

## Characteristics of the audiometric 4,000 Hz notch (744,553 veterans) and the 3,000, 4,000, and 6,000 Hz notches (539,932 veterans)

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**Abstract**—The purpose of this study was to examine the prevalence and characteristics of audiograms that are notched (1) at 4,000 Hz and (2) at 3,000, 4,000, and/or 6,000 Hz. Bilateral audiograms from 1,000,001 veterans were obtained from Department of Veterans Affairs archives; after “cleaning” algorithms were applied, 744,553 participants (mean age = 63.5 yr) were included in the 4,000 Hz notch analysis (group 1) and 539,932 participants (mean age = 62.2 yr) were included in the 3,000, 4,000, and/or 6,000 Hz notch analysis (group 2). A notch was defined when the threshold at the notch frequency (3,000, 4,000, or 6,000 Hz) minus the 2,000 Hz threshold and the threshold at the notch frequency minus the 8,000 Hz threshold both were greater than or equal to 10 dB. In group 1, 77.1% did not have a notch at 4,000 Hz. In group 2, 65.3% did not have a notch at 3,000, 4,000, or 6,000 Hz; 12.4% had bilateral notches, 11.7% had left ear notches, and 10.7% had right ear notches. The notches were about twice as deep on the low-frequency side of the notch than on the high-frequency side. The mean left ear and right ear notch depths were about the same (23 dB), with mode notch depths in the 15.0 to 17.5 dB range.

**Key words:** audiogram, bilateral, hearing loss, high-frequency, multisite, noise exposure, noise notch, notched audiogram, unilateral, veterans.

### INTRODUCTION

Air-conduction audiograms with 3,000, 4,000, and/or 6,000 Hz thresholds at higher hearing levels (HLs) than the adjacent 2,000 and 8,000 Hz thresholds are historically referred to as “notched audiograms.” Since the ini-

tial observations of the notched audiograms, noise exposure has been the designated causal factor [1–4].\* Evidence from more recent animal and human studies has led many investigators to question (1) whether or not noise exposure is the sole contributing factor to the notched audiogram and (2) the pathophysiology of noise-induced hearing loss [5–19]. Additionally, notched audiograms are reportedly associated with individuals who have no marked history of noise exposure; conversely, some individuals with a substantial history of noise exposure exhibit no evidence of a notched audiogram [14,20]. Intuitively, because noise exposure typically occurs in a

\*For a thorough review, see Wilson RH. Some observations on the nature of the audiometric 4000 Hz notch: data from 3430 veterans. *J Am Acad Audiol.* 2011;22(1):23–33.

**Abbreviations:** AU = *auris utraque*, DALC = Denver Acquisition and Logistics Center, EHLS = Epidemiology of Hearing Loss Study, HFPTA = high-frequency pure-tone average, HL = hearing level, LE = left ear, PTA = pure-tone average, QUA-SAR = Quality: Audiology and Speech Analysis and Reporting, RE = right ear, SD = standard deviation, VA = Department of Veterans Affairs, VistA = Veterans Health Information Systems and Technology Architecture.

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free or sound field, it is reasonable to expect both ears to be equally affected by noise incidences. This line of reasoning may not, in fact, be the case. Recent observations indicate that it is more common to observe unilateral high-frequency notches than bilateral high-frequency notches [20–23]. Support of this plethora of unilateral high-frequency notches was provided by Nondahl et al. [18, p. 698: Table 1], who evaluated audiometric notches of 2,159 participants in the Epidemiology of Hearing Loss Study (EHLS) at Beaver Dam, Wisconsin [24]. Nondahl et al. examined the high-frequency audiometric notches by using four algorithms [18, p. 698: Table 1], three of which required a notch be present in one or both ears [22,25–26], whereas the fourth required notches be present in both ears [27]. Using these strict definitions, 31.7 [25], 25.9 [22], 47.2 [26], and 11.7 percent [27] of the EHLS participants had notches. When the first three algorithms were adjusted to include a notch in both ears, the EHLS prevalences dropped to 9.1, 4.7, and 24.9 percent, respectively, which are in better agreement with the 11.7 percent prevalence reported for the Hoffman et al. algorithm [27]. The implication from these differing results is that there were more unilateral notches than bilateral notches in this population-based study.

A recent study from our laboratory substantiated this observation with data from 3,430 veterans [28]. In that study, notched audiograms at 4,000 Hz were observed in 41.1 percent of the participants in at least one ear, with 15.4 percent having bilateral notches (*auris utraque* [AU] or “both ears”), 13.8 percent having unilateral left ear (LE) notches, and 11.9 percent having unilateral right ear (RE) notches. (Note: These percentages are based on audiogram pairs that were not reported in the original report.) Thus, of the audiogram pairs with notches at 4,000 Hz, 37.5 percent had bilateral notches and 62.5 percent had unilateral notches.

Although the Wilson report had a sizable group of participants [28], previous multisite clinical trials in the Department of Veterans Affairs (VA) have revealed significant site differences based on geographic location. One example is a current VA Rehabilitation Research and Development-funded multisite study designed to look at the efficacy of computerized auditory training with more than 250 participants recruited from the (1) Bay Pines VA Healthcare System, Bay Pines, Florida; (2) James H. Quillen VA Medical Center, Mountain Home, Tennessee; and (3) Portland VA Medical Center, Portland, Oregon. Multiple significant baseline characteristic differences were found among sites. Specifically, participants

recruited from Bay Pines were significantly older with lower levels of education and reading ability than the participants recruited from the other two sites. There were no differences in pure-tone averages (PTAs); however, the participants from Bay Pines reported significantly fewer comorbidities and lower hearing handicap as measured by the Hearing Handicap Inventory for the Elderly [29]. Because of these recognized site differences, the current study purposed to extend the Wilson report [28] on veteran audiometric data to a substantially larger sample of participants from throughout the VA system and to include an examination of the interoctave frequencies that often are associated with high-frequency audiometric notches, viz., 3,000 and 6,000 Hz. Additionally, the larger sample enabled examination of several relationships among the audiometric-notch variables that were not possible to examine with the smaller data set. These goals were accomplished with audiometric data from 1,000,001 veterans who were entered through the Quality: Audiology and Speech Analysis and Reporting (QUASAR) Audiogram Module at VA facilities across the nation and archived at the Denver Acquisition and Logistics Center (DALC), which is the component of the VA through which hearing aids and associated devices are procured and dispensed to veterans. The QUASAR Audiogram Module, which is not restricted to patients receiving hearing aids, is a Windows-based graphical user interface, developed to simplify and enhance the entry, display, and use of information obtained during an audiometric examination of a patient, that can be accessed from the Computerized Patient Record System “Tools” menu. The QUASAR Audiogram Module includes components that reside on two systems (the local facility Veterans Health Information Systems and Technology Architecture [VistA] system and the DALC system) that use the VA VistA MailMan interface to pass data from the local site to the DALC database.

## METHODS

The data were collected by audiologists or audiology doctoral students during routine clinical evaluations. Earphone-specific information was not available in the DALC database, but a DALC survey indicated that insert earphones were used in a little over half the evaluations. Reports from a sampling of the VA clinics indicate that a majority use the modified Hughson-Westlake procedure to establish pure-tone thresholds [30].

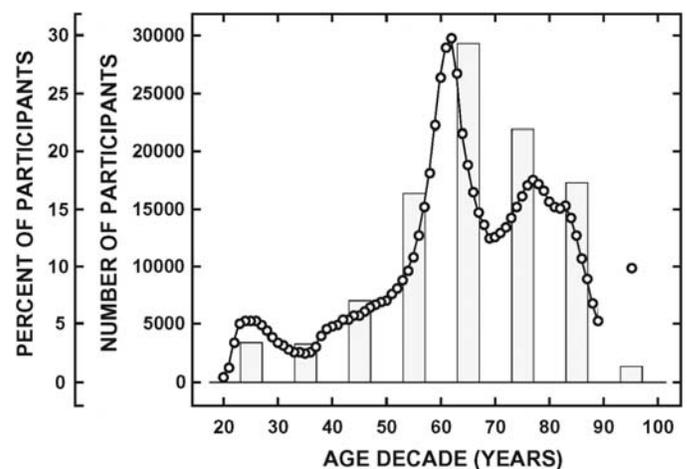
Throughout the analyses conducted in this study, the RE and LE audiograms of each participant were linked such that if the audiometric data from one ear did not meet the inclusion criteria, then that participant was excluded from the study. This coupling of the LE and RE audiograms of each participant (i.e., audiogram pairs) was necessary because of the prevalence issue of unilateral and bilateral notches being investigated. In addition to the pure-tone audiograms, the DALC repository provided the ages of the participants, except for those 90 yr and older. Because of privacy sensitivity issues, participants  $\geq 90$  yr are considered not by their individual ages but as a group age of 90 yr. Of the initial 1,000,001 audiometric data sets, 208 were  $< 20$  yr of age, which represented 0.02 percent of the participant pool. Because the age analyses planned were based on decade intervals, this small number of 18 and 19 yr-olds was eliminated from further analyses, leaving 999,793 veterans. A second exclusion criterion was a conductive component that was defined as an air-bone gap in either ear at 1,000 Hz of  $\geq 15$  dB. This criterion excluded 51,137 participants, leaving 948,656 participants or audiogram pairs. This article is descriptive in nature to illustrate audiometric configurations, specifically notched audiograms, with veteran sample sizes never before reported. Owing to the size of the data sets, trivial differences between groups become statistically significant. Given no hypotheses are being tested throughout this article, no inferential statistics are included.

The analyses of the data are descriptive from two points of view: age and depth of the audiometric notch. The analyses of the cross-sectional age data incorporated eight decade intervals from 20 to 29 yr to  $\geq 90$  yr. The audiometric notch was defined when the thresholds at 2,000 and 8,000 Hz were both minimally at HLs 10 dB lower than (better than) the threshold at the notch frequency of interest (3,000, 4,000, or 6,000 Hz), which is the same notch definition used in Wilson [28] and similar to the notch definition used by Coles et al. [25]. Although this rather liberal definition of an audiometric notch has been used previously and casts a wide net, in most of this report, the audiometric notches are analyzed in terms of nine notch depths from 10 dB to 50 dB<sup>+</sup> in 2.5 dB increments (10.0–12.5 dB, 15.0–17.5 dB, etc.), which enables examination of the data with respect to a multitude of notch-depth definitions.

Because the issue of unilateral and bilateral notches was paramount in this study, an additional inclusion crite-

ri- on was that each participant was required to have measurable thresholds in both ears at 2,000, 4,000, and 8,000 Hz, which were necessary to define a 4,000 Hz notch. Participants meeting these inclusion criteria were analyzed as group 1 (mean  $\pm$  standard deviation [SD] age = 63.5  $\pm$  16.1 yr). This criterion reduced the number of audiogram pairs to 744,553, which is about 75 percent of the original participant pool. The data in **Figure 1** depict the number of participants in each age year (circles) with a superimposed histogram that indicates the percentage of participants in each age decade. For the evaluation of the 3,000, 4,000, and 6,000 Hz notches, an additional criterion was that thresholds at 3,000 and 6,000 Hz also had to be measurable in both ears, which reduced the number of audiogram pairs to 539,932 for that particular analysis. The participants meeting these second inclusion criteria were analyzed as group 2 (mean  $\pm$  SD age = 62.2  $\pm$  16.3 yr).

Finally, the DALC database provided no indications of the types, amounts, and durations of noise exposure experienced by each participant, which precluded any examination of the possible relations between noise exposure and the pure-tone audiogram. It has long been assumed that military personnel experience more noise exposure than nonmilitary individuals. The implication of this assumption, therefore, has been that military personnel exhibit more hearing loss than nonmilitary individuals. Recent data from the EHLS [24] indicate that, on average, the pure-tone thresholds of male military veterans are not different from



**Figure 1.** Number of participants in each age year (circles) and histogram of percentage of participants in each of eight age decades.  $n = 744,553$  participants.

the thresholds of their male civilian counterparts [31]. The data from 995 veterans in that study also indicated that 72.1 percent of the veterans were not involved in the front-line or combat support activities where most noise exposure would be expected to occur; the DALC database should be characterized by similar distributions.

## RESULTS

The analyses and presentations of the data for group 1 and group 2 follow similar patterns, with each using three subheadings, viz., notch prevalence, notch depth, and mean audiograms. First, for each of the two groupings, the mean overall LE and RE audiograms are presented for group 1 and group 2. Second, the data are presented for each age decade in terms of the percentage of participants with unnotched audiograms and the percentage with notched audiograms. The notched category then is parsed into the percentage of participants with unilateral LE, unilateral RE, and bilateral notches. Third, the number and percentage of participants with notched audiograms are presented for each age group and each ear along with measures of central tendency for the notch depths. Fourth, a comparison by ear and by age group of the percentage of unilateral and bilateral notched audiograms is presented. Fifth, for each age group and each ear, the mean threshold differences between 2,000 and 4,000 Hz and between 800 and 4,000 Hz are listed, from which a symmetry ratio of the notch is defined and described. Sixth, the percentages of notched LE and RE audiograms in each of the nine notch-depth categories are presented and then expanded into a presentation of the notched depth by ear and by age decade. Seventh, the percentage of unilateral and bilateral RE notches is presented for each of the nine notch-depth categories. Eighth, for the individuals with bilateral notches, the notch depth of the RE is compared with the notch depth of the LE. Finally, the mean RE audiograms for the unnotched, notched, and

unnotched-notched combined groupings are presented for each of the age groups and are recast to show the notched and unnotched mean audiograms as a function of the age group. For several of the presentation sections, the data for one ear are graphed, whereas the data from the other ear are tabularized.

### Group 1 (4,000 Hz Data)

The mean audiograms for the LE and RE of the 744,553 participants included in the analyses of the 4,000 Hz notch data are listed in **Table 1**. The mean audiograms reflect mild-to-moderate, high-frequency sensorineural hearing losses with mean three-frequency PTAs (500, 1,000, and 2,000 Hz) of 30.4 and 29.5 dB HL [32] (SD of 16.8 and 16.6 dB) for the LE and RE, respectively. The mean high-frequency PTAs (HFPTAs) (1,000, 2,000, and 4,000 Hz) were 41.5 and 40.0 dB HL for the LE and RE, respectively (both with SD of 19.0 dB). The mean threshold differences between ears at 250, 500, and 1,000 Hz are <0.5 dB. At 2,000 and 4,000 Hz, however, the mean RE thresholds were at HLs about 2 dB lower (better) than the mean LE thresholds at those frequencies. At 8,000 Hz, the mean RE threshold was 1.1 dB lower than the mean LE threshold. Almost identical relations were observed between the mean frequency-specific thresholds for the LEs and REs in our earlier study with 3,430 veterans [28]. A common characteristic of large-scale studies, including those that are population based, is lower (better) high-frequency thresholds in the RE than in the LE [24,33–42]. Finally, from the mean threshold data in **Table 1**, there is no evidence of an audiometric notch at 4,000 Hz, the reason for which will become apparent as the data analyses develop in the subsequent sections.

### Group 1 Notch Prevalence

The percentage of participants in each of the eight age decades having air-conduction audiograms with no 4,000

**Table 1.**

Mean  $\pm$  standard deviation (SD) left ear (LE) and right ear (RE) pure-tone air-conduction thresholds (decibels hearing level [32]) from 744,553 individuals between ages of 20 and 90+ yr (mean  $\pm$  SD age 63.5  $\pm$  16.1).

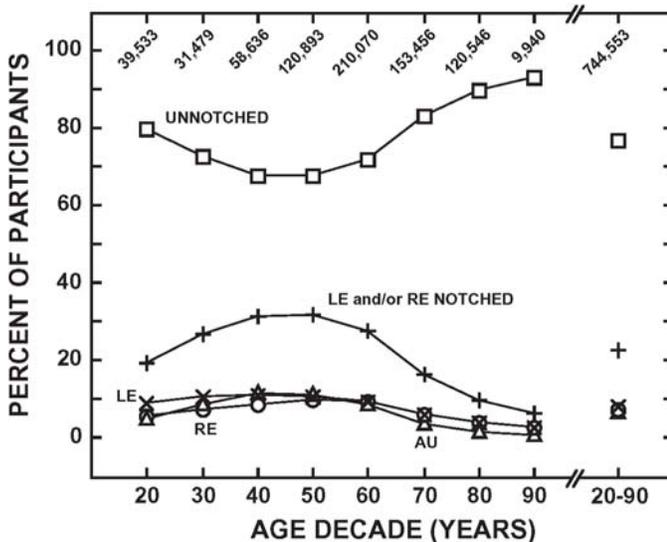
Ear	Frequency (Hz)					
	250	500	1,000	2,000	4,000	8,000
LE (Mean $\pm$ SD)	22.3 $\pm$ 14.3	23.7 $\pm$ 15.3	27.8 $\pm$ 17.7	39.6 $\pm$ 2.4	57.0 $\pm$ 23.9	60.5 $\pm$ 26.2
RE (Mean $\pm$ SD)	22.2 $\pm$ 14.1	23.5 $\pm$ 15.2	27.4 $\pm$ 17.3	37.5 $\pm$ 22.1	55.0 $\pm$ 24.5	59.4 $\pm$ 26.7
Difference (RE – LE)	-0.1	-0.2	-0.4	-2.1	-2.0	-1.1

Hz notches (squares) and with LE and/or RE 4,000 Hz notches (pluses) are shown in **Figure 2**. A breakdown of the LE and/or RE 4,000 Hz data also is provided with the percentage of participants with LE notches (Xs), RE notches (circles), and bilateral notches (AU, triangles) depicted. The number of participants in each age decade is listed on the upper abscissa. **Table 2** lists the numbers of participants by age and notch status category upon which the percentages in **Figure 2** are based. The majority of the 744,553 audiogram pairs (573,850 or 77.1%) did not have a 4,000 Hz notch in the air-conduction audiogram of either ear, which was the contributing factor to the mean unnotched audiograms in **Table 1**. Of the remaining 170,703 audiogram pairs with a 4,000 Hz notch in at least one ear (22.9%), 62,088 (8.3%) had a notch only in the LE, 56,884 (7.6%) had a notch only in the RE, and 51,731 (6.9%) had bilateral notches. Although the prevalence of notched audiograms is decreased in the current study (22.9%) in comparison with the Wilson study (41.1%) [28], the relation between the percentage of unilateral and bilateral notches observed in the earlier study is substanti-

ated in the current data. In the earlier study, 37.5 percent of the notched audiograms were bilateral, whereas 62.5 percent were unilateral. The corresponding numbers from the current study are similar, with 30.3 percent (51,731) having bilateral notches and 69.7 percent (118,972) having unilateral notches. The data indicate that unilateral 4,000 Hz notches are much more common than bilateral 4,000 Hz notches, with slightly more LE notches than RE notches. Data from other studies support the disparity between unilateral and bilateral notches. For example, Gates et al. indicated in a population-based study of 1,186 participants that 60 percent of the notches were unilateral, with the remaining 40 percent bilateral [21]. A higher ratio was reported by Osei-Lah and Yeoh [20], with 75 percent unilateral and 25 percent bilateral. Finally, depending on the notch definition, Nondahl et al. reported for the EHLS that 25.9 to 47.2 percent exhibited notched audiograms in at least one ear, with the prevalence dropping to 9.1 to 24.9 percent when notches in both ears were used in the definition of a notch [18].

As can be seen in **Figure 2**, the percentage of LE and/or RE notched audiograms (pluses) reaches a maximum in the 50 yr decade (32.1%), with declining numbers in the lower and higher decades. A similar observation was made in our earlier article in which the peak for each ear was in the 50 yr decade at 35 to 37 percent [28, p. 27: Figure 2]. For the unilateral LE and RE notch categories and the bilateral notch category, the percentage of participants is fairly constant at 9 to 11 percent between the 30 and 60 yr decade groups, declining rapidly thereafter to <3 percent with notches in the 90 yr decade. As others have indicated (e.g., Gates et al. [43]), the decline in the prevalence of notches as a function of age is attributable to aging effects on the auditory system that are reflected in increasingly higher (poorer) thresholds at 8,000 Hz that ultimately preclude the formation of a notch in that the 4,000 Hz minus 8,000 Hz threshold difference becomes <10 dB, progressing to a negative value.

The data in **Table 3** summarize by age decade the number of participants, the percentages of LE and RE notches at 4,000 Hz, and the mean notch depths in decibels that were obtained from the 744,553 veterans. The percentage of participants with 4,000 Hz notches increases for both the LEs and REs through the 40 and 50 yr decades (22%–23%), with a sharp decline thereafter through the 90 yr decade (4%). The prevalence and notch characteristics are remarkably similar for the LE and RE in each age decade. A consistent exception to this



**Figure 2.** Percentage of participants in each age group who had no 4,000 Hz audiometric notch (squares) or left ear (LE) and/or right ear (RE) 4,000 Hz notch (pluses) are shown. Latter category is parsed into three subgroups: unilateral LE 4,000 Hz notch (Xs), unilateral RE 4,000 Hz notch (circles), and bilateral 4,000 Hz notches (AU, triangles). Number of participants in each age group is indicated at top of graph.

**Table 2.**

Number of participants in each age decade who had no audiometric notch at 4,000 Hz or who had one or combination of 4,000 Hz notches.

Condition	Age Decade (yr)								Overall
	20s	30s	40s	50s	60s	70s	80s	90s	
<i>n</i>	39,533	31,479	58,636	120,893	210,070	153,456	120,546	9,940	744,553
No Notch	31,708	22,975	39,949	82,048	151,605	127,974	108,318	9,273	573,850
LE Notch	3,579	3,371	6,671	12,903	20,244	9,909	5,123	288	62,088
RE Notch	2,317	2,430	5,122	12,060	19,980	9,760	4,933	282	56,884
AU Notch	1,929	2,703	6,894	13,882	18,241	5,813	2,172	97	51,731
1 or 2 Notches	7,825	8,504	18,687	38,845	58,465	25,482	12,228	667	170,703

AU = *auris utraque* (both ears), LE = left ear, RE = right ear.**Table 3.**

Number, percentage, and notch depth of left and right ear 4,000 Hz notches.

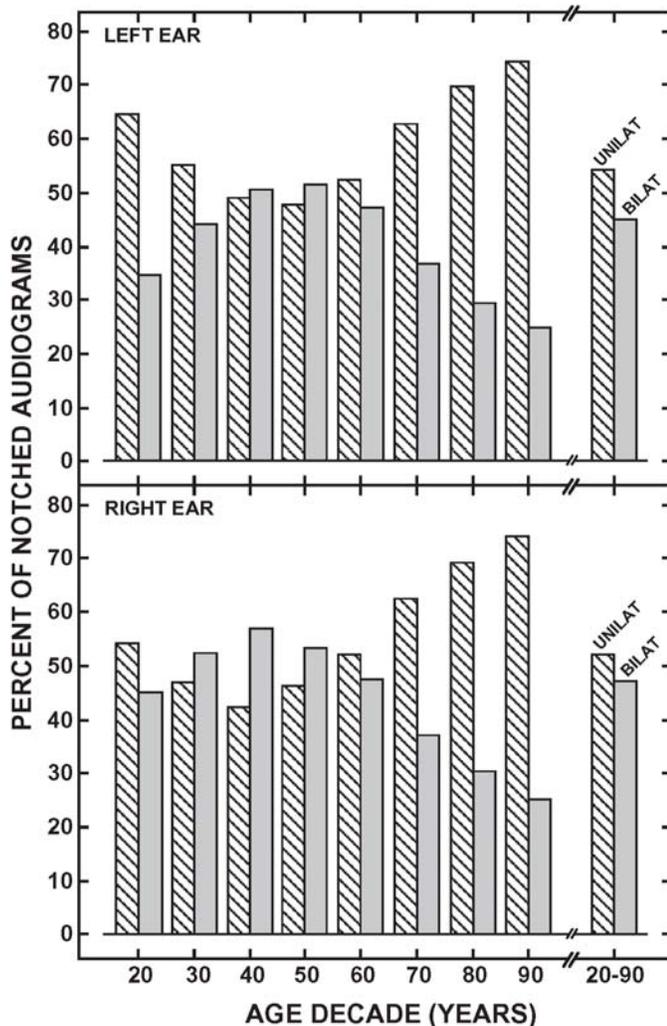
Age Decade (yr)	Total <i>n</i>	Left Ear			Right Ear		
		Notch <i>n</i>	%	Notch Depth (dB), Mean ± SD	Notch <i>n</i>	%	Notch Depth (dB), Mean ± SD
20s	39,533	5,507	13.9	22.2 ± 11.2	4,247	10.7	21.4 ± 11.1
30s	31,479	6,074	19.3	22.7 ± 10.5	5,133	16.3	22.3 ± 10.8
40s	58,636	13,565	23.1	23.9 ± 10.2	12,016	20.5	23.8 ± 10.2
50s	120,893	26,785	22.2	23.8 ± 9.2	25,942	21.5	24.7 ± 9.6
60s	210,070	38,485	18.3	23.8 ± 9.2	38,221	18.2	24.3 ± 9.3
70s	153,456	15,722	10.2	20.8 ± 8.3	15,573	10.1	21.4 ± 8.6
80s	120,546	7,295	6.1	18.8 ± 7.1	7,105	5.9	19.3 ± 7.4
90s	9,940	385	3.9	17.5 ± 6.3	379	3.8	17.9 ± 6.9
20s–90s	744,553	113,818	15.3	23.1 ± 9.5	108,616	14.6	23.4 ± 9.5

SD = standard deviation.

similarity is the ~3 percent higher prevalence of LE notches than RE notches in the 20 to 50 yr decades. Overall, there were 113,818 (15.3%) notched LE audiograms and 108,616 (14.6%) notched RE audiograms, which is about half the prevalence of notched audiograms found with the 3,430 veterans involved in our earlier study in which 28.8 percent of the LE audiograms and 27.1 percent of the RE audiograms were notched at 4,000 Hz [28, p. 28: Table 2]. Although both studies involved identical notch definitions, similar participant age ranges, and veterans who were seeking help for their hearing problems, the prevalence differences must be in part attributable to the different size samples and different sample characteristics that were involved in the two studies. The mean ages of the two studies were similar, 62.2 yr in the earlier study and 63.5 yr in the current study. The age SD (12.8 yr in the earlier study and 16.1 yr in the current study), however, suggested slightly different age distributions. Proportionally, the current study had 6 percent more participants in the age decades <60 yr and 8 percent more in the 80 yr decade. These slight differences in age distribu-

tions between the two studies could account for some of the discrepancy in notch prevalences, but probably not all. Another possible reason for the discrepancy between the notch prevalences in the current study and in the previous VA study might be related to the site differences, previously mentioned in the "Introduction," in which the rate of comorbidities and various auditory measures differed among VA facilities. Site-specific differences in prevalence will be explored in a future report.

Finally, regarding the prevalence of 4,000 Hz notches, we were interested in examining in more detail the prevalence of 4,000 Hz notches in terms of unilateral and bilateral occurrences. The histograms in **Figure 3** depict the prevalence of unilateral and bilateral 4,000 Hz notched audiograms for the LE and RE for each of the eight decades. The data indicate that the percentage of audiograms with a unilateral notch (striped) or bilateral notch (shaded) varied as a function of age and, to some degree, as a function of ear. The LE in the 20 and 30 yr decades clearly has more unilateral notches than bilateral notches, a relation that is only reflected in the RE by the



**Figure 3.** Histograms for eight age categories of percentage of notches present unilaterally (UNILAT) in target ear (striped) versus present in target ear when notches were present bilaterally (BILAT, shaded). Left ear  $n = 113,818$ ; right ear  $n = 108,616$ .

20 yr decade. In the 40 to 60 yr decades, the percentage of unilateral and bilateral notches is mixed, whereas in the 70 to 90 yr decades, there are increasingly far more unilateral notches than bilateral notches. The reason for such a discrepancy between the prevalence of unilateral and bilateral notches in the last three decades certainly suggests underlying mechanism differences between the individuals with unilateral and bilateral notches, but the nature of that mechanism cannot be determined from the current data.

#### Group 1 Notch Depths

A notch at 4,000 Hz was defined when the 4,000 Hz threshold minus the 2,000 Hz threshold and the 4,000 Hz threshold minus the 8,000 Hz threshold both were  $\geq 10$  dB. The mean notch depth (in decibels) was simply the average of the two aforementioned threshold differences, which, because of the 5 dB step sizes involved in the threshold measures, produced mean difference data in 2.5 dB intervals. From **Table 3**, the mean notch depth of the 113,818 LE notches was 23.1 dB and the mean notch depth of the 108,616 RE notches was 23.4 dB; both SD values were 9.5 dB. Because the two threshold differences constitute the opposing sides of the notch, their relation can be expressed as a symmetry ratio:

$$\text{Symmetry Ratio} = \frac{(4,000 \text{ Hz threshold} - 2,000 \text{ Hz threshold})}{(4,000 \text{ Hz threshold} - 8,000 \text{ Hz threshold})}$$

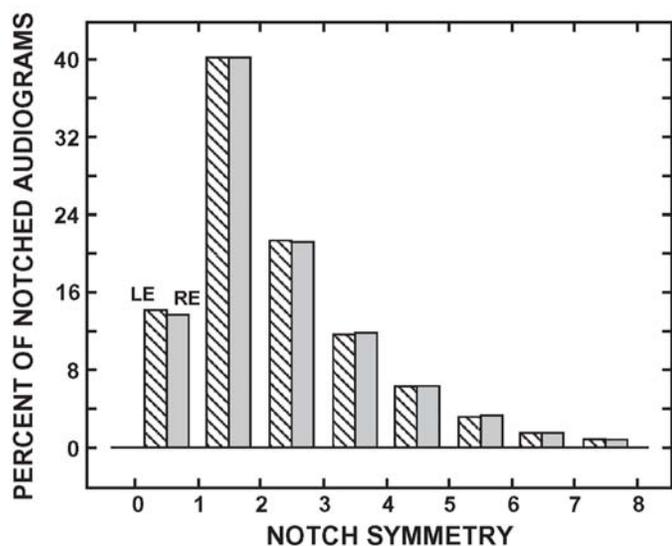
**Table 4** lists the respective mean threshold differences (and SD) and the corresponding mean symmetry ratios of the LE and RE notches as a function of age. For both ears, the low-frequency side of the 4,000 Hz notch was about twice as deep (or steep) as the high-frequency side of the notch with an overall  $\sim 30$  dB difference (SD = 16 dB) between the 4,000 and 2,000 Hz thresholds and a 16.6 dB difference (SD = 8.3 dB) between the 4,000 and 8,000 Hz thresholds. The overall mean symmetry ratios were 2.1 with SD of 1.4. As shown in **Table 4**, the symmetry ratio changed as a function of age, systematically increasing from 1.4 in the 20 yr decade to 1.9 to 2.3 in the 50 to 90 yr decades. Thus, the low-frequency side of the notch with the younger participants was only slightly larger (steeper) than the high-frequency side, whereas with the older participants the low-frequency side was substantially steeper than the high-frequency side. Finally, the histogram in **Figure 4** gives the distribution of the percentage of LEs and REs that had notch symmetry ratios in each of the eight symmetry categories, the first being 0 to 0.9. The distributions for both ears were essentially the same. About 75 percent of the symmetry ratios were  $< 3$ , with 40.3 percent of both ears having symmetry ratios between 1 and 1.9. Symmetry ratios  $> 4$  characterized only about 12 percent of the notches in each ear.

Four additional aspects of the notch depth data were evaluated. First were the overall distributions of LE and RE notch depths that are depicted by the histograms in **Figure 5**. The data indicate that the percentage of LE and RE notched audiograms are about the same for the various

**Table 4.**

Mean threshold differences (and standard deviation [SD]) between 4,000 and 2,000 Hz thresholds and between 4,000 and 8,000 Hz thresholds for left ear and right ear of various age groups, along with symmetry ratio of threshold differences.

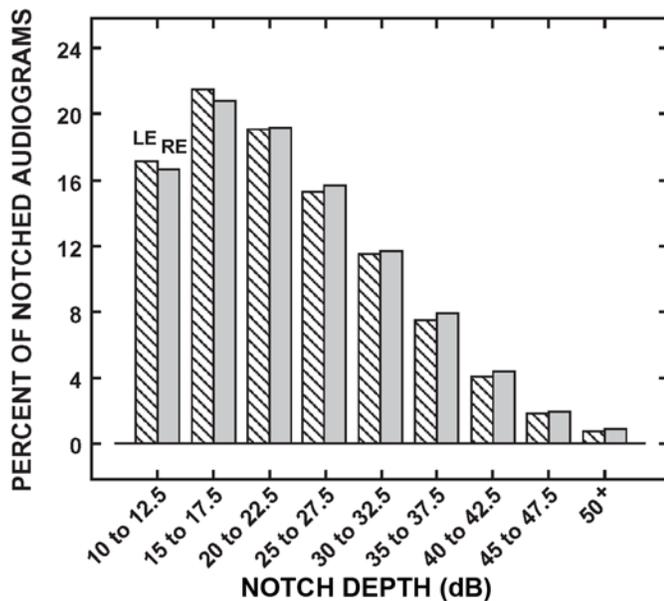
Age Decade (yr)	<i>n</i>	Threshold Difference (dB), Mean ± SD		Symmetry Ratio, Mean ± SD
		4,000 Hz – 2,000 Hz	4,000 Hz – 8,000 Hz	
<b>Left Ear</b>				
20s	5,508	24.8 ± 15.6	19.6 ± 10.6	1.4 ± 1.1
30s	6,074	25.6 ± 14.7	19.8 ± 10.3	1.5 ± 1.0
40s	13,565	28.4 ± 15.5	19.5 ± 9.9	1.7 ± 1.2
50s	26,785	31.5 ± 16.2	17.6 ± 8.6	2.1 ± 1.4
60s	38,484	31.8 ± 16.4	15.8 ± 7.3	2.3 ± 1.5
70s	15,722	28.0 ± 15.2	13.7 ± 5.4	2.2 ± 1.4
80s	7,295	24.8 ± 12.9	12.7 ± 4.5	2.1 ± 1.2
90s	385	22.6 ± 11.3	12.4 ± 4.3	1.9 ± 1.0
20s–90s	113,818	29.6 ± 16.0	16.6 ± 8.3	2.1 ± 1.4
<b>Right Ear</b>				
20s	4,247	23.7 ± 15.1	19.1 ± 10.3	1.4 ± 1.0
30s	5,133	25.0 ± 14.8	19.6 ± 10.3	1.4 ± 1.0
40s	12,016	28.3 ± 15.3	19.4 ± 9.8	1.7 ± 1.2
50s	25,942	31.6 ± 16.2	17.9 ± 8.8	2.1 ± 1.4
60s	38,221	32.4 ± 16.5	16.2 ± 7.7	2.3 ± 1.5
70s	15,573	28.9 ± 15.6	14.0 ± 5.9	2.3 ± 1.4
80s	7,105	25.8 ± 13.5	12.8 ± 5.1	2.2 ± 1.2
90s	379	22.8 ± 11.0	13.0 ± 7.7	1.9 ± 0.9
20s–90s	108,616	30.1 ± 16.1	16.7 ± 8.4	2.1 ± 1.4

**Figure 4.**

Histograms of percentage of left ear (LE) (striped) and right ear (RE) (shaded) 4,000 Hz notched audiograms for eight notch symmetries. LE *n* = 113,818; RE *n* = 108,616.

notch depths. Only 16 to 17 percent of the notches were observed at the minimum notch depth of 10.0 to 12.5 dB. Conversely, 83 to 84 percent of the notch depths were  $\geq 15.0$  dB. The distributions of notch depths maximize in the 15.0 to 17.5 dB notch depth category with a systematic decrease through the 50.0<sup>+</sup> dB depth. Although substantially fewer participants were involved in the earlier study of 3,430 veterans, almost identical 4,000 Hz notch depth characteristics were observed for the LEs and REs in that study [28, p. 28: Figure 3].

Second, the distributions of LE and RE notch depths for each of the eight decades were evaluated and are shown in **Figure 6**. In each age decade, the LE and RE histograms closely correspond, indicating similar notching patterns in the two ears as a function of age. The distributions are skewed for the shallower notch depths in the 20 and 30 yr decades, becoming somewhat rounded through the 40, 50, and 60 yr decades. In the latter three decades, the notch depths again progressively become skewed toward the shallower depths, with fewer and fewer deep notches from the 70 to 90 yr decades. As mentioned earlier, this latter phenomenon probably is

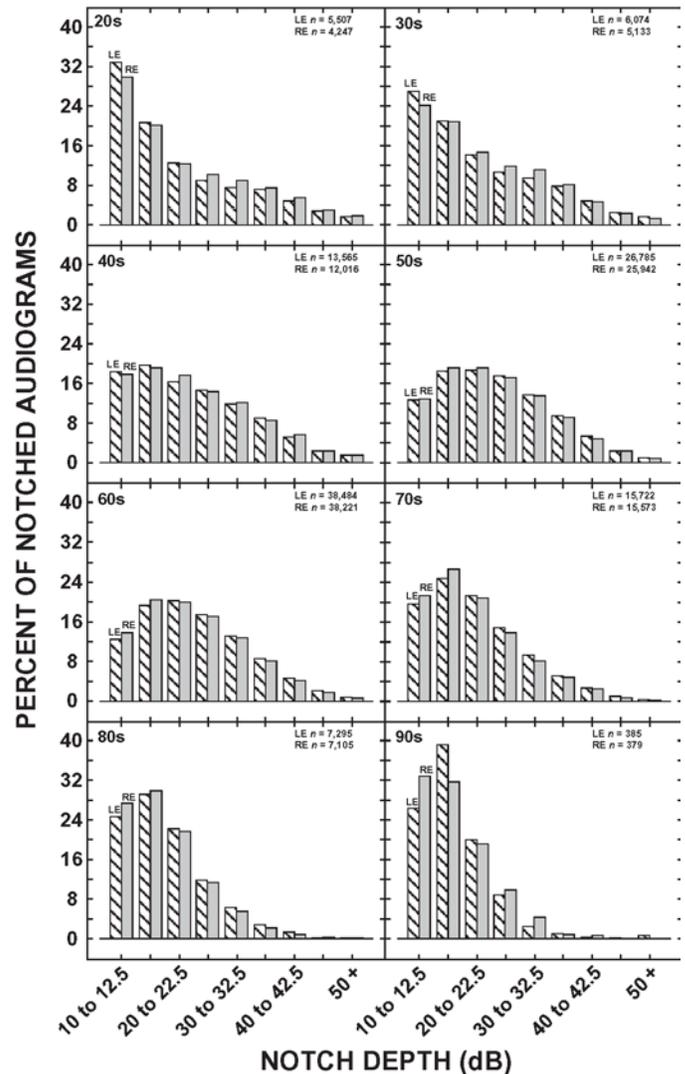


**Figure 5.**

Histograms of percentage of left ear (LE) (striped) and right ear (RE) (shaded) 4,000 Hz notched audiograms for nine notch depths. LE  $n = 113,818$ ; RE  $n = 108,616$ .

related to the threshold at 8,000 Hz increasingly becoming higher (poorer) as a function of age. Because the thresholds at 4,000 and 8,000 Hz approximate one another, the definition of a notch is precluded.

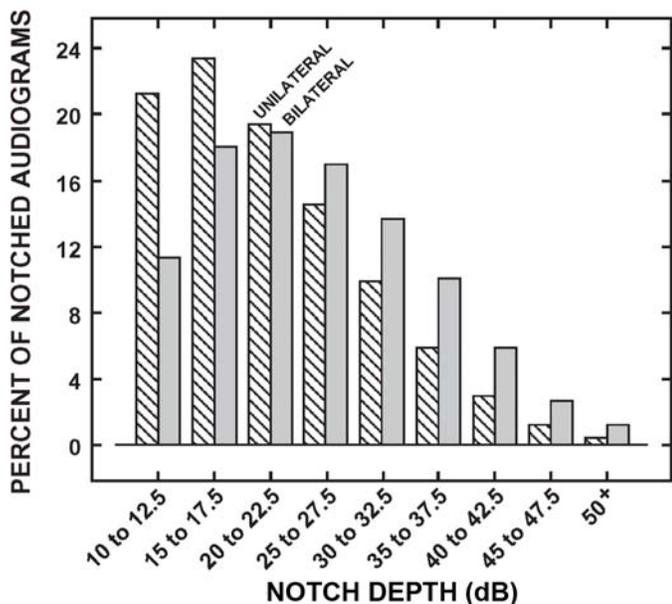
Third, the notch depths were studied with respect to the unilateral and bilateral occurrence of the notches. Specifically, the question was, What were the distributions of notch depths for the notches that occurred in a given ear of unilateral notches and the same ear of bilateral notches; i.e., Were the notches in these two notch conditions the same or different? For the 113,818 LE notched audiograms, the mean notch depths were 21.7 dB (62,088 LE unilateral) and 24.8 dB (51,731 LE of a bilateral notch) with SD values of 9.1 and 9.6 dB, respectively. Similarly, for the 108,616 RE notched audiograms, the mean notch depths were 21.7 dB (56,884 RE of a unilateral notch) and 25.3 dB (51,731 RE of a bilateral notch) with SD values of 9.0 and 9.8 dB, respectively. In addition to the ~3.5 dB deeper mean notch depth when the notching was bilateral, the histograms of the RE notch depths of unilateral notches (striped) and bilateral notches (shaded) shown in **Figure 7** demonstrate that the distributions of the unilateral and bilateral notch depths were different. (Note: The same plot of LE



**Figure 6.**

Histograms for eight age categories of percentage of left ear (LE) (striped) and right ear (RE) (shaded) 4,000 Hz notched audiograms for nine notch depths.

notch depths had similar distributions for the unilateral and bilateral notches.) When the notches were unilateral, 45 percent of the notch depths were 10.0 to 17.5 dB, whereas when the notches occurred in both ears, 30 percent of the notch depths were 10.0 to 17.5 dB. For both the LE and RE, the bilateral notches were more prevalent in the deeper notch depths than were the unilateral notches, which were reflected directly in the previously mentioned mean differences between unilateral and bilateral notches. In general, the bilateral notches are steeper

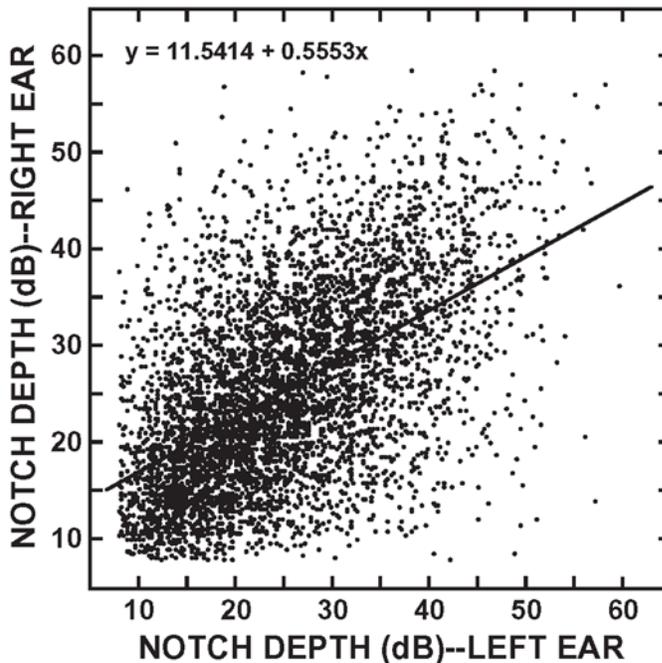


**Figure 7.**

Histograms of percentage of unilateral right ear (RE) (striped) and bilateral RE (shaded) 4,000 Hz notched audiograms for nine notch depths. Unilateral RE  $n = 56,885$ ; bilateral RE  $n = 51,731$ .

or deeper than the unilateral notches, the meaning of which is unclear.

Fourth, of the 51,731 participants with bilateral 4,000 Hz notches, 20,841 (40.3%) had LE notches that were deeper than the RE notches (LE mean  $\pm$  SD =  $29.2 \pm 9.5$  dB; RE mean  $\pm$  SD =  $21.3 \pm 8.3$  dB), 23,824 (46.1%) had RE notches that were deeper than the LE notches (LE mean  $\pm$  SD =  $21.4 \pm 8.2$  dB; RE mean  $\pm$  SD =  $29.5 \pm 9.5$  dB), and 7,066 (13.7%) had equivalent notch depths in the two ears (mean  $\pm$  SD =  $22.9 \pm 9.1$  dB). The overall mean notch depth for the LE was 24.8 dB (SD = 9.6 dB) and for the RE was 25.3 dB (SD = 9.8 dB). The mean absolute difference between the LE and RE notch depths was 6.9 dB (SD = 6.2 dB). A comparison of the LE and RE notch depths for the 51,731 participants with bilateral 4,000 Hz notches is illustrated\* in **Figure 8**. Interestingly, calculations with the linear regression equation indicate that only around a notch depth of 25 dB is there a one-to-one relation between the notch depths for the two ears. Below 25 dB, the RE notch depth is deeper than the LE notch depth; e.g., at an LE notch depth of 10 dB, the RE notch depth is 17.1 dB. Conversely, above 25 dB, the LE notch depth is deeper than the RE notch depth; e.g., at an LE notch depth of 60 dB, the RE notch depth is only 44.9 dB. These data indicate that when



**Figure 8.**

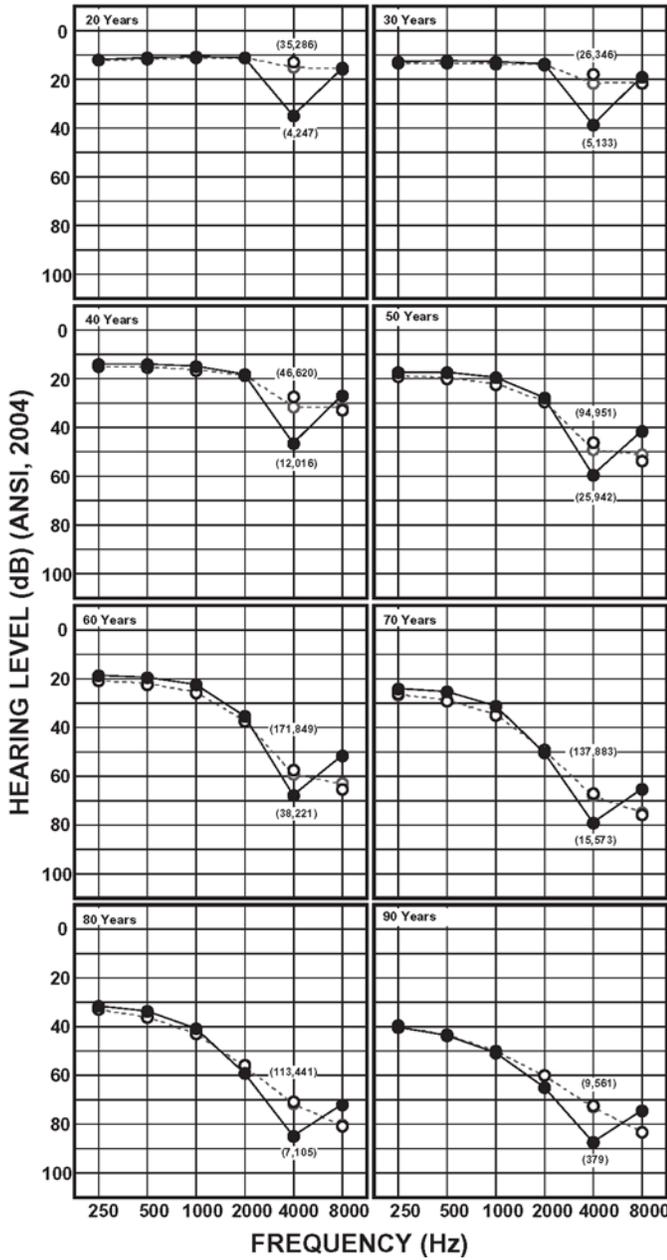
Bivariate illustration of notch depth (decibels) for right ear (ordinate) and left ear (abscissa) of 51,731 individuals with bilateral 4,000 Hz notches. For graphic clarity, (1) data points were jittered randomly using additive algorithm from  $-2.4$  dB to  $2.4$  dB in  $0.05$  dB steps, and (2) only every 10th data point is shown. Linear regression reflects 51,731 notch pairs ( $R^2 = 0.3$ ).

the 4,000 Hz notch is bilateral, a different dynamic is operating in the two ears. When the notch is shallow, the RE notch tends to be deeper than the LE notch. When the notch is deep, the LE notch tends to be deeper than the RE notch.

#### Group 1 Mean Audiograms

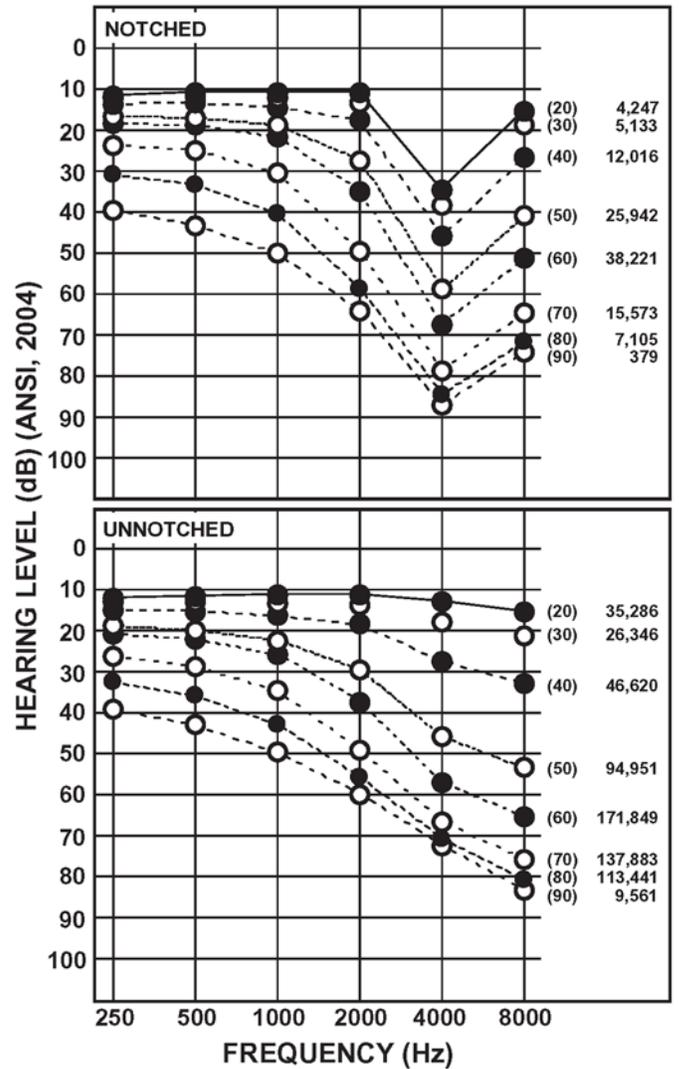
The mean audiograms for the REs are shown for the eight decades in **Figures 9** and **10**. In each panel of both figures, the number of participants is indicated. In **Figure 9**, three mean audiograms are depicted in each panel, including

\*Because plotting 51,731 datum points resulted in a black blob, a random sample of 5,173 datum points was used to illustrate the relationship between ears. The data were jittered randomly using an additive algorithm from  $-1.25$  to  $1.25$  in  $0.05$  steps. The linear regression shown in the figure, however, is based on the 51,731 individuals; a regression based on the 5,173 individuals provided essentially the same equation, thus ensuring that the plotted sample reflected accurately the full sample.



**Figure 9.** Mean right ear notched (filled circles) and unnotched (black open circles) audiograms for eight age groups. Gray open circles are average audiogram for the two groups in each panel. Numbers in parentheses indicate number of participants in each group. Hearing level as defined by American National Standards Institute (ANSI) [32].

notched audiograms (filled circles), unnotched audiograms (black open circles), and mean audiogram for notched and unnotched combined (gray open circles).



**Figure 10.** Mean right ear notched and unnotched audiograms for eight age groups (indicated in parentheses). Adjacent numbers are number of participants in each group. Notched  $n = 108,616$ ; unnotched  $n = 625,937$ . Hearing level as defined by American National Standards Institute (ANSI) [32].

Three relations are noteworthy in **Figure 9**. First, for each age group, the pure-tone thresholds at 250 to 2,000 Hz are essentially the same for the notched and unnotched groups. The equal mean 2,000 Hz thresholds for the notched and unnotched groups substantiate the appropriateness of using the 2,000 Hz threshold as the lower frequency anchor in the definition of the high-frequency audiometric notch. Second, in all age groups except the

20s, the mean threshold at 8,000 Hz for the notched group is lower (better) than the mean threshold at 8,000 Hz for the unnotched group. Perhaps this difference between groups at 8,000 Hz reflects the different pathophysiological processes involved with notched and unnotched audiograms or with noise-induced hearing loss and age-related hearing loss [44–45]. Finally, because the notch is present in a minority of participants in all age groups, the effect of the notched audiograms on the overall mean audiogram is minimal, with the mean audiograms not reflecting the presence of a 4,000 Hz notch.

The mean RE audiograms in **Figure 10** enable comparisons across ages of the notched ( $n = 108,616$ , 14.6%) and unnotched ( $n = 635,937$ , 85.4%) audiograms. As in the earlier Wilson article [28], the range of mean thresholds across the age decades is substantially less in the low frequencies than in the high frequencies. For both the notched and unnotched RE audiograms, the range at 250 Hz was 28 dB, increasing at 8,000 Hz to 59 dB (notched) and 68 dB (unnotched). These differences translate into rates of change over the 70 yr span of 0.4 dB/yr at 250 Hz and 0.8 to 1.0 dB/yr at 8,000 Hz. These differences across ages have been noted in several previous studies [38,46–50]. It is interesting in these cross-sectional data that the biggest threshold differences occurred in the two highest frequencies between the 40 and 50 yr decades, especially in the unnotched group. A similar observation can be made in the Wilson data [28, p. 25: Figure 1].

### Group 2 (3,000, 4,000, and 6,000 Hz Data)

The mean audiograms for the LE and RE of the 539,932 participants included in the analyses of the 3,000, 4,000, and 6,000 Hz notch data are listed in **Table 5**. Again, the mean audiograms reflect mild-to-moderate, high-frequency sensorineural hearing losses with mean PTAs 28.9 and 28.0 dB HL (SD = 16.6 and 16.4 dB) for the LE and RE, respectively, with corresponding HFPTAs of 39.7 and 38.2 dB HL (SD = 19.0 and 18.9 dB). As with the earlier threshold data in **Table 1**, of which the present

data are a subset, the mean threshold differences at 250, 500, and 1,000 Hz are <0.5 dB, with the mean RE thresholds in the 2,000 to 6,000 Hz range about 2 dB lower (better) than the mean LE thresholds at those frequencies. At 8,000 Hz, the mean RE threshold was 1.2 dB lower than the mean LE threshold.

### Group 2 Notch Prevalence

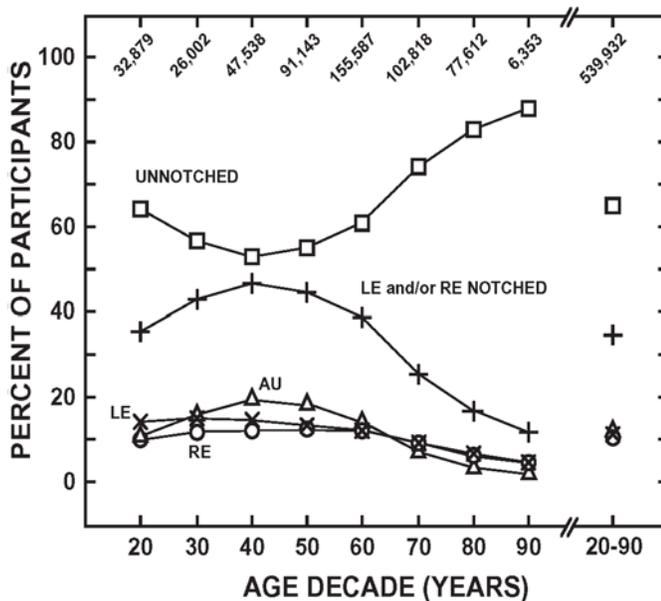
The audiogram pairs were analyzed for notches at 3,000, 4,000, and 6,000 Hz using the 10 dB criteria that was used with group 1's 4,000 Hz notch data. The majority of the 539,932 audiogram pairs (352,537 or 65.3%) did not have a notch in the air-conduction audiogram of either ear at 3,000, 4,000, or 6,000 Hz. Of the remaining 187,395 audiogram pairs, 120,817 (22.4%) were unilateral notches at one or more of the three notch frequencies (62,894 LEs, 11.6%; 57,923 REs, 10.7%) and 66,578 (12.3%) were bilateral notches at one or more of the three notch frequencies. Considering unilateral and bilateral notches collectively, 410,460 LEs (76.0%) and 415,431 REs (76.9%) did not have a notch at any of the three notch frequencies; conversely, 129,472 LEs (24.0%) and 124,501 REs (23.1%) had a notch minimally at one of the notch frequencies. Notches were measurable (1) at one frequency in 104,763 LEs (19.4%) and 101,470 REs (18.8%), (2) at two frequencies in 22,461 LEs (4.2%) and 21,170 REs (3.9%), and (3) at all three frequencies in 2,248 LEs (0.4%) and 1,861 REs (0.3%).

The data in **Figure 11** give the percentage of participants in each age decade who had unnotched (squares) and notched audiograms (pluses). For inclusion in the notched category, a notch was required at one of the three notch frequencies in either ear; thus, the notched category included three single notches (3,000, 4,000, or 6,000 Hz) and four multiple notch combinations (3,000 and 4,000 Hz; 3,000 and 6,000 Hz; 4,000 and 6,000 Hz; and 3,000, 4,000, and 6,000 Hz). As previously mentioned, overall 65.3 percent of the audiograms were unnotched and 34.7 percent were

**Table 5.**

Mean  $\pm$  standard deviation left ear (LE) and right ear (RE) pure-tone air-conduction thresholds (decibels hearing level [32]) from 539,932 individuals between ages of 20 and 90+ yr.

Ear	Frequency (Hz)							
	250	500	1,000	2,000	3,000	4,000	6,000	8,000
LE	21.4 $\pm$ 13.9	22.7 $\pm$ 15.0	26.4 $\pm$ 17.3	37.6 $\pm$ 22.4	49.1 $\pm$ 23.7	55.2 $\pm$ 24.3	57.4 $\pm$ 25.2	58.7 $\pm$ 26.7
RE	21.3 $\pm$ 13.7	22.5 $\pm$ 14.8	26.0 $\pm$ 16.9	35.4 $\pm$ 21.9	46.6 $\pm$ 23.9	53.0 $\pm$ 24.8	55.6 $\pm$ 25.7	57.5 $\pm$ 27.3
Difference (RE – LE)	-0.1	-0.2	-0.4	-2.2	-2.5	-2.2	-1.8	-1.2



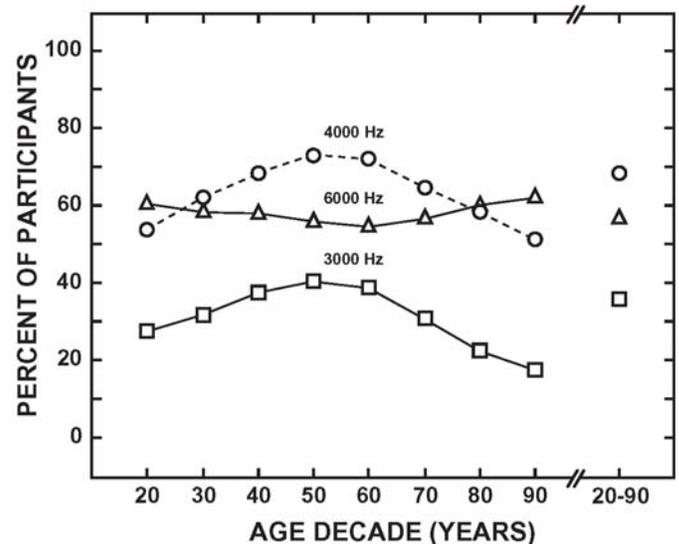
**Figure 11.**

Percentage of participants in each age group with no audiometric notch at 3,000, 4,000, and/or 6,000 Hz in either ear (squares) or with one or more notches in either ear at 3,000, 4,000, and/or 6,000 Hz (pluses) are shown. Notched category is parsed into three subgroups: unilateral left ear (LE) notches (Xs), unilateral right ear (RE) notches (circles), and bilateral notches (AU, triangles). Number of participants in each age group is indicated at top of graph.

notched at a minimum of one frequency. As a function of age in **Figure 11**, the percentage of participants with unnotched audiograms is characterized by a concave function, just as was observed with the 4,000 Hz notch data in **Figure 2**. The inclusion of 3,000 and 6,000 Hz in the notch frequency category differentially but systematically affected the percentage of unnotched audiograms in each age decade. From **Figure 11**, the minimum percentage of unnotched audiograms was in the 40 yr decade (53.1%) and the maximum percentage of unnotched audiograms was in the 90 yr decade (88.0%). Because the data in **Figure 11** are normalized, the notched data are the inverse of the unnotched data, with the maximum percentage of notched audiograms in the 40 yr decade (46.9%) and the minimum in the 90 yr decade (12.0%). When the unnotched data in **Figures 2 and 11** are compared, with three notch frequencies included in the criteria, the percentage of participants in each age decade with notched audiograms increased on average by ~12 percent, with the larger

increases in the lower age decades (~16%) than in the higher age decades (~6%). The notched audiograms in **Figure 11** are subdivided into the percentage of participants with LE notches (Xs), RE notches (circles), and bilateral notches (AU, triangles). Although in some age decades the percentage of bilateral notches is greater than the percentage of LE or RE unilateral notches, collectively, the percentage of bilateral notches is about equivalent to the percentage of LE or RE unilateral notches, with the three measures mostly fluctuating between 10 and 20 percent of the participants for the various decade intervals.

For a given ear of a participant in group 2, notches in the audiogram occurred at one frequency or a combination of the three notch frequencies. The percentage of participants with RE unilateral or bilateral notched audiograms are shown for the three notch frequencies in **Figure 12** at each of the decade intervals; although not illustrated, LE plots of the same data parameters were essentially identical. The data for the same LE conditions are listed in the lower portions of the two sections in **Table 6**, which includes a complete listing of the raw prevalence data and the corresponding prevalence percentages for the LE, respectively. In both panels of **Table 6**, the number and corresponding percentage of LEs



**Figure 12.**

Percentage of participants with right ear notched audiograms in each age group that had single notches or notches in combination with other frequencies at 3,000 (squares), 4,000 (circles), and 6,000 Hz (triangles) are shown.

**Table 6.**

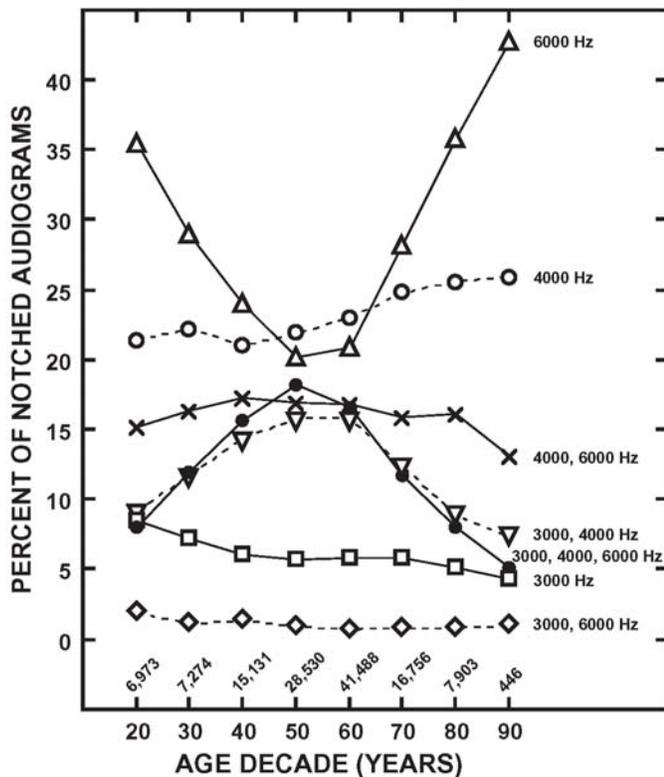
Number of left ears (LEs) in each age category that were unnotched or notched and that had notches at one, two, or three notch frequencies. Total for each notch frequency is sum of notches for particular notch frequency. Mean percentage of unnotched and notched LE audiograms in each age category and mean percentage of notched audiograms represented by various notched categories.

Condition	Age Decade (yr)								
	20s	30s	40s	50s	60s	70s	80s	90s	20–90
<i>n</i>	32,879	26,002	47,538	91,143	155,587	102,818	77,612	6,353	539,932
<b>Participants (No.)</b>									
Unnotched	24,546	17,855	31,010	61,814	113,989	85,819	69,523	5,904	410,460
Notched	8,333	8,147	16,528	29,329	41,598	16,999	8,089	449	129,472
3,000 Hz	725	559	1,045	1,779	2,528	969	416	26	8,047
4,000 Hz	1,722	1,697	3,446	6,285	9,554	4,230	2,093	107	29,134
6,000 Hz	2,707	2,186	3,732	5,881	8,831	4,964	2,843	179	31,323
3,000, 4,000 Hz	872	1,081	2,497	4,942	6,714	2,054	693	30	18,883
3,000, 6,000 Hz	166	116	207	318	398	174	92	4	1,475
4,000, 6,000 Hz	1,238	1,377	2,768	4,766	6,712	2,636	1,291	76	20,864
3,000, 4,000, 6,000 Hz	903	1,131	2,833	5,358	6,861	1,972	661	27	19,746
Total 3,000 Hz	2,666	2,887	6,582	12,397	16,501	5,169	1,862	87	48,151
Total 4,000 Hz	4,735	5,286	11,544	21,351	29,841	10,892	4,738	240	88,627
Total 6,000 Hz	5,014	4,810	9,540	16,323	22,802	9,746	4,887	286	73,408
<b>Participants (%)</b>									
Unnotched	74.7	68.7	65.2	67.8	73.3	83.5	89.6	92.9	76.0
Notched	25.3	31.3	34.8	32.2	26.7	16.5	10.4	7.1	24.0
3,000 Hz	8.7	6.9	6.3	6.1	6.1	5.7	5.1	5.8	6.2
4,000 Hz	20.7	20.8	20.8	21.4	23.0	24.9	25.9	23.8	22.5
6,000 Hz	32.5	26.8	22.6	20.1	21.2	29.2	35.1	39.9	24.2
3,000, 4,000 Hz	10.5	13.3	15.1	16.9	16.1	12.1	8.6	6.7	14.6
3,000, 6,000 Hz	2.0	1.4	1.3	1.1	1.0	1.0	1.1	0.9	1.1
4,000, 6,000 Hz	14.9	16.9	16.7	16.3	16.1	15.5	16.0	16.9	16.1
3,000, 4,000, 6,000 Hz	10.8	13.9	17.1	18.3	16.5	11.6	8.2	6.0	15.3
Total 3,000 Hz	32.0	35.4	39.8	42.3	39.7	30.4	23.0	19.4	38.7
Total 4,000 Hz	56.8	64.9	69.8	72.8	71.7	64.1	58.6	53.5	71.2
Total 6,000 Hz	60.2	59.0	57.7	55.7	54.8	57.3	60.4	63.7	59.0

with single notches and multiple notch combinations are listed for each of the eight age decades and overall (20–90 yr). The RE percentage data for the same seven notch combinations are plotted in **Figure 13**; although not shown, the same plot of the LE notch data was almost identical to the RE data, the exception being the slightly higher overall prevalence of notches in the LE than in the RE.

Several observations are notable from the data in **Table 6** and **Figures 12** and **13**. First, in **Figure 12** (RE) and the lower panel of **Table 6** (LE), overall 4,000 Hz notches are the most common with 6,000 Hz notches the second most common, followed at a distant third by 3,000 Hz notches. There are differences, however, among the age decades. Second, 4,000 Hz notches are the most prevalent in the 40 to 70 yr decades, 6,000 Hz notches are the most prevalent

in the 20 and 90 yr decades, and there is equal prevalence in the 30 and 80 yr decades. Third, for the LE and RE, the prevalence of both the 3,000 and 4,000 Hz notches increases from the 20 to the 50 to 60 yr decades, after which there is a steady decline to the 90 yr decade. The increase in the earlier years suggests the cumulative effects of continued exposure to whatever the causal agent is, whereas the decrease in the later years is probably related to the 8,000 Hz threshold increasingly lowered (becoming poorer) owing to various aging factors. As suggested earlier in this article and others, because the 8,000 Hz threshold is found at increasingly higher HLs with increasing age, the requirements for a notch dissolve from  $\geq 10$  dB to  $< 0$  dB. Interestingly, the prevalence of the 6,000 Hz notch is somewhat stable across the age decades for both ears (**Figure 12**). Fourth, considering the various combinations



**Figure 13.**

Percentage of right ear in each age group that had one of seven combinations of 3,000, 4,000, and/or 6,000 Hz audiometric notch are shown. Notches are at 3,000 Hz only (squares); 4,000 Hz only (open circles); 6,000 Hz only (triangles); 3,000 and 4,000 Hz only (inverted triangles); 3,000 and 6,000 Hz only (diamonds); 4,000 and 6,000 Hz only (Xs); and 3,000, 4,000, and 6,000 Hz (filled circles). Number of participants in each age group is indicated at bottom of graph.

of single notches and multiple notches (**Figure 13**, RE; and **Table 6**, LE), single notches at 4,000 and 6,000 Hz are essentially equal in overall prevalence and are the most prevalent notch frequencies (22%–24%). The second group of most prevalent notches (14%–16%) includes the 3,000 and 4,000 Hz multiple notch; the 4,000 and 6,000 Hz multiple notch; and the 3,000, 4,000, and 6,000 Hz multiple notch. The least common notches were the 3,000 Hz single notch (5%–6%) and the 3,000 and 6,000 Hz multiple notch (1%–2%).

Finally regarding the prevalence of 3,000, 4,000, and 6,000 Hz notches, the 63 notch combinations that were the product of the three notch frequencies and the two ears were examined. The data are presented in **Table 7**, in

which the notch frequency/ear is coded in the first six columns with the number of participants in each category and corresponding percentage of the 187,395 participants listed in the final two columns of the table. The data are sorted from the most prevalent to the least prevalent. The “1” in each row designates the frequency or frequencies at which a notch occurred. For example, the data in the 1st row indicate that 19,960 (10.65%) only had a notch in the LE at 6,000 Hz with no notch in the RE. The data in the 13th row indicate that 5,056 participants (2.70%) had a notch in the LE at 4,000 Hz and a notch in the RE at 4,000 Hz. Interestingly, the most prevalent notches were unilateral. The data in the first eight rows represent only unilateral notches, with the first four rows representing single frequency notches (36.4% of all notches) and the second four rows representing double frequency combination notches (16.6% of all notches). The most prevalent notch was 6,000 Hz in the LE, followed by 6,000 Hz in the RE, 4,000 Hz in the LE, and 4,000 Hz in the RE. The most prevalent notch combination was 4,000 and 6,000 Hz in the LE, with no notch in the RE followed by the same combination in the RE with no notch in the LE. The 3,000, 4,000, and 6,000 Hz bilateral notch combination was 12th on the list ( $n = 5,241$  or 2.8%). The least prevalent notch combination (row 63) was 3,000 and 6,000 Hz in both ears ( $n = 37$  or 0.02%). (Note: These data are listed by age decade in the **Appendix**, available online only.)

#### Group 2 Notch Depths

The mean notch depths from the 187,395 participants with at least one notch were essentially identical in the two ears. The mean values were 3,000 Hz (LE, mean  $\pm$  SD =  $21.1 \pm 8.6$  dB; RE, mean  $\pm$  SD =  $21.1 \pm 8.6$  dB), 4,000 Hz (LE, mean  $\pm$  SD =  $23.6 \pm 9.6$  dB; RE, mean  $\pm$  SD =  $23.9 \pm 9.7$  dB), and 6,000 Hz (LE, mean  $\pm$  SD =  $22.4 \pm 9.2$  dB; RE, mean  $\pm$  SD =  $22.7 \pm 9.4$  dB). Overall, the mean notch depths for bilateral notches (23.5 dB) were slightly deeper than the unilateral notches (21.0 dB). At 3,000 and 4,000 Hz, the bilateral notches were 3.1 to 3.5 dB deeper than the unilateral notches but only 0.7 to 1.2 dB deeper at 6,000 Hz. The histograms in **Figure 14** depict the percentage of LE and RE notched audiograms for the three notch frequencies according to the notch depths (in decibels). The distributions by ear and by notch frequency closely approximate one another. The majority of notch depths are in the 10.0 to 27.5 dB range, with the notch depth modes at the 15.0 to 17.5 dB range. It is tempting to speculate that the

**Table 7.**

Number and percentage of 187,395 participants for each of 63 notch configurations. Data are ranked according to prevalence. Notch frequency is indicated by "1" in ear/frequency column.

Row	Left Ear (Hz)			Right Ear (Hz)			n	%
	3,000	4,000	6,000	3,000	4,000	6,000		
1	0	0	1	0	0	0	19,960	10.65
2	0	0	0	0	0	1	17,818	9.51
3	0	1	0	0	0	0	15,766	8.41
4	0	0	0	0	1	0	14,654	7.82
5	0	1	1	0	0	0	9,074	4.84
6	0	0	0	0	1	1	8,071	4.31
7	1	1	0	0	0	0	7,071	3.77
8	0	0	0	1	1	0	6,963	3.72
9	0	0	1	0	0	1	6,279	3.35
10	1	1	1	0	0	0	5,705	3.04
11	0	0	0	1	1	1	5,407	2.89
12	1	1	1	1	1	1	5,241	2.80
13	0	1	0	0	1	0	5,056	2.70
14	1	0	0	0	0	0	4,558	2.43
15	0	0	0	1	0	0	4,374	2.33
16	1	1	0	1	1	0	4,222	2.25
17	0	1	1	0	1	1	4,188	2.23
18	1	1	0	1	1	1	2,811	1.50
19	0	1	1	0	0	1	2,646	1.41
20	0	1	0	0	1	1	2,580	1.38
21	1	1	1	0	1	1	2,510	1.34
22	1	1	1	1	1	0	2,446	1.31
23	0	1	1	0	1	0	2,380	1.27
24	1	1	0	0	1	0	2,320	1.24
25	0	0	1	0	1	1	2,119	1.13
26	1	1	1	0	1	0	2,101	1.12
27	0	1	0	1	1	0	1,885	1.01
28	0	1	0	1	1	1	1,776	0.95
29	0	1	1	1	1	1	1,724	0.92
30	0	1	0	0	0	1	1,584	0.85
31	0	0	1	0	1	0	1,388	0.74
32	1	1	1	0	0	1	1,103	0.59
33	1	0	0	1	1	0	1,024	0.55
34	1	1	0	0	1	1	958	0.51
35	1	1	0	1	0	0	910	0.49
36	1	0	0	1	0	0	859	0.46
37	0	0	1	1	1	1	837	0.45
38	1	0	1	0	0	0	760	0.41
39	0	0	0	1	0	1	636	0.34
40	0	1	1	1	1	0	627	0.33
41	1	0	0	1	1	1	565	0.30
42	1	0	0	0	1	0	522	0.28
43	1	1	0	0	0	1	499	0.27
44	1	1	1	1	0	0	463	0.25
45	0	1	0	1	0	0	422	0.23
46	0	0	1	1	1	0	383	0.20
47	1	0	0	0	0	1	259	0.14
48	0	0	1	1	0	0	221	0.12
49	1	0	0	0	1	1	190	0.10

**Table 7. (cont)**

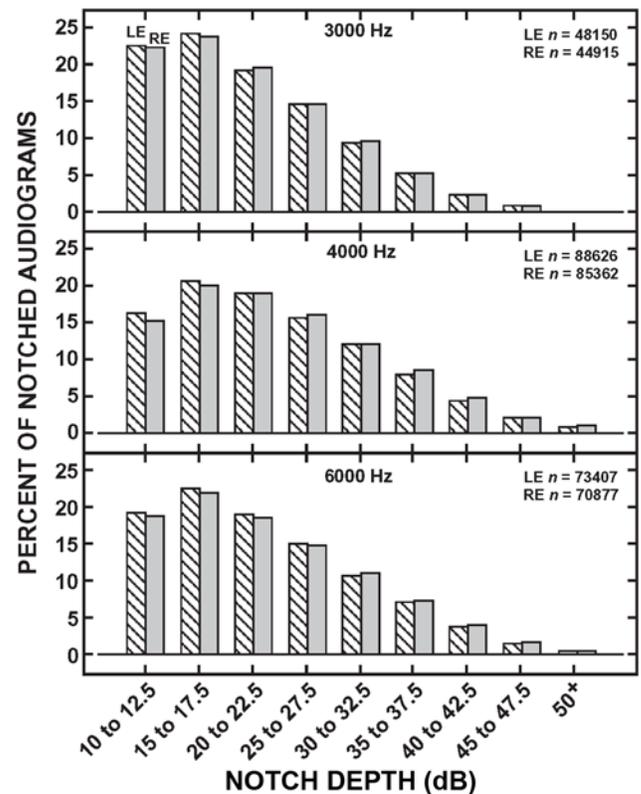
Number and percentage of 187,395 participants for each of 63 notch configurations. Data are ranked according to prevalence. Notch frequency is indicated by "1" in ear/frequency column.

Row	Left Ear (Hz)			Right Ear (Hz)			n	%
	3,000	4,000	6,000	3,000	4,000	6,000		
50	1	0	1	0	0	1	186	0.10
51	1	1	1	1	0	1	177	0.09
52	1	0	1	1	1	1	152	0.08
53	0	1	1	1	0	0	139	0.07
54	0	0	1	1	0	1	136	0.07
55	1	0	1	0	1	0	100	0.05
56	1	1	0	1	0	1	92	0.05
57	1	0	1	1	1	0	87	0.05
58	0	1	1	1	0	1	86	0.05
59	1	0	1	1	0	0	78	0.04
60	1	0	1	0	1	1	75	0.04
61	1	0	0	1	0	1	70	0.04
62	0	1	0	1	0	1	65	0.03
63	1	0	1	1	0	1	37	0.02
Total							187,395	100.00

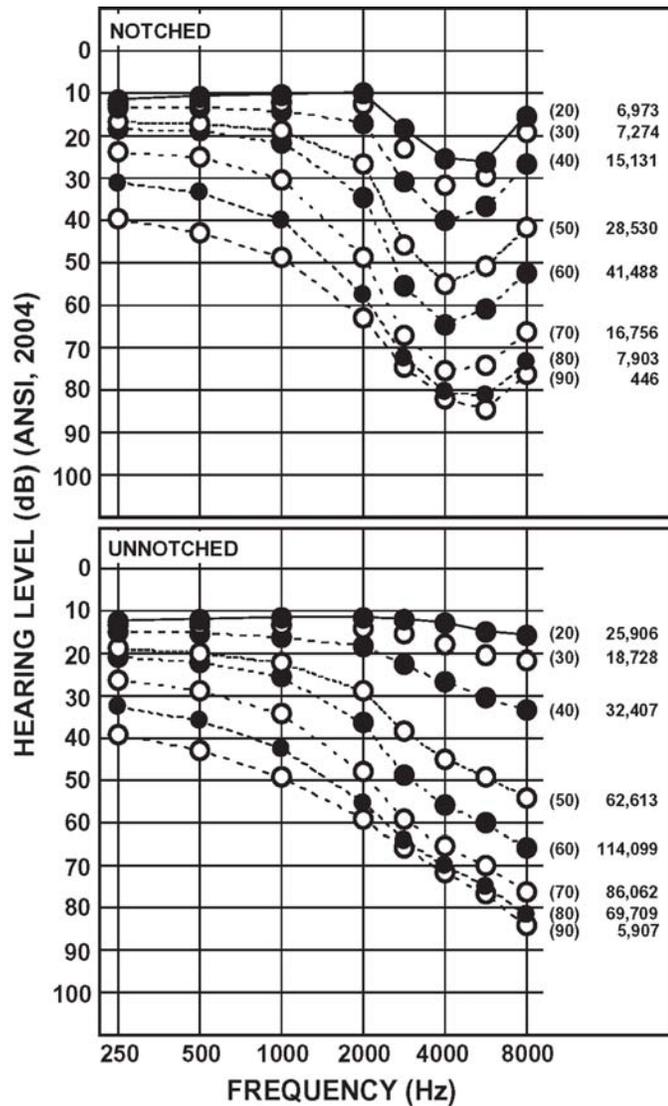
different depths/widths of these notches reflect the combined influences of different magnitudes/durations of noise exposure and individual susceptibility to acoustic trauma. Without a direct cause and effect link, however, speculation is just that, speculation.

#### Group 2 Mean Audiograms

The mean audiograms for the RE are shown for the eight decades in **Figures 15** and **16**. In each panel of both figures, the number of participants is indicated. As presented earlier with the group 1 data, three mean audiograms are depicted in each panel of **Figure 15**, including notched audiograms (filled circles), unnotched audiograms (black open circles), and mean audiograms (gray open circles). As with the 4,000 Hz data in **Figure 9**, the following three relations are noteworthy in **Figure 15** (again, the data in **Figure 15** are a subset of the data in **Figure 9**): (1) the pure-tone thresholds at 250 to 2,000 Hz are essentially the same for the notched and unnotched groups; (2) in all age groups except the 20s, the mean threshold at 8,000 Hz for the notched group is lower (better) than the mean threshold at 8,000 Hz for the unnotched group; and (3) the effect of the notched audiograms on the overall mean audiogram is minimal, with the mean audiograms not reflecting the presence of a notch. **Figure 16** shows the mean 3,000, 4,000, and 6,000 Hz notched ( $n = 124,501$ , 23.1%) and unnotched ( $n = 415,431$ , 76.9%) RE audiograms for the eight decade groups. Again, the data are very similar to the data shown



**Figure 14.** Histograms of percentage of left ear (LE) (striped) and right ear (RE) (shaded) notched audiograms at 3,000, 4,000, and 6,000 Hz for nine notch depths.

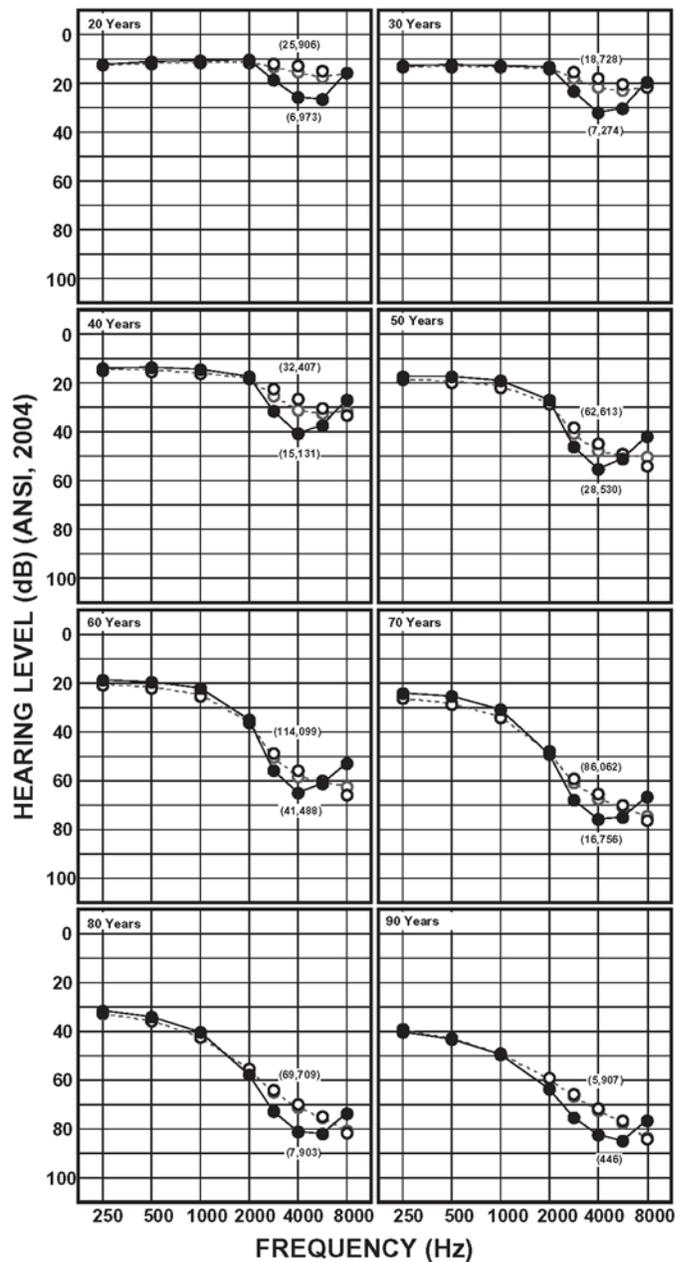


**Figure 15.** Mean right ear notched and unnotched audiograms for eight age groups (indicated in parentheses). Adjacent numbers are number of participants in each group. Notched  $n = 124,501$ ; unnotched  $n = 445,431$ . Hearing level as defined by American National Standards Institute (ANSI) [32].

for the 4,000 Hz data in **Figure 10**, except the data in **Figure 16** include the 3,000 and 6,000 Hz thresholds.

**DISCUSSION**

As indicated in the “Introduction,” this study proposed to extend the findings regarding high-frequency



**Figure 16.** Mean right ear notched (filled circles) and unnotched (black open circles) audiograms for eight age groups. Gray open circles are average audiogram for the two groups in each panel. Numbers in parentheses indicate number of participants in each group. Hearing level as defined by American National Standards Institute (ANSI) [32].

notched audiograms from a previous local group of veterans ( $n = 3,430$ ) to a substantially larger group that represented veterans from across the country. The mean ages

of the participants in both studies were similar, ~63 yr. In the original Wilson study [28], only audiometric notch data at 4,000 Hz were examined because the majority of the participants did not have thresholds at 3,000 and 6,000 Hz; the larger number of participants in the current study permitted examination of data from these two additional high frequencies. With the original report involving 3,430 veterans, 41.1 percent had a 4,000 Hz notch in at least one ear (15.4% bilateral, 13.8% LE unilateral, 11.9% RE unilateral). In the current group of 744,553 veterans, only 22.9 percent had a 4,000 Hz notch in at least one ear (6.9% bilateral, 8.3% LE unilateral, 7.6% RE unilateral). Although the overall prevalence of 4,000 Hz notches is about half in the current study with the larger number of participants, the results from both studies indicate about twice as many individuals with unilateral notches as with bilateral notches. Three other direct comparisons can be made between the two studies. Consider the distribution of notches by age. In the original study [28, p. 27: Figure 2], the percentage of participants with notches was much smaller in the two earliest decades (20s and 30s) than in the middle decades, whereas in the current data, the percentage of participants with notches is relatively equally distributed from the 20s through the 60s (**Figure 3**). In contrast to the above two relations between the two studies, the distributions of the percentage of notched audiograms (at 4,000 Hz) by the nine notch depths were very similar ([28, p. 28: Figure 3] and **Figure 5** in the current report). A final similarity between the two studies can be observed with the mean audiograms plotted for the unnotched participants and the notched participants ([28, p. 29: Figure 5] and **Figure 10** in the current report). Interestingly, in both studies for both the unnotched and notched audiograms the largest differences between the mean data occur between the 40 and 50 yr decades. These cross-sectional data suggest a nonlinear change in high-frequency thresholds across the age span.

The definition of the “audiometric notch” used in this project was simple to implement and at the same time provided substantial flexibility in the analyses of the data. To be considered a notch, the threshold at the target frequency had to be bordered at 2,000 and 8,000 Hz by thresholds that were both minimally at HLs 10 dB lower (better) than the threshold at the target frequency. These minimal notch criteria were the starting point, with subsequent analyses able to parse the notch depths into 17 bins in 2.5 dB steps. With this technique of analyses and

reporting, in many instances the reader can apply his or her own notch-depth criteria and interpret the data from that point of view. For example with the 4,000 Hz notch data (group 1) in **Figures 5, 6, and 7**, if a notch depth of 10.0 to 12.5 dB is considered too liberal, then the 10.0 to 12.5 dB data can be ignored and the minimal notch depth increased to 15.0 dB, etc.

Finally, as commented by Jerger [51], the assumption is that most high levels of noise are experienced in a sound- or free-field environment. Exposure to excessive noise in this environment would be expected under most circumstances to have an equal effect on both ears. Why, then, are there more unilateral high-frequency notches than bilateral high-frequency notches? The presence of more unilateral notches than bilateral notches prompts at least two lines of thought. First, the high-frequency notches are caused by a multitude of factors including excessive noise exposure. Second, the ears are differentially sensitive to whatever factors are eventually found to be responsible for high-frequency audiometric notches. Both lines of reasoning deserve further investigation.

## CONCLUSIONS

The 4,000 Hz notch data from 744,553 participants and the 3,000, 4,000, and 6,000 Hz notch data from 539,932 participants reveal several new characteristics about and several relations among high-frequency audiometric notches that can be summarized as follows:

1. The mean LE and RE pure-tone thresholds are equal at 250, 500, and 1,000 Hz, but in the higher frequencies, the mean RE thresholds are about 2 dB lower (better) than the corresponding LE thresholds.
2. The majority of audiogram pairs did not exhibit a high-frequency notch. With the 4,000 Hz data, 77.1 percent of the participants did not have a notch in either ear, whereas with the 3,000, 4,000, and 6,000 Hz data, 65.3 percent did not have a notch.
3. Unilateral 3,000, 4,000, and 6,000 Hz notches are more prevalent than bilateral notches at those same frequencies, with unilateral LE, unilateral RE, and bilateral notches having roughly the same prevalence.
4. LE 3,000, 4,000, and 6,000 Hz notches are slightly more prevalent than RE notches at those same frequencies.
5. Of the 63 combinations of notch frequency and ear, the most prevalent notch configuration was 6,000 Hz

in the LE, followed by 6,000 Hz in the RE, 4,000 Hz in the LE, and 4,000 Hz in the RE. The fifth and sixth most prevalent were the 4,000 and 6,000 Hz combination in the LE and the 4,000 and 6,000 Hz combination in the RE. The least prevalent was the bilateral 3,000 and 6,000 Hz combination.

6. The prevalence of notches maximizes in the 40 to 50 yr decades, decreasing substantially in the 70 to 90 yr decades.
7. The prevalence of unilateral 4,000 Hz notches was greater than the prevalence of bilateral 4,000 Hz notches for the two shallow notch depths (10.0 to 12.5 and 15.0 to 17.5 dB), a relation that was just reversed for the notch depths >25.0 dB, at which the prevalence of bilateral notches was greater.
8. Notches at 3,000, 4,000, and 6,000 Hz are asymmetric, with the low-frequency side typically twice as deep (or steep) as the high-frequency side.
9. With the younger participants, the low-frequency side of the notch was only slightly steeper than the high-frequency side, whereas with the older participants, the low-frequency side was substantially steeper than the high-frequency side.
10. Bilateral notches on average are several decibels deeper than unilateral notches.
11. The LE and RE notch depths are about the same, with mean depths of ~23 dB. The most prevalent notch depth for 3,000, 4,000, and 6,000 Hz was 15.0 to 17.5 dB.
12. The distributions of notch depths vary as a function of age, with skewed distributions at the age extremes and more normal distributions in the 40 to 60 yr decades.
13. Comparison of the mean notched and unnotched audiograms reveals comparable thresholds 250 to 2,000 Hz. In the higher frequencies, however, the mean thresholds for the notched group were higher (poorer) at the notch frequency, but typically lower (better) at 8,000 Hz than the mean thresholds for the unnotched group.

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### Author Contributions:

*Study concept and design:* R. H. Wilson, R. McArdle.

*Acquisition of data:* R. McArdle, R. H. Wilson.

*Analysis and interpretation of data:* R. H. Wilson, R. McArdle.

*Drafting of manuscript:* R. H. Wilson, R. McArdle.

*Critical revision of manuscript for important intellectual content:* R. H. Wilson, R. McArdle.

*Statistical Analysis:* R. McArdle, R. H. Wilson.

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