Some Observations on the Nature of the Audiometric 4000 Hz Notch: Data from 3430 Veterans

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Abstract

Background: Pure-tone, air-conduction audiograms notched at 4000 Hz have long been considered the signature configuration for noise-induced hearing loss even though there is an extensive literature that does not mesh with this simple explanation. There are many reports of notched audiograms from individuals with no history of noise exposure and, conversely, reports of audiograms with no notches from individuals with a history of noise exposure. Recent reports increasingly suggest that unilateral 4000 Hz notches are common. The prevalence of notched audiograms at 4000 Hz is dependent on the definition of the notch and the population under study.

Purpose: To examine the prevalence and characteristics of audiograms that are notched at 4000 Hz.

Research Design: Retrospective, descriptive.

Study Sample: The participants were 3430 veterans evaluated in the Audiology Clinic at the VA Medical Center, Mountain Home, Tennessee. The mean age was 62.3 yr.

Data Collection and Analyses: The data were collected in the course of a 60 min, routine audiological evaluation. In addition to pure-tone audiometry, a history, otoscopy, speech audiometry in quiet and in noise, and aural-acoustic immittance measures were included in the clinic protocol but were not evaluated in this report. A notch was defined when the 4000 Hz threshold minus the 2000 Hz threshold and the 4000 Hz threshold minus the 8000 Hz threshold both were ≥10 dB.

Results: Overall the mean LE (left ear) thresholds at 2000, 3000, and 4000 Hz were at hearing levels 2–3 dB higher than the hearing levels for the corresponding mean RE (right ear) thresholds; the differences were significant. A notched audiogram was observed in 40.6% of the participants in at least one ear with 15.4% having bilateral notches, 28.8% LE notches, and 27.1% RE notches. Unilateral 4000 Hz notches were almost twice as prevalent as bilateral 4000 Hz notches. Viewed as a function of age, notched audiograms were most common (~35% of the participants) in the 40 and 50 yr groups with a diminishing prevalence in the 60–80 yr groups. The mean notch depth at 4000 Hz was consistently 20–26 dB across the seven age groups. In comparison to the thresholds of the audiograms that were not notched, the thresholds of the audiograms with 4000 Hz notches (1) at 250–2000 Hz were at hearing levels 2–3 dB lower, (2) at 3000 and 4000 Hz were at hearing levels 8–17 dB higher, and (3) at 8000 Hz were at hearing levels 3–4 dB lower; the threshold differences were significant at all frequencies for both ears.

Conclusions: The data suggest that unilateral, 4000 Hz notched audiograms are as common or more common than bilateral notched audiograms and that unilateral notched audiograms are equally common for the LE and RE. The prevalence and characteristics of 4000 Hz notched audiograms in this veteran sample are similar to those observed in the population as a whole.

Key Words: 4000 Hz notched audiogram, audiogram, hearing loss

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Abbreviations: HFPTA = high-frequency pure-tone average (1000, 2000, and 4000 Hz); LE = left ear; PTA = pure-tone average (500,1000, and 2000 Hz); RE = right ear

Pure-tone audiograms with the 4000 Hz, air-conduction threshold at a hearing level higher than the hearing levels for the 2000 and 8000 Hz thresholds are signature audiograms for noise induced hearing loss, at least that has been the plurality of thinking for the past 80 yr or so (Fowler, 1928; Lehnhardt, 1967). This audiometric configuration is known as the "noise notch." In actuality, the notch occurs in the 3000–6000 Hz range, which typically is reflected at 4000 Hz on the octave-frequency audiogram (Gravendeel and Plomp, 1958; Murai, 1997; Rabinowitz et al, 2006). Over the years, earphone specific calibration issues may have introduced pseudo-dips in audiograms, especially at 6000 Hz (Robinson, 1988; Lutman and Qasem, 1998). Although episodes of noise exposure have long been linked to the high-frequency, notched audiogram, evidence from both animal and human studies questions the strict authenticity of noise as the lone culprit (Loch, 1943; Lehnhardt, 1967; Hunter-Duvar and Elliott, 1973; Cooper and Owen, 1976; Clark and Bohne, 1978; Sataloff, 1980; Humes, 1984; Henderson et al, 1993; Murai, 1997; Luxon, 1998; Committee on Noise-Induced Hearing Loss and Tinnitus Associated with Military Service from World War II to the Present, 2006; Talaska and Schacht, 2007; Nondahl et al, 2009). Indirect evidence comes from the reports of notched audiograms from individuals with no history of noise exposure and, conversely, from the reports of audiograms without notches from individuals with a history of noise exposure (Luxon, 1998; Osei-Lah and Yeoh, 2010). The relation between noise exposure and the notched audiogram is confounded by the fact that self-reported noise exposure histories necessarily involve so many variables that the histories are often of little help in establishing a causal relation between exposures to noise and notched audiograms (Gates et al, 1999; Nondahl et al, 2009). Additionally, identical noise exposures have differential effects on individual auditory systems (Taylor et al, 1965). The issue is complicated further when the two most common causes of hearing loss, noise exposure and aging, interact to produce an evolved audiogram with no high-frequency notch, which is ablated by the increasing hearing loss at 8000 Hz that is associated with aging (Gallo and Glorig, 1964; Gates et al, 1990; Gates et al, 2000; Dobie, 2008). Finally, and somewhat perplexing, unilateral high-frequency notches are common, perhaps more common than bilateral high-frequency notches (Gates et al, 1999; McBride and Williams, 2001a; Phillips et al, 2010; Osei-Lah and Yeoh, 2010). Lutman and Coles indicated that noise-induced hearing loss "sometimes appears to be considerably greater in one ear than the other for no apparent reason" (2009, p. 317). The purpose of this paper is to analyze the notches in the audiograms of a large sample of individuals complaining of hearing loss in an attempt to disentangle at least some of these notch-related issues including prevalence, age, and pure-tone hearing loss. Specifically the issue of unilateral versus bilateral notch prevalence is addressed. To the extent that notches result from noise exposure in the sound field, intuitively notches should be bilateral. A major question is whether the prevalence of unilateral notches is consistent with a simple noise-induced hypothesis.

Just after the development of the functional audiometer following World War I (see historical review by Mester and Stephens, 1984), the 4000 Hz notch was recognized as a unique characteristic of many audiograms. In an early paper, Fowler (1928) reported on a "marked dip" in the audiogram "most often about 3,000 to 4,000" (Hz). Fowler proposed four possible explanations for the dip, one of which was a defect in Corti's organ, which he seemed to favor. Drury (1929) suggested that a "luetic taint" (i.e., a trace of syphilis) might be responsible for the "dip at 4096." Ciocco (1932) obtained audiograms with the Western Electric 1-A audiometer from 1980 cases and noted that the "4096 dip" was often unilateral and was thought to be "the first sign of degenerative change in hearing." Further Ciocco observed that the 4096 dip was more common in males than in females, a fact he attributed to either a "true" sex difference or occupational factors that exposed the males to "injurious noises". In a human histological study, Wever (1942) examined 79 ears of individuals upon whom audiograms were available, including 50 ears that had a tonal dip at 4096 cycles. Wever reported that "it still appears possible that the 4,096 cycle dip is due to impaired functioning of the organ of Corti in the region of the lower basal half-turn" (1942, p. 186). At the same time, Rosenblith (1942) reported that 6000 Hz was the notch locus in a group of noise-exposed factory workers. In 1950 a study on humans by Davis et al observed that temporary threshold shift occurred a half an octave above the frequency of the exposure tone (500 Hz was the lowest exposure tone) and covered a range up to two octaves.

Noise exposure is thought to injure the cochlea in two ways (Clark and Bohne, 1999). First, exposure to sounds >140 dBA produces *acoustic trauma*, which occurs quickly and produces a permanent hearing loss. The insult is mechanical that results in scar tissue replacing many of the cochlear structures. Second, noise exposure to sounds in the 90–140 dBA range produces *noise-induced hearing loss* that is caused by metabolic damage to the cochlear structures, which is cumulative and

depends on the duration and level of the noise exposure. Initially, the noise-induced hearing loss is temporary, but with repeated exposures the hearing loss becomes permanent and progressively can affect more extended regions of the cochlea. In this paper, no differentiation is made between these two types/mechanisms of hearing loss, although all thresholds reported here reflect permanent, rather than temporary, threshold elevations.

The prevalence of high-frequency notched audiograms depends on several factors, the most basic of which are the definition of the notch and the population under study (Coles et al, 2000; McBride and Williams, 2001b; Dobie and Rabinowitz, 2002; Rabinowitz and Dobie, 2003; Hoffman et al, 2006). Of 1662 participants in the 1983–1985 Framingham study, 50.1% had audiometric notches at 4000 or 6000 Hz; by gender, 66% of the men and 40% of the women had notches (Gates et al, 1990). In the Beaver Dam Epidemiology of Hearing Loss Study, the prevalence of notched audiograms ranged from 11.7 to 47.2%, depending on which of four methods was used to calculate the notch (Nondahl et al, 2009). In a recent study of 149 consecutive outpatients, 62 (41.6%) had notched audiograms with only 3 of the participants reporting histories of noise exposure (Osei-Lah and Yeoh, 2010). The data from these studies suggest that the prevalence of notched audiograms is somewhere in the 25–50% range, again with a primary dependence on the definition of the notch.

During an analysis of audiometric data from several thousand veterans (Wilson, 2010), the mean audiograms were plotted by age in 10 yr increments from 20 through 89 yr; the mean left-ear audiograms from 3395 participants are depicted in Figure 1. The audiograms have the typical characteristics of such a plot with the range of mean thresholds across age in the low frequencies (19.1 dB at 250 Hz) substantially less than the range of mean thresholds across age in the higher frequencies (61.8 dB at 8000 Hz); this relation has been noted in a number of previous studies (Bunch, 1929; Glorig and Davis, 1961; Rosen et al, 1962; Robinson and Sutton, 1979; Chung et al, 1983; Brant and Fozard, 1990). The rates of change for these cross-sectional data over the 60 yr span were 0.3 dB/yr at 250 Hz and 1.0 dB/year at 8000 Hz, which compare favorably with the rates reported for longitudinal data over a shorter, older age span by Lee et al (2005) of 0.7 dB/yr and 1.2 dB/yr at the same frequencies. In Figure 1 for all age groups except the 80-yr-olds, the mean threshold at 4000 Hz was at a higher hearing level (poorer) than the mean threshold at 8000 Hz, peaking with a mean 7.6 dB difference in the 40-yr-old group. Although diminutive in the mean data, the difference in thresholds at the two highest frequencies prompted further study of the underlying dynamics that were thought to be related to averaging data from audiograms that were notched at 4000 Hz with the data from audiograms that were not notched at 4000 Hz.[1] The underlying assumption is that the notched and not-notched audiometric configurations reflect in part different cochlear pathophysiology.

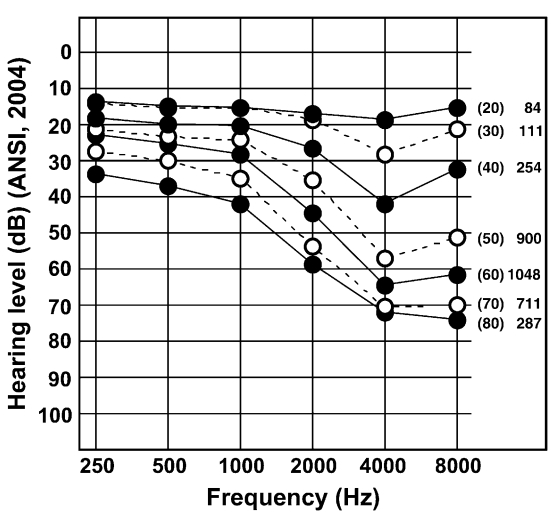

Figure 1. The mean right-ear, pure-tone audiograms for 3416 veterans in seven decade groups. The decade in parenthesis and the number of participants in each decade are indicated to the right of the audiogram.

In defining a high-frequency notch in a pure-tone audiogram, consideration must be given the test, retest characteristic of the psychometric instrument. In one of the original clinical studies of audiograms, Witting and Hughson reported, "an inherent error of slightly less than 5 dcb., [decibels] the error being a function of frequency with 1,024 cycles showing the smallest error" (1940, p. 268). (Note: this is the root of 1000 Hz being the first frequency tested in pure-tone audiometry.) More recently, Schmuziger et al (2004) reported that with insert earphones, 95–99% of 138 listeners had test, retest differences in pure-tone thresholds ≤5 dB over the 500–8000 Hz range. Because pure-tone testing typically is performed in 5 dB steps, and because 5 dB is a good test, retest estimate, it seems reasonable that the definition of a notch use 10 dB as a minimum difference between thresholds of the octave frequencies adjacent to 4000 Hz. For this study then, a notch at 4000 Hz was defined when the thresholds at 2000 and 8000 Hz were both minimally at hearing levels 10 dB lower than (better than) the threshold at 4000 Hz, which is consistent with the definition of an audiometric notch described by Coles et al (2000).

METHODS

Participants

The 3430 participants were consecutive patients at the Audiology Clinic, VA Medical Center, Mountain Home, Tennessee. The ages ranged from 20 to 89 yr (mean = 62.3 yr; SD = 12.8 yr). Gender was not

Table 1. Mean Pure-Tone Thresholds, PTA, HFPTA, and SDs for the REs of the 3384 Veterans Whose Audiograms Notched at 4000 Hz

			Frequency (Hz)								
Age decade	Mean Age (yr)	n	250	500	1000	2000	3000*	4000	8000	PTA	HFPTA
			Means (dB HL)								
20s	25.0	84	14.1	15.4	14.6	15.8	14.9	16.3	12.6	15.3	15.6
30s	35.1	111	16.0	17.3	16.0	18.3	28.1	25.8	22.2	17.2	20.0
40s	45.3	254	18.3	20.3	20.2	24.5	38.2	39.6	32.7	21.7	28.1
50s	55.9	895	21.2	23.1	23.8	32.9	49.0	53.4	49.1	26.7	36.7
60s	63.7	1043	23.3	25.5	27.7	41.9	58.4	63.1	60.9	31.7	44.2
70s	74.1	708	27.5	30.6	34.8	51.6	64.6	69.6	70.1	39.0	52.0
80s	82.6	289	33.3	36.1	41.1	55.8	65.4	71.7	75.3	44.8	56.0
20s–80s	62.2	3384	23.6	25.9	28.0	40.0	55.1	58.5	56.4	31.4	42.1
	SD of Age		SDs (dB)								
20s	2.4	84	7.8	8.4	9.9	10.2	8.5	14.1	18.5	8.7	9.3
30s	2.8	111	11.1	10.8	11.5	14.0	22.1	20.7	21.0	11.1	13.7
40s	2.7	254	12.5	12.6	13.8	15.8	22.0	22.1	23.3	12.9	14.6
50s	2.6	895	11.8	11.8	13.1	18.1	20.9	22.3	23.2	12.4	14.8
60s	2.9	1043	12.8	12.8	14.1	20.1	19.6	19.7	19.4	13.5	15.1
70s	2.7	708	13.5	14.0	15.5	17.9	16.6	16.6	15.8	13.8	13.8
80s	2.8	289	14.3	14.1	15.0	15.5	15.0	14.7	13.7	13.7	12.3
20s–80s	12.8	3384	13.4	13.6	15.5	20.9	21.6	23.3	24.7	15.0	17.3

*3000 Hz was tested in 70.8% of the participants.

recorded in the database; however, only 1.5% of the veterans evaluated during the study period were female.

Procedures

All data were collected during the course of a 60 min evaluation that consisted of a case history, otoscopic examination, aural-acoustic immittance measures, pure-tone audiometry, and speech audiometry both in quiet and in noise. The modified Hughson-Westlake method (Carhart and Jerger, 1959) was used with pure-tone audiometry with bone-conduction testing as indicated. The six octave frequencies were tested with interoctave frequencies tested when the thresholds at adjacent octaves differed by ≥20 dB. The 3000 Hz thresholds were available from 67–90% of the participants; however, there were so few 6000 Hz thresholds that they were not included in the database. Because of the incomplete interoctave threshold data, only the thresholds at 2000, 4000, and 8000 Hz were considered in the notch definition. Audiometers (Grason-Stadler, Model 61) with ER-3A insert earphones were used. The audiometers were calibrated biannually (ANSI, 2004) with intra- and interaudiometer calibration maintained ±1 dB over the period of data collection. Testing was conducted in double-wall sound booths.

RESULTS AND DISCUSSION

For a variety of reasons including ears with no responses at any octave frequencies, data validation issues, and so forth, data from 35 left ears (LE) and 46 right ears (RE) were eliminated from the original 3430 data set. Thus, 3395 LE and 3384 RE audiograms were analyzed. Again, the mean LE audiograms are depicted in Figure 1, and the mean RE thresholds for the seven-decade age intervals (and SDs) are listed in Table 1 along with the three-frequency pure-tone average (PTA; 500, 1000, and 2000 Hz) and the high-frequency pure-tone average (HFPTA; 1000, 2000, and 4000 Hz). Overall, the mean LE threshold minus RE threshold differences were −0.1 dB (250 Hz), −0.1 dB (500 Hz), 0.4 dB (1000 Hz), 2.5 dB (2000 Hz), 2.3 (3000 Hz), 2.0 dB (4000 Hz), and 0.8 dB (8000 Hz). Examination of the distributions of the thresholds at each frequency in each ear revealed unequal variances. Thus, a conservative approach was used to compare the data between ears; that is to say, a one-way ANOVA with an asymptotic F distribution (Welch) and a Bonferroni correction for multiple comparisons. Only the mean threshold differences between ears at 2000, 3000, and 4000 Hz were significant (adjusted $p < .007$) [2]. Lower (better) high-frequency thresholds in the RE than in the LE are a common characteristic of large scale studies including those that are population-based (Ward, 1957; Corso, 1963; Kannan and Lipscomb, 1974; Sutherland and Gasaway, 1978; Axelsson et al, 1981; Chung et al, 1983; Pirilä et al, 1991, 1992; Cox and Ford, 1995; Cruickshanks et al, 1998; Allen and Eddins, 2010).

Of the 3349 participants with LE and RE audiograms, 517 (15.4%) had notches at 4000 Hz in both ears.

Of the 3395 LE audiograms, 978 (28.8%) had 4000 Hz notches, whereas 917 of the 3384 RE audiograms (27.1%) had 4000 Hz notches. Recently, Krishnamurti (2009), using the same notch definition used in the current study, reported almost identical results in that 38 of 136 ears (27.9%) had 4000 Hz notches with more LE notches than RE notches. In a follow-up of the Framingham cohort, Gates et al (2000) observed slightly more notches in the LE than the RE, but the difference was not significant. Osei-Lah and Yeoh (2010) also observed more notches in the LE than in the RE. The 15.4% of the participants with bilateral notches in the present study is similar to the bilateral prevalence reported by Nondahl et al (2009), which ranged from 4.7 to 24.9% depending on the definition of a notch, and by Phillips et al (2010), which was 11.5%. Of the 517 participants with bilateral notches, the mean depths of the notches were 26.1 dB (LE) and 26.9 dB (RE) with 207 (40.0%) of the notches deeper in the LE, 253 (48.9%) deeper in the RE, and 57 (11.0%) of equal depth. The difference between ears in the mean depths of the 4000 Hz notches was not statistically significant. Collectively, 1378 participants (40.6%) had a notched audiogram in at least one ear, which is lower than the 50.1% reported by Gates et al (1990), the 47.2–71.2% reported by Nondahl et al, and 45% reported by Phillips et al, but almost identical to the 41% recently reported for males by Gates et al (2008), all of whom used slightly different definitions of an audiometric notch.

Of the 1378 participants with a notch in at least one ear, 517 participants (37.5%) had bilateral notches, and 861 participants (62.5%) had unilateral notches. Thus, unilateral 4000 Hz notches were almost twice as common as bilateral 4000 Hz notches, which is a relation reported in several recent studies. Data from Gates et al (1999, table 3) in a population-based study indicate similar results with 623 of 1186 participants (52.5%) having notched audiograms of which 371 (60%) were unilateral notches and 252 (40%) were bilateral notches. In a study of 5249 children 6–19 yr of age, Niskar et al (2001) found that 12.5% had noise-induced hearing loss with the majority having only one ear and one frequency affected; Green (2002), however, suggested that the estimate was "unexpectedly high." Osei-Lah and Yeoh (2010) reported a similar disparity with 75% of their participants having unilateral notches and 25% having bilateral notches. In a study of music 329 students, Phillips et al (2010) found 144 (43.8%) had a 4000 or 6000 Hz notch in at least one ear, of which 116 (80.6%) had unilateral notches and 28 (19.4%) had bilateral notches. Thus, there is mounting evidence that bilateral, notched audiograms are less common than unilateral, notched audiograms and that unilateral notched audiograms are equally common for the LE and RE. Typically in the veteran population, high-frequency notched audiograms have been thought to be more often associated with the LE than with the RE because right-handed individuals receive more direct noise exposure from a rifle muzzle in their LE than in their RE. With 90–95% of the population right-handed, this scenario would predict substantially more LE high-frequency hearing losses than RE hearing losses. This relation was not observed in the current study as the distribution of high-frequency notches was about equal for the ears.

Finally, of the notched audiograms, 3000 Hz thresholds were available on 834 LEs (85.3%) and 800 REs (87.2%). Of these, 69 LEs (8.3%) and 58 REs (7.3%) had thresholds at 3000 Hz that were at higher hearing levels than the thresholds at 4000 Hz. This is by no means an exhaustive examination of notch width and depth but an indication of the complexities that are probably involved in notched audiograms over the 3000–6000 Hz range.

The percentages of ears with notched audiograms at 4000 Hz are shown for the LE and RE in Figure 2 as a function of age group. The distributions for both ears appear normal with the peak reached in the 40 and 50 yr groups at around 35% of the ears. As age progresses above the 50 yr group, there is a steady decline in the percent of ears that exhibit notched audiograms. Recently, similar observations were made by Nondahl et al (2009) with three of their four notch definitions and by Osei-Lah and Yeoh (2010). Traditionally, the decrease in the prevalence of notched audiograms in the older population is attributed to the effects that age has on lowering the 8000 Hz threshold disproportionately to the lowering that occurs with the 4000 Hz threshold. Areas of the cochlea that have not been previously damaged (e.g., the region that mediates 8000 Hz) are more susceptible to the detrimental effects of aging than are areas of the cochlea that have received earlier damage (e.g., the region that mediates 4000 Hz). As succinctly stated by Gates et al, "hair cells lost from one cause

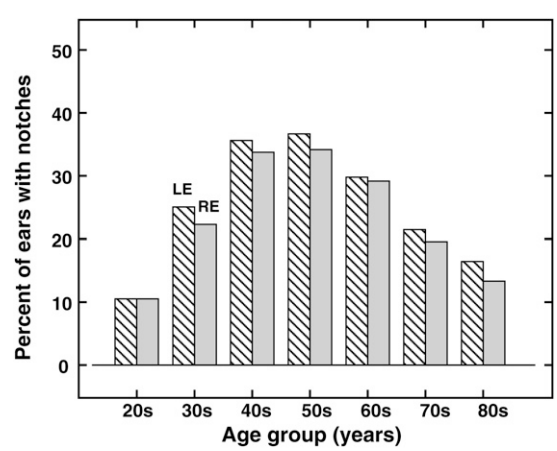

Figure 2. Histograms of the percent of LEs (stripes) and REs (shaded) with notches for seven age groups (LE, $n = 3395$; RE, $n = 3384$).

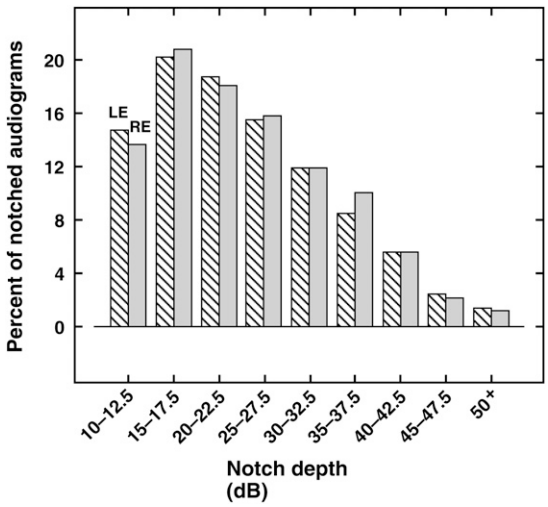

Figure 3. Histograms of the percent of LE (stripes) and RE (shaded) notched audiograms for the for nine notch depths (LE, $n = 3395$; RE, $n = 3384$).

cannot be 're-lost' for another cause.... the first cause is noise damage and the other cause is 'aging' of the ear (2000, p. 227). For the most part this attribute of the dynamic between the 4000 and 8000 Hz thresholds across age is based on cross-sectional data such as those presented here. Verification of this supposed threshold dynamic awaits longitudinal threshold data that can follow the evolvement of the high-frequency thresholds over several decades.

The notch depth, which was obtained by averaging the 4000 Hz threshold minus the 2000 Hz threshold and the 4000 Hz threshold minus the 8000 Hz threshold, was quantified in 2.5 dB steps. The histogram in Figure 3 shows the percent of LE (striped) and RE (shaded) notched audiograms in each of the nine notch-depth categories from 10 to 50^+ dB. The percentages of ears in each of the nine categories are similar in the first four categories, ranging from 15 to 20% with the mode at the 15 to 17.5 dB bin. The mean notch depths and SDs for the LEs and REs are listed by age group in Table 2. For both ears, the mean notch depths were consistently 22-26 dB across the 20- to 50 yr groups with a 1 to 2 dB/decade decrease in depth between the 50- and 80 yr groups. Throughout the groupings the SDs were 9–12 dB. From the Framingham Cohort, Gates et al (1999) reported a mean notch depth of 30 dB for 1186 participants. In another report, Gates et al (2000) observed that notch depth did not vary appreciably as a function of age. Although Osei-Lah and Yeoh (2010) used a notch definition almost identical to the one used in the current study, they reported that 72% of the notch depths were <20 dB, whereas in the current study, only 35% had notch depths <20 dB. The difference between findings is probably because Osei-Lah and Yeoh excluded participants who had a history of significant occupational noise, whereas the current study had no such exclusionary criteria.

The LE mean audiograms by age group and overall (i.e., all participants combined) are depicted in Figures 4 and 5 by the notched (filled circles) and not-notched (open circles) categories. The two figures illustrate different aspects of the relations among the data. In Figure 4 the audiograms are shown for each age group with the number in each group indicated in parenthesis, whereas in Figure 5 the audiograms are compiled for the notched (top panel) and not-notched (bottom panel) categories with the age group indicated in parenthesis with the number of participants adjacent. The mean RE audiograms by age group (and SDs) are listed in Table 3 for the 917 participants with notches and in Table 4 for the 2467 participants with no notches. Different degrees of hearing loss but similar audiometric patterns are observed across the seven age groups for both ears. Three general observations can be made from the overall data (i.e., the 20–80 yr grouping) in Figures 4 and 5 and in Tables 3 and 4, which are reflective of the data for the individual age groups. First, at 250–2000 Hz, the mean thresholds in the notched category are 2–3 dB better (i.e., at lower hearing levels) than the mean thresholds in the not-notched category. Second, at

Table 2. Number, Percent, and Notch Depth of Participants with Notched Audiograms at 4000 Hz

	Left ear					Right ear				
				Notch depth (dB)					Notch depth (dB)	
Age decade	Total n	n	%	Mean	SD	Total n	n	%	Mean	SD
20s	84	9	10.7	26.4	9.9	84	9	10.7	22.2	9.1
30s	111	28	25.2	23.0	10.3	111	25	22.5	22.5	11.9
40s	254	91	35.8	26.8	10.0	254	86	33.9	25.1	10.0
50s	900	332	36.9	26.3	10.4	895	309	34.5	25.5	10.3
60s	1048	315	30.1	23.8	9.7	1043	308	29.5	24.7	9.5
70s	711	155	21.8	21.0	9.1	708	141	19.9	22.6	8.6
80s	287	48	16.7	19.7	6.8	289	39	13.5	21.0	9.1
20s–80s	3395	978	28.8	24.3	10.8	3384	917	27.1	24.2	9.7

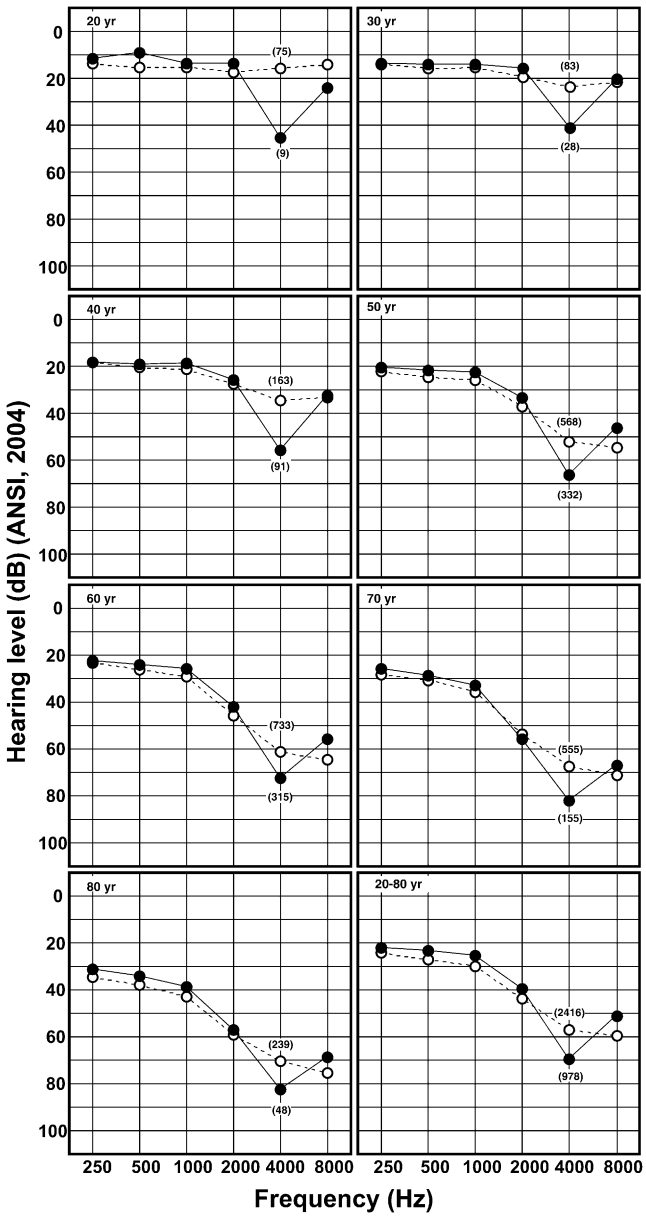

Figure 4. Mean LE notched (filled symbols) and not-notched (open symbols) audiograms for the seven age groups and for the age groups combined. The numbers in parenthesis indicate the number of participants in each group.

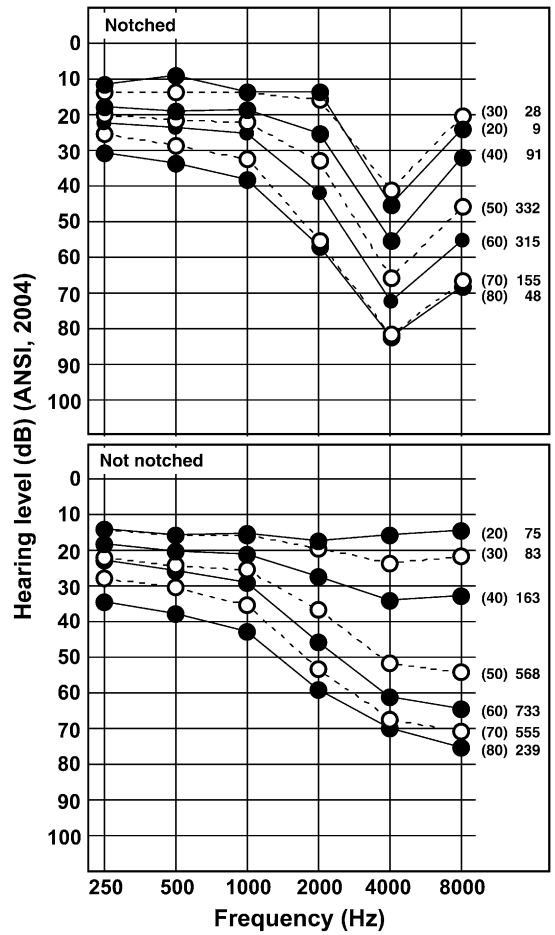

Figure 5. Mean LE notched (top panel) and not-notched (bottom panel) audiograms for the seven age groups (indicated in parentheses). The adjacent numbers are the number of participants in each group. ($n = 978$ notched; $n = 2416$ not notched)

3000 and 4000 Hz the mean thresholds in the notched category are 8–10 dB and 16–17 dB poorer (i.e., at higher hearing levels), respectively, than the mean thresholds in the not-notched category. Third, at 8000 Hz, except for the 20 yr group, the mean thresholds in the notched category are 3–4 dB better (i.e., at lower hearing levels) than the mean thresholds in the not-notched category. The exception at 8000 Hz was with the 20 yr group that had poorer mean thresholds for the notched category, which compels speculation that the mechanism that caused the 4000 Hz notches in the 20 yr group also caused some depression of the thresholds at 8000 Hz. The mean thresholds for each frequency were compared using multiple independent t-tests between the notched and not-notched groups. Given the significant unequal sample sizes between the notched and not-notched data sets, the t-test results for unequal variance were used and indicated that the seven aforementioned threshold differences were statistically significant (adjusted $p < .007$).[2]

In Figure 5 the 4000 Hz notch not only is perpetuated across the age groups but the mean thresholds are at progressively higher hearing levels across the age groups. These data suggest that the notched 4000 Hz threshold is not static as a function of age but, rather, it continues to decrease (become poorer) as a function of age. Because of the cross-sectional nature of the data, it is difficult to interpret these relations as the unknown factor is the number of participants who at one time were in the notched category but as they become older were categorized in the not-notched category because of threshold changes, particularly at 8000 Hz. Clarification of this issue awaits longitudinal data.

Table 3. Mean Pure-Tone Thresholds, PTA, HFPTA, and SDs for the REs of the 917 Veterans Whose Audiograms Notched at 4000 Hz

		Frequency (Hz)								
Age decade	n	250	500	1000	2000	3000*	4000	8000	PTA	HFPTA
		Means (dB HL)								
20s	9	11.1	11.7	8.9	8.3	14.0	33.9	15.0	9.6	17.0
30s	25	12.8	15.2	14.0	18.0	37.5	40.6	18.2	15.7	24.2
40s	86	17.7	19.5	18.4	22.4	42.8	51.9	31.3	20.1	30.9
50s	309	20.3	22.0	22.4	31.6	53.2	63.1	43.8	25.6	39.1
60s	308	22.1	23.8	25.7	40.6	63.9	72.7	55.3	30.0	46.4
70s	141	26.4	28.4	32.9	52.0	72.7	82.0	67.2	37.7	55.5
80s	39	31.0	32.2	37.2	56.5	72.2	84.1	69.7	42.5	59.3
20s–80s	917	21.8	23.5	25.0	37.4	59.1	68.2	50.2	28.7	43.5
		SDs (dB)								
20s	9	7.4	6.6	7.4	7.5	11.9	17.5	19.4	5.2	7.2
30s	25	7.5	6.7	8.4	16.2	26.9	22.1	19.8	9.4	14.2
40s	86	10.0	10.5	11.1	12.2	19.8	17.6	19.1	10.0	11.0
50s	309	11.1	10.8	12.0	16.3	20.8	19.1	21.9	11.4	12.7
60s	308	12.5	12.6	13.7	19.4	19.5	17.1	20.2	13.2	14.1
70s	141	12.8	13.3	15.0	19.1	16.2	15.9	16.9	13.5	13.8
80s	39	13.8	15.3	17.1	19.9	20.7	16.3	15.3	15.9	14.8
20s–80s	917	12.3	12.4	14.1	20.3	22.1	20.7	23.6	13.8	15.8

*3000 Hz was tested in 87.2% of the participants.

Finally, the data in Figures 4 and 5 directly address the question that triggered this study of audiograms, that is, why in a sample of 3395 participants was the mean threshold at 4000 Hz at a higher hearing level than the mean threshold at 8000 Hz? The mean audiograms in Figures 4 and 5 clearly indicate that the diminutive notch observed in the overall mean audiogram (Fig. 1) was the result of averaging audiograms that were notched with audiograms that were not notched. In fact, notched audiograms were in the minority. Although the mean notch depth was sizable, typically 20–25 dB, the notched audiograms constituted

Table 4. Mean Pure-Tone Thresholds, PTA, HFPTA, and SDs for the REs of the 2467 Veterans Whose Audiograms Did Not Contain a Notch at 4000 Hz

		Frequency (Hz)								
Age decade	n	250	500	1000	2000	3000*	4000	8000	PTA	HFPTA
		Means (dB HL)								
20s	75	14.5	15.9	15.3	16.7	15.0	14.2	12.3	16.0	15.4
30s	86	17.0	17.9	16.6	18.4	23.4	21.4	23.4	17.6	18.7
40s	168	18.7	20.8	21.1	25.6	34.3	33.3	33.4	22.5	26.7
50s	586	21.6	23.7	24.5	33.6	46.1	48.3	51.9	27.3	35.4
60s	736	23.8	26.3	28.5	42.5	55.3	59.2	63.3	32.4	43.2
70s	568	27.8	31.1	35.3	51.5	62.0	66.6	70.8	39.2	50.9
80s	250	33.6	37.8	41.7	55.7	64.2	69.7	76.2	45.2	55.5
20s–80s	2467	24.3	26.8	29.1	41.0	53.1	54.9	58.6	32.4	41.6
		SDs (dB)								
20s	75	7.9	8.5	10.0	10.2	8.1	12.2	18.5	8.8	9.5
30s	86	11.8	11.7	12.2	13.4	18.0	18.2	21.3	11.5	13.4
40s	168	13.6	13.5	15.0	17.2	23.1	21.5	25.2	14.1	16.0
50s	586	12.2	12.2	13.6	18.9	20.5	22.1	23.4	13.0	15.7
60s	736	12.9	12.9	14.2	20.4	19.0	19.4	18.7	13.6	15.5
70s	568	13.6	14.1	15.6	17.5	15.9	15.3	15.5	14.0	13.9
80s	250	14.4	21.7	14.6	14.7	13.4	13.4	13.2	13.3	11.9
20s–80s	2467	13.7	14.0	15.8	21.1	21.1	23.2	24.7	15.3	17.8

*3000 Hz was tested in 65% of the participants.

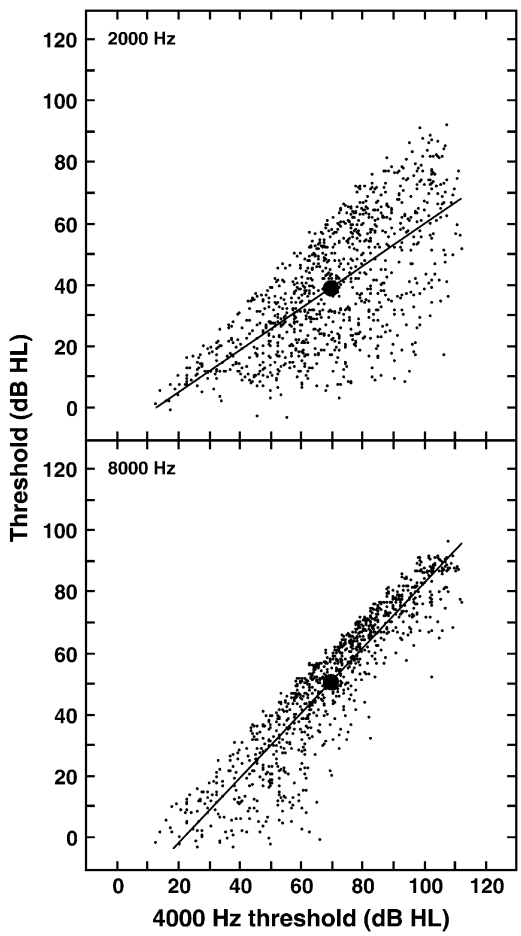

Figure 6. Bivariate plots of the 978 individual LE thresholds for 4000 Hz (abscissa) versus 2000 Hz (ordinate, top panel) and 8000 Hz (ordinate, bottom panel). The large symbols are the mean datum points, and the lines through the datum points are linear regressions fit to the data.

<30% of the audiograms, which minimized but did not obscure the 4000 Hz notches observed in the mean audiograms in Figure 1. The data in Figure 6 are bivariate plots of the 978, LE, 4000 Hz thresholds (abscissa) versus (1) the LE, 2000 Hz thresholds (ordinate, top panel), and (2) the LE, 8000 Hz thresholds (ordinate, bottom panel). For graphic clarity, the individual data were jittered using a random, additive algorithm that ranged from 2.5 to −2.5 in 0.5 steps. The 2000 and 4000 Hz data are much more variable than the 8000 and 4000 Hz data, a relation that is reflected in the respective R^2 values of 0.47 and 0.84 from the linear regressions and the slopes of the regressions. The slope of the regression for the 2000 and 4000 Hz data are gradual (0.68 dB/dB), which indicates a somewhat random relation between the two thresholds. In contrast, the slope of the regression for the 8000 and 4000 Hz data approaches unity (1.05 dB/dB), which reflects a consistent and systematic difference between the two thresholds regardless of the degree of hearing loss. For the 4000 and 8000 Hz thresholds, the high correlation (>0.9) and the parallel progression of hearing loss across ages (unity slope) implies that similar mechanisms are involved with both thresholds, whereas the lower correlation and nonunity slope observed with the 2000 and 4000 Hz thresholds suggests dissimilar underlying mechanisms.

Lastly, the symmetry of the 4000 Hz notch was quantified as a ratio between the 4000 Hz threshold minus the 2000 Hz threshold and the 4000 Hz threshold minus the 8000 Hz threshold. As the results from both ears were nearly identical, only the LE data are presented. The ratios for the 978 participants ranged from 0.2 to 7.5 with a mode of 1. The mean ratio was 1.94 (SD = 1.3), meaning on average the 4000, 2000 Hz threshold difference was about twice the 4000, 8000 Hz threshold difference. The ratios were slightly smaller in the 20–40 yr groups (1.3 to 1.7) than in the four older groups (1.8 to 2.1), which reflected larger threshold differences between 2000 and 8000 Hz in the older groups than in the younger groups.

SUMMARY

Although 40.6% of the participants had a 4000 Hz notched audiogram in at least one ear, only 15.4% had bilateral notches, 28.8% had LE notches, and 27.1% had RE notches. On an individual participant basis, unilateral 4000 Hz notches were almost twice as common as bilateral 4000 Hz notches. Notched audiograms were most prevalent in the 40 and 50 yr groups (∼35%), after which prevalence progressively diminished across the 60–80 yr groups. The mean notch depth was stable at 22–26 dB for the 20–50 yr groups, but decreased 1 to 2 dB/decade across the 50–80 yr groups. The thresholds in the notched group (1) at 250 through 2000 Hz were 2–3 dB lower (better) than the thresholds from the not-notched group, (2) at 3000 and 4000 Hz were 8–17 dB higher (poorer) than the thresholds from the not-notched group, and (3) at 8000 Hz were 3–4 dB lower (better) than the thresholds from the not-notched group; the differences were significant at all frequencies for both ears. The ratio between the threshold differences at 2000 and 4000 Hz and at 4000 and 8000 Hz was used to quantify the notch symmetry. The ratio was slightly smaller in the three younger groups (1.3 to 1.7) than with the four older groups (1.8 to 2.1).

The prevalence and characteristics of the 4000 Hz notches observed in the current group of veterans was similar to the prevalence and characteristics of 4000 Hz notches reported for nonveteran groups in previous studies. The current data plus the plethora of data reviewed urge caution when interpreting the causal factors associated with an audiogram that is notched at 4000 Hz. Often 4000 Hz notches appear in audiograms

of individuals with no appreciable exposure to noise, and conversely, 4000 Hz notches are absent in audiograms of individuals with extensive exposure to noise. In some ways, 4000 Hz notches almost appear to be a random occurrence in that most notches are unilateral with an equal likelihood of occurrence in the LE or RE. If noise exposure occurs in a free- or sound-field environment and the ears of a given individual are not differentially sensitive to the effects of noise exposure, then both ears should be equally affected by the noise exposure. This is not the case as unilateral high-frequency notches appear to be more prevalent than bilateral notches with an equal distribution of high-frequency notches between ears.

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NOTES

1. To a lesser degree, the number of "no responses" at the limits of the audiometer output was thought to contribute to the notching that was observed in the mean data. For the right ears at 4000 and 8000 Hz, 22 and 195 "no responses," respectively, were recorded with the number of "no responses" in the remaining frequencies in the single digits. When 90 (dB HL) was substituted for the "no responses" at 8000 Hz, negligible changes were observed in the mean data, and further inquiry in this line of reasoning was abandoned.
2. Bonferroni correction was used to adjust the p-value based on the number of analyses.

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