



High-Frequency Vulnerability and Sex Differences in Age-Related Hearing Loss: A Cross-Sectional Audiometric Analysis of Older Chinese Otolaryngology Outpatients

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ABSTRACT

Objective: To determine the prevalence, severity, and audiometric characteristics of age-related hearing loss (ARHL) in older Chinese adults attending a tertiary otolaryngology clinic, with emphasis on age- and sex-specific patterns based on the updated World Health Organization (WHO 2020) criteria. **Methods:** In this cross-sectional study, 1,000 adults aged ≥ 60 years underwent otologic examination, tympanometry, and pure-tone audiometry at a tertiary medical center between March 2022 and January 2023. Individuals with abnormal tympanograms or evidence of middle ear disease were excluded. Pure-tone averages (0.5, 1, 2, and 4 kHz) from the better ear were used to define and grade ARHL. Age- and sex-related differences in hearing thresholds were assessed using chi-square tests, t-tests, and two-way ANOVA. **Results:** Within this tertiary-care outpatient cohort, the prevalence of hearing loss according to WHO 2020 criteria was 84.1%, rising from 78.3% in the 60s to 100% in those aged over 90 years. Hearing thresholds showed a consistent high-frequency-sloping configuration, with high-frequency (8,000 Hz) thresholds declining at nearly double the rate of low-to-mid frequencies (11.7 dB vs. 4.5–6.3 dB per decade). The steepest decadal deterioration occurred between the 70s and 80s, characterized by a transition from high-frequency sensory loss to generalized cochlear decline. A sex-dependent "crossover" was observed: females exhibited superior hearing in their 60s and 70s but experienced more rapid deterioration in late life, resulting in comparable or poorer thresholds than males by their 80s and 90s. **Conclusion:** In this tertiary-care outpatient cohort of older Chinese adults, ARHL demonstrated distinct age- and sex-specific trajectories, including disproportionate high-frequency vulnerability and a late-life sex crossover effect. Adoption of WHO 2020 criteria substantially increased hearing-loss identification, particularly among adults in their 60s and 70s.

KEYWORDS

age-related, hearing, loss, pure-tone, audiometry, hearing, thresholds, sex, differences.

1 Introduction

Age-related hearing loss (ARHL), or presbycusis, is the leading cause of sensory deprivation in the aging population, strongly associated with social isolation, cognitive decline, and reduced quality of life (Bowl and Dawson, 2019). While ARHL is characterized by progressive, bilateral sensorineural degeneration, its trajectory is highly heterogeneous. Emerging evidence suggests that biological sex and environmental exposures create distinct audiometric "signatures." However, data utilizing the updated World Health Organization (WHO 2021) classification—which lowered the threshold for hearing impairment to >20 dB HL—remains limited. This study aims to characterize the severity and audiometric features of ARHL in a cohort of older Chinese adults attending a tertiary otolaryngology clinic and to evaluate the impact of the WHO 2020 hearing-loss classification. Particular attention was given to frequency-specific deterioration and the crossover effects of biological sex on hearing trajectories in late life.

2 Material and Method

2.1 Study Design and Participants

This cross-sectional study analyzed data from adults aged 60 and older, collected from March 2022 to February 2023 at Department of Ear, Nose, and Throat of Peking University Shenzhen Hospital. Participants were consecutive adults aged ≥ 60 years attending the otolaryngology outpatient clinic who underwent audiometric evaluation during the study period. Although many participants presented with hearing-related complaints, recruitment was not population-based and therefore represents a health-seeking clinical cohort. The inclusion criteria required participants to live independently and walk unaided. Inclusion required independent living and the ability to complete comprehensive audiometric testing.

2.2 Inclusion and Exclusion Criteria

To isolate ARHL from other otologic pathologies, we excluded

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individuals with: (1) abnormal tympanograms (Types B or C); (2) conductive or mixed hearing loss (air-bone gap >10 dB); (3) history of ototoxic medication or ear surgery. The study was approved by the Clinical Research Ethics Committee of Peking University Shenzhen Hospital.

2.3 Methods

Audiometric assessments included tympanometry and pure-tone audiometry, conducted by trained audiometricians. Tympanometry was performed using an impedance audiometer (Interacoustics A/S, Middelfart, Denmark) with a 226 Hz probe tone, and the results were classified according to the Liden and Jerger system (Lidén, 1969; Jerger, 1970). Tympanograms classified as type A (normal tympanogram with a peak within the reference range), type As (hypomobile eardrum with admittance < 0.30 mmho), or type Ad (hypermobile eardrum with admittance > 1.60 mmho) indicated normal middle ear function and were included in the study. Pathological tympanograms (types B, C, or D) were excluded. Pure-tone audiometry was performed in a sound-attenuated room using a GSI 61 audiometer (Grason-Stadler, USA), equipped with TDH39 supra-aural earphones and a B-71 bone oscillator. The equipment was calibrated to national standards (GB/T 16403-1996), and background noise levels were controlled accordingly. Air-conduction thresholds were measured at frequencies of 125, 250, 500, 1,000, 2,000, 3,000, 4,000, and 8,000 Hz, while bone-conduction thresholds were recorded at 250, 500, 1,000, 2,000, and 4,000 Hz. The pure-tone average (PTA) at 500, 1,000, 2,000, and 4,000 Hz was used to assess the degree of sensorineural hearing loss (SNHL) and identify the better ear for each participant, following the WHO 2020 classification (Humes, 2019). Additional averages were calculated to evaluate hearing thresholds across different frequency ranges. Hearing loss severity was classified according to the World Health Organization's hearing-impairment grading system, which was developed by an expert group as part of the Global Burden of Disease (GBD) project (GBD 2019 Hearing Loss Collaborators, 2021). The WHO classification defines hearing as follows: (1) Normal: <20 dB HL; (2) Mild: 20–34 dB HL; (3) Moderate: 35–49 dB HL; (4) Moderately severe: 50–64 dB HL; (5) Severe: 65–79 dB HL (6) Profound: 80–94 dB HL (7) Complete: 95+ dB.

2.4 Statistical Analysis

SPSS version 23 was used for statistical analysis. Categorical data were presented as frequencies and percentages, while continuous data were summarized using means and standard errors. Differences in hearing-loss prevalence between groups were

assessed using chi-square tests. Age- and sex-related differences in hearing thresholds were analyzed using one-way or two-way ANOVA, followed by Tukey or Šídák post hoc testing where appropriate. Differences in PTA between consecutive age groups were assessed using Welch-corrected t-tests. Statistical significance was defined as $p < 0.05$.

3 Results

3.1 Participant Characteristics

The study population comprised 1,000 participants (2,000 ears) with a mean age of 70.4 ± 7.6 years (range: 60–95 years). The cohort was 55.1% female. Age-based stratification revealed that 51.5% of the participants were in their 60s, 33.7% in their 70s, 13.6% in their 80s, and 1.2% were aged 90 years or older (Figure 1).

3.2 Tympanometry Results

Tympanometric evaluation confirmed normal middle ear function across the study population, consistent with the inclusion criteria. Of the 2,000 ears assessed, 79.6% exhibited Type A (normal) curves, while 5.6% and 14.7% showed Type Ad (hypermobile) and Type As (hypomobile) configurations, respectively. No Type B or C tympanograms—indicative of middle ear effusion or eustachian tube dysfunction—were identified.

3.3 Age-Specific Prevalence and Severity

Applying the updated World Health Organization (WHO 2021) criteria (PTA at 0.5, 1, 2, and 4 kHz > 20 dB HL in the better ear), the overall prevalence of ARHL was 84.1%. Prevalence increased linearly with age: 78.3% in the 60s, 86.7% in the 70s, 98.5% in the 80s, and 100% in those 90 years and older. A slight sex-based discrepancy was noted, with females (80.2%) exhibiting a higher prevalence than males (77.7%) (Table 1).

Application of the WHO 2020 hearing loss classification substantially increased the proportion of participants classified as having hearing loss. Under the legacy WHO criteria, 697 of 1,000 participants (69.7%) met the definition of hearing loss, compared with 841 participants (84.1%) under the WHO 2020 criteria. Overall, 144 participants (14.4%) were reclassified from normal hearing under the legacy WHO criteria to hearing loss under the WHO 2020 classification. The impact of the revised criteria varied across age groups. The largest absolute reclassification occurred among participants in their 60s and 70s, with 85 (16.5%) and 52

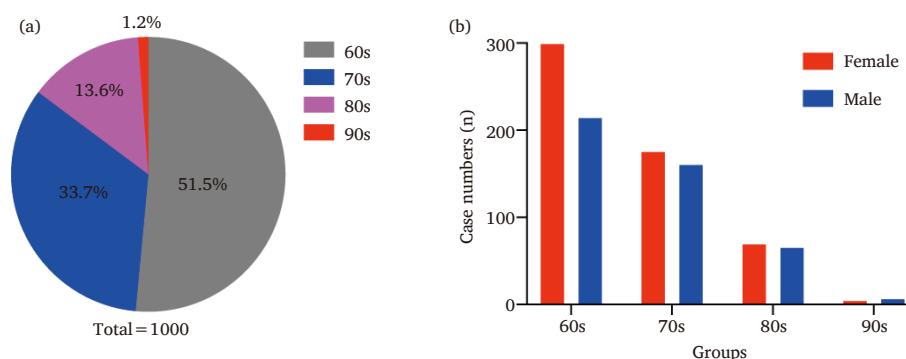


Figure 1 Participant Demographics. (A) Distribution of participants across age groups: 51.5% were in their 60s, 33.7% in their 70s, 13.6% in their 80s, and 1.2% were older than 90 years. (B) Distribution of males and females was observed across all age groups.

Table 1 Prevalence of Hearing Loss in the Participants

	No.	Normal Hearing	Hearing Loss	Prevalence Rate	P Value
Sex					<0.05
Male	449	100	349	77.73%	
Female	551	109	442	80.22%	
Age					<0.0001
60-69	515	112	403	78.25%	
70-79	337	45	292	86.65%	
80-89	136	2	134	98.53%	
90-99	12	0	12	100%	

(15.4%) individuals, respectively, being newly classified as having hearing loss under the WHO 2020 criteria. In contrast, only seven participants (5.1%) in their 80s were reclassified, and no reclassification occurred among participants aged 90 years or older because all individuals in this age group met both classification criteria. McNemar testing demonstrated a significant difference in hearing loss prevalence between the legacy WHO and WHO 2020 classifications both overall ($p < 0.001$) and within the 60s, 70s, and 80s age groups. These findings indicate that lowering the diagnostic threshold from 25 dB HL to 20 dB HL substantially increases the identification of hearing loss, particularly among younger older adults (Table 2).

Hearing severity worsened progressively with advancing age (Figure 2A). While normal-to-mild hearing loss predominated in the 6th and 7th decades, moderate-to-severe loss became the standard in the 8th and 9th decades. The mean PTA increased from 32.7 dB HL (60s) to 51.0 dB HL (90s). Notably, the steepest decadal deterioration occurred between the 70s and 80s, with a PTA shift of 8.5 dB (Figure 2B).

Table 2 Reclassification of hearing loss status according to WHO 2020 criteria

Age Group	Legacy WHO HL n (%)	WHO 2020 HL n (%)	Reclassified n (%)	McNemar p value
60–69	318 (61.7)	403 (78.3)	85 (16.5)	<0.001
70–79	240 (71.2)	292 (86.6)	52 (15.4)	<0.001
80–89	127 (93.4)	134 (98.5)	7 (5.1)	0.023
90–99	12 (100)	12 (100)	0 (0)	N/A
Total	697 (69.7)	841 (84.1)	144 (14.4)	<0.001

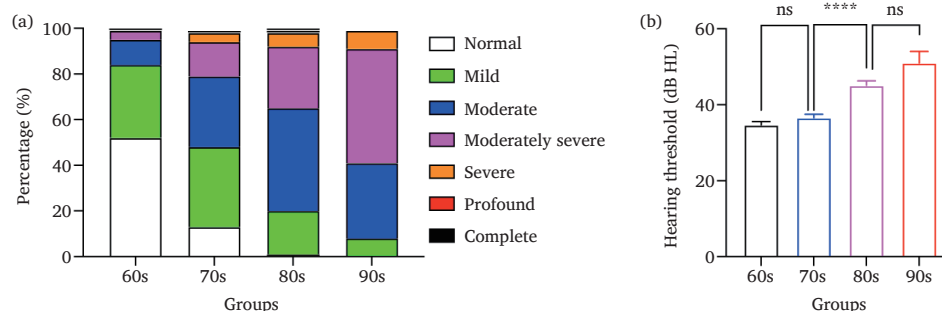


Figure 2 Progressive age-related decline in hearing. (A) The 60s group had the highest proportion of individuals with normal hearing. Hearing loss severity increased progressively with age: mild loss predominated in the 70s, moderate loss in the 80s, and moderately severe loss in the 90+ group. (B) Mean hearing thresholds rose steadily across age groups, increasing from 32.7 dB in the 60s to 36.6 dB in the 70s, 45.1 dB in the 80s, and 51.0 dB in participants aged 90 and above. ns, not significant, * $p < 0.05$, ** $p < 0.002$, *** $p < 0.0002$, **** $p < 0.0001$, as determined by unpaired t-test with Welch's correction. Data are presented as mean $\pm$ SEM.

3.4 Audiometric Configuration and Frequency-Specific Vulnerability

Hearing loss was primarily bilateral and symmetrical. The mean air-bone gap (ABG) remained <10 dB across all age groups, corroborating the sensorineural nature of the impairment. Audiometric configurations demonstrated a consistent downward-sloping pattern, with significantly poorer thresholds at higher frequencies (Figure 3A). Two-way ANOVA demonstrated significant main effects of both age cohort ($F(3, 6972) = 179.5$, $p < 0.0001$) and audiometric frequency ($F(6, 6972) = 125.2$, $p < 0.0001$). A significant age-by-frequency interaction was also observed ($F(18, 6972) = 17.95$, $p < 0.0001$), indicating that the magnitude of age-related hearing loss varied across frequencies.

Frequency-specific analysis revealed a threshold decline of 4.5–6.3 dB per decade at low-to-mid frequencies (125–4,000 Hz), compared to a more severe decline of 11.7 dB per decade at 8,000 Hz. Between the 60s and 70s, significant threshold elevations were localized to the extreme low (125–250 Hz) and high (8,000 Hz) ends of the spectrum. However, the transition from the 70s to the 80s was characterized by generalized cochlear decline, with statistically significant threshold increases (6.3–8.8 dB) across the entire frequency range (Figure 3B–H). Auditory deterioration appeared to plateau between the 80s and 90s, as no significant threshold changes were observed in the oldest cohort.

3.5 Sex-Specific Trajectories

Both males and females exhibited age-related auditory decline, yet their trajectories differed significantly (Figure 4A, B). The ordinary two-way ANOVA evaluating sex-stratified cohorts revealed highly significant main effects for both frequency ($F(6, 3829) = 52.17$, $p < 0.0001$) and the combined age-gender classification groups ($F(3, 3829) = 152.5$, $p < 0.0001$). Additionally, a highly significant interaction effect between the age-gender groups and audiometric frequencies was established ($F(18, 3829) = 11.36$, $p < 0.0001$). This interaction mathematically validates that the

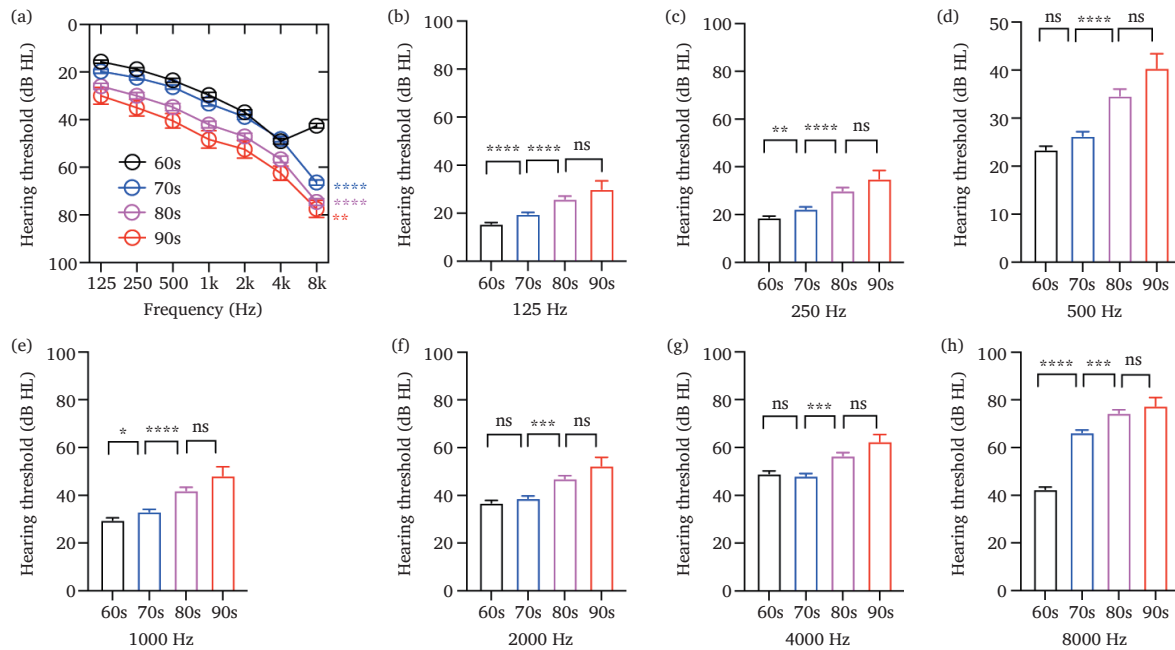


Figure 3 Age- and frequency-specific hearing thresholds. (A) Mean air-conduction thresholds across frequencies (125–8,000 Hz) for each age group, illustrating a downward-sloping audiometric configuration. ns, not significant, * $p < 0.05$, ** $p < 0.002$, *** $p < 0.0002$, **** $p < 0.0001$ by two-way ANOVA. (B–H) Frequency-specific hearing thresholds at 125 Hz (B), 250 Hz (C), 500 Hz (D), 1,000 Hz (E), 2,000 Hz (F), 4,000 Hz (G), and 8,000 Hz (H) across age cohorts. ns, not significant, * $p < 0.05$, ** $p < 0.002$, *** $p < 0.0002$, **** $p < 0.0001$ by one-way ANOVA with Tukey's multiple-comparison correction. Data are shown as mean $\pm$ SEM.

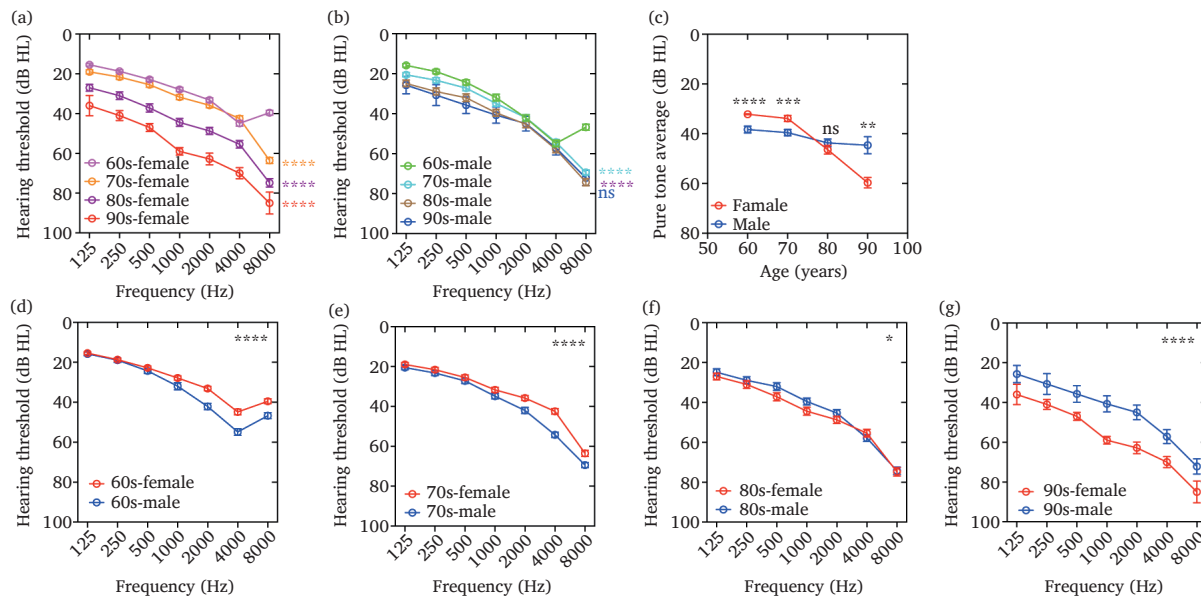


Figure 4 Sex-based differences in age-related hearing loss. (A, B) Mean air-conduction hearing thresholds across audiometric frequencies (125–8,000 Hz) in female (A) and male (B) participants stratified by age decade (60s, 70s, 80s, and 90s). Significance markers on the right indicate post hoc pairwise comparisons between consecutive age decades within each frequency following two-way ANOVA with Tukey's multiple-comparison correction. (C) Pure-tone average (PTA) thresholds across age decades in female and male participants. Significance markers indicate post hoc pairwise comparisons between sexes within each age decade following two-way ANOVA with Šídák's multiple-comparison correction. (D–G) Frequency-specific comparisons of air-conduction hearing thresholds between female and male participants in the 60s (D), 70s (E), 80s (F), and 90s (G) age cohorts. Significance markers indicate post hoc pairwise comparisons between sexes at each frequency following two-way ANOVA with Šídák's multiple-comparison correction. ns, not significant, * $p < 0.05$, ** $p < 0.002$, *** $p < 0.0002$, **** $p < 0.0001$ by two-way ANOVA. Data are shown as mean $\pm$ SEM.

physical rate and configuration of age-related threshold shifts over time differ fundamentally depending on the pitch being tested.

In the 60s and 70s, females demonstrated superior overall hearing (PTA) and significantly better high-frequency sensitivity (2,000–8,000 Hz) than males (Figure 4C–E). However, a sex-dependent "crossover" was observed in late life. Females experienced a more accelerated deterioration between the 7th and 8th decades, leading

to a more pronounced downward-sloping audiogram. By the 80s and 90s, the initial female advantage was lost, with males demonstrating comparable or superior thresholds across nearly all frequencies (Figure 4F, G). These data suggest that while males experience earlier high-frequency deficits, females undergo a more rapid, generalized decline in late life.

4 Discussion

Application of the WHO 2020 hearing-loss classification substantially increased the proportion of older adults identified as having hearing loss within this tertiary-care outpatient cohort. Compared with the legacy WHO criterion (>25 dB HL), the revised threshold (>20 dB HL) reclassified 14.4% of participants from normal hearing to hearing loss, increasing the overall proportion meeting hearing-loss criteria from 69.7% to 84.1%. The impact of the revised classification was most pronounced among participants in their 60s and 70s, in whom approximately one-sixth of individuals were newly identified as having hearing loss. These findings highlight the greater sensitivity of the WHO 2020 criteria for detecting early-stage auditory decline. By recognizing individuals with hearing thresholds in the 20–25 dB HL range as having mild hearing loss rather than normal hearing, the revised classification may better capture auditory deficits that can affect everyday communication and increase listening effort in older adults [9]. Earlier identification of hearing impairment may facilitate timely counseling, hearing rehabilitation, and preventive interventions before more substantial deterioration in auditory function occurs. Although the proportion of participants meeting hearing-loss criteria in our study was higher than that reported in many population-based studies (Rigters et al., 2018; Kim et al., 2020; Li et al., 2021; De Raedemaeker et al., 2022), this difference likely reflects both the lower diagnostic threshold of the WHO 2021 classification and the health-seeking nature of our study population, which consisted of older adults attending an otolaryngology clinic for audiological evaluation.

A key finding of our analysis is the non-linear progression of hearing thresholds. While hearing sensitivity declined across all frequencies, the steepest deterioration in the pure-tone average (PTA) occurred between the 70s and 80s (+8.5 dB shift). This suggests a critical window of physiological transition. In the 60s and 70s, the decline was largely confined to the high frequencies (8,000 Hz), characteristic of sensory presbycusis—the loss of hair cells at the basal turn of the cochlea. However, the 80s cohort demonstrated a generalized "flattening" of the audiometric curve, with significant threshold elevations even at low and mid frequencies (125–2,000 Hz). This generalized decline likely represents the cumulative effect of metabolic and neural presbycusis, including strial atrophy and spiral ganglion cell loss, which affects the cochlea more broadly (Gates and Cooper, 1991; Linssen et al., 2014).

Consistent with the base-to-apex gradient of cochlear vulnerability, our results showed that 8,000 Hz thresholds declined at a rate of 11.7 dB per decade—nearly double the rate of low-frequency decline (4.5–6.3 dB). Interestingly, our data suggests a "plateau effect" between the 80s and 90s, where no statistically significant threshold changes were detected. This may indicate a "ceiling effect" in audiometric testing, where thresholds in the very elderly reach the maximum output of the audiometer, or a survival bias, where individuals with extremely rapid auditory and systemic aging do not survive into the 90s cohort.

Sexual dimorphism in Age-Related Hearing Loss (ARHL) has been widely documented, though findings often vary by age and frequency. Classic cross-sectional and longitudinal studies suggest that males generally exhibit poorer pure-tone averages (PTAs) and more pronounced high-frequency deficits, whereas females often demonstrate greater low-frequency involvement and more gradual overall deterioration (Davis, 1989; Lin et al., 2011; Rigters et al., 2016; De Raedemaeker et al., 2022). Our findings align with these

established patterns within the "younger-old" cohorts (60s–70s). In these age ranges, females exhibited a significant "female advantage," characterized by superior overall PTA and notably better high-frequency sensitivity (2,000–8,000 Hz) relative to males. This physiological edge is frequently attributed to the neuroprotective effects of estrogen on the auditory system, alongside a historically lower likelihood of occupational noise exposure among women of this generation (Davis, 1989).

However, the most striking finding of our study is the emergence of a "crossover effect" during the eighth decade. While males initially presented with poorer auditory profiles, females underwent a significantly steeper rate of deterioration between their 70s and 80s. By the 80s and 90s, the initial female advantage vanished, with males demonstrating comparable or even superior thresholds across nearly all measured frequencies. This late-life acceleration in females suggests a distinct pathophysiological trajectory. While male hearing loss often begins earlier due to environmental and lifestyle factors, female hearing loss appears to accelerate more rapidly in advanced age. Although the mechanisms remain uncertain, potential explanations include post-menopausal hormonal changes, sex-specific cochlear aging processes, and differential cumulative environmental exposures across the lifespan.

This study has several limitations. First, this study was not designed to estimate population prevalence. Participants were recruited from a tertiary otolaryngology clinic and therefore represent a health-seeking population enriched for hearing-related concerns. Consequently, the prevalence estimates reported here are likely higher than those observed in community-based cohorts and should not be generalized to the broader older Chinese population. Future multi-center, community-based epidemiological studies are needed to validate these findings in more representative populations. Second, although pure-tone average (PTA) forms the basis of the WHO hearing loss classification, it primarily reflects peripheral auditory sensitivity and does not fully capture speech recognition, hearing-in-noise performance, or the functional impact of hearing loss. Future studies should combine PTA-based classification with functional auditory assessments and validated patient-reported outcome measures to better evaluate the real-world consequences of hearing loss in older adults.

In this tertiary-care outpatient cohort, age-related hearing loss demonstrated characteristic high-frequency vulnerability, progressive worsening across advancing age, and distinct sex-specific trajectories. Hearing decline accelerated most prominently between the seventh and eighth decades of life, coinciding with a transition from predominantly high-frequency impairment to more generalized cochlear dysfunction. Application of WHO 2020 criteria substantially increased the identification of hearing loss, particularly among adults in their 60s and 70s. These findings support earlier detection and individualized hearing-care strategies in older adults.

Data Availability Statement

The datasets generated and analyzed during the current study are not publicly available because they contain potentially identifiable patient information and are subject to institutional and ethical restrictions. The data are available from the corresponding author on reasonable request, subject to approval by the Ethics Committee of Peking University Shenzhen Hospital and applicable data protection regulations.

Ethical Approval

This retrospective study was reviewed and approved by the Ethics Committee of Peking University Shenzhen Hospital (Approval No. [2022014]). The study was conducted in accordance with the principles of the Declaration of Helsinki and its subsequent amendments. As this study involved the retrospective analysis of existing clinical data and posed minimal risk to participants, no additional interventions were performed.

Informed Consent Statement

The requirement for informed consent was waived by the Ethics Committee of Peking University Shenzhen Hospital because this was a retrospective study based on existing clinical records. The study involved no direct participant contact or intervention, and all data were anonymized prior to analysis, posing no more than minimal risk to participants. The waiver of informed consent did not adversely affect the rights or welfare of the participants.

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