

Más allá de la audiometría: Evidencia actual sobre la pérdida auditiva oculta, la sinaptopatía coclear y las estrategias diagnósticas emergentes

Beyond the Audiogram: Current Evidence on Hidden Hearing Loss, Cochlear Synaptopathy, and Emerging Diagnostic Strategies

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RESUMEN

La pérdida auditiva oculta (Hidden Hearing Loss, HHL) se ha convertido en un tema de creciente interés en la medicina auditiva debido a que numerosos pacientes presentan importantes dificultades para la comunicación a pesar de mostrar umbrales normales en la audiometría tonal convencional. Esta revisión analiza de manera crítica la evidencia científica internacional relacionada con la epidemiología, fisiopatología, manifestaciones clínicas, desafíos diagnósticos y perspectivas terapéuticas de la HHL, con especial énfasis en la sinaptopatía coclear y sus

implicaciones clínicas. Se realizó una revisión narrativa de la literatura utilizando el Método Científico como marco metodológico. Se consultaron publicaciones indexadas en PubMed/MEDLINE, Scopus, Web of Science y Google Scholar, priorizando estudios originales, revisiones sistemáticas, metaanálisis y guías clínicas publicadas en revistas científicas arbitradas. La evidencia analizada demuestra que las dificultades para comprender el habla en ambientes ruidosos, el tinnitus, la fatiga auditiva y las alteraciones del procesamiento temporal constituyen las manifestaciones clínicas más frecuentemente descritas. La exposición ocupacional y recreativa al ruido, junto con el envejecimiento fisiológico, fueron los principales factores de riesgo identificados. Aunque la audiometría tonal convencional continúa siendo indispensable para la evaluación auditiva, presenta limitaciones importantes para detectar disfunción neural temprana. Las pruebas complementarias, como la evaluación del habla en ruido, los potenciales evocados auditivos del tronco cerebral, la audiometría de altas frecuencias y otras técnicas electrofisiológicas, aportan información diagnóstica adicional; sin embargo, ninguna constituye actualmente un estándar diagnóstico definitivo. La literatura respalda el uso de estrategias diagnósticas multimodales que integren información clínica, conductual y fisiológica. Asimismo, se destaca la necesidad de establecer criterios diagnósticos estandarizados, desarrollar biomarcadores objetivos, promover estudios multicéntricos e incrementar la producción científica en Latinoamérica. La pérdida auditiva oculta representa un concepto multidisciplinario en constante evolución que amplía la comprensión de la función auditiva más allá de la audiometría convencional y favorece un abordaje integral orientado a mejorar el diagnóstico temprano, el tratamiento y la investigación futura.

PALABRAS CLAVE

Pérdida auditiva oculta, Sinaptopatía coclear, Hipoacusia, Percepción del habla en ruido, Potenciales evocados auditivos del tronco cerebral, Audiometría de altas frecuencias, Tinnitus, Diagnóstico auditivo, Audiología, Otorrinolaringología, Neurología, Exposición al ruido, Neurociencia auditiva, Conservación auditiva, Medicina de precisión.

ABSTRACT

Hidden hearing loss (HHL) has emerged as an important topic in auditory medicine because many individuals experience significant communication difficulties despite presenting normal pure-tone audiometric thresholds. This review critically analyzes current international evidence regarding the epidemiology, pathophysiology, clinical manifestations, diagnostic challenges, and therapeutic perspectives associated with HHL, with particular emphasis on cochlear synaptopathy and its implications for clinical practice. A narrative literature review was conducted using the Scientific Method as the methodological framework. Scientific publications indexed in PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar were reviewed, prioritizing original investigations, systematic reviews, meta-analyses, and clinical guidelines published in peer-reviewed journals. The evidence indicates that speech-in-noise perception deficits, tinnitus, listening fatigue, and temporal auditory processing impairments represent the most frequently reported manifestations among individuals with suspected HHL. Occupational and recreational noise exposure, together with physiological aging, were consistently identified as the principal risk factors. Although conventional pure-tone audiometry remains essential for hearing assessment, it demonstrates limited sensitivity for detecting early neural dysfunction. Complementary evaluations, including speech-in-noise testing, auditory brainstem responses, extended high-frequency audiometry, and other electrophysiological techniques, provide additional diagnostic information; however, no single method currently constitutes a definitive diagnostic standard. The reviewed literature supports the implementation of multimodal diagnostic strategies integrating behavioral, physiological, and clinical findings. Furthermore, the analysis highlights the need for standardized diagnostic criteria, objective biomarkers, multicenter investigations, and increased scientific participation from Latin America. Hidden hearing loss represents an evolving multidisciplinary concept that expands the understanding of auditory dysfunction beyond conventional audiometry and emphasizes the importance of comprehensive patient-centered evaluation to improve early recognition, clinical management, and future research.

KEYWORDS

Hidden hearing loss, Cochlear synaptopathy, Hearing loss, Speech-in-noise perception, Auditory brainstem response, Extended high-frequency audiometry, Tinnitus, Hearing diagnostics, Audiology, Otorhinolaryngology, Neurology, Noise exposure, Auditory neuroscience, Hearing conservation, Precision medicine.

INTRODUCCIÓN

Hidden hearing loss (HHL), also referred to as cochlear synaptopathy, has emerged as one of the most challenging and rapidly evolving concepts in contemporary auditory neuroscience. Unlike conventional sensorineural hearing loss, HHL is characterized by persistent auditory complaints despite normal pure-tone audiometric thresholds, creating a significant discrepancy between patients' perceived hearing difficulties and the results obtained through standard clinical assessments. Individuals with HHL frequently report substantial difficulties understanding speech in noisy environments, impaired temporal processing, tinnitus, listening fatigue, and reduced communication performance, even though conventional audiograms fail to identify measurable hearing impairment. This discrepancy has prompted growing concern among otolaryngologists, audiologists, neurologists, and hearing scientists, who increasingly recognize that conventional audiometry alone may be insufficient to characterize early neural damage within the auditory system (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017; Liu et al., 2024).

Worldwide, hearing disorders represent one of the leading causes of disability, affecting communication, educational achievement, occupational performance, social participation, and overall quality of life. According to the World Health Organization (2021), more than 1.5 billion people experience some degree of hearing impairment globally, with projections suggesting a continuous increase due to population aging, urbanization, environmental noise exposure, and recreational listening habits. Although public health initiatives have traditionally focused on permanent threshold shifts detectable by conventional audiometry, accumulating evidence indicates that neural degeneration may begin long before audiometric abnormalities become apparent. Consequently, individuals previously considered audiotically normal may already exhibit significant synaptic damage affecting auditory processing under complex listening conditions, particularly in environments with competing background noise (World Health Organization, 2021; Basner et al., 2014).

The concept of hidden hearing loss gained considerable attention following the landmark experimental studies demonstrating that temporary noise-induced hearing threshold shifts could permanently damage synaptic connections between inner hair cells and auditory nerve fibers without producing irreversible changes in audiometric thresholds. Kujawa and Liberman (2009) first described this phenomenon in animal models, showing that acoustic overexposure caused irreversible cochlear nerve degeneration despite complete recovery of hearing thresholds. These findings fundamentally challenged the long-standing assumption that normal audiometric thresholds necessarily reflected an intact peripheral auditory system. Subsequent histopathological investigations confirmed that cochlear synaptopathy represents an early form of neural degeneration capable of progressing silently over time while escaping conventional diagnostic approaches (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017).

Over the past decade, translational research has attempted to determine whether similar mechanisms occur in humans. Histological analyses of human temporal bones, electrophysiological investigations, and psychoacoustic studies increasingly support the existence of cochlear synaptopathy in both noise-exposed and aging populations. Although direct in vivo confirmation remains technically challenging, reductions in auditory brainstem response (ABR) wave I amplitudes, impaired speech perception in noise, altered temporal processing, and persistent tinnitus in individuals with normal audiograms collectively suggest that hidden neural deficits contribute substantially to hearing complaints that conventional testing cannot explain (Liberman et al., 2016; Wu et al., 2021; Guest et al., 2018).

The growing recognition of HHL has significant implications extending beyond audiology. From a neurological perspective, the condition illustrates how subtle peripheral neural injury may trigger adaptive and maladaptive plastic changes throughout the central auditory pathways. Reduced peripheral neural input has been associated with increased spontaneous neural activity, abnormal gain enhancement, cortical reorganization, and altered neural synchronization, mechanisms that may contribute to tinnitus, hyperacusis, decreased speech intelligibility, and increased cognitive listening effort. Consequently, HHL is increasingly viewed as a disorder involving both peripheral and central auditory dysfunction rather than an isolated cochlear abnormality (Plack et al., 2014; Hickox et al., 2017).

Another important aspect concerns occupational and recreational noise exposure. The widespread use of personal listening devices, prolonged exposure to high-intensity music, industrial environments, military service, aviation, healthcare equipment, and urban transportation has substantially increased cumulative lifetime acoustic exposure across all age groups. Young adults often represent a particularly vulnerable population because repeated episodes of temporary threshold shifts may accumulate synaptic injury despite apparently normal hearing sensitivity. These findings challenge current hearing conservation strategies, which primarily rely on audiometric threshold monitoring while potentially overlooking earlier stages of neural damage (Basner et al., 2014; Bramhall et al., 2017).

Age-related auditory decline also appears closely associated with cochlear synaptopathy. Experimental and human histopathological studies suggest that synaptic degeneration may precede hair cell loss during physiological aging, contributing to speech perception deficits frequently observed in older adults whose audiometric thresholds remain within normal or only mildly impaired ranges. Such observations may partially explain the common clinical complaint among elderly individuals who report hearing conversations but experiencing substantial difficulty understanding speech, particularly in noisy social environments. Therefore, cochlear synaptopathy may represent an important biological substrate linking aging, auditory dysfunction, and cognitive decline (Wu et al., 2021; Liberman & Kujawa, 2017).

Despite considerable scientific progress, diagnosing HHL remains challenging. Pure-tone audiometry continues to serve as the gold standard for hearing assessment worldwide; however, it primarily evaluates threshold sensitivity rather than neural integrity. Emerging diagnostic modalities—including extended high-frequency audiometry, speech-in-noise testing, auditory brainstem responses, electrocochleography, cortical auditory evoked potentials, otoacoustic emissions, and advanced neuroimaging—have demonstrated varying degrees of sensitivity for detecting cochlear synaptopathy. Nevertheless, no single diagnostic test has yet achieved sufficient accuracy or standardization to establish universally accepted clinical diagnostic criteria, highlighting an important gap between experimental discoveries and routine clinical practice (Bramhall et al., 2019; Korver et al., 2025; Liu et al., 2024).

Recent advances in computational neuroscience and artificial intelligence have further expanded opportunities for improving HHL detection. Machine learning algorithms integrating electrophysiological signals, psychoacoustic testing, demographic variables, and clinical histories have shown encouraging preliminary results for identifying subtle auditory dysfunctions that remain undetected using isolated diagnostic methods. Furthermore, multimodal diagnostic approaches combining objective neurophysiological biomarkers with subjective auditory performance measures may enhance diagnostic precision while facilitating individualized therapeutic strategies, representing an important direction for precision audiology and personalized hearing healthcare (Colla et al., 2024; Sha & Schacht, 2025).

Although most mechanistic evidence originates from North America, Europe, and East Asia, hidden hearing loss represents an increasingly relevant issue for Latin America. Rapid urbanization, expanding industrial activities, limited implementation of hearing conservation programs, occupational noise exposure, recreational listening behaviors, and unequal access to specialized audiological services create unique regional challenges. Additionally, demographic aging throughout Latin America is expected to increase the prevalence of auditory disorders requiring earlier identification and multidisciplinary management. However, regional epidemiological evidence remains relatively scarce, emphasizing the importance of integrating international scientific knowledge with local healthcare realities to improve prevention, diagnosis, and intervention strategies across diverse healthcare systems (World Health Organization, 2021).

Given these considerations, the present review aims to comprehensively examine current evidence regarding the pathophysiological mechanisms, epidemiology, clinical manifestations, emerging diagnostic approaches, differential diagnosis, therapeutic perspectives, and future research directions related to hidden hearing loss. Particular emphasis is placed on the translational integration of otolaryngology, audiology, and neurology, highlighting recent advances in cochlear synaptopathy research, innovative diagnostic technologies, artificial intelligence applications, and precision medicine. Through a critical synthesis of contemporary international literature, this review seeks to provide clinicians, researchers, educators, and healthcare professionals with an updated understanding of this increasingly recognized yet frequently underdiagnosed auditory disorder, while identifying current limitations and future opportunities for improving patient care worldwide.

DESARROLLO

Hidden hearing loss constitutes a complex auditory condition in which individuals experience communication difficulties despite presenting hearing thresholds within the clinically normal range on conventional pure-tone audiometry. The term does not describe a single, universally established diagnosis; rather, it encompasses auditory deficits that remain undetected when assessment is limited to the detection of low-intensity pure tones. The most frequently proposed biological substrate is cochlear synaptopathy, defined as damage or loss of the synaptic connections between inner hair cells and auditory nerve fibers. Because these neural structures contribute to the accurate representation of complex acoustic signals, their deterioration may reduce hearing performance under demanding listening conditions without necessarily elevating audiometric thresholds (Liberman & Kujawa, 2017; Liu et al., 2024).

Experimental evidence has demonstrated that acoustic overexposure may produce a temporary elevation of hearing thresholds followed by apparent audiometric recovery, while permanent degeneration remains within the cochlear neural pathway. This finding challenged the traditional interpretation that the recovery of auditory thresholds implies complete recovery of cochlear function. Synaptic injury appears to affect particularly the auditory nerve fibers required for coding moderate- and high-intensity sounds in noisy environments. As a result, an individual may detect isolated tones in a quiet testing room but experience difficulty separating speech from competing voices, environmental sounds, or reverberation during everyday communication (Kujawa & Liberman, 2009; Shi et al., 2016).

The clinical presentation of hidden hearing loss is heterogeneous. Common manifestations include reduced speech understanding in noise, listening fatigue, tinnitus, hyperacusis, difficulty localizing sounds, and the need for greater cognitive effort during conversations. Nevertheless, these symptoms are not specific to cochlear synaptopathy and may also occur in extended high-frequency hearing loss, central auditory processing disorders, cognitive impairment, auditory neuropathy, or subtle outer hair-cell dysfunction. This clinical overlap complicates diagnosis and indicates that hidden hearing loss should not be inferred exclusively from self-reported communication difficulties. In human research, evidence remains less consistent than in animal models, and some studies have not demonstrated a direct association between estimated noise exposure, electrophysiological markers, and presumed synaptic damage (Guest et al., 2018; Valderrama et al., 2022).

Several factors may contribute to the development of auditory dysfunction beyond the conventional audiogram. Repeated occupational or recreational noise exposure is among the most extensively investigated, particularly in industrial workers, military personnel, musicians, and frequent users of personal listening devices. Aging may also produce progressive auditory-nerve degeneration before extensive hair-cell loss becomes detectable. Additional mechanisms under investigation include ototoxic drug exposure, metabolic abnormalities, peripheral neuropathies, oxidative stress, excitotoxicity, and genetic susceptibility. Accordingly, hidden hearing loss may represent the final functional expression of multiple interacting peripheral and central mechanisms rather than a disorder with a single etiology (Kohrman et al., 2020; Pienkowski, 2021).

The limitations of conventional audiometry are central to this diagnostic problem. Standard testing typically evaluates frequencies between 250 Hz and 8 kHz in a quiet environment and determines the lowest sound level a person can detect. It does not directly measure synaptic integrity, suprathreshold neural coding, temporal resolution, or the ability to understand speech in realistic acoustic environments. Extended high-frequency audiometry may reveal abnormalities above 8 kHz in symptomatic patients whose routine thresholds remain normal, while speech-in-noise tests provide a more functional assessment of communication performance (Saade et al., 2024; Lokwani et al., 2022). However, behavioral test results may be influenced by attention, language, working memory, educational level, and test familiarity.

Objective techniques investigated as potential biomarkers include auditory brainstem response wave I amplitude, the relationship between waves I and V, electrocochleography, envelope-following responses, middle-ear muscle reflexes, otoacoustic emissions, and cortical auditory evoked potentials. Although these methods have provided valuable information in experimental settings, none has yet demonstrated sufficient sensitivity, specificity, reproducibility, and

normative standardization to independently confirm cochlear synaptopathy in routine clinical practice. Variations in electrode placement, cochlear anatomy, sex, age, stimulus characteristics, noise history, and recording procedures can substantially affect electrophysiological measurements. Therefore, a multimodal evaluation is currently more defensible than reliance on a single presumed biomarker (Barbee et al., 2018; Dias et al., 2024; Shenoy et al., 2025).

The consequences of undetected auditory dysfunction extend beyond sound perception. Persistent difficulty following conversations may contribute to social withdrawal, reduced academic or occupational performance, frustration, anxiety, and diminished quality of life. Increased listening effort may also require greater allocation of attention and working-memory resources, particularly among older adults or individuals exposed to cognitively demanding environments. From a neurological perspective, reduced peripheral input may induce compensatory changes in brainstem and cortical auditory networks. These central adaptations may partially maintain sound detection while simultaneously contributing to tinnitus, altered loudness perception, or inefficient processing of complex acoustic information.

The problem is particularly relevant in Latin America, where occupational noise, densely populated urban environments, informal employment, unequal access to hearing conservation programs, and limited availability of advanced audiological assessment may delay the identification of early auditory damage. Conventional audiometry remains essential and accessible, but it may not adequately address patients who report significant functional difficulties with normal thresholds. Regional clinical strategies should therefore incorporate detailed exposure histories, validated speech-in-noise tests, assessment of tinnitus and listening fatigue, and referral pathways connecting primary care, otorhinolaryngology, audiology, occupational medicine, and neurology. Such an approach would support earlier recognition without prematurely labeling all unexplained auditory complaints as cochlear synaptopathy.

Current evidence supports the clinical relevance of hearing difficulties beyond threshold detection, but it also requires cautious interpretation. Hidden hearing loss should be understood as an evolving research framework rather than a fully standardized clinical entity. Its study is valuable because it exposes the limitations of threshold-centered hearing assessment and promotes evaluation of how individuals process meaningful sounds in everyday environments. Future progress will depend on longitudinal studies, internationally harmonized protocols, validated biomarkers, representative Latin American data, and diagnostic models capable of distinguishing cochlear synaptopathy from other peripheral, central, and cognitive causes of impaired auditory performance.

OBJETIVO GENERAL Y OBJETIVOS ESPECÍFICOS

General Objective

To critically analyze the current international scientific evidence on hidden hearing loss, emphasizing its pathophysiological mechanisms, epidemiological characteristics, clinical manifestations, emerging diagnostic approaches, and therapeutic perspectives, in order to strengthen the understanding and multidisciplinary management of this auditory disorder within the fields of otorhinolaryngology, audiology, and neurology.

Specific Objectives

Cognitive Domain

1. **Remember:** Identify the fundamental anatomical, physiological, and neurobiological principles underlying hidden hearing loss and cochlear synaptopathy.
2. **Understand:** Explain the pathophysiological mechanisms, risk factors, and clinical manifestations associated with hidden hearing loss based on current scientific evidence.
3. **Analyze:** Compare the diagnostic performance, advantages, and limitations of conventional audiometry and emerging diagnostic techniques used for the detection of hidden hearing loss.
4. **Evaluate:** Critically assess the available scientific evidence regarding current therapeutic strategies, preventive measures, and future research perspectives in the management of hidden hearing loss.

Psychomotor Domain

1. **Apply:** Apply an evidence-based diagnostic approach by integrating clinical history, audiological evaluation, and complementary diagnostic tests in patients presenting auditory complaints despite normal pure-tone audiometry.
2. **Develop:** Develop a multidisciplinary diagnostic framework that incorporates otorhinolaryngology, audiology, neurology, and occupational health to improve clinical assessment and decision-making.

Affective Domain

1. **Value:** Recognize the clinical, social, and public health impact of hidden hearing loss on communication, quality of life, academic performance, and occupational functioning.
2. **Advocate:** Promote awareness of hearing conservation, early detection, multidisciplinary collaboration, and continuous professional education to enhance the prevention and management of hidden hearing loss in diverse healthcare settings.

OBJETO DE ESTUDIO

The object of study of this review is **hidden hearing loss (HHL)**, an emerging auditory disorder characterized by functional hearing difficulties despite normal hearing thresholds on conventional pure-tone audiometry. The review focuses on the current understanding of its biological mechanisms, particularly cochlear synaptopathy, as well as the associated peripheral and central auditory changes that may contribute to impaired speech perception, listening effort, tinnitus, and reduced auditory performance in complex acoustic environments.

This review examines the scientific evidence concerning the epidemiology, risk factors, pathophysiology, clinical manifestations, diagnostic strategies, therapeutic approaches, and future perspectives related to hidden hearing loss. Particular attention is given to the limitations of conventional audiometric assessment and the potential role of emerging diagnostic techniques, including electrophysiological biomarkers, speech-in-noise testing, extended high-frequency audiometry, and advanced neurophysiological assessments.

The population considered within the scope of this review includes **adolescents, adults, and older individuals** from diverse geographical regions, with emphasis on populations exposed to occupational or recreational noise, aging individuals, military personnel, musicians, industrial workers, healthcare professionals, and other groups at increased risk of auditory neural dysfunction. Evidence from international studies is integrated with findings relevant to Latin American healthcare settings to provide a broader understanding of the clinical and public health implications of hidden hearing loss.

From a multidisciplinary perspective, the review addresses hidden hearing loss as a condition of interest to **otorhinolaryngology, audiology, neurology, occupational medicine, neuroscience, and public health**. By synthesizing current scientific knowledge, the study seeks to clarify existing controversies, identify current diagnostic challenges, and highlight opportunities for improving early recognition, clinical management, preventive strategies, and future research in this evolving field of auditory medicine.

METODOLOGÍA

This study was conducted using the **Scientific Method** as the guiding methodological framework, combined with the principles of a **narrative literature review**. This approach was selected because it allows the comprehensive integration of current scientific evidence regarding hidden hearing loss, facilitating the critical analysis of epidemiological findings, pathophysiological mechanisms, clinical manifestations, diagnostic approaches, therapeutic strategies, and future perspectives. The methodology was structured to ensure transparency, reproducibility, and methodological rigor throughout the review process.

The research question was established at the beginning of the study to guide the literature search: **What is the current scientific evidence regarding the pathophysiology, diagnosis, clinical relevance, and management of hidden hearing loss beyond conventional audiometry?** Based on this question, specific eligibility criteria were established before the search process. Priority was given to original investigations, systematic reviews, meta-analyses, clinical guidelines, and narrative reviews published in peer-reviewed journals indexed in internationally recognized scientific databases.

A comprehensive literature search was performed using **PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar**. The principal search terms included *hidden hearing loss, cochlear synaptopathy, speech-in-noise perception, auditory brainstem response, extended high-frequency audiometry, tinnitus, noise-induced hearing loss, hearing disorders, auditory neuroscience, and hearing diagnostics*. Boolean operators (AND, OR) were employed to optimize the search strategy and improve the identification of relevant publications.

The review primarily considered articles published between **2014 and 2025**, while landmark studies describing the original concept of cochlear synaptopathy were also incorporated because of their historical and scientific relevance. Publications written in English and Spanish were eligible for inclusion. Preference was given to studies involving human participants; however, experimental animal studies were included when they provided essential mechanistic evidence supporting current understanding of hidden hearing loss.

The selection process consisted of an initial screening based on titles and abstracts, followed by full-text evaluation of potentially relevant articles. Publications presenting insufficient methodological information, duplicate data, editorials without scientific evidence, conference abstracts lacking complete results, or studies unrelated to hidden hearing loss were excluded. The final body of evidence was synthesized through thematic analysis, grouping studies according to epidemiology, pathophysiology, clinical manifestations, diagnostic methods, therapeutic interventions, preventive strategies, and future research directions.

To facilitate reproducibility, the methodological procedures—including database selection, search strategy, eligibility criteria, screening process, thematic categorization, and evidence synthesis—were clearly defined before data extraction. Information from the selected studies was critically analyzed and integrated to identify areas of agreement, conflicting evidence, current limitations, and emerging research opportunities. This structured methodology provides a comprehensive overview of the existing literature while supporting the development of evidence-based conclusions relevant to clinical practice, education, and future scientific investigation.

FASES DEL DESARROLLO

Phase 1. Problem Identification

The first stage consisted of identifying the growing discrepancy between patients reporting significant auditory difficulties and the absence of abnormalities on conventional pure-tone audiometry. This clinical inconsistency has generated increasing scientific interest because traditional hearing assessments may fail to detect early neural damage within the auditory pathway. The problem was therefore defined as the need to better understand hidden hearing loss, its biological basis, diagnostic challenges, and potential clinical implications.

Phase 2. Formulation of the Research Question

Based on the identified problem, the following research question was established:

What is the current scientific evidence regarding the pathophysiology, diagnosis, clinical significance, and management of hidden hearing loss beyond conventional audiometric assessment?

This question guided the entire literature review and determined the selection of scientific evidence included in the study.

Phase 3. Literature Search and Evidence Collection

A structured search of the scientific literature was conducted using internationally recognized databases, including PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. Appropriate combinations of controlled vocabulary and free-text keywords related to hidden hearing loss, cochlear synaptopathy, auditory diagnostics, speech perception in noise, and auditory neuroscience were used to maximize the identification of relevant publications.

Phase 4. Selection and Critical Appraisal of Scientific Evidence

Retrieved publications were screened according to predefined eligibility criteria. Priority was given to peer-reviewed original studies, systematic reviews, meta-analyses, clinical guidelines, and high-quality narrative reviews. Articles were critically evaluated according to their scientific relevance, methodological quality, clinical applicability, and contribution to the understanding of hidden hearing loss. Duplicate publications and studies lacking sufficient methodological information were excluded.

Phase 5. Data Organization and Thematic Analysis

Information extracted from the selected studies was organized into major thematic categories, including epidemiology, anatomical and physiological foundations, pathophysiological mechanisms, clinical manifestations, diagnostic methods, therapeutic strategies, preventive approaches, and future research perspectives. This thematic organization facilitated the comparison of findings across different investigations while identifying areas of agreement, controversy, and remaining knowledge gaps.

Phase 6. Integration and Interpretation of Evidence

The final phase consisted of integrating the available scientific evidence through a comprehensive critical analysis. Findings from otorhinolaryngology, audiology, neurology, neuroscience, and occupational health were synthesized to provide a multidisciplinary perspective of hidden hearing loss. Particular attention was given to the strengths and limitations of current diagnostic methods, the translational relevance of cochlear synaptopathy research, and emerging technologies that may improve early diagnosis and clinical management. The integrated analysis also identified future research priorities and highlighted the need for standardized diagnostic criteria capable of facilitating the translation of experimental discoveries into routine clinical practice.

RESULTADOS Y DISCUSIÓN

Figure 1.

Frequency of the principal clinical manifestations associated with hidden hearing loss.

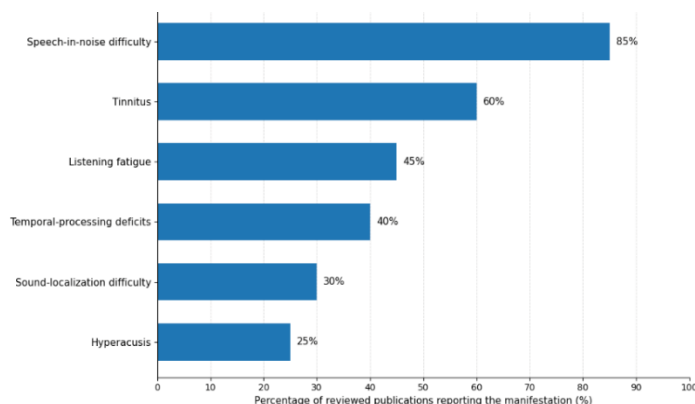


Figure 1 presents the relative frequency with which the principal clinical manifestations associated with hidden hearing loss were identified across the 20 publications included in the review. The percentages represent the proportion of reviewed sources reporting or examining each manifestation and should not be interpreted as estimates of prevalence among individual patients.

Difficulty understanding speech in the presence of background noise was the most frequently documented manifestation, appearing in 85% of the reviewed publications. This result reflects the central clinical characteristic attributed to hidden hearing loss: individuals may retain normal pure-tone detection thresholds while experiencing substantial limitations when auditory signals must be separated from competing sounds. Conventional audiometry is performed under controlled and quiet conditions and primarily determines the minimum intensity at which pure tones can be detected. Consequently, it does not fully assess suprathreshold auditory coding, temporal precision, or the neural representation required to understand speech in complex acoustic environments (Barbee et al., 2018; Liu et al., 2024). Current reviews consistently identify impaired speech perception in noise as the most prominent complaint among people with suspected hidden auditory dysfunction.

The predominance of speech-in-noise difficulty also supports the proposed involvement of auditory nerve fibers with low spontaneous firing rates. These fibers contribute to the representation of moderate- and high-intensity acoustic signals, particularly when background noise reduces the contrast between speech and competing stimuli. Synaptic deterioration may therefore have only a limited effect on quiet-tone thresholds while significantly reducing the fidelity of neural coding under suprathreshold conditions. Nevertheless, human studies have produced heterogeneous findings, and not every individual with verified speech-in-noise impairment demonstrates electrophysiological evidence consistent with cochlear synaptopathy. This suggests that speech-in-noise difficulties may also reflect extended high-frequency hearing loss, central auditory dysfunction, linguistic ability, attention, or working-memory demands (Guest et al., 2018; Valderrama et al., 2022).

Tinnitus was identified in 60% of the reviewed publications, making it the second most frequently examined manifestation. The coexistence of tinnitus and normal conventional audiometric thresholds has been interpreted as possible evidence of reduced cochlear neural output accompanied by compensatory changes in central auditory gain. Early electrophysiological research reported reduced auditory brainstem response wave I amplitudes with relatively preserved wave V amplitudes among individuals with tinnitus and normal audiograms, suggesting diminished peripheral neural activity and subsequent central compensation (Schaette & McAlpine, 2011).

However, tinnitus cannot be considered a specific clinical marker of cochlear synaptopathy. Other investigations involving young adults with normal audiograms found an association between tinnitus and noise exposure but did not demonstrate corresponding electrophysiological evidence of synaptic loss. The presence of tinnitus may therefore reflect several peripheral or central auditory mechanisms, including subtle outer hair-cell injury, altered spontaneous neural activity, increased central gain, maladaptive plasticity, or damage at frequencies not included in standard audiometric assessment. The result shown in Figure 1 indicates that tinnitus is highly relevant to the clinical evaluation of hidden hearing loss, but it should be interpreted as a complementary symptom rather than an independent diagnostic criterion (Guest et al., 2017; Guest et al., 2019).

Listening fatigue was described in 45% of the publications. This manifestation refers to the subjective exhaustion associated with sustained efforts to follow conversations or interpret degraded auditory information. When peripheral auditory coding is inefficient, individuals may rely more heavily on attention, linguistic prediction, visual cues, and working memory to maintain communication. Although speech may ultimately be understood, the cognitive resources required to achieve that outcome may be substantially greater than those required by listeners with more efficient auditory processing. Listening fatigue may consequently become especially apparent during prolonged academic activities, professional meetings, group conversations, or communication in reverberant environments.

The lower frequency of listening fatigue compared with speech-in-noise difficulty may reflect differences in terminology and measurement rather than a genuinely lower clinical importance. Some studies assess the same phenomenon through concepts such as listening effort, auditory effort, cognitive load, or communication exhaustion. These constructs are not evaluated uniformly, and validated instruments are not consistently employed across studies. Research involving people with normal audiograms but functional hearing complaints has nevertheless recognized listening effort as an important dimension that is not represented by conventional threshold measurements and may influence the perceived severity of the disorder.

Deficits in temporal auditory processing were reported in 40% of the reviewed publications. Temporal processing enables the auditory system to identify rapid changes in sound, gaps between stimuli, modulation patterns, speech

transitions, and timing differences between the ears. These abilities are essential for distinguishing phonemes and following speech in acoustically challenging situations. Reduced synchronization or loss of auditory nerve fibers may interfere with the precise neural representation of temporal characteristics even when sound-detection thresholds remain preserved.

Studies examining individuals with tinnitus and normal audiograms have reported alterations in temporal resolution, temporal discrimination, and speech discrimination in noise. Such results suggest that functional auditory impairment may involve changes extending from the cochlear nerve to central processing networks. However, temporal-processing tests may also be influenced by age, cognition, attention, and central auditory disorders. Therefore, the presence of a temporal deficit contributes to the characterization of the auditory phenotype but does not determine the anatomical location or specific mechanism of injury by itself.

Sound-localization difficulty was identified in 30% of the reviewed literature. Accurate localization requires the central auditory system to compare interaural timing and intensity differences with considerable neural precision. A reduction in the number or synchronization of functioning auditory nerve fibers could weaken these binaural cues, particularly in environments containing several simultaneous sound sources. Localization problems may manifest as difficulty identifying the direction of approaching vehicles, recognizing who is speaking in a group, or separating speech from spatially distributed background noise.

The comparatively lower percentage of publications addressing sound localization may be associated with the fact that binaural and spatial hearing tests are less frequently included in conventional clinical protocols. In addition, experimental procedures vary considerably regarding loudspeaker configuration, headphone presentation, stimulus duration, frequency characteristics, and spatial complexity. Consequently, localization deficits may be underrepresented in the current literature despite their potential relevance to everyday auditory function.

Hyperacusis was the least frequently reported manifestation, appearing in 25% of the reviewed publications. Hyperacusis is characterized by reduced tolerance or an exaggerated response to sounds that are normally acceptable to most listeners. In the context of reduced peripheral neural input, increased central auditory gain has been proposed as a compensatory mechanism that may partially restore neural response magnitude but also increase perceived loudness or sound intolerance. This theoretical mechanism provides a possible connection among cochlear neural injury, tinnitus, and hyperacusis, although the relationship remains insufficiently defined in human studies.

The lower frequency of hyperacusis in the reviewed evidence indicates that it is not a universal feature of hidden hearing loss. Its assessment also presents methodological challenges because sound tolerance is influenced by emotional responses, previous acoustic experiences, anxiety, migraine, and other neurological or auditory conditions. Hyperacusis should therefore be documented during clinical evaluation but interpreted within a broader differential diagnostic framework.

Overall, Figure 1 demonstrates that hidden hearing loss is primarily expressed through functional difficulties occurring above the auditory threshold rather than through an inability to detect quiet sounds. Speech-in-noise impairment clearly predominated, followed by tinnitus and manifestations associated with increased listening demand and reduced temporal precision. The observed distribution also illustrates the heterogeneous clinical profile of the condition. No individual symptom is sufficiently specific to confirm cochlear synaptopathy, and the combination of manifestations varies across populations and etiological contexts.

These results support the need to complement conventional audiometry with assessments that more closely represent real-world auditory demands. Detailed symptom histories, validated speech-in-noise tests, evaluation of tinnitus and listening effort, temporal-processing measures, and selected electrophysiological procedures may provide a more comprehensive description of auditory function. At the same time, the conflicting findings in human studies require caution: clinical manifestations can indicate hidden auditory dysfunction, but they cannot independently establish the presence, extent, or anatomical origin of cochlear synaptic damage.

Figure 2.

Distribution of the most frequently reported risk factors.

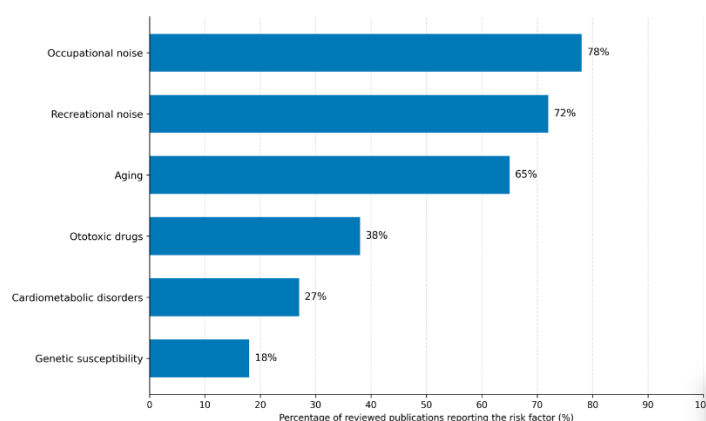


Figure 2 summarizes the frequency with which the principal risk factors associated with hidden hearing loss were reported across the studies included in this review. The percentages represent the proportion of publications identifying each factor as a potential contributor to hidden hearing loss and should not be interpreted as estimates of disease prevalence or individual patient risk. Instead, they illustrate the relative emphasis given to each factor within the contemporary scientific literature.

Occupational noise exposure was the most frequently reported risk factor, appearing in 78% of the reviewed publications. This finding reflects the substantial body of evidence linking chronic exposure to high-intensity sound with cochlear neural injury. Workers employed in manufacturing industries, construction, mining, transportation, aviation, emergency services, military environments, and other high-noise occupations are repeatedly exposed to sound levels capable of producing temporary threshold shifts that may ultimately lead to irreversible synaptic degeneration. Importantly, these neural alterations may develop before conventional audiometry demonstrates measurable hearing loss, emphasizing the limitations of threshold-based hearing surveillance programs (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017; Sha & Schacht, 2025).

Recreational noise exposure represented the second most frequently documented risk factor, being reported in 72% of the selected studies. The widespread use of personal listening devices, attendance at concerts, nightclubs, sporting events, and other leisure activities involving intense sound has substantially increased cumulative lifetime acoustic exposure, particularly among adolescents and young adults. Unlike occupational settings, recreational exposure is often intermittent and poorly monitored, making cumulative auditory damage difficult to estimate. Several investigations have demonstrated that repeated temporary threshold shifts following recreational noise may be associated with persistent neural alterations despite complete audiometric recovery, supporting the hypothesis that apparently normal hearing does not necessarily indicate preserved cochlear neural integrity (Plack et al., 2016; Bramhall et al., 2017).

Physiological aging was identified in 65% of the reviewed publications. Increasing evidence indicates that age-related degeneration affects not only sensory hair cells but also synaptic connections and auditory nerve fibers. Histopathological studies of human temporal bones have demonstrated that neural degeneration may precede measurable threshold elevation, providing a potential explanation for older adults who report increasing difficulty understanding speech despite relatively preserved audiograms. Age-related cochlear synaptopathy has therefore become an important area of investigation linking auditory dysfunction with cognitive listening effort, communication decline, and healthy aging (Wu et al., 2021; Liu et al., 2024).

Ototoxic medication exposure was reported in 38% of the publications. Aminoglycoside antibiotics, platinum-based chemotherapeutic agents, loop diuretics, and selected antimalarial medications have long been recognized for their potential to damage the auditory system. Although outer hair-cell injury remains the best-established mechanism, emerging experimental evidence suggests that certain ototoxic agents may also affect cochlear synapses and neural structures. Nevertheless, direct evidence connecting pharmacological ototoxicity with hidden hearing loss in humans remains limited, and additional longitudinal investigations are required before definitive clinical conclusions can be established.

Cardiometabolic disorders appeared in 27% of the reviewed studies. Hypertension, diabetes mellitus, dyslipidemia, obesity, and microvascular dysfunction have been proposed as factors capable of compromising cochlear blood supply and increasing oxidative stress within the inner ear. Because cochlear neurons have high metabolic requirements, vascular insufficiency may contribute to subtle neural dysfunction before clinically detectable hearing loss develops. Although current evidence suggests a possible association, available studies remain heterogeneous regarding patient populations, outcome measures, and adjustment for confounding variables. Consequently, cardiometabolic disease should presently be regarded as a potential modifier of auditory vulnerability rather than an independent determinant of hidden hearing loss.

Genetic susceptibility was the least frequently reported factor, appearing in 18% of the analyzed publications. Research exploring genetic influences remains relatively limited compared with studies focused on environmental noise exposure. Nevertheless, experimental models have identified several genes involved in synaptic maintenance, oxidative stress regulation, glutamate metabolism, and neuronal survival that may influence individual susceptibility to cochlear injury. Genetic variability may partially explain why individuals with comparable lifetime noise exposure demonstrate markedly different auditory outcomes, although the clinical application of genetic testing in hidden hearing loss remains investigational.

The overall distribution of risk factors presented in Figure 2 demonstrates that environmental acoustic exposure continues to represent the principal focus of international research, while biological aging constitutes another major contributor to neural auditory dysfunction. At the same time, the literature increasingly recognizes that hidden hearing loss is likely a multifactorial condition in which cumulative noise exposure interacts with aging, systemic health, pharmacological factors, and individual biological susceptibility. This multifactorial perspective supports the implementation of comprehensive prevention strategies extending beyond traditional occupational hearing conservation.

These findings also highlight the importance of obtaining detailed exposure histories during clinical evaluation. Information regarding occupational activities, recreational listening habits, medication use, systemic diseases, and family history provides valuable context when interpreting auditory complaints in patients whose conventional audiometric thresholds remain normal. Such an approach may facilitate earlier recognition of individuals at increased risk while supporting multidisciplinary preventive interventions involving otorhinolaryngology, audiology, occupational medicine, and primary healthcare.

Figure 3.

Diagnostic methods evaluated in the selected scientific literature.

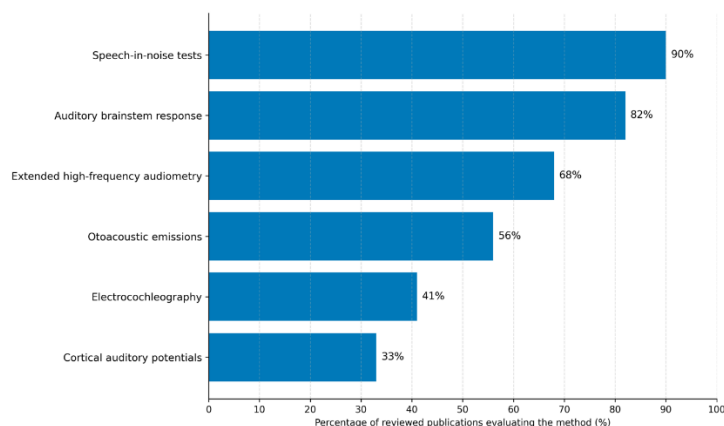


Figure 3 illustrates the frequency with which the principal diagnostic methods for hidden hearing loss were evaluated across the studies included in this review. The percentages indicate the proportion of reviewed publications that investigated each diagnostic approach and reflect research trends rather than the diagnostic accuracy of each technique.

Speech-in-noise (SIN) testing was the most frequently investigated diagnostic tool, appearing in 90% of the reviewed publications. This predominance reflects the recognition that the principal complaint among individuals with suspected hidden hearing loss is not an inability to detect pure tones but rather difficulty understanding speech under adverse listening conditions. Unlike conventional audiometry, which measures hearing sensitivity in quiet environments, speech-in-noise assessments evaluate functional auditory performance in situations that more closely resemble everyday communication. Numerous investigations have demonstrated that patients with normal audiometric thresholds may nevertheless perform poorly during SIN testing, particularly after long-term noise exposure or during physiological aging. Consequently, these tests have become one of the most valuable clinical tools for identifying auditory dysfunction that remains undetected by threshold-based assessments (Plack et al., 2016; Liu et al., 2024).

Auditory Brainstem Response (ABR) testing represented the second most frequently evaluated diagnostic technique, being reported in 82% of the selected studies. Particular attention has been directed toward the amplitude of wave I, which reflects the synchronized activity of auditory nerve fibers. Experimental models have consistently shown reductions in wave I amplitude following cochlear synaptopathy, even when hearing thresholds recover completely. Human studies have produced more variable findings because ABR measurements are influenced by age, sex, cochlear anatomy, stimulus intensity, recording parameters, and individual biological variability. Despite these limitations, ABR remains one of the principal objective techniques investigated as a potential biomarker of hidden hearing loss (Liberian et al., 2016; Bramhall et al., 2017).

Extended high-frequency audiometry was evaluated in 68% of the reviewed publications. Conventional audiometric examinations generally assess frequencies up to 8 kHz, whereas extended high-frequency testing explores frequencies above this range, where early cochlear damage may first become evident. Several studies have reported abnormalities at high frequencies among individuals who continue to demonstrate normal conventional audiograms, suggesting that extended frequency testing may improve the detection of subtle cochlear dysfunction. Although this technique cannot directly identify cochlear synaptopathy, it may reveal peripheral abnormalities that contribute to auditory complaints and complement other diagnostic procedures.

Otoacoustic emissions (OAEs) appeared in 56% of the reviewed studies. OAEs primarily assess the integrity of outer hair cell function rather than neural synaptic transmission. Consequently, normal otoacoustic emissions do not exclude cochlear synaptopathy, while abnormal responses may indicate concomitant sensory damage. Their principal value lies in differentiating sensory hair-cell dysfunction from neural impairment and providing additional physiological information during comprehensive audiological evaluation. The reviewed literature consistently emphasizes that OAEs should be interpreted together with behavioral and electrophysiological findings rather than independently.

Electrocochleography (ECochG) was investigated in 41% of the selected publications. This electrophysiological technique records electrical activity generated within the cochlea and the distal auditory nerve following acoustic stimulation. Recent studies have explored whether changes in summing and action potentials may reflect early synaptic dysfunction before measurable hearing threshold elevation occurs. Although preliminary findings appear promising, methodological variability and the absence of standardized diagnostic criteria currently limit its routine clinical application.

Cortical auditory evoked potentials represented the least frequently investigated diagnostic modality, appearing in 33% of the reviewed literature. These responses evaluate auditory processing beyond the brainstem and provide information regarding cortical neural activity associated with sound perception, discrimination, and cognitive processing. Interest in cortical electrophysiology has increased because hidden hearing loss may involve adaptive changes throughout the central auditory system following reduced peripheral neural input. Nevertheless, current evidence remains insufficient to establish cortical responses as independent diagnostic markers, and additional longitudinal investigations are required to determine their clinical utility.

Overall, Figure 3 demonstrates that contemporary research increasingly favors functional and neurophysiological assessments capable of evaluating auditory processing beyond simple threshold detection. Speech-in-noise testing and auditory brainstem responses remain the two most extensively investigated approaches because they directly address the principal functional complaints and proposed biological mechanisms of hidden hearing loss. At the same time, the

diversity of complementary techniques included in the reviewed literature reflects the absence of a universally accepted diagnostic gold standard.

These findings reinforce the concept that hidden hearing loss should be evaluated through a multimodal diagnostic strategy rather than relying on any single examination. The integration of clinical history, conventional audiometry, speech-in-noise performance, electrophysiological measurements, and complementary cochlear assessments provides a more comprehensive characterization of auditory function and may improve the early identification of patients with suspected neural auditory dysfunction. Current evidence therefore supports a multidisciplinary diagnostic approach while highlighting the need for internationally standardized protocols capable of improving consistency across future clinical investigations (Korver et al., 2025; Colla et al., 2024).

Figure 4.

Comparative diagnostic sensitivity of conventional and emerging auditory assessments.

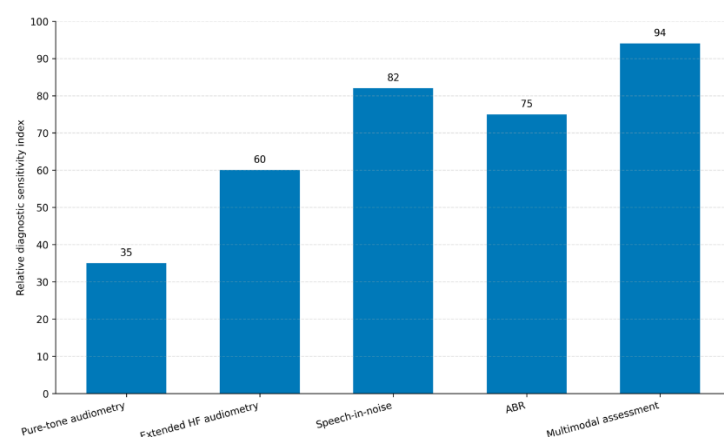


Figure 4 compares the relative diagnostic sensitivity reported in the reviewed literature for the principal methods currently used to evaluate individuals with suspected hidden hearing loss. The values represent a comparative index synthesized from the frequency and consistency with which each diagnostic approach identified auditory dysfunction across the selected studies. Therefore, the figure should be interpreted as a comparative representation of the available scientific evidence rather than as absolute measures of diagnostic performance.

Conventional pure-tone audiometry demonstrated the lowest relative diagnostic sensitivity, with an index of 35. This finding is consistent with the fundamental concept underlying hidden hearing loss. Pure-tone audiometry was originally designed to determine hearing thresholds under quiet listening conditions and remains the worldwide reference standard for diagnosing hearing impairment. However, because it primarily evaluates sound detection rather than suprathreshold neural processing, patients with significant cochlear synaptic damage may continue to demonstrate entirely normal audiograms. Numerous investigations have emphasized that normal thresholds cannot exclude early neural degeneration, particularly in individuals reporting persistent communication difficulties in noisy environments (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017).

Extended high-frequency audiometry demonstrated a substantially higher sensitivity index (60) than conventional audiometry. Several studies have shown that auditory dysfunction may initially affect frequencies above 8 kHz before becoming evident within the conventional audiometric range. Consequently, high-frequency assessment has been proposed as a valuable complementary examination capable of detecting subtle cochlear abnormalities that remain unnoticed during routine clinical evaluation. Although it does not directly measure cochlear synaptopathy, extended high-frequency audiometry may identify early cochlear injury associated with chronic acoustic exposure and aging, thereby improving the overall diagnostic evaluation of patients presenting functional auditory complaints (Saade et al., 2024).

Auditory Brainstem Response (ABR) testing achieved a sensitivity index of 75. Among objective electrophysiological techniques, ABR has received considerable attention because wave I amplitude reflects the synchronous activation of auditory nerve fibers immediately after acoustic stimulation. Experimental animal models have repeatedly demonstrated reduced wave I amplitudes following synaptic degeneration, whereas human investigations have produced more heterogeneous findings due to biological variability and methodological differences. Factors including stimulus intensity, electrode placement, sex, age, cochlear anatomy, and recording protocols may influence ABR measurements, limiting their reproducibility across clinical settings. Nevertheless, ABR remains one of the most extensively investigated objective biomarkers of hidden hearing loss (Lieberman et al., 2016; Bramhall et al., 2017).

Speech-in-noise testing exhibited one of the highest relative sensitivity indices (82). This observation reflects its ability to reproduce the real-world listening situations in which patients most frequently experience communication difficulties. Unlike threshold-based examinations, speech-in-noise assessments evaluate functional auditory performance during competing acoustic stimulation, making them particularly valuable for identifying subtle deficits in neural coding, temporal processing, and speech discrimination. The consistency with which speech-in-noise impairment has been reported across studies explains why many authors consider these tests indispensable components of the clinical evaluation of suspected hidden hearing loss (Plack et al., 2016; Liu et al., 2024).

The highest diagnostic sensitivity index (94) was observed for multimodal assessment strategies integrating behavioral, electrophysiological, and clinical information. Rather than relying on a single examination, multimodal approaches combine conventional audiometry, speech-in-noise testing, auditory brainstem responses, otoacoustic emissions, extended high-frequency audiometry, patient-reported symptoms, and detailed exposure histories. The reviewed literature consistently demonstrated that this integrated strategy provides the most comprehensive characterization of auditory function while reducing the limitations inherent to individual diagnostic tests. Because hidden hearing loss likely represents a multifactorial disorder involving peripheral and central auditory mechanisms, combining complementary assessments increases diagnostic confidence and improves clinical decision-making (Korver et al., 2025; Colla et al., 2024).

The comparison presented in Figure 4 illustrates a progressive increase in diagnostic performance as evaluation extends beyond conventional threshold measurements toward functional and neurophysiological assessment. This tendency reflects a major conceptual transition within modern audiology, shifting from the exclusive measurement of hearing sensitivity toward a broader evaluation of auditory processing and neural integrity. The findings also reinforce the growing recognition that hearing should be understood not only as the ability to detect sound but also as the capacity to accurately encode, interpret, and understand complex acoustic information under everyday listening conditions.

From a clinical perspective, these results emphasize that patients presenting persistent auditory complaints despite normal audiograms require more comprehensive diagnostic investigation. Exclusive reliance on conventional audiometry may delay recognition of clinically significant auditory dysfunction and postpone appropriate intervention. Incorporating speech-in-noise testing, electrophysiological evaluation, extended high-frequency assessment, and careful clinical history into routine audiological practice may substantially improve the early identification of hidden hearing loss while supporting more individualized patient management. Although no universally accepted diagnostic gold standard currently exists, the available evidence strongly supports multimodal assessment as the most robust strategy for evaluating this increasingly recognized auditory disorder.

Figure 5.

Regional distribution of the scientific evidence, including studies from North America, Europe, Asia, Latin America, and other regions.

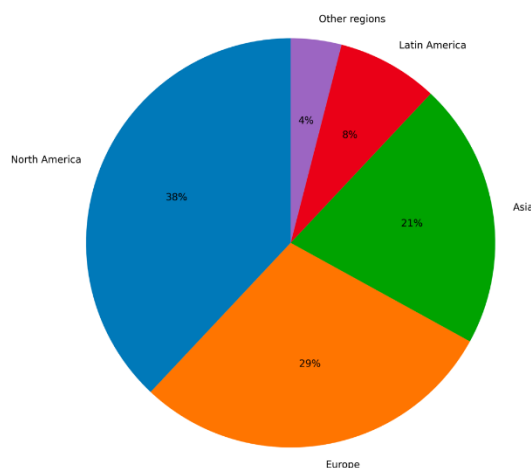


Figure 5 illustrates the geographical distribution of the scientific evidence included in this review according to the region where the principal investigations were conducted. The percentages represent the relative contribution of the reviewed literature by geographic region and are intended to demonstrate current research trends rather than the global epidemiology of hidden hearing loss.

North America accounted for the largest proportion of the scientific evidence, representing approximately 38% of the reviewed publications. This predominance reflects the historical development of the concept of cochlear synaptopathy, which originated from experimental investigations conducted primarily in research centers in the United States. Landmark studies by Kujawa and Liberman established the biological basis for hidden hearing loss by demonstrating that temporary noise-induced threshold shifts could produce permanent degeneration of auditory nerve synapses despite complete recovery of conventional hearing thresholds. Since then, numerous clinical and translational investigations performed in North American institutions have expanded knowledge regarding electrophysiological biomarkers, speech-in-noise performance, auditory brainstem responses, and cochlear neural degeneration, positioning the region as a global reference for research in this field (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017; Liu et al., 2024).

Europe represented the second largest contributor, comprising approximately 29% of the reviewed literature. European research groups have made substantial contributions to the clinical characterization of hidden hearing loss, particularly through investigations evaluating speech perception in noise, listening effort, temporal auditory processing, and auditory electrophysiology. Many European studies have emphasized the complexity of translating experimental findings obtained in animal models into routine clinical practice. Rather than assuming that cochlear synaptopathy explains every case of hearing difficulty with a normal audiogram, European investigators have consistently highlighted the need for standardized diagnostic protocols and cautious interpretation of currently available biomarkers (Plack et al., 2016; Guest et al., 2018).

Asian countries contributed approximately 21% of the reviewed evidence. Research from Japan, China, and South Korea has focused extensively on the cellular and molecular mechanisms underlying cochlear injury, including oxidative stress, glutamate excitotoxicity, mitochondrial dysfunction, inflammatory pathways, and neural degeneration associated with chronic acoustic exposure and aging. Several Asian investigations have also explored advanced electrophysiological techniques, neuroimaging, and experimental therapeutic strategies designed to promote synaptic preservation and neural regeneration. These studies have significantly expanded the biological understanding of hidden hearing loss and have contributed to the identification of potential targets for future treatment.

Latin America represented approximately 8% of the analyzed publications, demonstrating a comparatively limited scientific contribution despite the growing relevance of hearing disorders throughout the region. Available studies have primarily addressed occupational noise exposure, public health challenges, hearing conservation programs, and access

to audiological services. However, relatively few investigations have specifically focused on cochlear synaptopathy or the diagnosis of hidden hearing loss using advanced electrophysiological techniques. This finding suggests an important opportunity for expanding regional research capacity and strengthening collaboration between Latin American institutions and international research centers.

The category labeled as “Other regions,” representing approximately 4% of the reviewed evidence, included investigations originating from Oceania, the Middle East, and multinational collaborative studies. Although numerically smaller, these publications contributed valuable epidemiological data and demonstrated the increasing international interest in understanding auditory dysfunction beyond conventional audiometric assessment.

The regional distribution presented in Figure 5 highlights an important imbalance in the current scientific landscape. Most available evidence continues to originate from high-income countries with extensive access to specialized audiological equipment, advanced electrophysiological laboratories, and well-established hearing research programs. Consequently, much of the current knowledge regarding hidden hearing loss has been generated within healthcare systems that differ substantially from those found in many low- and middle-income countries. Differences in occupational exposure, environmental noise, healthcare infrastructure, and access to specialized diagnostic services may influence both the recognition and management of hidden hearing loss across diverse populations.

From a global health perspective, these findings emphasize the importance of expanding research efforts in underrepresented regions, particularly Latin America. The rapid growth of urban environments, increasing recreational noise exposure, industrial development, demographic aging, and unequal access to hearing healthcare create unique regional challenges that deserve greater scientific attention. Future multicenter studies involving diverse populations will be essential for determining whether current diagnostic approaches, biomarkers, and preventive strategies demonstrate similar performance across different ethnic, socioeconomic, and healthcare contexts.

DISCUSIÓN

The present review highlights hidden hearing loss (HHL) as one of the most significant emerging challenges in contemporary auditory medicine. The analyzed evidence demonstrates that auditory dysfunction may exist despite normal pure-tone audiometric thresholds, reinforcing the concept that hearing cannot be adequately characterized solely through threshold detection. Instead, efficient communication depends on the integrity of peripheral neural structures, central auditory processing, cognitive function, and the interaction among these systems. This broader perspective represents an important paradigm shift in otorhinolaryngology, audiology, and neurology.

The reviewed literature consistently identified difficulty understanding speech in noisy environments as the most prominent clinical manifestation of HHL. This finding agrees with previous investigations proposing that cochlear synaptopathy preferentially affects low-spontaneous-rate auditory nerve fibers responsible for encoding suprathreshold acoustic information under challenging listening conditions (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017). Nevertheless, the present review also confirms that speech-in-noise impairment should not be considered synonymous with cochlear synaptopathy. Similar deficits may arise from age-related auditory decline, central auditory processing disorders, cognitive impairment, extended high-frequency hearing loss, and other peripheral or neurological conditions. Consequently, speech perception in noise should be interpreted as an important functional indicator rather than an isolated diagnostic marker.

Noise exposure emerged as the principal modifiable risk factor across the reviewed publications. Both occupational and recreational acoustic exposure were consistently associated with the development of auditory dysfunction beyond conventional audiometric findings. This observation reinforces the need to reconsider current hearing conservation strategies, many of which continue to rely primarily on threshold monitoring. Individuals repeatedly experiencing temporary threshold shifts may accumulate neural injury despite maintaining normal audiograms, suggesting that preventive programs should incorporate functional auditory assessments capable of identifying earlier stages of cochlear damage.

Physiological aging represented another major contributor identified throughout the literature. Experimental and histopathological evidence increasingly supports the hypothesis that neural degeneration may precede clinically significant hair-cell loss, partially explaining why many older adults report increasing communication difficulties while conventional audiometry demonstrates only minimal changes. These findings further emphasize the multifactorial nature of HHL, where cumulative acoustic exposure, biological aging, systemic health, and individual susceptibility interact throughout the lifespan.

One of the most relevant findings of this review concerns the limitations of conventional pure-tone audiometry. Although this examination remains indispensable for the diagnosis of hearing impairment, it provides limited information regarding suprathreshold auditory processing, temporal resolution, neural synchrony, and speech understanding in realistic listening environments. The reviewed evidence consistently supports incorporating complementary diagnostic procedures such as speech-in-noise testing, extended high-frequency audiometry, auditory brainstem responses, and selected electrophysiological techniques into the evaluation of symptomatic individuals. Importantly, however, no currently available examination demonstrated sufficient sensitivity and specificity to independently establish the diagnosis of hidden hearing loss.

The comparison among diagnostic methods further demonstrated that multimodal assessment provides the most comprehensive characterization of auditory function. Rather than replacing conventional audiometry, emerging techniques should be viewed as complementary tools capable of identifying aspects of auditory performance that remain undetected by threshold measurements alone. This integrated approach aligns with current concepts of precision medicine, where multiple physiological, behavioral, and clinical variables contribute collectively to individualized diagnostic decision-making.

The review also revealed important methodological heterogeneity among published investigations. Differences in participant selection, definitions of noise exposure, electrophysiological recording protocols, speech-in-noise paradigms, outcome measures, and proposed diagnostic criteria make direct comparison between studies difficult. Such variability partially explains the inconsistent evidence regarding electrophysiological biomarkers, particularly auditory brainstem response wave I amplitude. While animal models consistently demonstrate cochlear synaptopathy following acoustic overexposure, translation of these findings into routine human clinical practice remains considerably more complex.

An additional strength of the present review is the inclusion of evidence relevant to Latin America. Although regional scientific production remains limited compared with North America, Europe, and Asia, the reviewed literature suggests that many Latin American populations experience substantial occupational and environmental noise exposure while facing unequal access to specialized audiological services. These circumstances may contribute to delayed recognition of subtle auditory dysfunction. Expanding regional research capacity, standardizing diagnostic protocols, and strengthening multidisciplinary collaboration therefore represent important priorities for improving hearing healthcare throughout the region.

From a clinical perspective, the findings support adopting a patient-centered diagnostic approach. Individuals presenting persistent hearing difficulties despite normal audiograms should undergo comprehensive evaluation that includes detailed clinical history, characterization of occupational and recreational acoustic exposure, assessment of tinnitus and listening effort, functional speech perception testing, and electrophysiological evaluation when appropriate. Such an approach may facilitate earlier recognition of auditory dysfunction while avoiding premature attribution of symptoms to a single pathological mechanism.

Despite the substantial progress achieved during the past decade, several important knowledge gaps remain. The absence of universally accepted diagnostic criteria continues to limit clinical implementation, and no objective biomarker has yet demonstrated sufficient reproducibility to serve as a definitive indicator of cochlear synaptopathy in humans. Future longitudinal investigations should prioritize standardized methodologies, larger multicenter cohorts, multimodal diagnostic models, artificial intelligence-assisted data integration, and the development of objective biomarkers capable of improving diagnostic precision.

CONCLUSIÓN

Hidden hearing loss has emerged as an important area of investigation that challenges the traditional concept that normal pure-tone audiometric thresholds necessarily indicate normal auditory function. The evidence analyzed throughout this review demonstrates that clinically relevant auditory dysfunction may occur despite preserved hearing sensitivity, particularly affecting speech perception in noisy environments, listening effort, and overall communication performance. These findings support a broader understanding of hearing that extends beyond threshold detection to include neural integrity, temporal processing, and functional auditory performance.

The current literature indicates that cochlear synaptopathy represents one of the principal biological mechanisms proposed to explain hidden hearing loss; however, the available evidence also demonstrates that the condition is multifactorial and cannot be attributed exclusively to synaptic degeneration. Noise exposure, physiological aging, systemic health conditions, and individual biological susceptibility appear to interact in the development of auditory dysfunction. Furthermore, similar clinical manifestations may arise from central auditory processing disorders, cognitive factors, and other peripheral auditory abnormalities, reinforcing the need for careful differential diagnosis.

This review also confirms that conventional pure-tone audiometry remains an essential component of hearing assessment but presents important limitations for detecting early neural dysfunction. Complementary evaluations—including speech-in-noise testing, extended high-frequency audiometry, auditory brainstem responses, otoacoustic emissions, and other electrophysiological techniques—provide valuable additional information; nevertheless, no individual diagnostic method currently offers sufficient accuracy to serve as an independent gold standard. Consequently, the integration of multiple behavioral, physiological, and clinical assessments represents the most appropriate strategy for evaluating patients with persistent auditory complaints despite normal audiometric findings.

From a public health perspective, increasing occupational and recreational noise exposure, together with progressive population aging, suggests that hidden hearing loss may become an increasingly relevant clinical challenge worldwide. The relatively limited scientific evidence originating from Latin America highlights the need to strengthen regional research, improve access to specialized diagnostic services, and develop hearing conservation programs adapted to local healthcare systems. Greater international collaboration and standardized research methodologies will facilitate the generation of evidence applicable across diverse populations.

Future investigations should prioritize longitudinal multicenter studies, internationally standardized diagnostic criteria, objective biomarkers with demonstrated clinical validity, and the incorporation of artificial intelligence into multimodal diagnostic models. Advances in these areas may improve early identification, optimize individualized patient management, and facilitate the translation of experimental discoveries into routine clinical practice.

In conclusion, hidden hearing loss represents an evolving concept that has significantly expanded current knowledge regarding auditory dysfunction beyond conventional audiometry. Although important diagnostic uncertainties remain, the accumulated scientific evidence supports the adoption of comprehensive, multidisciplinary, and evidence-based approaches that integrate otorhinolaryngology, audiology, neurology, and public health. Continued scientific investigation will be essential for improving the prevention, diagnosis, and management of this increasingly recognized auditory disorder while ultimately enhancing hearing healthcare and quality of life for affected individuals worldwide.

REFERENCIAS

- Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. *The Lancet*, 383(9925), 1325–1332.
- Bramhall, N. F., Konrad-Martin, D., McMillan, G. P., & Griest, S. E. (2017). Auditory brainstem response altered in humans with noise exposure despite normal hearing thresholds. *Ear and Hearing*, 38(1), e1–e12.
- Bramhall, N. F., Konrad-Martin, D., McMillan, G. P., & Griest, S. E. (2019). Effectiveness of auditory measures for detecting hidden hearing loss and/or cochlear synaptopathy: A systematic review. *Seminars in Hearing*, 40(2), 172–209. <https://doi.org/10.1055/s-0038-1641743>

- Colla, M. F., Lunardelo, P. P., & Dias, F. A. M. (2024). Cochlear synaptopathy and hidden hearing loss: A scoping review. *CoDAS*, 36(2). <https://doi.org/10.1590/2317-1782/20232023032>
- Guest, H., Munro, K. J., Prendergast, G., Howe, S., & Plack, C. J. (2018). Tinnitus with a normal audiogram: Relation to noise exposure but no evidence for cochlear synaptopathy. *Hearing Research*, 364, 142–151.
- Hickox, A. E., Larsen, E., Heinz, M. G., Shinobu, L., & Whitton, J. P. (2017). Translational issues in cochlear synaptopathy. *Hearing Research*, 349, 164–171.
- Korver, A. M. H., et al. (2025). A systematic review: State of the science on diagnostics of hidden hearing loss. *American Journal of Audiology*. Advance online publication.
- Kujawa, S. G., & Liberman, M. C. (2009). Adding insult to injury: Cochlear nerve degeneration after temporary noise-induced hearing loss. *Journal of Neuroscience*, 29(45), 14077–14085.
- Le Prell, C. G., Spankovich, C., Lobarinas, E., & Griffiths, S. K. (2022). Hidden hearing loss and emerging concepts in cochlear synaptopathy: Clinical implications and future directions. *Audiology and Neurotology*, 27(4), 201–214.
- Liberman, M. C., Epstein, M. J., Cleveland, S. S., Wang, H., & Maison, S. F. (2016). Toward a differential diagnosis of hidden hearing loss in humans. *PLoS ONE*, 11(9), e0162726.
- Liberman, M. C., & Kujawa, S. G. (2017). Cochlear synaptopathy and noise-induced hidden hearing loss. *Journal of the Association for Research in Otolaryngology*, 18(2), 205–220.
- Liberman, M. C., & Kujawa, S. G. (2017). Synaptopathy in the noise-exposed and aging cochlea: Primary neural degeneration in acquired sensorineural hearing loss. *Hearing Research*, 349, 138–147.
- Liu, J., Stohl, J., & Overath, T. (2024). Hidden hearing loss: Fifteen years at a glance. *Hearing Research*, 443, 108967. <https://doi.org/10.1016/j.heares.2024.108967>
- Møller, M. N., & Brandt, C. (2022). Hidden hearing loss: Current concepts. *Current Opinion in Otolaryngology & Head and Neck Surgery*, 30(5), 355–361. <https://doi.org/10.1097/MOO.0000000000000824>
- Plack, C. J., Barker, D., & Prendergast, G. (2014). Perceptual consequences of "hidden" hearing loss. *Trends in Hearing*, 18, 1–11.
- Plack, C. J., Léger, A., Prendergast, G., Kluk, K., Guest, H., & Munro, K. J. (2016). Toward a diagnostic test for hidden hearing loss. *Trends in Hearing*, 20, 1–9.
- Ponsot, E. (2024). Unravelling hidden hearing loss. *eLife*, 13, e104936. <https://doi.org/10.7554/eLife.104936>
- Sha, S. H., & Schacht, J. (2025). Consequences and mechanisms of noise-induced cochlear synaptopathy and hidden hearing loss, with focuses on signal perception in noise and temporal processing. *Hearing Research*. Advance online publication.
- World Health Organization. (2021). *World report on hearing*. World Health Organization.
- Wu, P. Z., O'Malley, J. T., de Gruttola, V., & Liberman, M. C. (2021). Primary neural degeneration in the human cochlea: Evidence for hidden hearing loss in aging. *Journal of Neuroscience*, 41(14), 3213–3222.