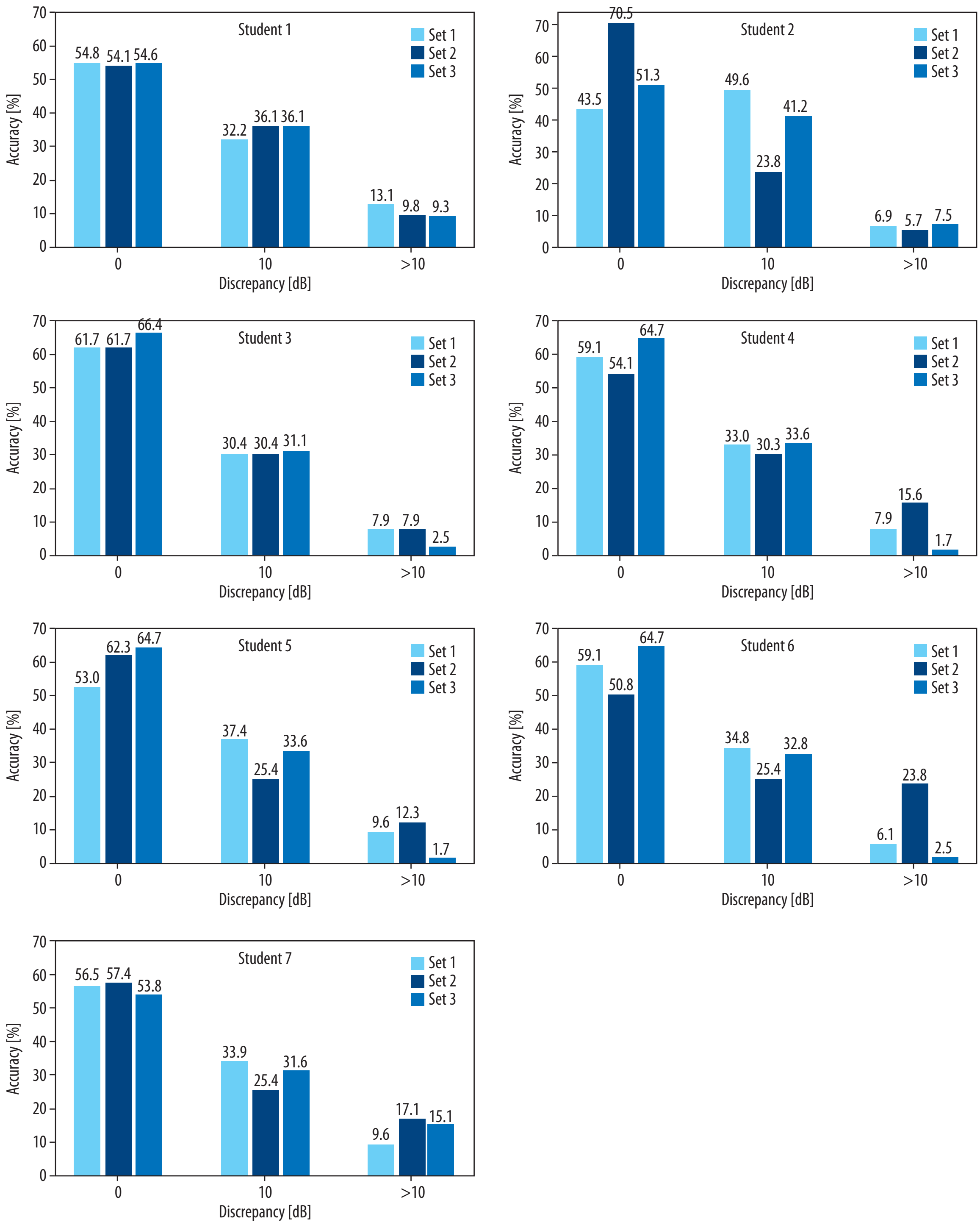

Figure 2. Mean performance of 7 students across 3 sets of ABR interpretations

sources of error were clarified. This interactive format not only reinforced the rules for wave V identification but also provided practical guidance for resolving ambiguity in complex cases. A second dataset, including recordings from 30 patients (122 cases) was subsequently distributed and analysed using the same procedure. Results were assessed in relation to expert judgments, after which group discussions addressed common sources of discrepancy.

Step 4 – Case-based learning and peer discussion

To support further learning, an expert-prepared catalogue of ABR examples was provided, including normal-hearing cases and ears with different types of auditory pathology. The catalogue included principles of frequency specificity, threshold testing procedures, and common errors in interpretation. Using this resource, students selected three

Table 1. Discrepancies (dB, absolute values) in the ratings of 115 ABR records in set no. 1 between students and the expert; values are presented as percentages [%]

Discrepancy [dB]	Student						
	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	6 [%]	7 [%]
0	54.8	43.5	61.7	59.1	53.0	59.1	56.5
10	32.2	49.6	30.4	33.0	37.4	34.8	33.9
20	9.6	6.0	7.9	7.0	6.1	5.2	6.1
30	2.6	0.9		0.9	1.7	0.9	1.7
40					0.9		0.9
50	0.9						
80					0.9		0.9

Table 2. Discrepancies (dB, absolute values) in the ratings of 122 ABR records in set no. 2 between students and the expert; values are presented as percentages [%]

Discrepancy [dB]	Student						
	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	6 [%]	7 [%]
0	54.1	70.5	54.9	54.1	62.3	50.8	57.4
10	36.1	23.8	28.7	30.3	25.4	25.4	25.4
20	6.6	4.1	9.8	7.4	9.8	13.9	9.8
30	1.6	1.6	4.9	6.6	2.5	7.4	4.9
40	0.8		1.6	1.6		2.5	1.6
50	0.8						0.8

particularly challenging or informative cases from their daily tasks – such as technical errors, atypical morphology, or diagnostic ambiguity – and presented them during a seminar session for collective discussion.

Step 5 – Self-directed analysis with expert feedback

Throughout the project, participants engaged in independent practice with continuous access to expert evaluations, which allowed them to compare their judgments with expert results and review differences in wave V identification. They discussed their interpretations within the group, and unresolved cases were clarified through consultation with the expert.

Step 6 – Advanced dataset evaluation

After 4 months of training, a final dataset comprising 21 patients (120 cases) was introduced to assess progress. Although not deliberately selected for difficulty, this consecutive clinical sample naturally happened to include more complex cases (e.g., lower signal-to-noise ratio, atypical morphology). This presented an unplanned but valuable additional challenge for the trainees, while maintaining a comparable total number of cases to earlier sessions. This approach enabled a direct comparison with previous exercises, while controlling for sample size, and thus allowed assessment of the effect of systematic training on student performance in advanced ABR analysis.

Results

Set no. 1

Set no. 1 comprised 117 recordings. The expert provided valid assessments for 115 cases, while 2 cases were deemed unsuitable for evaluation. Therefore, the analyses were conducted with $N = 115$. In this set, the differences between the students' and the expert's assessment ranged from 0 to 80 dB (**Table 1**), with a mean difference of 11.7 dB (SD = 10.4). Full agreement (0 dB difference) ranged from 43.5% to 61.7% across students, while differences of 10 dB occurred in 32.2–49.6% of cases. Differences above 10 dB were observed in 6.1–13.1% of cases.

Set no. 2

Set 2 comprised 122 ABR recordings, all of which were assessed by the expert. In set no. 2, the differences between the students' assessments and the expert's assessment ranged from 0 to 50 dB (**Table 2**), with a mean difference of 11.1 dB (SD = 10.5). Full agreement was observed in 50.8–70.5% of cases. Differences of 10 dB occurred in 23.8–36.1% of cases. Differences above 10 dB were observed in 5.7–17.1% of cases.

Table 3. Discrepancies (dB, absolute values) in the ratings of 119 ABR records in set no. 3 between students and the expert; values are presented as percentages [%]

Discrepancy [dB]	Student						
	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	6 [%]	7 [%]
0	54.6	51.3	66.4	64.7	64.7	64.7	53.8
10	36.1	41.2	31.1	33.6	33.6	32.8	31.1
20	5.9	6.7	2.5	1.7	1.7	2.5	13.4
30	3.4	0.8					1.7

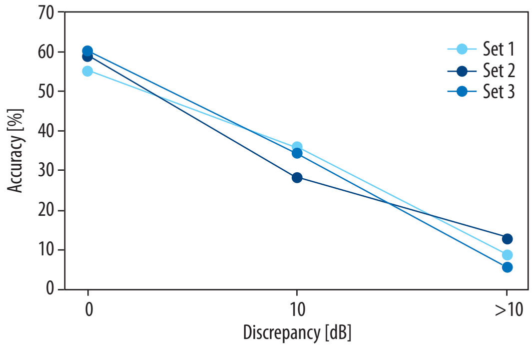

Figure 3. Changes in students' agreement with the expert across 3 successive sets of ABR assessments

Set no. 3

Set no. 3 comprised 120 recordings. The expert provided valid assessments for 119 cases, while 1 case was deemed unsuitable for evaluation. Therefore, the analyses were conducted with $N = 119$. In this set, the differences between the students' assessments and the expert's assessment ranged from 0 to 30 dB (**Table 3**), with a mean difference of 10.1 dB (SD = 7.3). Full agreement ranged from 51.3 to 66.4% across students, while differences of 10 dB occurred in 31.1–41.2% of cases. Differences above 10 dB were observed in 1.7–15.1% of cases.

General student performance

Overall, participants demonstrated measurable improvement in ABR threshold estimation over the course of the training (**Figure 2**). The mean accuracy relative to expert assessments (0 dB difference) increased slightly across the three datasets, from 55.4% in Set 1 to 58.7% in Set 2, and 60.0% in Set 3. This gradual rise indicates a steady enhancement in students' ability to correctly identify the ABR threshold.

At the same time, the proportion of responses differing by more than 10 dB from the expert benchmark decreased markedly, from 8.7% in Set 1 to 5.8% in Set 3, reflecting a meaningful reduction in major errors. Minor discrepancies (≤ 10 dB) fluctuated slightly –35.9%, 28.1%, and 34.2% for Sets 1–3, respectively – suggesting that while some variability persisted, students became more consistent in distinguishing near-threshold responses.

Taken together, these observations suggest that structured expert guidance was associated with an improvement and a clinically meaningful reduction in large errors in ABR interpretation, even though small inter-individual variability remained.

Individual student progress

To examine the learning progress of individual students, the percentage of full agreement with the expert's assessments (0 dB difference) and size of differences were analysed across the three sets. This allowed for the evaluation of both inter-individual variability and changes in accuracy over time.

Figure 3 shows that there were varying learning dynamics among the trainees. While some participants demonstrated steady, progressive improvement in full agreement with the expert (e.g., students 3, 4, and 5), others exhibited more fluctuation across the successive datasets (e.g., students 2 and 6). However, despite these individual variations in exact threshold matching, a common trend emerged: for the majority of participants, repeated practice and guided feedback were associated with a distinct consolidation of skills and a marked reduction in large discrepancies (>10 dB) by the final assessment.

Discussion

The results of this preliminary descriptive study indicate that the multi-stage training process was associated with an improvement in accuracy and a clinically meaningful reduction in large errors during ABR threshold estimation. Full agreement (0 dB difference) was achieved in 43.5–70.5% of cases, with the highest concordance observed in Set 2, while discrepancies within 10 dB occurred in approximately one-third of cases across all sets, suggesting that most deviations were small and clinically acceptable. Large discrepancies (>10 dB) were relatively infrequent, with the mean frequency across all students decreasing from 9.4% in Set 1 to 6.6% in Set 3, despite a temporary increase to 12.6% in Set 2, likely due to more challenging or complex cases. This reduction in major errors reflects a gradual improvement in consistency and supports the potential value of systematic, expert-led practical training, which is particularly important clinically to ensure reliable hearing threshold estimation and reduce the risk of misdiagnosis.

Analysis of individual and group performance revealed measurable improvement across all students. Overall mean accuracy relative to expert assessments increased from 55.4% in Set 1 to 60.0% in Set 3. All participants, despite varying levels of baseline theoretical knowledge prior to the project, demonstrated measurable improvement. This highlights that systematic, supervised practice can enhance interpretive accuracy and reduce errors in novice learners.

The greatest progress was observed between set 2 and set 3, mainly due to a reduction in large errors (>10 dB). This improvement highlights the potential utility of strategies such as direct expert feedback, case-based discussions, and regular comparison of students' assessments with expert evaluations over a longer period of time. This approach facilitated faster reduction of large errors and supported the consolidation of interpretive skills. Early, intensive application of case-based learning and interactive correction sessions appeared particularly beneficial, proving more effective than relying only on oral instructions [25], which may provide only limited improvement in interpretive accuracy without hands-on practice and individual feedback.

These findings are consistent with previous reports on learning ABR interpretation. Dzulkarnain and colleagues [24] showed that direct, interactive expert-led training is more effective than simulator- or computer-based instruction. Our descriptive observations support the notion that structured, multi-stage training may help enhance accuracy in ABR interpretation and reduce the incidence of large errors. At the same time, the literature on training novice ABR interpreters remains limited, and our observations provide a useful contribution to the development of educational strategies in audiology.

It is important to note that even among experts, some degree of disagreement exists in ABR threshold estimation. As some studies suggest [14,26], inter-expert differences can exceed 10 dB in certain cases, indicating that complete agreement among students with expert assessments is unrealistic. This variability leaves room for artificial intelligence (AI) systems, which, once properly trained, might provide more consistent and objective threshold evaluations [27], reducing the subjectivity inherent in human interpretation.

While the present study focused exclusively on traditional, expert-guided learning to establish a human-annotated baseline, in the future ML and AI systems could play a significant role in supporting student education [28,29], for example by offering real-time guidance or highlighting key ABR features in recordings. Such tools could accelerate the reduction of large errors [30] and shorten the time needed to acquire proficiency in ABR threshold estimation.

Overall, the study met its objectives: it was found that students demonstrated measurable progress across successive training stages, the multi-stage training was associated with enhanced ABR interpretation accuracy, and the students' performance could be reliably compared with expert judgements, highlighting the importance of structured, feedback-based learning.

Limitations

There are several limitations of this study. First, the small number of participants ($N = 7$) limits the generalisability of the results. Second, since the recordings consisted of consecutive clinical cases, the difficulty of the datasets was not controlled. Thus, the third dataset contained more complex recordings and was reported by students as being the most challenging, and therefore would have affected the recorded differences and rules out direct comparison of progress across datasets. Future studies should aim to standardise dataset difficulty to allow better assessment of training effectiveness.

Conclusions

This preliminary descriptive study demonstrated that structured, expert-guided multi-stage training was associated with a modest improvement in students' exact agreement with expert ABR threshold estimations, alongside a clinically meaningful reduction in large errors (>10 dB). These findings add to the limited literature on training novice ABR interpreters and indicate that AI systems may in the future support both educational processes and the standardisation of threshold assessment. Despite limitations related to sample size and unequal dataset difficulty, the study highlights the potential of structured training and ML/AI support to accelerate the learning curve and improve the reliability of ABR interpretation.

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SACCULO-COLLIC FUNCTION IN 8 CHILDREN BEFORE AND AFTER COCHLEAR IMPLANTS

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Abstract

Introduction: Cochlear implantation is a standard intervention for children with severe to profound sensorineural hearing loss. However, the procedure may affect vestibular function due to its anatomical proximity to the cochlea. This study evaluated sacculo-collic pathway function using cervical vestibular evoked myogenic potentials (cVEMPs) in children undergoing unilateral cochlear implantation, comparing responses at three times: pre-operative (pre-op), immediate post-operative (post-op), and at a 3-month follow-up.

Material and methods: This longitudinal study was conducted on 9 children (mean age 3.7 ± 1.4 years) with congenital bilateral severe-to-profound sensorineural hearing loss who all received a CI in the right ear. Assessments were done at 3 time points using cVEMPs. Parameters analysed comprised P1 and N1 latencies, P1–N1 amplitude, and interaural amplitude asymmetry ratio. Responses for 1 child could not be recorded at any time point, so reported data relate to the remaining 8 children.

Results: At the pre-op stage, normal cVEMP responses were observed in 8 of the 9 children, with normal P1–N1 amplitudes and latencies. Post-operatively, 4 of the 8 exhibited absent or markedly reduced responses in the implanted (right) ear, with a significant decrease in amplitude (mean 15.1 ± 21.2 μV vs pre-op 101.5 ± 90.2 μV; $p = 0.029$). At the follow-up, partial recovery of amplitude was noted (mean 35.1 ± 30.3 μV). No statistically significant changes were found in latency across the different time points ($p > 0.05$), and responses in the non-implanted (left) ear remained relatively stable. However, 6 participants showed amplitude asymmetry > 33% post-operatively, with 4 exhibiting complete (100%) asymmetry; this difference was statistically significant $p < 0.001$).

Conclusions: Findings suggest that cochlear implantation in children may induce temporary alterations in sacculo-collic function, mainly evidenced by a reduction in cVEMP amplitude post-operatively. The observed partial recovery at follow-up suggests reversible vestibular changes, possibly due to central compensation. This underscores the importance of ongoing vestibular assessment in pediatric CI recipients to monitor potential transient dysfunction and recovery patterns.

Keywords: cVEMP • cochlear implantation • pediatric vestibular function • sacculo-collic reflex

FUNKCJA DROGI WORECZKOWO-SZYJNEJ U 8 DZIECI PRZED I PO IMPLANTACJI ŚLIMAKOWEJ

Streszczenie

Wprowadzenie: Implantacja ślimakowa stanowi standardową metodę leczenia dzieci z głębokim lub znacznym odbiorczym ubytkiem słuchu. Ze względu jednak na bliskie sąsiedztwo anatomiczne ślimaka i narządu przedsionkowego zabieg może wpływać na czynność układu przedsionkowego. W niniejszym badaniu oceniano funkcję drogi woreczkowo-szyjnej za pomocą szyjnych przedsionkowych mięśniowych potencjałów wywołanych (cVEMP, cervical vestibular evoked myogenic potentials) u dzieci poddawanych jednostronnej implantacji ślimakowej. Wyniki porównano w trzech punktach czasowych: przed operacją (*pre-op*), bezpośrednio po operacji (*post-op*) oraz po 3 miesiącach obserwacji.

Materiał i metody: Badanie o charakterze podłużnym przeprowadzono u 9 dzieci (średni wiek: 3,7 ± 1,4 roku) z wrodzonym obustronnym znacznym do głębokiego niedosłuchem odbiorczym, u których wszczepiono implant ślimakowy do prawego ucha. Oceny wykonywano w trzech punktach czasowych z wykorzystaniem badania cVEMP. Analizowane parametry obejmowały latencje fal P1 i N1, amplitudę zespołu P1–N1 oraz międzyuszną proporcję asymetrii amplitudy. U jednego dziecka nie udało się zarejestrować odpowiedzi w żadnym punkcie czasowym, dlatego przedstawione wyniki dotyczą pozostałych 8 pacjentów.

Wyniki: Przed zabiegiem prawidłowe odpowiedzi cVEMP stwierdzono u 8 z 9 dzieci, z prawidłowymi wartościami amplitudy P1–N1 oraz latencji. Bezpośrednio po operacji u 4 spośród 8 dzieci zaobserwowano brak odpowiedzi lub wyraźne zmniejszenie odpowiedzi w uchu implantowanym (prawym), czemu towarzyszył istotny statystycznie spadek amplitudy (średnio 15,1 ± 21,2 μV wobec 101,5 ± 90,2 μV przed operacją; $p = 0{,}029$). W badaniu kontrolnym po 3 miesiącach odnotowano częściową poprawę amplitudy odpowiedzi (średnio 35,1 ± 30,3 μV).

Nie wykazano istotnych statystycznie zmian latencji pomiędzy poszczególnymi punktami czasowymi ($p > 0,05$), a odpowiedzi rejestrowane z ucha nieimplantowanego (lewego) pozostawały względnie stabilne. Jednocześnie u 6 uczestników po operacji stwierdzono asymetrię amplitudy przekraczającą 33%, przy czym u 4 dzieci występowała całkowita (100%) asymetria. Różnica ta była istotna statystycznie ($p < 0,001$).

Wnioski: Uzyskane wyniki sugerują, że implantacja ślimakowa u dzieci może powodować przejściowe zaburzenia funkcji drogi woreczkowo-szyjnej, manifestujące się przede wszystkim zmniejszeniem amplitudy odpowiedzi cVEMP po zabiegu. Obserwowana częściowa poprawa w badaniu kontrolnym wskazuje na możliwość odwracalnego charakteru zmian przedsionkowych, prawdopodobnie związanego z procesami kompensacji ośrodkowej. Wyniki te podkreślają znaczenie regularnej oceny funkcji przedsionkowych u dzieci korzystających z implantów ślimakowych w celu monitorowania przejściowych zaburzeń oraz przebiegu ich ustępowania.

Słowa kluczowe: cVEMP • implant ślimakowy • funkcje przedsionkowe u dzieci • odruch woreczkowo-szyjny

Introduction

In 2018, the World Health Organisation (WHO) reported a prevalence of hearing impairment of approximately 6.3% in India, where adult-onset deafness is estimated at 7.6%, while childhood-onset deafness stands at 2% [1]. Among children above 3 months old, sensorineural hearing loss affects about 16% of the population. The primary interventions for this type of hearing loss include the use of amplification devices and cochlear implants (CIs). A child with bilateral sensorineural hearing loss of 80 dB HL or greater, who shows no improvement after 6 months of rehabilitation with hearing aids, is considered an ideal candidate for cochlear implantation [2].

A CI is an electronic device containing a current source and an electrode array implanted into the cochlea; an electrical current is then used to stimulate the surviving auditory nerve fibres [3]. Optimal electrode placement is a prerequisite for maximising CI success. Standard CI surgery includes a mastoidectomy and facial recess approach to the middle ear and cochlea. Electrodes are placed in the scala tympani through the round window with a cochleostomy [4]. An ideal cochleostomy is inferior and slightly anterior to the round window membrane. A superior position results in injury to the spiral ligament and basilar membrane and risks insertion into the scala vestibule [4]. Other than the risk of insertion in the wrong partition of the cochlea, many traumas are associated with the insertion of electrodes. Thus, cochlear implantation can affect the vestibular system through various mechanisms such as direct trauma caused by electrode insertion, acute serous labyrinthitis due to cochleostomy, foreign body reaction with labyrinthitis, endolymphatic hydrops, and electrical stimulation from the implant itself [5]. These mechanisms can alter vestibular function temporarily or may cause permanent damage. Therefore, vestibular testing is helpful for pre-, post-, and follow-up in CI surgery to assess the extent of dysfunction and monitor patient recovery. Compared to adults, assessing vestibular function in children is not easy. Nevertheless, the current study aimed to examine the vestibular function in children with severe to profound hearing loss before and after a CI.

Material and methods

A longitudinal comparative study was conducted to evaluate the sacculo-collic pathway using cervical vestibular evoked myogenic potential (cVEMP) measurements at three defined times points: before cochlear implantation (pre-op), on the switch-on day of the implant system (post-op), and after 3 months of surgery (follow-up). Initially, 18 children aged 2 to 5 years with congenital bilateral severe-to-profound sensorineural hearing loss were enrolled, but those with middle ear history, pre-existing vestibular dysfunction, neuromuscular or musculoskeletal deficits, and cognitive impairments were excluded from the study. Therefore, only 9 participants completed all assessments – comprising 5 boys and 4 girls – with a mean age of 3.7 ± 1.4 years at implantation, all receiving unilateral right-ear implants (**Table 1**). Switch-on for all the participants was done after 2 weeks.

Table 1. Ages of participants; F, female; M, male

Case no.	Gender	Age at implantation [years]
1	F	5
2	F	2
3	M	2
4	F	5
5	M	3
6	M	5
7	F	5
8	M	2
9	M	5

cVEMP measurements were performed using the Eclipse instrument (Interacoustics). Key cVEMP parameters analysed were P1 and N1 latencies, P1–N1 amplitude, and P1–N1 amplitude asymmetry ratio across the three time points. Latency of P1 of more than 20 ms and N1 of more than 30 ms were considered abnormal. Interaural latency difference of more than 3.5 ms for each component was considered abnormal, as was amplitude asymmetry greater than 33% [6].

Ethical approval was obtained from the Institutional Ethical Committee, and written informed consent was secured from parents or guardians before data collection.

Audiological testing was performed in a sound-treated environment conforming to ANSI S3.1(1991) standards for ambient noise. During cVEMP recordings, each child was seated comfortably either in a chair or the caregiver's lap and instructed to turn their head away from the test ear without torso rotation, maintaining an awake and stable posture. The active electrode was placed on the

Table 2. ANOVA results for both ears of 8 children for P1 latency, N1 latency, and P1–N1 amplitude at three time points

Parameter	Ear	Pre-op	Post-op	Follow-up	*F*-value	*p*-value
P1 latency (mean ± SD) [ms]	right	11.76 ± 4.43	8.22 ± 7.96	12.07 ± 4.60	2.373	0.162
	left	12.66 ± 4.81	10.55 ± 6.32	12.40 ± 4.72	1.463	0.262
N1 latency (mean ± SD) [ms]	right	19.09 ± 7.35	11.92 ± 11.52	18.75 ± 7.26	4.222	0.073
	left	19.99 ± 7.69	15.97 ± 9.50	19.31 ± 7.53	2.607	0.143
P1–N1 amplitude (mean ± SD) [μV]	right	101.49 ± 90.20	15.14 ± 21.18	35.08 ± 30.25	6.658	**0.029***
	left	95.13 ± 75.95	64.47 ± 59.85	74.08 ± 55.05	2.507	0.145

* Statistically significant ($p < 0.05$)

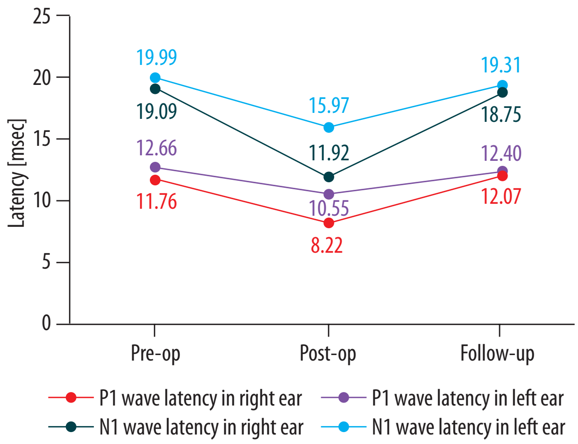

Figure 1. Mean P1 and N1 wave latency at 3 time points – before, immediately after, and at 3 months follow-up – in 8 children implanted with a CI in the right ear

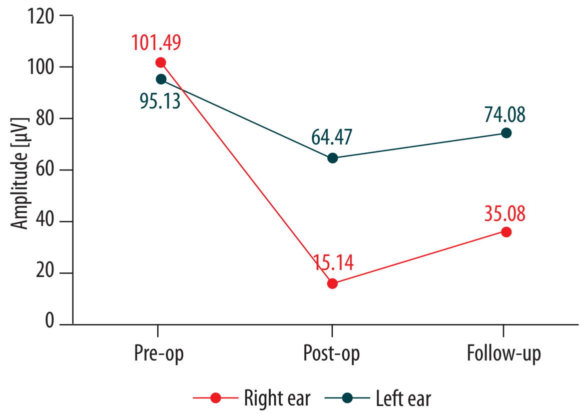

Figure 2. Mean P1–N1 amplitude at 3 time points – before, immediately after, and at 3 months follow-up – in 8 children implanted with a CI in the right ear

upper one-third of the sternocleidomastoid muscle (SCM), the reference electrode was placed on the junction of the sternum and clavicle, and the ground was positioned on the lower forehead. Tone burst stimuli of 500 Hz at 95 dB nHL were used. To sustain adequate SCM muscle tension for reliable signal acquisition, visual stimuli such as videos were presented on tablets positioned to engage the child's gaze throughout testing.

Statistical analysis

The data obtained were subjected to statistical analysis using SPSS v.25. The normality of data distribution was confirmed using a Shapiro–Wilk test. The data was normally distributed, and so an analysis of variance (ANOVA) included Mauchly's test of sphericity, and a Greenhouse–Geisser test was applied to compare P1 and N1 latency and amplitude across three time points. Post hoc tests with Bonferroni adjustment compared specific time points (pre-op vs post-op, pre-op vs follow-up, and post-op vs follow-up) separately for each ear.

Results

Baseline sacculo-collic function was assessed using cVEMPs before CI surgery. Responses (P1 and N1 peaks) were present bilaterally in 8 of the 9 participants. Mean P1 latency in the to-be-implanted ear (right ear) was 11.76 ± 4.43 ms, with a mean N1 latency of 19.09 ± 7.35 ms. The non-implanted (left ear) showed comparable values with P1 latency of 12.66 ± 4.81 ms and N1 latency of 19.99 ± 7.69 ms (**Table 2**). P1–N1 peak-to-peak amplitude averaged 101.49 ± 90.20 μV in the right ear versus 95.13 ± 75.95 μV in the left ear, with no statistically significant interaural differences. One child (subject nr 2 in **Table 1**) demonstrated absent cVEMP responses bilaterally across all time points, suggesting preexisting vestibular dysfunction. The following data, therefore relates to the remaining 8 children.

On the day of switch-on, cVEMP responses were absent in 4 participants in the right ear and 2 in the left ear. The major difference was seen in the latency shift of P1 and N1. Mean P1 latency shortened to 8.22 ± 7.96 ms (implanted right ear) and 10.55 ± 6.32 ms (non-implanted

Table 3. Post hoc pairwise comparisons (estimated marginal means with Bonferroni correction)

Parameter	Comparison	Mean difference	Standard error	*p*-value
Implanted ear amplitude	pre-op vs post-op	86.36 µV	30.31	**0.043***
	pre-op vs follow-up	66.41 µV	24.52	**0.042***
	post-op vs follow-up	–19.95 µV	10.55	0.240
Non-implanted ear amplitude	pre-op vs post-op	30.66 µV	11.04	**0.044***
	pre-op vs follow-up	21.05 µV	6.75	**0.027***
	post-op vs follow-up	–9.61 µV	5.08	0.239
Asymmetry ratio	pre-op vs post-op	–58.78%	14.67	**0.012***
	pre-op vs follow-up	–25.34%	12.45	**0.045***
	post-op vs follow-up	33.44%	9.96	**0.030***

* $p < 0.05$. Positive mean differences indicate a reduction from the first to the second time point. Negative mean differences for asymmetry ratio indicate an increase in asymmetry

left ear), while N1 latency reduced to 11.92 ± 11.52 ms and 15.97 ± 9.50 ms, respectively (**Figure 1**). As seen in **Figure 2**, mean P1–N1 peak-to-peak amplitude in the right ear decreased substantially to 15.1 ± 21.2 µV, representing an approximately 85% reduction from baseline values. However, the left ear showed a less pronounced decline to 64.5 ± 59.9 µV (a 32% reduction) (**Table 2**).

Statistical analysis using repeated measure ANOVA with Greenhouse–Geisser correction revealed that amplitude changes in the implanted ear pre and post implant were statistically significant ($F = 6.658$, $p = 0.029$). Post hoc pairwise comparisons with Bonferroni correction were conducted for the implanted ear amplitude. Significant differences were observed between pre-operative and post-operative measurements ($p = 0.043$), indicating immediate post-surgical amplitude reduction (**Table 3**). The difference between pre-operative and follow-up remained significant ($p = 0.042$), demonstrating incomplete recovery at 3 months. The post-operative to follow-up comparison showed a trend toward recovery but did not reach statistical significance ($p = 0.240$) (**Table 3**).

However, latency changes did not show any significance between these two time points (P1 latency: $p = 0.162$; N1 latency: $p = 0.073$) (**Table 2**).

However, in terms of amplitude, post hoc pairwise comparisons revealed that, for the non-implanted ear, there was a significant difference between pre-operative and post-operative measurements. **Table 3** shows that for this ear there was a significant difference between pre-op and post-op ($p = 0.044$), while the comparison between pre-op and follow-up was also significant ($p = 0.027$). However, the post-op to follow-up comparison was not significant ($p = 0.239$).

Turning to asymmetry ratio, post hoc analysis of changes demonstrated highly significant increases from pre-op to post-op ($p = 0.012$) and from post-op to follow-up ($p = 0.030$), reflecting initial deterioration and then partial recovery of interaural symmetry (**Table 3**). Interaural amplitude asymmetry ratio exceeded 33% in 6 cases post-operatively, compared to only 1 pre-operatively, representing a statistically significant change ($F = 12.34$, $p = 0.001$).

At 3 months follow-up, substantial recovery of sacculo-collic function was seen (**Figures 1** and **2**). cVEMP responses were present in 8 children bilaterally, matching pre-operative response rates. Mean P1 latency in the implanted ear returned to near-baseline values at 12.07 ± 4.60 ms, with N1 latency at 18.75 ± 7.26 ms. The non-implanted ear demonstrated a similar trend with P1 latency of 12.40 ± 4.72 ms and N1 latency of 19.31 ± 7.53 ms (**Table 2**).

Nevertheless, P1–N1 amplitude recovery remained incomplete. The implanted ear showed a mean amplitude of 35.08 ± 30.25 µV, representing 34.6% of preoperative values, while the non-implanted ear recovered to 74.08 ± 55.05 µV (77.9% of baseline) (**Table 2**). Despite overall amplitude reduction, statistical analysis demonstrated no significant differences compared to baseline for the non-implanted ear ($p = 0.145$), whereas the implanted ear changes remained significant ($p = 0.029$). Interaural asymmetry ratios were normal in most cases, with only 2 children showing persistent asymmetry exceeding the 33% mark.

Discussion

Post-operative changes in vestibular function, as measured through cVEMP, were evident in the present study. Pre-operatively, cVEMP was present in 8 out of 9 participants for both ears. (One participant showed absent VEMP responses across all time periods bilaterally.) Post-operatively, however, cVEMPs were absent in 4 implanted ears and 2 non-implanted ears. But at the 3-month follow-up, responses were once again present in both ears of 8 participants, indicating there had been a partial recovery over time. We note that participants with absent responses did not report any dizziness or vertigo pre- or post-implantation, suggesting subclinical vestibular involvement.

Similar patterns have been reported by Jin et al., where 11 of 12 children demonstrated absent VEMP responses following cochlear implantation [7]. Similar results are reported in [8]. However, Psillas et al. [9] observed reappearance of responses in half the participants at 6 months post-surgery, despite a complete loss immediately after surgery. These findings, along with the present results, highlight transient vestibular dysfunction following cochlear implantation, likely associated with insertion-related trauma.

To check the effect of insertion on vestibular functions, a few authors have tried to see VEMP responses intraoperatively and postoperatively with the device "on" and "off". Jin et al. [12] did not find any response on electromyographic VEMP testing even after 6 weeks post surgery. They stated that the absence of a recordable wave postoperatively may be due to the mechanical block of the auditory signal by the CI, indicating a direct correlation of electrode insertion with vestibular function. In another study, Xu et al. explored the activation of the vestibular nerve due to cochlear implantation. Post-operatively, 11 of 12 children exhibited absent VEMP responses; however, with the device on, normal responses were restored in 3 children, with increased amplitude in only one child. They concluded that electrical stimulation delivered by the cochlear implant may partially activate the vestibulocochlear nerve, thereby compensating for vestibular dysfunction resulting from electrode insertion trauma [13].

In the current study, the latency of wave P1 and N1 did not differ significantly ($p > 0.05$) across pre-op, post-op, and follow-up periods for either ear. This aligns with Jin et al., who also reported the same in their follow-up study [12]. Conversely, Xu et al. found shortened N1 and P1 latency and reduced amplitude post-surgery. These changes in the implanted ear were attributed as direct injury of the saccular or utricular structures during electrode insertion. The authors further stipulated that minor trauma may still permit VEMP generation with minimal latency changes [13].

While latencies remained stable in our study, a significant difference ($p = 0.029$) was observed in P1–N1 amplitude between pre- and post-operative measurements in implanted ears. The initial amplitude reduction post--surgery, followed by partial recovery at follow-up, implies transient vestibular pathway disruption. Histopathological investigations of the implanted ear have also demonstrated structural alterations post-surgery. Fibrosis in the vestibule, saccule membrane distortion, new bone formation, and reactive neuromas were observed. The scala vestibuli damage due to osseous spiral lamina or basilar membrane involvement in the cochlear basal turn was observed in most (75%) patients, supporting the likelihood of peripheral injury [14]. Similarly, morphological findings – such as cochlear hydrops with collapsed saccule – have been reported by Handzel et al. in 59% of their patients, reinforcing the notion of vestibular involvement post-implantation [15].

Despite all participants undergoing implantation via the round window approach, 3 exhibited absent and 4 reduced post-operative VEMP responses. Though generally associated with less vestibular trauma than alternative approaches, the round window technique can still cause some damage. Comparative studies have confirmed that even this technique is not entirely devoid of vestibular risk [16].

Additionally, significant post-operative asymmetry in P1–N1 amplitude ($p < 0.001$) between ears was observed, implying alterations in unilateral vestibular functioning due to cochlear implantation. 4 participants showed complete (100%) asymmetry, while 2 showed greater than 33% asymmetry post-operatively. However, no participant demonstrated any change in vestibular symptoms, suggesting possible central compensation masking the peripheral level damage. Supporting evidence from animal models by Ris has demonstrated restoration of neural activity within one week after labyrinthectomy, indicating early central adaptation following peripheral vestibular injury [17].

Notably, the non-implanted ear exhibited a smaller but statistically significant postoperative amplitude reduction, which was not detected by overall ANOVA but was revealed by post hoc testing. This contralateral effect, persisting at borderline significance at follow-up, suggests that even the non-implanted ear should be tested post operatively for vestibular changes. The reason for changes in contralateral ear are unclear but could be due to either subclinical bilateral vestibular vulnerability in severe-profound SNHL or surgical factors, such as labyrinthine hydrops propagation, which became apparent after the stress of surgery [18,19].

In the present study, although latency values varied across the three time periods, these differences did not reach statistical significance, likely due to the small sample size, a limitation of our study. These differences between pre-op and post-op responses, and between recovery and follow-up, need to be explored further.

Conclusions

The present study aimed to assess vestibular function in children with severe to profound hearing loss before and after cochlear implantation to understand the extent of dysfunction and to investigate recovery patterns. The findings demonstrated that implantation can lead to changes in vestibular functions that are seen in reduced amplitudes or absent responses in the implanted ear. Restoration of function occurred throughout the recovery period up to follow-up. We believe that cVEMPs can be an effective objective tool for monitoring vestibular function before and after a CI.

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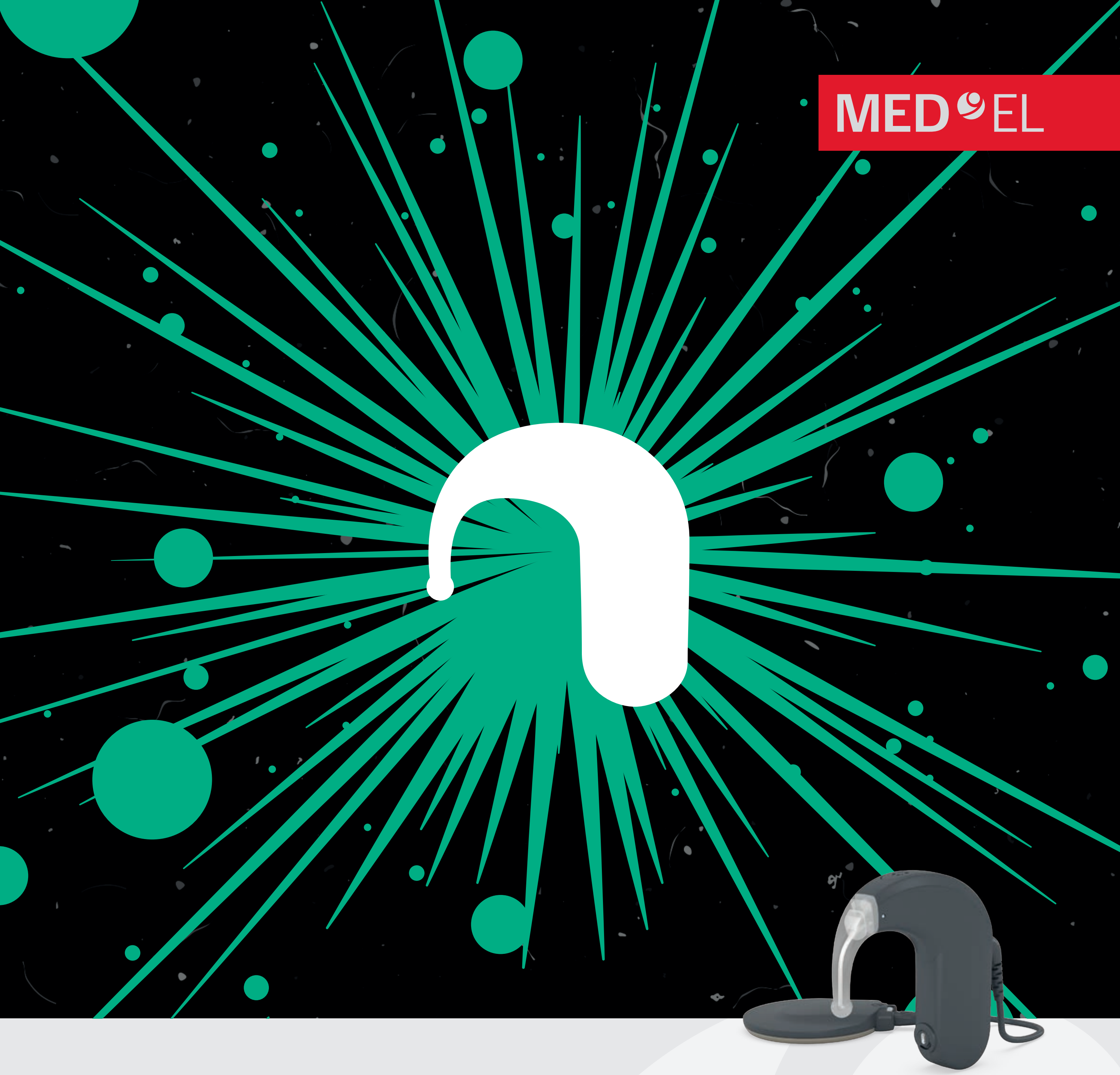

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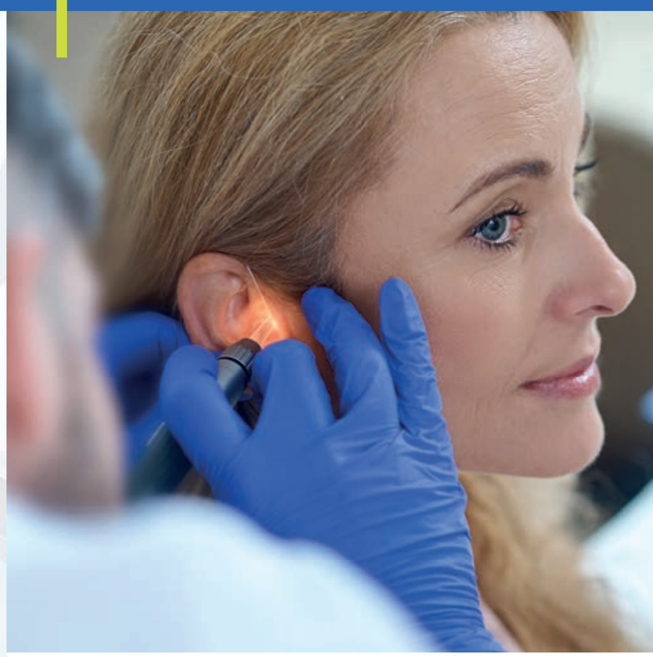

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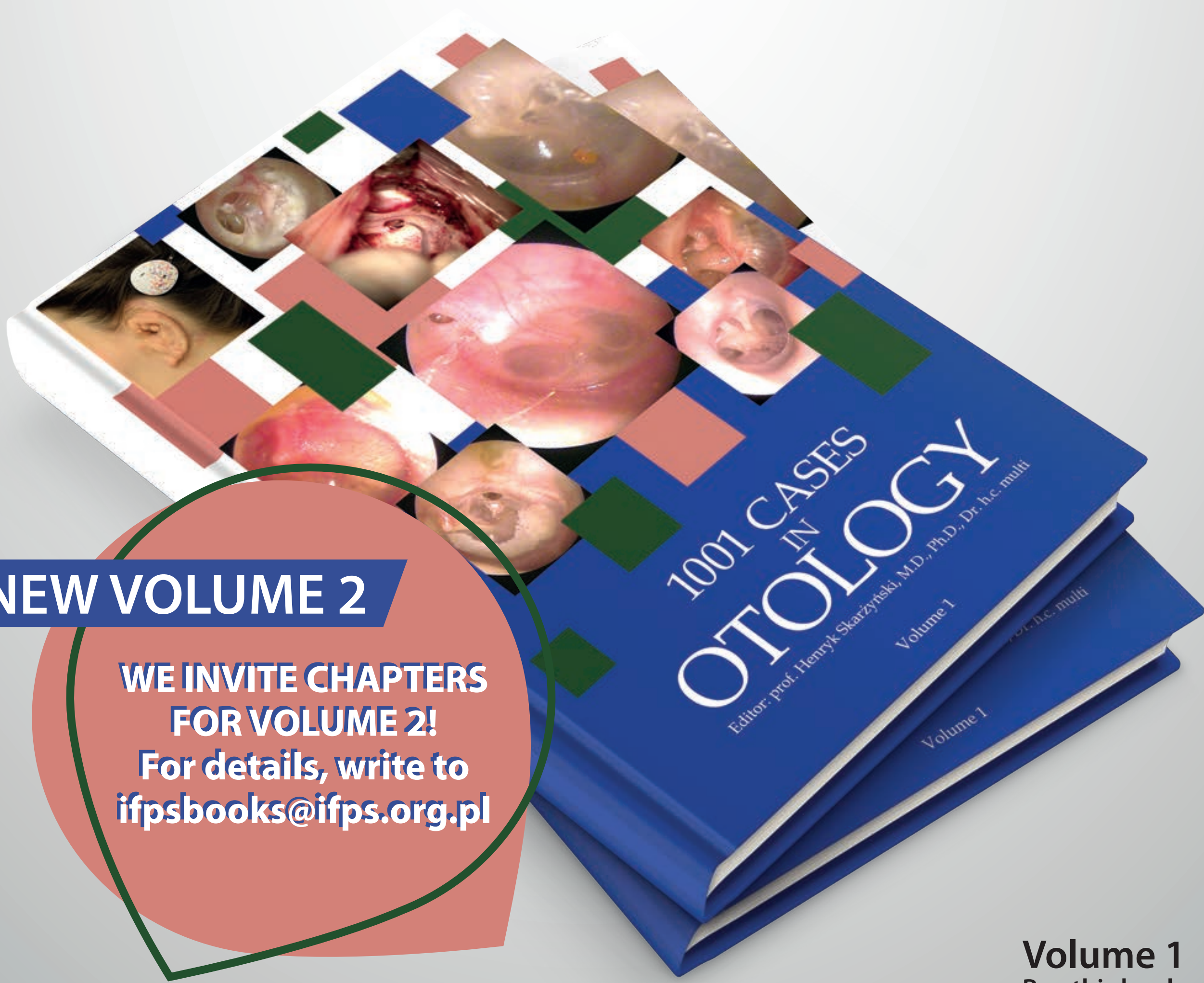

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