Published in final edited form as:

Ear Hear. 2009 December ; 30(6): 696–703. doi:10.1097/AUD.0b013e3181b1d418.

Notched Audiograms and Noise Exposure History in Older Adults

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Abstract

OBJECTIVE—Using data from a population-based cohort study, we compared four published algorithms for identifying notched audiograms, along with how their resulting classifications compare with noise exposure history.

DESIGN—Four algorithms: 1) Coles, Lutman & Buffin (2000), 2) McBride & Williams (2001), 3) Dobie & Rabinowitz (2002), and 4) Hoffman et al. (2006) were used to identify notched audiograms. Audiometric evaluations were collected as part of the Epidemiology of Hearing Loss Study 10-year follow-up examinations, in Beaver Dam, WI (2003–2005, n=2395). Detailed noise exposure histories were collected by interview at the baseline examination (1993–95) and updated at subsequent visits. An extensive history of occupational noise exposure, participation in noisy hobbies, and firearm usage were used to evaluate consistency of the notch classifications with history of noise exposure.

RESULTS—The prevalence of notched audiograms varied greatly by definition (31.7%, 25.9%, 47.2%, and 11.7% for methods 1, 2, 3, and 4, respectively). In this cohort, a history of noise exposure was common (56.2% for occupational noise, 71.7% for noisy hobbies, 13.4% for firearms, 81.2% for any of these three sources). Among participants with a notched audiogram, almost one third did not have a history of occupational noise exposure (31.4%, 33.0%, 32.5%, and 28.1% for methods 1, 2, 3, and 4, respectively) and approximately 11% did not have a history of exposure to any of the three sources of noise (11.5%, 13.6%, 10.3%, and 7.6%). Discordance was greater among women than men.

CONCLUSIONS—These results suggest that there is poor agreement across existing algorithms for audiometric notches. In addition, notches can occur in the absence of a positive noise history. In the absence of an objective consensus definition of a notched audiogram, and in light of the degree of discordance in women between noise history and notches by each of these algorithms, researchers should be cautious about classifying noise-induced hearing loss by notched audiograms.

Keywords

noise-induced hearing loss; diagnosis; notched audiogram

Introduction

Noise-induced hearing loss (NIHL), as opposed to acute acoustic trauma, can be defined as hearing loss that develops slowly over a long period of time (several years) as the result of exposure to continuous or intermittent loud noise (ACOEM, 2003). NIHL is a common type of sensorineural hearing loss. However, since multiple factors can contribute to hearing loss, the exact prevalence of NIHL is unknown.

Exposure to sufficiently loud occupational noise for extended periods of time, however, can increase the risk of developing NIHL. Many Americans are exposed to hazardous levels of noise in the workplace, especially in industries using noisy machinery, such as metalworking, stone cutting, woodcutting, transportation, agriculture and the military.

Non-occupational noise may also contribute to NIHL. Noisy recreational activities like woodworking, metalworking, or the use of power tools have been associated with high frequency hearing loss (Dalton et al, 2001). Motorcycle riding has also been associated with hearing loss (McCombe & Binnington, 1994; McCombe et al, 1995), as has the use of firearms during hunting or target shooting (Taylor & Williams, 1966; Prosser, Tartari, & Arslan, 1988; Nondahl et al, 2000).

People with NIHL have structural damage in their cochlea (Rabinowitz, 2000; ACOEM, 2003). The sensory cells in the basal portion of the cochlea concerned with the reception of sound at 3–6 kHz are more vulnerable to damage from noise than those tuned to lower and higher frequencies (Johnsson & Hawkins Jr, 1976). Thus the worsening of sound perception typically starts in the 3–6 kHz range for people with NIHL (Gallo & Glorig, 1964; McBride & Williams, 2001). This may be reflected in the audiogram as hearing thresholds that reach a maximum between 3–6 kHz and then return toward the normal level at higher frequencies, forming a noise notch. A notched audiogram, together with a positive history of noise exposure, has been gradually accepted as a clinical sign of NIHL (McBride & Williams, 2001).

However, there is little agreement about a formal definition of a notched audiogram. In the McBride & Williams (2001) study, three raters with experience assessing audiograms (an otolaryngologist, an audiometrician, and an occupational physician) were asked to inspect the audiograms of 634 individuals (one audiogram for each ear) and assess whether a notch was present in the audiogram of either ear: a notch which, if a suitable noise history were obtained, would be attributed to noise exposure in that person. Agreement between the raters was poor: Raters 1, 2 and 3 identified 26%, 49%, and 68% of the individuals as having a notched audiogram, respectively. Intraclass correlations between the ratings of pairs of raters ranged from 0.14 to 0.52. The poor agreement among the three raters indicated visual inspection of the audiograms was not a reliable method for identifying notches.

Several studies have suggested algorithms to more objectively define the presence of a notched audiogram (Kramer & Wood, 1982; West & Evans, 1990; Coles, Lutman & Buffin, 2000; McBride & Williams, 2001; Niskar et al, 2001; Dobie & Rabinowitz, 2002; Hoffman et al, 2006). Three of these (Kramer & Wood, 1982; West & Evans, 1990; Niskar et al, 2001) were carried out among children and young adults who typically have fewer competing factors contributing to the audiometric shape, thus making notches more easily recognized. Since the present study focused on older adults, these three studies were not considered further here. Validation studies as well as studies comparing algorithms among older adults are still needed. Consequently, the purpose of this study was to compare four algorithms for identifying audiometric notches (Coles, Lutman & Buffin (2000); McBride & Williams, 2001; Dobie & Rabinowitz, 2002; Hoffman et al, 2006) using data from a population-based cohort study of older adults.

Materials and Methods

The Epidemiology of Hearing Loss Study (EHLS) is a population-based study of hearing loss in adults 48–92 years of age (Cruickshanks et al, 1998). During 1987–88, residents of the city or township of Beaver Dam, Wisconsin who were 43–84 years of age ($n=5,924$) were identified through a private census and invited to participate in a study of age-related ocular disorders (The Beaver Dam Eye Study; 1988–90; $n=4,926$) (Klein et al, 1991). All those who participated in the baseline eye examination and were alive as of March 1, 1993 were eligible to participate in the hearing study (EHLS; $n=4,541$). Of those eligible, 3,753 (82.6%) participated, 42.3% of whom were male (Cruickshanks et al, 1998). The mean age of the cohort was 65.8 years.

A five-year follow-up examination was conducted from 1998 to 2000. Of 3407 eligible, 2800 participated (82.2%); 41.4% of the participants were male. The mean age at the five-year follow-up was 69.3 years.

A ten-year follow-up examination was conducted from 2003 to 2005. Of 2902 eligible, 2395 participated (82.5%); 41.0 percent of the participants were male. The mean age at the ten-year follow-up was 72.7 years (range 58–100 years). The EHLS was approved by the Human Subjects Committee of the University of Wisconsin-Madison. Informed consent was obtained from each participant at the beginning of the examinations. Hearing loss data used in the current analyses were obtained from the 10-year follow-up examination of the EHLS study.

The examination included a questionnaire about medical history as well as noise exposure. For history of occupational noise exposure, history of engaging in noisy hobbies, and history of recreational firearm exposure, information was gathered at the baseline examination (lifetime up to that time), and again at the 5-year follow-up examination (past year exposure) and 10-year follow-up examination (past year exposure), and combined into three cumulative exposure variables. A history of occupational noise exposure was considered present if the participants reported having had a full-time job at which they spoke in a raised voice or louder in order to be heard by another person two feet away; or having been a farmer and driven a tractor, at least half the time without a cab; or having participated in any of the following activities during military service: working as a pilot or crew member on an aircraft, working as a crew member on a tracked vehicle, working in an engine room aboard a ship, spending time on weapons ranges at least seven times a year, using grenades, mortars or shoulder-held grenade launchers, or using a weapons system requiring more than one person for operation (Popelka et al., 2000). Participants who reported doing carpentry/woodworking, metalworking, riding motorcycles or other noisy recreational vehicles, yard work with power tools, or using a chain saw at least once a month (on average) for a year were classified as having participated in noisy hobbies (Dalton et al, 2001). Finally, firearm use was defined as ever hunting (and firing their gun), or reporting target shooting at least once a month (on average) for a year (Nondahl et al, 2000).

Pure-tone air conduction audiometry was conducted to determine each participant's hearing threshold at 0.5, 1, 2, 3, 4, 6 and 8 kHz, and bone-conduction thresholds were determined at 0.5, 2 and 4 kHz. Audiometric testing was conducted in sound treated booths (Industrial Acoustics Company, Bronx, New York) using GSI-61 audiometers (Grason-Stadler, Madison, Wisconsin) equipped with TDH-50 earphones. Insert earphones (E-A-Rtone 3A; Aearo Company, Indianapolis, Indiana) and masking were used as necessary. People unable to travel to the clinic site (34 nursing home residents, 18 group home residents, and 129 others) were tested at their place of residence using a Beltone 112 portable audiometer (Beltone Electronics Corp., Glenview, Illinois). All audiometric equipment complied with American National Standards Institute standards (ANSI, 1996; ANSI, 2004). The pure-tone audiometric testing was done in accordance with American Speech-Language-Hearing Association guidelines

(ASHA, 1978). Ambient noise levels were routinely monitored at the clinic site at the Beaver Dam Community Hospital and were measured at each home or nursing home visit to ensure that testing conditions complied with American National Standards Institute standards (ANSI, 1999) over the frequency range tested. Audiometers were calibrated every six months.

Four algorithms were used to identify notched audiograms. Coles, Lutman & Buffin (2000) defined a high-frequency notch as “the hearing threshold level (HTL) at 3 and/or 4 and/or 6 kHz, after any due correction for earphone type, is at least 10 dB greater than at 1 or 2 kHz and at 6 or 8 kHz.” The McBride and Williams (2001) algorithm was based on narrow notches and wide notches in the audiograms. A narrow or V-shaped notch is one with only one frequency in the depth of the notch and a wide or U-shaped notch has more than one frequency in the depth the notch. They suggested “...the narrow notches should be at least 15 dB in depth and that broad notches should have a depth of 20 dB, with a recovery of at least 10 dB at the high end.” (To determine depth, comparison was made with the mean of the thresholds at the next lower and higher frequency.) In the current study, the presence of either a V-shaped or a U-shaped notch was sufficient for an audiogram to be classified as having a notch. Dobie and Rabinowitz (2002) defined a Notch Index (NI), which was calculated by deducting the mean of the thresholds of 2, 3 and 4 kHz from the mean of the thresholds of 1 and 8 kHz. $NI > 0$ dB may indicate the presence of a bulge or a notch. Although in that study a NI of -6 dB was the criterion that best classified audiograms from cases and non-cases of NIHL (judged by clinical experts), we used the more conservative cut-point of 0 dB for our analyses. In addition, for comparison purposes, we report results obtained when using a higher cut-point ($NI > 5$) to potentially improve accuracy (Dr. Robert Dobie, personal communication). Finally, Hoffman et al. (2006) defined a notch as present when “...any threshold at 3, 4 or 6 kHz exceeds by 15 decibels (dB) the average threshold in the low/middle frequencies, .5 and 1 kHz, and the threshold at 8 kHz is at least 5 dB better (lower) than the maximum threshold at 3, 4 or 6 kHz.”

In the current study, for the Coles, Lutman & Buffin (2000), McBride & Williams (2001) and Dobie and Rabinowitz (2002) algorithms, a person was considered to have a notched audiogram if a notch was identified on the audiogram of either ear. This facilitated person-level comparisons with history of noise exposure. The Hoffman et al. (2006) algorithm required a notch to be present on the audiograms of both ears in order for a person to be classified as having a notch; consequently the notch status of 23 participants with audiometric data from only one ear could not be determined with the Hoffman et al. algorithm. For convenience, the four algorithms will be referred to as the Coles, McBride, Dobie, and Hoffman algorithms in the text that follows.

Statistical analyses were carried out using the SAS System (SAS Institute, Inc., Gary, NC). Sex-specific differences in prevalence of noise exposure, prevalence of notched audiograms, and percent agreement were tested with the chi-square test for association. For some analyses, participants were divided into three age groups (58–69, 70–79, 80–100 years). Age group trends were tested with the Mantel-Haenszel test for trend. To assess the similarity of the four algorithms, tetrachoric correlations were calculated and then analyzed with principal components factor analysis. Multiple logistic regression models were used to assess the odds of having a notched audiogram (as classified by the four algorithms) associated with age, sex and the three sources of noise exposure.

Results

The prevalence of notched audiograms varied for the four algorithms (Table 1). Using the Dobie algorithm, 1019 (47.2%) participants were classified as having a notched audiogram, while the Coles, McBride and Hoffman algorithms resulted in lower prevalences of 31.7%, 25.9% and 11.7%, respectively. The prevalence of notched audiograms for men was about

twice that of women for the Coles, McBride and Dobie algorithms, with the difference being even greater for the Hoffman algorithm (Chi-square test, $p < 0.0001$ for each algorithm). Under the Dobie algorithm, the prevalence of notched audiograms was not associated with age, while for the Coles, McBride and Hoffman algorithms there was a decreasing prevalence of notches with age (Mantel-Haenszel test for trend, $p = .70$ for the Dobie algorithm, and $p < .0001$ for the Coles, McBride, and Hoffman algorithms). The prevalence of notched audiograms was 30.3% when using $NI > 5$, but the gender and age patterns remained unchanged (data not shown).

For three of the algorithms (Coles, McBride, and Dobie), participants were classified as having a notched audiogram if either ear met the notch criteria under consideration. Asymmetry in notch status between ears was fairly high, with 71.2% (Coles), 81.7% (McBride) and 47.2% (Dobie) of participants classified as having a notched audiogram based on only one ear with a notch. If these three algorithms had required both ears to have a notch in order for the person to be classified as having a notched audiogram (as did the Hoffman algorithm), the prevalence of notched audiograms would have decreased to 9.1% (Coles), 4.7% (McBride) and 24.9% (Dobie), closer to the 11.7% identified by the Hoffman algorithm.

Figure 1 illustrates the overlap in notch classifications among the 2136 participants who were classified by all four algorithms. The largest overlap between two algorithms occurred with the Dobie and Coles algorithms, where 523 participants were classified as having a notched audiogram by both algorithms. Three hundred eighty-eight participants were classified as having a notched audiogram with the Dobie algorithm but not the other three. In contrast, no participants were classified as having a notched audiogram by the Hoffman algorithm alone. Out of 1246 participants classified as having a notched audiogram by at least one of the algorithms, only 131 (10.5%) were classified as having a notched audiogram by all four algorithms. The audiograms of 890 participants were considered free of notches by all four algorithms, resulting in an overall rate of agreement of 47.8% $((131 + 890)/2136)$. Using $NI > 5$ improved overall agreement slightly to 56.7% $((115 + 1097)/2136)$.

In an attempt to assess which algorithms were most similar to one another, we calculated tetrachoric correlations for each of the six pairs of algorithms (Table 2). The correlation between the McBride and Dobie algorithms was lowest, while the highest correlation was between the Coles and Hoffman algorithms. The tetrachoric correlations were then analyzed with principal components factor analysis. A single factor (presumably a measure of “notchiness”) explained 72% of the variance. Although factor loadings were reasonably high for all four algorithms, the McBride and Dobie algorithms contributed somewhat less to the factor than the others. Using $NI > 5$ resulted in almost identical findings (data not shown).

In this cohort, noise exposure was common. As Table 3 shows, 56.2% of participants reported exposure to excessive noise at their workplace, 71.7% reported participating in noisy hobbies and 13.4% reported exposure to firearms. Overall, 81.2% reported having been exposed to at least one of the three sources of noise. Men were more likely to have been exposed to noise than women ($p < .0001$ for all four noise exposure comparisons).

Although not a focus of the present study, Receiver Operating Characteristic (ROC) curves were generated to determine the NI cut-point that would maximize sensitivity and specificity for each of the three types of noise exposure. The optimal cut points were > 2 , > 0 , and > -2 for firearms, occupational noise, and noisy hobbies, respectively.

Logistic regression models were used to assess the odds of having a notched audiogram associated with age, sex, and the three sources of noise. Table 4 shows the results of three models (overall, women, and men) for each of the four algorithms. Age was positively associated with the NI, but was negatively associated with notches for the other three

algorithms. Being male was consistently associated with higher odds of having a notched audiogram. With the Dobie algorithm, men were more likely than women to have notched audiograms (Odds Ratio (OR) = 4.36, 95% Confidence Interval (CI) = 3.45, 5.50), even after adjusting for the sources of noise exposure.

The three sources of noise exposure differed in their association with notched audiograms, depending on which algorithm was under consideration (Table 4). For example, occupational noise was most strongly associated with notches as defined by the Coles algorithm (OR = 1.34, 95% CI = 1.08, 1.66). Noisy hobbies were only significantly associated with notches as defined by the Dobie algorithm (OR = 1.29, 95% CI 1.02, 1.64), although the Hoffman algorithm also produced a suggestive but nonsignificant result (OR = 1.42, 95% CI 0.87, 2.30). Exposure to firearms was associated with notches as defined by both the Coles (OR = 1.36, 95% CI 1.03, 1.80) and the McBride (OR = 1.46, 95% CI = 1.10, 1.93) algorithms. Models that included only one source of noise exposure at a time (e.g., age, sex, occupational noise) demonstrated the same relations as the combined models, suggesting that collinearity did not significantly influence results of the combined models.

Gender-specific results are also shown in Table 4. For women, there was a significant association between having a history of noisy hobbies and having a notched audiogram as defined by the Dobie algorithm (OR = 1.44, 95% CI 1.12, 1.84). For men, occupational noise exposure was associated with having a notched audiogram as defined by the Coles algorithm (OR = 1.55, 95% CI 1.09, 2.21) and the Dobie algorithm (OR = 1.72, 95% CI 1.22, 2.44). Also for men, using firearms was associated with having a notched audiogram as defined by the Coles algorithm (OR = 1.37, 95% CI 1.03, 1.83) and the McBride algorithm (OR = 1.44, 95% CI 1.07, 1.94). Among men, there was no association between noisy hobbies and notches. Using NI > 5 yielded similar results (data not shown).

Table 5 shows the percent agreement between classification of notched audiograms and noise exposure. Agreement was considered present if participants either: 1) were classified as having a notched audiogram and reported a history of occupational noise exposure, or 2) were classified as not having a notched audiogram and did not report a history of occupational noise exposure.

Overall, percent agreement ranged from 47.3% to 58.8% for occupational noise, 36.2% to 58.5% for noisy hobbies, 58.5% to 80.5% for firearms. With the exception of firearms, percent agreement was highest for the Dobie algorithm, and lowest for the Hoffman algorithm. The opposite was true for firearms: percent agreement was lowest for the Dobie algorithm and highest for the Hoffman algorithm. Generally, agreement was higher for women than for men. Using NI > 5, overall agreement was similar for occupational noise (56.0%), somewhat lower for noisy hobbies (50.4%), and higher for firearms (71.1%) compared to using a cut point of > 0.

It was not uncommon for participants to be classified as having a notched audiogram by one or more of the algorithms but not report certain noise exposures (Table 6). For example, 31.4% of those who were classified as having a notched audiogram based on the Coles algorithm did not report occupational noise exposure, and 11.5% did not report any history of noise exposure. Similarly, 33.0%, 32.5%, and 28.1% of those classified as having a notched audiogram based on the McBride, Dobie and Hoffman algorithms, respectively, did not report occupational noise exposure, while 13.6%, 10.3%, and 7.6%, respectively, did not report any history of noise exposure.

This pattern was more common for women than men (Table 6; $p < 0.0001$ for all sex comparisons). Among men classified as having a notched audiogram, about 16% did not report occupational noise exposure (15.3%, 16.6%, 16.4%, and 17.5% for the Coles, McBride, Dobie,

and Hoffman algorithms, respectively), and less than 1% of men reported no noise exposure history (1.0%, 0.6%, 0.8% and 0.6% for the Coles, McBride, Dobie, and Hoffman algorithms, respectively). However, these percentages were much higher for women than for men. More than 50% of women classified as having a notched audiogram did not report a history of occupational noise exposure (54.0%, 55.8%, 59.1%, and 57.6% for the Coles, McBride, Dobie, and Hoffman algorithms, respectively), and more than 25% did not report any noise exposure (26.3%, 31.8%, 26.0%, and 27.3% for the Coles, McBride, Dobie, and Hoffman algorithms respectively). Using $NI > 5$ lowered the overall percentages not reporting each noise exposure by about 5% compared to using a cut point of > 0 .

Because of concerns about the potential impact of over-reporting of noise exposure due to our inclusive definitions, we repeated these analyses using more restrictive definitions for occupational noise exposure (ever holding a fulltime job where one had to speak in a raised voice or louder to be heard by a person two feet away, but excluding military exposure and tractor driving) and noisy hobbies (requiring 40 or more cumulative years of participation in any of the noisy hobbies). Percent agreement improved slightly (range across algorithms of 56.3–63.6% for occupational noise history and 63–64% for 40 or more years of noisy hobbies) with a corresponding increase in the percent of participants with notched audiograms who did not report noise exposure (from 11.5% to 30.7% for the Coles, from 13.6% to 30.8% for the McBride, from 10.3% to 30.7% for the Dobie, and from 7.6% to 26.5% for the Hoffman algorithms).

Discussion

This study compared four algorithms for identifying notched audiograms with each other and with reported history of noise exposure. There was significant disagreement in the prevalence of notched audiograms across the four algorithms. About half of participants (47.2%) were classified as having a notched audiogram by the Dobie algorithm, while the Coles, McBride and Hoffman algorithms resulted in lower prevalences of 31.7%, 25.9% and 11.7%, respectively.

The appropriate cut-point for the NI remains controversial. Dobie and Rabinowitz (2002) found a criterion of -6 dB resulted in the best agreement with consensus cases judged by clinical experts. More recently, Rabinowitz, et al. (2006) reported results from a small study ($n=58$) where 2 dB appeared to be the best criterion for classifying a set of audiograms consistently scored as notched or not notched by a panel of experts. In personnel communication, Dr. Dobie suggested that $NI > 5$ might improve accuracy. Using a NI cut point of > 5 instead of > 0 lowered the prevalence estimate from the Dobie algorithm to a level similar to that of Coles but did not resolve the lack of agreement across algorithms. Among those classified as having a notch by any of the algorithms (using $NI > 0$), only 10.5% were consistently classified as having notches. Using $NI > 5$, this proportion was similar (11.1%). ROC curves suggested that the optimal cut-points for the NI to maximize sensitivity and specificity ranged from -2 to 2 depending on the noise source, consistent with published reports (Dobie and Rabinowitz 2002; Rabinowitz et al., 2006). Regardless of the cut-point used for the NI there was substantial disagreement in the classification of notches across algorithms.

Our results suggest the need for a standardized notch definition. This would facilitate comparisons of research results across studies and be useful clinically when serial audiograms are not available to detect threshold shifts after noise exposure. Observational and experimental translational studies of NIHL would be greatly facilitated by a consensus, objective definition. A factor analysis of tetrachoric correlations suggested that both the Coles and the Hoffman algorithms may capture the concept of “notchiness” a little better than the other two algorithms.

Self-reported noise exposure was often associated with increased odds of having a notched audiogram, although some relations were not statistically significant. History of occupational noise and history of firearm usage were both significantly associated with increased odds of having a notched audiogram as defined by the Coles algorithm, suggesting that this algorithm may be slightly preferred for identifying notched audiograms resulting from these two major noise exposures.

In this paper, participants were classified as having a notched audiogram if either ear met the notch criteria when using the Coles, McBride and Dobie algorithms. This was done to facilitate a person-level comparison between being classified with “any” notch and their report of noise exposure. Yet asymmetry in notch status between ears was fairly high and may have inflated the prevalence estimates. Using a two-ear approach lowered the prevalence of notched audiograms by these three methods closer to the 11.7% identified by the Hoffman algorithm. However, the Hoffman approach is likely to underestimate the prevalence of NIHL because it is well known that one ear may have greater noise exposure, and therefore greater damage, than the other due to the location of the noise source.

Notched audiograms were sometimes identified with no accompanying report of significant noise exposure. While this was relatively infrequent among men (where few men did not report noise exposure), it was much more common among women, with more than 25% of women with notched audiograms not reporting any of the noise exposures, and more than 50% not reporting occupational noise exposure. Many studies of NIHL have focused on men (Brühl, Ivarsson, Toremalm, 1994; Prince, 2002; Hong, 2005; Rabinowitz et al, 2006) or were drawn from groups who were known to have significant noise exposure (Cooper & Owen, 1976; Brühl, Ivarsson, Toremalm, 1994; Rabinowitz et al, 2006), so findings about notched algorithms from those studies might not be applicable to a general population. The appearance of notches in the absence of reported noise exposure may reflect under-reporting of noise exposure in this study by women, suggest that exposure to noise below traditionally accepted standards for hazardous noise or from other unexplored noise sources may also cause notched audiograms, or suggest that non-noise exposures or other factors may contribute to notched audiograms.

In the current study, history of noise exposure was based on self-report, so it might be possible that participants in general underreported their noise exposure. The Epidemiology of Hearing Loss Study questionnaire included an extensive occupational noise history, probing for noise exposure in the current job, longest-held job, and any other jobs where the participant had to speak in raised voice or louder to be heard within two feet. To avoid misclassifying exposure due to farming, as some farmers may report only their non-farm jobs in the occupation history, separate farming questions were asked to detect noise exposure from tractors. Participants were asked if they had ever served in the military and about exposure to specific potentially noisy activities and duties during their service. In addition to any gun use while hunting, the firearms questions ascertained target shooting at least once a month for one year. Neither occupational nor firearms exposure classifications considered the use of hearing protective devices which may have attenuated any noise exposure. The hobby questions included woodworking, metalworking, use of chain saws, yard work with power tools and driving motorcycles and other noisy recreational vehicles. These hobbies have been shown in previous work to be associated with high-frequency hearing loss (Dalton et al, 2001). Again, attenuating effects from the use of hearing protection were not considered. While it is possible that infrequent hobby exposure (less than once a month for one year) may cause hearing damage, there is little evidence to support this idea. Tambs et al (2006) suggest that people who know they have a hearing loss may more often remember, or even falsely recall, exposure to noise than people with better hearing. Thus, it is likely that noise exposure variables in this study were biased

toward classifying people with infrequent, little, or no noise exposure as noise exposed rather than misclassifying noise exposed participants as unexposed.

To address this concern, we repeated analyses using stricter definitions for noise exposure at work and from hobbies. Percent agreements between these noise exposure indicators and notched audiograms improved slightly, as would be expected from reducing the number of people with no notches who were considered noise exposed compared to when the more inclusive definition was employed. However, there was a substantial increase in the percent of participants with notched audiograms who were now classified as having no history of noise exposure. Thus, the choice of an inclusive definition of potential exposure to noise had the intended effect of maximizing the number of people with notched audiograms who had positive noise histories. These results suggest that the choice of definition of noise exposure cannot completely explain the low agreement with notch definitions.

The high proportion of women reporting no noise exposure (original definition) may suggest that these questions incompletely capture important sources of leisure noise exposure in women but additional questions about more female-oriented exposures such as hair dryers, vacuums, and kitchen appliances did not demonstrate any association with high frequency hearing loss. (Dalton et al. 2001). These exposures are usually lower intensity and/or short duration and therefore theoretically less likely to be associated with cochlear damage. Alternatively, one might hypothesize that female ears are more sensitive to noise than male ears, but there is no evidence to support this notion. It appears the most likely explanation for the discordance between noise history and the presence of notched audiograms in women is that notched audiograms are an imperfect marker of NIHL.

It is possible that notches may occur because of other factors. Animal studies have suggested that there may be exogenous factors such as drugs, chemical agents, and smoking that may combine in an additive or synergistic manner with noise to influence one's susceptibility to NIHL, although there is not sufficient evidence to confirm this finding in humans (Committee on Noise-Induced Hearing Loss, 2006). The basal section of the cochlea most commonly associated with hearing loss in the 3–6 kHz range (Johnsson & Hawkins Jr, 1976) may also be more susceptible to environmental insults other than noise.

While the reliance on self-reported measures of noise exposure is a limitation of the study, the population-based design is a major strength. Participants were often unaware of their hearing impairment and results would not affect their employment or benefit status, minimizing the potential to over-report noise exposure. Hearing was measured with standardized techniques and algorithms were applied without knowledge of the reported noise history.

Conclusion

This study demonstrated significant disagreement among four algorithms for identifying notched audiograms. While the challenges of notch classification have been recognized, this study demonstrates that available algorithms may not perform as expected when applied in population-based studies. These results highlight the pressing need for a standardized notch definition to ensure study results are comparable and to enable studying preventive measures.

In addition, the presence of notched audiograms in the absence of positive noise exposure histories supports the idea that audiometric shape is not a clear indication of the underlying pathology or etiologic pathway. While this is generally accepted (NIH, 1990; McBride & Williams, 2001; ACOEM, 2003; Dobie, 2005), our findings suggest that non-noise factors may contribute to a notch in an audiogram.

Acknowledgments

This research was supported by National Institutes of Health grant AG1099 (KJC)

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Figure 1.

Overlap among four notch algorithms. Numbers within the ovals represent participants in the 10-year follow-up examination of the Epidemiology of Hearing Loss Study classified as having a notched audiogram by at least one of the algorithms, while the remaining 890 were not classified as having a notch by any of the algorithms. Overlapping regions are not proportional in size.

Prevalence of notched audiograms among participants in the 10-year follow-up examination of the Epidemiology of Hearing Loss Study.

Table 1

Group	Coles et al (n=2159)		McBride & Williams (n=2159)		Dobie & Rabinowitz (n=2159)		Hoffman et al (n=2136)	
	n	%	n	%	n	%	n	%
All	685	31.7	558	25.9	1019	47.2	249	11.7
Gender								
Female	285	22.8	233	18.6	384	30.7	66	5.3
Male	400	44.2	325	35.9	635	70.1	183	20.4
Age Group								
58–69 yrs	380	38.0	312	31.2	456	45.7	139	14.0
70–79 yrs	212	30.6	167	24.1	351	50.7	80	11.7
80–100 yrs	93	19.9	79	16.9	212	45.4	30	6.5

Table 2
Results from principal components factor analyses of tetrachoric correlation matrices

Algorithm	Tetrachoric Correlations				Factor Analysis		
	Coles	McBride	Dobie	Hoffman	Factor Loadings	Variance Explained	
Coles	1.0000				0.92905	0.7232	
McBride	0.7441	1.0000			0.77866		
Dobie	0.6137	0.3673	1.0000		0.78519		
Hoffman	0.7763	0.5502	0.7015	1.0000	0.89831		

Table 3
Noise exposure among participants in the 10-year follow-up examination of the Epidemiology of Hearing Loss Study.

Type of Noise Exposure	Prevalence of Exposure (n, %)							
	All		Women		Men			
	n	%	n	%	n	%		
Occupational noise	1346	56.2	556	39.3	790	80.5		
Noisy hobbies	1716	71.7	758	53.6	958	97.7		
Firearms	322	13.4	18	1.3	304	31.0		
Any of above	1944	81.2	971	68.7	973	99.2		

Table 4

Results of logistic regression models assessing odds of having a notched audiogram as classified by several algorithms among participants in the 10-year follow-up examination of the Epidemiology of Hearing Loss Study. (Odds ratios and 95% confidence intervals.) Results from statistically significant noise exposures are boxed.

	Coles et al (n=2159)	McBride & Williams (n=2159)	Dobie & Rabinowitz (n=2159)	Hoffman et al (n=2136)
Models	OR (95%CI)	OR (95%CI)	OR (95%CI)	OR (95%CI)
Individual age- and sex-adjusted models				
Occupational noise	1.36 (1.10, 1.68)	1.18 (0.95, 1.48)	1.20 (0.98, 1.47)	1.08 (0.78, 1.49)
Noisy hobbies	1.06 (0.82, 1.38)	0.90 (0.68, 1.19)	1.32 (1.04, 1.67)	1.43 (0.88, 2.32)
Firearms	1.39 (1.06, 1.84)	1.47 (1.10, 1.94)	1.23 (0.91, 1.66)	1.13 (0.80, 1.59)
Multivariate models				
<u>All</u>				
Age (unit = 5 yrs)	0.82 (0.78, 0.87)	0.84 (0.79, 0.89)	1.06 (1.01, 1.12)	0.85 (0.78, 0.93)
Male sex	2.09 (1.64, 2.66)	2.08 (1.61, 2.69)	4.36 (3.45, 5.50)	3.64 (2.52, 5.28)
Occupational noise	1.34 (1.08, 1.66)	1.18 (0.94, 1.48)	1.17 (0.95, 1.43)	1.05 (0.76, 1.45)
Noisy hobbies	1.02 (0.78, 1.32)	0.87 (0.66, 1.15)	1.29 (1.02, 1.64)	1.42 (0.87, 2.30)
Firearms	1.36 (1.03, 1.80)	1.46 (1.10, 1.93)	1.21 (0.89, 1.63)	1.12 (0.79, 1.58)
<u>Women</u>				
Age (unit = 5 yrs)	0.80 (0.74, 0.87)	0.87 (0.80, 0.95)	1.11 (1.03, 1.18)	0.76 (0.65, 0.89)
Occupational noise	1.21 (0.92, 1.59)	1.15 (0.86, 1.53)	0.98 (0.77, 1.26)	0.90 (0.54, 1.51)
Noisy hobbies	1.09 (0.83, 1.43)	0.92 (0.69, 1.23)	1.44 (1.12, 1.84)	1.63 (0.95, 2.80)
Firearms	1.78 (0.62, 5.05)	1.38 (0.43, 4.36)	0.96 (0.33, 2.80)	2.13 (0.46, 9.85)
<u>Men</u>				
Age (unit = 5 yrs)	0.84 (0.77, 0.91)	0.81 (0.74, 0.88)	0.99 (0.91, 1.08)	0.89 (0.80, 0.99)
Occupational noise	1.55 (1.09, 2.21)	1.25 (0.87, 1.80)	1.72 (1.22, 2.44)	1.13 (0.74, 1.74)
Noisy hobbies	0.46 (0.18, 1.15)	0.59 (0.23, 1.51)	0.35 (0.10, 1.21)	0.65 (0.23, 1.84)
Firearms	1.37 (1.03, 1.83)	1.44 (1.07, 1.94)	1.18 (0.86, 1.63)	1.14 (0.80, 1.61)

Table 5

Percent agreement between notch classification and noise exposure among participants in the 10-year follow-up examination of the Epidemiology of Hearing Loss Study. Groups in **bold face** demonstrated a statistically significant difference by sex (Chi-Square test for association, $p < 0.05$).

Exposure	Coles et al (n=2159)		McBride & Williams (n=2159)		Dobie & Rabinowitz (n=2159)		Hoffman et al (n=2136)	
	n	%	n	%	n	%	n	%
<u>Occupational noise</u>								
All	1167	54.1	1102	51.0	1269	58.8	1010	47.3
Women	717	57.2	713	56.9	670	53.5	720	58.1
Men	450	49.7	389	42.9	599	66.1	290	32.3
<u>Noisy hobbies</u>								
All	1012	46.9	915	42.4	1264	58.5	773	36.2
Women	614	49.0	586	46.8	643	51.3	580	46.8
Men	398	43.9	329	36.3	621	68.5	193	21.5
<u>Firearms</u>								
All	1478	68.5	1557	72.1	1264	58.5	1720	80.5
Women	964	76.9	1012	80.8	863	68.9	1161	93.7
Men	514	56.3	545	60.2	401	44.3	559	62.3

Table 6

Among those classified as having a notched audiogram, percent without noise exposure. Data are from the 10-year follow-up examination of the Epidemiology of Hearing Loss Study

NIHL Algorithm	No occupational noise (%)	No noisy hobbies (%)	No firearms (%)	No noise exposure (%)
<u>Coles et al.</u>				
All	31.4	18.7	77.7	11.5
Women	54.0	41.1	97.9	26.3
Men	15.3	2.8	63.3	1.0
<u>McBride & Williams</u>				
All	33.0	20.3	76.9	13.6
Women	55.8	45.1	98.3	31.8
Men	16.6	2.5	61.5	0.6
<u>Dobie & Rabinowitz</u>				
All	32.5	16.6	79.1	10.3
Women	59.1	39.6	98.7	26.0
Men	16.4	2.7	67.2	0.8
<u>Hoffman et al</u>				
All	28.1	10.4	73.5	7.6
Women	57.6	31.8	97.0	27.3
Men	17.5	2.7	65.0	0.6