Original Study

Audiometric Predictors of Bothersome Tinnitus in a Large Clinical Cohort of Adults With Sensorineural Hearing Loss

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Objective: To identify demographic and audiometric predictors of bothersome tinnitus within a large clinical cohort.
Study Design: Retrospective chart review.
Setting: Tertiary care hospital.
Patients: 51,989 English-speaking patients between 18 and 80 years of age that received initial audiometric evaluations at the Massachusetts Eye and Ear Infirmary between the years 2000 and 2016.
Main Outcome Measures: Patients were categorized according to whether or not tinnitus was the primary reason for their visit. The likelihood of tinnitus as a primary complaint (TPC) was evaluated as a function of age, sex, and audiometric configuration. Patient-reported tinnitus percepts were qualitatively assessed in relation to audiometric configuration.
Results: Approximately 20% of adults who presented for an initial hearing evaluation reported TPC. The prevalence of TPC increased with advancing age until approximately 50 to 54 years, and then declined thereafter. In general, men were significantly more likely to report TPC than women. TPC was statistically associated with specific audiogram configurations. In particular, TPC was most prevalent for notched and steeply sloping hearing losses, but was relatively uncommon in adults with flat losses. Patients with frequency-restricted threshold shifts often reported tonal tinnitus percepts, while patients with asymmetric configurations tended to report broadband percepts.
Conclusions: The probability of seeking audiological evaluation for bothersome tinnitus is highest for males, middle-aged patients, and those with notched or high-frequency hearing losses. These findings support the theory that tinnitus arises from sharp discontinuities in peripheral afferent innervation and cochlear amplification, which may induce topographically restricted changes in the central auditory pathway.
Key Words: Aging—Audiogram—High-frequency hearing loss—Normal hearing—Prevalence—Tinnitus.

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Tinnitus is the perception of sound in the head or ears that occurs in absence of a physical correlate, with common qualitative descriptors including ‘‘ringing,’’ ‘‘buzzing,’’ or ‘‘hissing’’. Tinnitus affects between 5 and 42% of the population worldwide (1), where the incidence rate depends upon subject age, hearing status, and history of noise exposure (2–5). Population-based studies are critical to understanding the incidence and prevalence of tinnitus in the overall population. Taken as a whole, however, the epidemiologic literature offers contradictory results: many assert that males are more likely to report tinnitus (1), while others report just the opposite (6). Statistical associations between hearing loss and tinnitus have been reported, though this connection must be interpreted cautiously as hearing status in these studies is often determined through subjective self-report (1,7,8). Small studies with detailed qualitative measures of tinnitus (such as pitch matching) have demonstrated an association between tinnitus pitch perception and audiometric configuration, but such analyses have not been reported in large hospital-based populations (9–11).

Approximately 3 to 9% of individuals with tinnitus report more than slight tinnitus-related handicap (6,7,12). Unfortunately, there are no widely effective treatments for patients with bothersome tinnitus. Left unmanaged, chronic tinnitus is associated with increased anxiety,

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R.M.L. and D.B.P. conceptualized and designed the study. R.M.L. collected and analyzed the data using an audiology database provided by W.B.G. with custom scripts written by A.P. to access the data. K.N.J. performed statistical analyses. R.M.L. and K.N.J. developed figures. R.M.L., D.B.P., and K.N.J. wrote the manuscript. This work was supported by NIH P50 DC015817 (to D.B.P.).

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depression, and maladaptive behaviors such as perseverating on tinnitus-related distress (13). An improved understanding of the relationship between tinnitus perception, audiometric thresholds, and age could prove useful in guiding targeted audiological care, tinnitus education, and counseling.

In a large hospital-based population, we distinguish between patients who sought medical attention for tinnitus as a primary complaint (hereafter, TPC) and those who sought medical attention for other reasons (e.g., decreased hearing). The goals of this study are to characterize the prevalence of TPC between sexes and across multiple decades of life, with a focus on audiometric configurations and patient-generated tinnitus descriptors.

METHODS

Massachusetts Eye and Ear Infirmary Audiology Database

All procedures were approved by the Human Studies Committee at the Massachusetts Eye and Ear Infirmary. Records from patients seen at the Massachusetts Eye and Ear Infirmary audiology clinic between the years 1993 and 2016 were compiled. If a patient had multiple records, we limited our investigation to their initial visit. Every record contained bilateral air conduction thresholds for standard audiometric frequencies (250, 500, 1000, 2000, 4000, 8000 Hz) and bone conduction thresholds for most of those frequencies (250, 500, 1000, 2000, 4000 Hz). Air conduction thresholds for interoctave frequencies (750, 1500, 3000, and 6000 Hz) were routinely collected when there was a difference of 20 dB HL or greater between thresholds at standard octaves, and were otherwise collected by the audiologist based on clinical judgement. Each record also contained the patient's age and sex, and a written report completed by a licensed audiologist or a supervised audiology extern. To allow for consistent language analysis of tinnitus descriptors (described in Methods section), we limited this analysis to English-speaking patients.

To evaluate audiometric predictors among patients with presumed sensorineural hearing loss, we removed records with conductive components of 15 dB HL or more at any given frequency, and 10 dB HL or more at two consecutive frequencies. Bone conduction thresholds marked as ''no response'' at the upper limits of the audiometer were not considered to be potential conductive components. Air conduction thresholds marked as ''no response'' at the upper limit of the audiometer were also included to preserve audiometric diversity of this population. As a result of these selection criteria, thresholds included in this study range from normal to profound hearing loss.

The ''Reason for Test'' section of the report was used to determine which patients reported TPC. Records that included ''tinnitus'' as the reason for the test were coded as ''TPC''; patients for whom tinnitus was not listed as their primary reason for test were coded as ''non-TPC.'' Other common patient-reported reasons for visit included decreased hearing, asymmetric hearing, vertigo, otitis media, tympanic membrane damage, Menière's disease, or routine physical examination. The ''Reason for Test'' section was not included in the database until year 2000; therefore, only records since year 2000 were analyzed. These selection criteria reduced the total number of available records from 117,164 to 51,989.

Classification of Audiometric Configurations

Records were classified into five groups based on audiometric configuration: normal hearing, notched loss, steeply sloping loss, flat loss, and/or asymmetric loss. Normal hearing records required all measured thresholds to be less than or equal to 25 dB HL bilaterally. Notched losses required thresholds that were at least 15 dB HL better than the poorest measured air conduction threshold at neighboring octave frequencies; when the next octave frequency was unavailable, the nearest available interoctave frequency was substituted for comparison. Notches could be present either unilaterally or bilaterally.

Steeply sloping loss was defined as the presence of a threshold that was 20 dB HL poorer than the octave below for that same ear. A record was classified as flat hearing loss when all measured thresholds were poorer than 25 dB HL bilaterally, with each threshold being no more than 20 dB HL different from the average threshold of the corresponding ear. Sloping and flat losses were bilateral. Records with considerable interaural threshold differences were classified as asymmetric. Asymmetry was defined according to the Mangham screening criteria (14,15), which specifies an average interaural threshold difference of greater than 10 dB HL across 1, 2, 4, and 8 kHz.

Classifications were not mutually exclusive; a record could have been classified into multiple categories. To assign each patient to one category for final analysis, a ranked order was implemented, as follows: 1) normal hearing, 2) notched, 3) steeply sloping, 4) flat, 5) asymmetric.

Qualitative Tinnitus Descriptors

Patient-reported qualitative tinnitus descriptors were analyzed using the history section of the report. Each word or phrase found within quotation marks was examined by the first author. The descriptors were ranked by overall occurrence across all records, irrespective of audiometric configuration. From a list of 369 total descriptors, the 20 most common descriptors were included in subsequent analyses. Three descriptors—''muffled,'' ''blocked,'' and ''echo''—were removed due to the likelihood that patients were describing their hearing as opposed to their tinnitus quality. The remaining 17 descriptors were ultimately categorized into three qualitative groups: tonal, broadband, and periodic. The three most frequent tonal descriptors were ''ringing,'' ''hissing,'' and ''high-pitched''; the most frequent broadband descriptors were ''buzzing,'' ''whooshing,'' and ''swooshing''; and the most frequent periodic descriptors were ''clicking,'' ''popping,'' and ''fluttering''.

RESULTS

Prevalence of Bothersome Tinnitus as a Function of Age and Sex

Of the 51,989 records, 10,532 (20.26%) indicated TPC. Between the years 2000 and 2016, the number of patients seen in the clinic grew (Fig. 1A), while the prevalence of patients reporting TPC remained relatively stable (Fig. 1B). Although females consistently comprised the majority of the clinical population (Fig. 1A), males generally demonstrated a higher prevalence of TPC across calendar years (Fig. 1B).

A multiple logistic regression analysis was performed to quantitatively assess the influence of age and sex, and the interaction between the two variables, on the

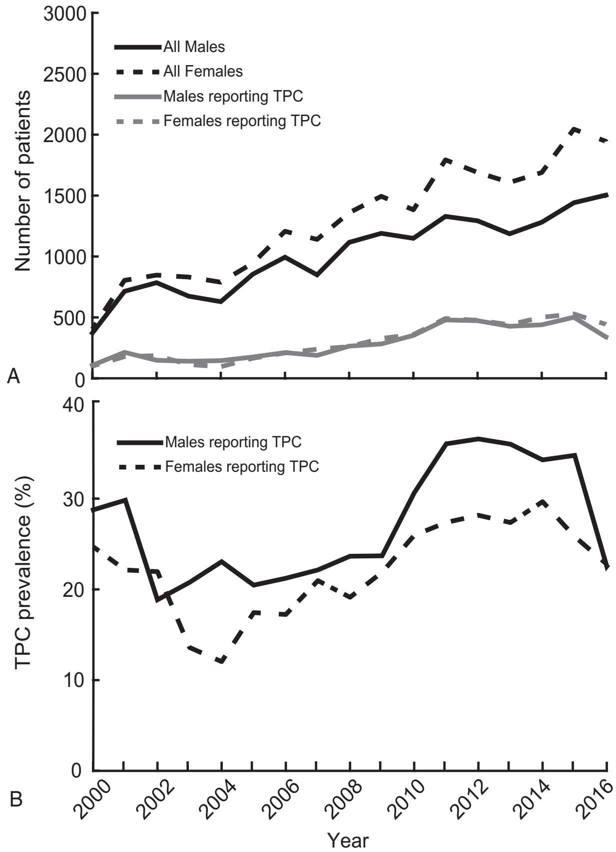

FIG. 1. Patients who visited the MEEI audiology clinic between the years 2000 and 2016. *A,* Total number of patients who visited the clinic (males: solid black line; females: dashed black line) compared with total number of patients who reported tinnitus as a primary complaint (TPC; males: solid gray line; females: dashed gray line). *B,* Total number of patients who visited the clinic and reported TPC (males: solid line; females: dashed line). Note that the scale in (*B*) ranges from 0 to 40%. MEEI indicates Massachusetts Eye and Ear Infirmary; TPC, tinnitus as a primary complaint.

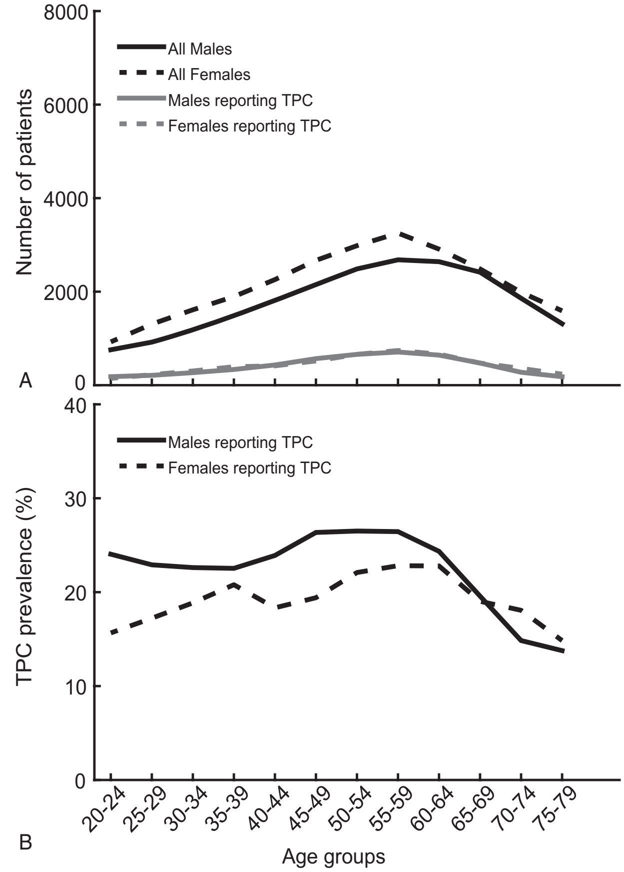

FIG. 2. Age and sex distribution of patients who visited the MEEI audiology clinic between the years 2000 and 2016. *A,* Total number of patients who visited the clinic (males: solid black line; females: dashed black line) compared with total number of patients who reported tinnitus as a primary complaint (TPC; males: solid gray line; females: dashed gray line) across half-decade timespans. *B,* Prevalence (%) of TPC as a function of age for males (solid line) and females (dashed line). Note that the scale in panel B ranges from 0 to 40%. MEEI indicates Massachusetts Eye and Ear Infirmary; TPC, tinnitus as a primary complaint.

likelihood that a patient presented with TPC. For this analysis, age was modeled as a continuous variable. Descriptive analyses (Fig. 2) suggested a nonmonotonic relationship between TPC and age. To test this observation, linear and squared versions of the *Age* variable were entered into the model sequentially. The linear set of predictors (age, sex, and age × sex interaction) provided a significantly better fit than the null model, $\chi^2(3) = 198.90$, $p < 0.001$. Entering Age^2 into the equation significantly improved the model fit, $\chi^2(1) = 409.38$, $p < 0.001$, suggesting that a quadratic model was a better fit than a linear model.

Both the linear ($\chi^2(1) = 332.1$, $p < 0.001$, odds ratio [OR] = 1.08), and quadratic ($\chi^2(1) = 381.9$, $p < 0.001$, $OR = 1.00$) trends for age were significant. Overall, the likelihood of TPC decreased significantly, albeit modestly, as a function of age. More specifically, however, the prevalence of TPC increased through middle age, reaching a peak around 55 to 59 years for females (22.82%) and around 50 to 54 years for males (26.51%; Fig. 2). Thereafter, the likelihood of reporting TPC declined with advancing age, and was lowest between 75 and 79 years, the oldest age group evaluated in this study (13.77 and 14.84% for males and females, respectively; Fig. 2B).

Sex also significantly predicted TPC, wherein males were 1.93 times more likely to report TPC than females ($\chi^2(1) = 67.80$, $p < 0.001$, $OR = 1.93$). The interaction between Sex and Age was significant ($\chi^2(1) = 39.00$, $p < 0.001$, $OR = 0.99$). Figure 2 shows that males reported TPC more often than females through age 65 to 69 years. Thereafter, TPC prevalence was similar for both sexes.

Prevalence of Bothersome Tinnitus as a Function of Audiometric Configuration

Of the 51,989 total records, 41,294 audiograms met our classification criteria and were used in audiometric

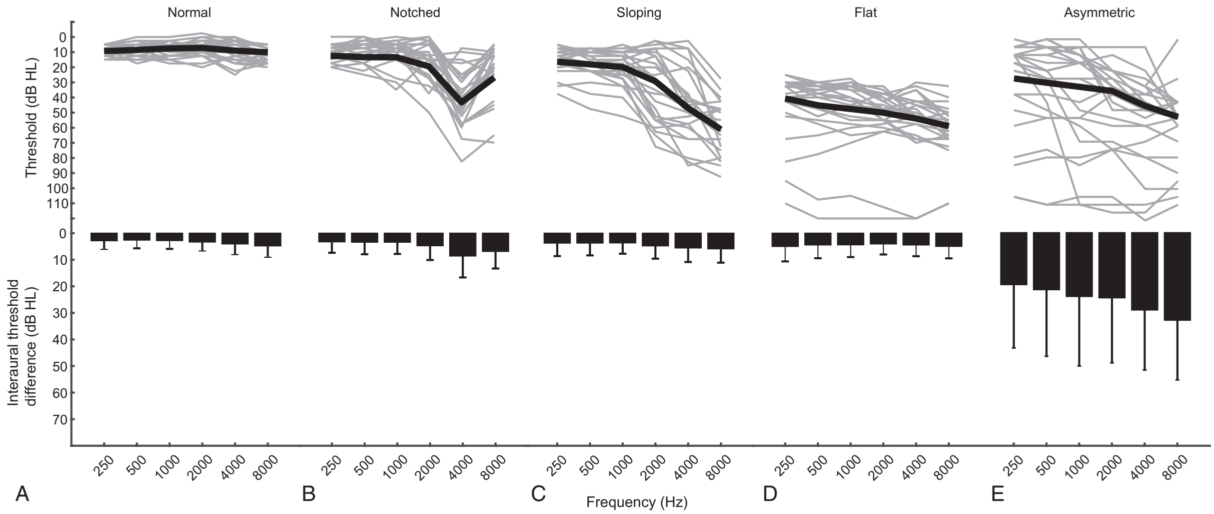

FIG. 3. Audiometric thresholds for patients with tinnitus as a primary complaint (TPC), stratified by audiometric configuration. The top row shows average thresholds for each category (thick black line) across standard audiometric frequencies, and 25 randomly selected example audiograms (thin gray lines). Averaged bilateral thresholds are presented for *(A)* normal, *(B)* notched, *(C)* steeply sloping, and *(D)* flat configurations, while the poorer ear is plotted for *(E)* asymmetric. The bottom row shows the average (+ 1 *SD*) interaural threshold difference across standard audiometric frequencies for each configuration.

configuration analyses. Figure 3 (top row) shows the average thresholds of patients with TPC for each audiometric configuration (thick black line) along with 25 randomly selected examples of each profile. Notched hearing loss was most often centered around 4 kHz (Fig. 3B). As expected, relatively large interaural threshold differences distinguish asymmetric hearing loss from the other configurations (Fig. 3, bottom row).

Figure 4A shows the prevalence of each audiometric configuration as a function of age for the entire sample. Across all ages assessed in this study (18–80 yr), the prevalence of each audiometric configuration was as follows: normal hearing (43.66%), steeply sloping (34.28%), asymmetric (13.16%), notched (5.33%), and flat (3.56%). Unsurprisingly, the vast majority of young adults (age 20–39 yr) had normal hearing (83.81%) and the prevalence of normal hearing declined with age. Older adults (age 60–79 yr) had the highest prevalence of steeply sloping loss (65.12%).

Figure 4B shows the prevalence of TPC within each of the audiometric configurations and age groups plotted above in Figure 4A. Across all ages included in this study (18–80 yr), the prevalence of TPC within each audiometric configuration was as follows: notched loss (23.65%), steeply sloping (21.09%), normal (20.78%), asymmetric (17.85%), and flat (9.59%). This pattern of TPC as a function of audiometric configuration was similar across age groups.

A multiple logistic regression was performed to quantitatively assess the likelihood of reporting TPC as a function of audiometric configuration. Age and sex were included in the model to control for their known contributions to the probability of TPC. The set of predictors (configuration, age, sex) provided a significantly better fit than the null model, $\chi^2(6) = 273.38$, $p < 0.001$. Overall, results indicated that the likelihood of TPC was significantly influenced by hearing loss configuration ($\chi^2(4) = 131.2$, $p < 0.001$). Figure 5A shows the predicted probability of TPC for each of the five hearing loss configurations as a function of sex, holding age constant at the sample mean (52.78 yr). The probability of TPC was highest for notched and sloping losses, and lowest for flat losses. The predicted probability of TPC for normal and asymmetric configurations fell in-between. Notably, males reported TPC more often than females, irrespective of audiometric configuration.

These results suggest that patients with notched and high-frequency hearing losses are most likely to present with TPC at an initial hearing evaluation, whereas those with flat losses are the least likely to present with TPC. Although males are more likely to present with TPC than females, the pattern of predicted probabilities as a function of audiometric configuration is consistent across sexes. Figure 5B shows the predicted probability of TPC for males as a function of audiometric configuration and age. Evidently, the probability of TPC declines with age, but the pattern of TPC across audiometric configurations remains consistent throughout adulthood.

Associations Between Patient-reported Tinnitus Percept and Audiogram Shape

We performed an exploratory descriptive analysis of the association between patient-reported tinnitus quality and audiometric configuration. A subset (1,661 records) of the 10,532 TPC reports contained any patient quote. Of those 1,661 reports, 575 records were included in this exploratory analysis based on strict inclusion criteria (see *Methods*).

Figure 6 shows the prevalence of each primary tinnitus descriptor as a function of audiometric configuration.

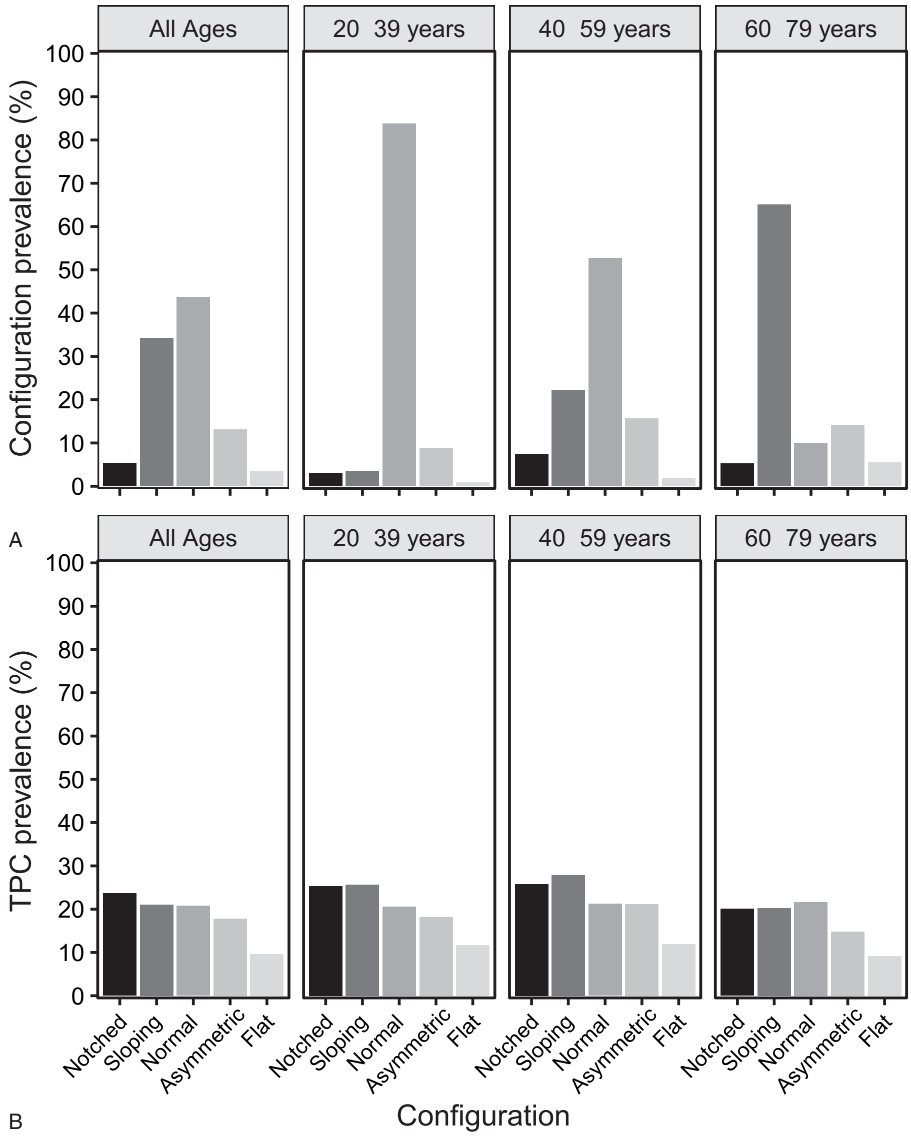

FIG. 4. *A,* Prevalence of each audiometric configuration within the entire sample, stratified by age group. *B,* Prevalence of tinnitus as a primary complaint (TPC) as a function of audiometric configuration, stratified by age group. The "All Ages" panels represent ages 18 through 80 years.

Patients with steeply sloping (n = 198), notched (n = 38), and normal hearing (n = 263) most often described tonal tinnitus percepts. Those with asymmetric configurations (n = 71) most often reported broadband tinnitus. Individuals with flat profiles (n = 5) most often reported either tonal or broadband qualities; however, data from the flat group should be interpreted with caution, as only five records were available. Across all audiometric profiles, periodic tinnitus was the least common descriptor.

DISCUSSION

These data extend upon previous epidemiologic studies of hospital-based populations that indicate age, sex, and hearing loss as predictors of tinnitus prevalence. Specifically, we demonstrate that high-frequency hearing loss is related to increased likelihood of TPC. Our findings also identify a considerable population of patients who have normal clinical audiograms but report TPC. Importantly, in this hospital-based population, younger, or middle-aged patients (aged 20–59 yr) are more likely to report TPC than older patients (aged 60–79 yr). We also demonstrate that audiometric configuration may relate to a patient's qualitative tinnitus description.

It must be emphasized that the present study did not seek to characterize all patients that experience tinnitus. Rather, we assessed the population of individuals who determined that their tinnitus was sufficiently bothersome to seek clinical evaluation. Differences between these populations help distinguish simple presence of tinnitus from bothersome tinnitus that drives an

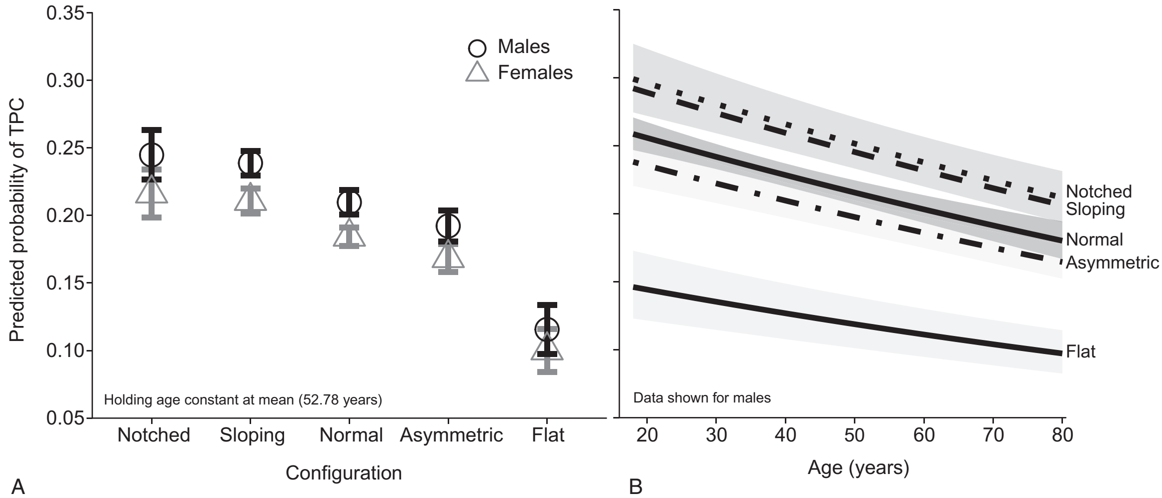

FIG. 5. Probability of reporting tinnitus as a primary complaint (TPC) predicted by multiple logistic regression. *A,* Predicted probability of reporting TPC as a function of audiometric configuration for both sexes, holding age constant at the sample mean (52.78 yr). *B,* Predicted probability of reporting TPC as a function of audiometric configuration and age, holding sex constant (data shown for males). Shaded regions represent 95% confidence intervals.

individual to seek professional assistance. Such distinctions are crucial in the absence of routine clinical quantification of tinnitus severity.

Tinnitus Prevalence in Community- and Hospital-based Populations

In the present study, males were more likely to present with TPC than females across most age groups, irrespective of audiometric configuration. This is consistent with tinnitus prevalence data from hospital-based populations (16), the general public (7), and veterans (5). It is often suggested that the preponderance of tinnitus in men compared with women may be due to sex differences in exposure to environmental and occupational hazards such as loud noise or neurotrauma (5,16).

We also demonstrate that TPC prevalence increases through middle age, and declines after approximately age 60 years. Although changes in TPC prevalence with age were modest in this study, similar age trajectories in tinnitus self-report have been described previously (7,12,16). One interpretation is that tinnitus is superceded by other otolaryngologic disease in older adults as the primary reason for their visit, leaving open the question of how the absolute prevalence of tinnitus varies with age. This study focused on the first visit without evaluating long-term outcomes; future studies may wish to evaluate longitudinal changes in audiometric characteristics with consideration to a patient's primary complaint.

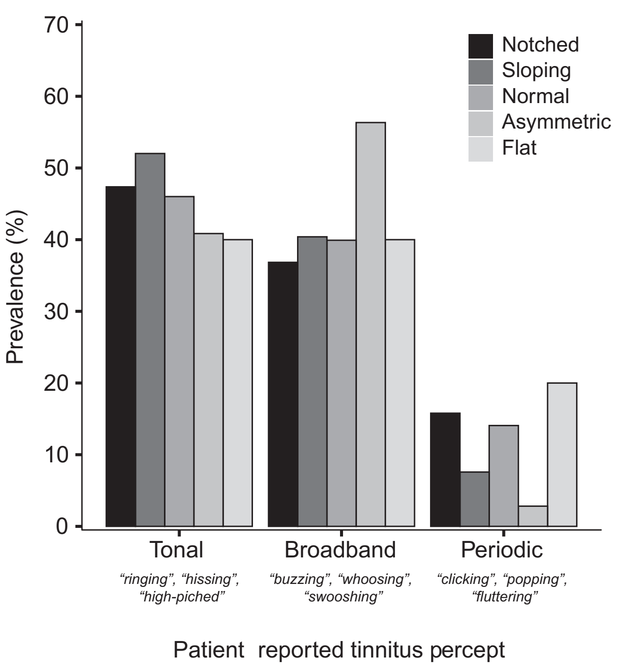

FIG. 6. Prevalence of patient-generated tinnitus descriptors as a function of audiometric configuration. The top three descriptors in each category are listed beneath the primary categories on the *x* axis. Note that the scale ranges from 0 to 70%.

Patients With Tinnitus and Normal Hearing or High-frequency Hearing Loss

We demonstrated that patients with high-frequency hearing loss (notched and steeply sloping) are most likely to report TPC, whereas those with broadband (i.e., flat) hearing loss are least likely to report TPC. A relatively large percentage of the patients with normal hearing also reported TPC (20.78%). Despite sex- and age-related differences in TPC prevalence, the relationship between TPC and audiometric configuration was consistent across sexes and age groups.

Clinical assessments of hearing status largely aim to characterize a patient's sensitivity to pure tone stimuli within a frequency range determined to be critical for speech understanding. However, the present results suggest that further evaluation is needed to determine whether evidence of hearing damage exists for patients with normal hearing accompanied by bothersome tinnitus. Additional testing may include extended high-frequency audiometry (i.e., beyond 8 kHz) or a host of other physiologic measures; however, it is important to note that none of these auditory measures reliably define the presence or absence of tinnitus.

Noise exposure can induce tinnitus in human listeners without causing permanent audiometric threshold shift (17,18). Evidence from several animal models demonstrates that synapses responsible for relaying information from auditory hair cells to spiral ganglion neurons are particularly vulnerable to noise exposure, resulting in reduced auditory processing capabilities (19–21). It is possible that patients with tinnitus who demonstrate normal hearing thresholds could have a loss of synaptic afferent connections that are not captured by the audiogram; however, there is no definitive noninvasive test for cochlear synaptopathy in humans (22). Further research is needed to determine how best to evaluate synaptopathy clinically and whether primary cochlear afferent degeneration is related to tinnitus.

Moreover, work from human subjects and animal models demonstrates that sharp decreases in hearing sensitivity across frequency, as in steeply sloping or notched configurations, are linked to tinnitus perception in the area of diminished hearing sensitivity (10,11,23,24). Peripheral damage to the cochlea is known to drive expanded representation in the topographic map of the auditory cortex due to frequency-specific auditory deprivation (25). Central auditory regions compensate for a loss of afferent input from the cochlea through a combination of neural disinhibition and neural sensitization, which are understood to produce a hyper-excitable state linked to the perception of phantom auditory events (17,23,26–35). Consistent with these reports, the present study determined that patients with high-frequency hearing loss are most likely to report TPC.

Patients With Tinnitus and Broadband Hearing Loss

The present study demonstrates that individuals with flat hearing loss are relatively unlikely to complain of bothersome tinnitus. In general, flat hearing loss is considered an aging auditory phenotype without history of substantial noise exposure (36). Tinnitus, however, is often associated with insults such as noise exposure (37) or ototoxicity (38), which, in turn, are associated with high frequency hearing impairment.

In this dataset, patients with asymmetric configurations did not report TPC as often as those with steeply sloping, notched, or normal hearing. Asymmetric or unilateral sensorineural loss can be acquired as an adult due to underlying etiologies like vestibular schwannoma (39) or sudden sensorineural hearing loss (40), or from a host of childhood etiologies (41,42). While approximately half of patients with idiopathic sudden sensorineural hearing loss also present with tinnitus (43,44), it is presumed that adults with sudden hearing loss are more likely to report reduced hearing as a primary complaint. Likewise, it is possible that adults with childhood-onset asymmetric hearing loss are not as bothered by tinnitus as someone with adult-onset hearing impairment. Research on longitudinal outcomes of children with asymmetric hearing loss and tinnitus is needed.

Limitations of This Study

Retrospective study designs introduce a similar set of limitations, caveats, and provisos linked to potential uncertainties about data uniformity. Although audiogram measurement methodologies at our clinic were standardized throughout this period, the clinical records were obtained by several audiologists over a 16-year span, with potential for differing and evolving habits in recording TPC and associated percepts. Further, it is likely that this study underreports the number of hospital-based patients with tinnitus, as we only highlighted patients that stated tinnitus was the reason for their visit. In other words, it is likely that some fraction of patients in the comparison group also had tinnitus, even if it was not their primary complaint.

Clinical standards regarding measurement of interoctave frequencies (e.g., 3 and 6 kHz) and extended high frequencies (beyond 8 kHz) are evolving. Due to limited frequency sampling, our study likely underestimates the number of patients with tinnitus who demonstrate a notched audiogram. Had extended high frequencies been tested, it is also likely that some patients may have been classified differently. Clinicians should consider the importance of measuring interoctave and extended high frequencies for patients with tinnitus, particularly when searching for evidence of hearing loss. Moreover, qualitative tinnitus matching was not performed, and no questionnaires for tinnitus-related complaints or quality of life were available. Future research should include questionnaires and tinnitus matching data to elucidate finer associations between audiometric configuration and tinnitus perception.

CONCLUSIONS

The present study demonstrates that approximately 20% of adults who arrive at a hospital for initial hearing evaluation report tinnitus as their primary reason for visit, with the greatest prevalence of TPC found among middle-aged men. The probability of bothersome tinnitus is nearly doubled in patients with abrupt high-frequency threshold elevation compared with those with broadband hearing loss, independent of sex and age. Patients with high-frequency hearing loss often report tonal tinnitus percepts, whereas those with broadband losses typically report broadband tinnitus quality. These patterns suggest that tinnitus arises from sharp discontinuities in peripheral afferent innervation and cochlear amplification, which may induce topographically restricted changes in the central pathway linked to the reported bandwidth of tinnitus perception.

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