Americans Hear as Well or Better Today Compared With 40 Years Ago: Hearing Threshold Levels in the Unscreened Adult Population of the United States, 1959–1962 and 1999–2004

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Objectives: (1) To present hearing threshold data from a recent nationally representative survey in the United States (National Health and Nutrition Examination Survey, 1999–2004) in a distributional format that might be appropriate to replace Annex B in international (ISO-1999) and national (ANSI S3.44) standards and (2) to compare these recent data with older survey data (National Health Examination Survey I, 1959–1962) on which the current Annex B is based.

Design: Better-ear threshold distributions (selected percentiles and their confidence intervals) were estimated using linear interpolation. The 95% confidence intervals for the medians for the two surveys were compared graphically for each of the four age groups and for both men and women. In addition, we calculated odds ratios comparing the prevalences of better-ear hearing impairment (thresholds $>$ 25 dB HL) between the two surveys, for 500, 1000, 2000, and 4000 Hz, and for their four-frequency average.

Results: Across age and sex groups, median thresholds were lower (better) in the 1999–2004 survey at 500, 3000, 4000, and 6000 Hz (8000 Hz was not tested in the 1959–1962 survey). For both men and women, the prevalence of hearing impairment was significantly lower in 1999–2004 at 500, 2000, and 4000 Hz, but not at 1000 Hz.

Conclusions: For men and women of a specific age, high-frequency hearing thresholds were lower (better) in 1999–2004 than in 1959–1962. The prevalences of hearing impairment were also lower in the recent survey. Differences seen at 500 Hz may be attributable at least in part to changes in standards for ambient noise in audiometry. The National Health and Nutrition Examination Survey 1999–2004 distributions are offered as a possible replacement for Annex B in ISO-1999 and ANSI S3.44.

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INTRODUCTION

Both international (ISO-1999, 1990) and national (ANSI S3.44-1996) standards describe the distributions of hearing thresholds (10th, 50th, and 90th percentiles, for 0.5 to 6 kHz) associated with age and sex. These standards also describe the distributions of threshold shifts associated with noise exposures of specified levels and durations, along with a model for combining age-related and noise-induced components to predict the resultant distributions for noise-exposed populations. ISO-1999 gives two databases for age-related hearing loss: Annex A is based on studies of "highly screened" people who are otologically normal and report minimal occupational or nonoccupational noise exposure, whereas Annex B is based on the U.S. National Health Examination Survey (NHES) of 1959–1962 (summarized by Glorig & Roberts 1965) and is considered to be unscreened, that is, no exclusion of subjects in the sample based on otologic or noise exposure history. The Annex B data base is now quite old, and the International Organization for Standardization is considering whether to revise it (Blaeser 2008).

Since the 1960s, the U.S. Federal government has conducted several subsequent audiometric surveys, but not until the late 1990s did it again collect nationally representative data, in the current continuous National Health and Nutrition Examination Survey (NHANES), that were complete enough to possibly replace Annex B. Some summaries of the 1999–2004 NHANES data for U.S. adults have been published (Agrawal et al. 2008, 2009), but not in the distribution format of the ISO and ANSI standards.

The primary purposes of this study are as follows: (1) to present the NHANES 1999–2004 data in the appropriate distributional format as a table that might be appropriate to replace Annex B when ISO-1999 and ANSI S3.44 are updated and (2) to compare these recent data with the data on which the current Annex B is based. In making these comparisons, the original 1959–1962 NHES I data were reanalyzed using the same methods that have been applied to the current NHANES 1999–2004 data.

MATERIALS AND METHODS

The National Health and Nutrition Examination Survey

The U.S. NHESs (NHES I and NHANES 1999–2004) were complex, multistage, stratified, cluster-sample design surveys conducted by the U.S. National Center for Health Statistics, Centers for Disease Control and Prevention. The surveys were designed to assess the health status of the civilian, noninstitutionalized U.S. population by a health-related household questionnaire, medical examinations, physiological measurements, and laboratory tests. Detailed information on the NHES I and NHANES 1999–2004 protocols is available elsewhere (National Center for Health Statistics 2009). NHES I did not over-sample any specific demographic subgroups; however, to produce reliable statistics in key population subgroups, NHANES 1999–2004 over-sampled low-income persons, ad-

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olescents 12 to 19 yrs, persons older than 60 yrs of age, African Americans, and Mexican Americans.

NHES I conducted hearing examinations on the full sample of adults aged 18 to 79 yrs, with a response rate of 86% (6645 people tested). NHANES 1999–2004 conducted audiometric examinations on one-half of the sampled U.S. adults aged 20 to 69 yrs, with a response rate of 73% (5742 people tested). For comparability to Annex B, we analyzed the audiometric data for the subset of men and women between 25 and 64 yrs of age, which resulted in a sample size of 5021 adults in NHES I and 4218 adults in NHANES 1999–2004. Both surveys were conducted with Institutional Review Board approval and written consent of all participants.

The NHES I survey included an otoscopic examination conducted by a physician and air conduction pure-tone audiometric testing conducted by trained technicians from October 1959 to December 1962. The household questionnaire included only a few hearing-related questions on tinnitus, dizziness, and medical conditions known to affect hearing. In NHANES 1999–2004, the audiometry examination component included otoscopy, tympanometry, and air conduction pure-tone audiometry, all conducted by trained health technicians. Household questionnaire items were more extensive and included questions about subjective hearing loss, hearing aid use, tinnitus, balance, and both occupational and nonoccupational noise exposure.

In NHES I, audiometric testing was conducted manually, and thresholds were sought through a bracketing technique and then determined on the basis of decreasing presentations (Glorig & Roberts 1965). The bracketing technique called for a threshold search beginning at 40 dB HL, increasing to higher levels if necessary to obtain a definite response, then decreasing in intensity until the response became “doubtful.” The examiner then reset the intensity to the last level at which there had been a definite response and decreased in 5-dB steps until the subject no longer responded. Threshold was defined as the level of the last definite response. Tones were presented using an audiometer and TDH-39 headphones calibrated with a 6 cm^3 coupler, and the first test ear was alternated to avoid a learning effect. Testing included 0.5, 1, 2, 3, 4, and 6 kHz in each ear. Masking was not used. A retest threshold was obtained at 1000 Hz to confirm threshold consistency; however, only the better threshold was retained in the data.

For NHANES 1999–2004, audiometric testing was conducted in a sound booth (Acoustic Systems, Austin, TX, model Delta 143) installed in a dedicated testing room in the mobile examination center (four trailers that were linked together for use at each testing site or “stand”). Ambient room noise under the conditions that would exist during a typical examination was measured at the beginning and end of each stand (survey location) and weekly throughout the stand using a Quest 1800 sound level meter and OB-300 filter set. Background noise levels in the audiometric test room never exceeded and were generally better than the maximum permissible ambient noise levels specified by Table 2 in ANSI S3.1-1991 for testing with ears covered in the frequency range of 500 to 8000 Hz. Although this standard was revised in 1999, the 1991 standard continued to be used through the 2004 examination cycle, because the revised standard was released too late to be incorporated into survey planning. In addition, background noise was monitored continually throughout each examination using a Quest BA-201-25 bioacoustic simulator and octave band monitor. The octave monitor was programmed to the ANSI S3.1-1991 ambient noise standard at all frequencies except 500 Hz; because of microphone limits, the octave monitor could only indicate noise levels exceeding 25.0 dB (rather than the required 19.5 dB) at this frequency. Audiometric testing was conducted using an Interacoustics AD226™ microprocessor audiometer. Thresholds were obtained using a pulsed-tone stimulus, representing a change from previous surveys, which used a steady tone. Studies indicate that a pulsed signal reduces the number of false-positive responses (Dancer & Conn 1983) without an effect on the thresholds obtained (Hamill & Haas 1986). A pulsed-tone stimulus is permitted by American Speech-Language-Hearing Association guidelines for pure-tone audiometry (ASHA 1978).

The calibration of all equipment was checked on a regular basis. The output and linearity of the audiometer were checked at the beginning and end of each stand using a Quest 1800 sound level meter and OB-300 filter connected to a Quest model EC-9A 6 cm^3 earphone coupler (supra-aural headphones) or a Brüel and Kjær model DB 0138 2 cm^3 coupler (insert earphones). Headphone calibration met the reference equivalent sound pressure levels specified by Table 6 for TDH-39 headphones and Table 7 for insert earphones calibrated with an HA-2 coupler in ANSI S3.6-1996 adjusted at 3000 to 8000 Hz to correct for the Quest filter slope. A tolerance of ±3 dB at 500 to 4000 Hz and ±5 dB at 6000 to 8000 Hz was permitted for output, and a tolerance of ±1 dB was permitted for linearity as specified by ANSI S3.6-1996. Calibration was monitored daily using the Quest BA-201-25 bioacoustic simulator. Any daily calibration value >5 dB from the reference value triggered a re-evaluation of the audiometer using the sound level meter. A daily listening check was also performed. Audiometers received a comprehensive calibration traceable to the National Institute of Standards and Technology annually.

Unlike NHES I, the current NHANES 1999–2004 audiometric thresholds were generally obtained using a specially programmed automated test based on the Hughson-Westlake procedure (Carhart & Jerger 1959). The tones were initially presented at a presumably comfortable listening intensity (e.g., 40 dB HL), then followed the “up 5-dB/down 10-dB” method of threshold search. Threshold was defined as the level at which the subject responded at least 50% of the time (two of three or three of five trials) to ascending or descending presentations. This change was introduced to reduce threshold variability, on the basis of studies which have shown that within-subject threshold differences are significantly lower with computer-controlled audiometry, while the thresholds obtained differ by <5 dB from those obtained manually (Harris 1979; Jerlvall et al. 1983). Technicians did conduct testing manually as necessary when, for example, the subject was unable to operate the response switch, did not respond within the time window of the audiometer, or demonstrated a high false-positive rate. Thresholds were usually obtained using TDH-39P earphones; insert transducers (EARtone 3A) were used in participants with collapsing ear canals or when marked interaural asymmetry was found. Thresholds were obtained for each ear at 0.5, 1, 2, 3, 4, 6, and 8 kHz, and a retest threshold was obtained at 1000 Hz in each ear to confirm threshold measurement consistency. The first test ear was alternated, and masking was not used. However, thresholds were retested in the poorer ear with insert earphones when marked interaural asymmetry was found.

Audiometry in NHES I, like all audiometry in the U.S. until 1964, used the old ASA Z24.5-1951 calibration standard, based on hearing surveys done in the 1930s. By 1964, ISO had reviewed newer studies showing that most young healthy adults had thresholds lower (better) than the audiometric zero of the 1951 standard and recommended a new audiometric calibration standard (ISO-R389 1964); this was adopted by ANSI in 1969 and is the basis of current international (ISO-389-1 1998) and American (ANSI S3.6-2004) standards. Thus, audiograms done in the U.S. before 1964 (and some done in the late 1960s) cannot be compared with those done after 1969 without correcting for the change in calibration. When Glorig and Roberts (1965) presented the NHES I data, they included an appendix that showed the necessary correction factors that needed to be added for each frequency to allow comparability with the new recommended standard; Johnson (1978) used those factors in constructing the Tables in Annex B. We used the same factors, rounded to whole decibels, in our analyses of NHES I thresholds, by adding 14, 10, 9, 9, 6, and 10 dB HL, to thresholds at 0.5, 1, 2, 3, 4, and 6 kHz, respectively.

The Annex B Format

Annex B describes the distributions of better-ear hearing thresholds for each of several age/sex groups (e.g., women aged 50, who are 45 to 54 yrs, etc.) at each frequency, by three numbers, the 10th, 50th, and 90th percentiles. Neither Glorig and Roberts (1965) nor any of the other Federal reports of the NHES I hearing threshold data define the term "better ear," but analysis of the raw data tapes makes it clear that this was determined on a frequency by frequency basis. In other words, the better-ear threshold at each frequency was simply the threshold of the ear with the lower threshold for that frequency (we determined this by comparing distributions obtained with this definition to the tables published by Glorig and Roberts). The percentile values in Annex B were estimated by Johnson (1978) using the distributions by Glorig and Roberts . In each case, he simply plotted a cumulative distribution on probability paper, then used a ruler to draw two straight lines by hand that seemed to best fit the right and left halves of the distribution, with the constraint that the lines intersect at the 50th percentile. The estimated 10th, 50th, and 90th percentiles could then be read off the "best-fit" lines. Using the data file for the NHES I audiometry, we re-estimated the distributions using the same methods described below that were applied to the NHANES data.

Statistical Analysis

The statistical programs SAS™ version 9.2 (SAS Institute Inc., Cary, NC) and SUDAAN™ (Research Triangle Institute, Research Triangle, NC) were used to assemble the data and to account for the complex-survey design in the analysis. Population estimates for medians and percentiles were weighted using the NHANES examination sample weights to produce nationally representative estimates. The NHANES examination sample weights incorporate the differential probabilities of selection and include adjustments for over-sampling of selected populations, noncoverage, and nonresponse (in the context of survey research, noncoverage refers to the potential problem that some groups in the population do not appear in the sampling frame). Standard errors were estimated using SUDAAN by Taylor series linearization. Estimates for each frequency, for each of the eight subgroups based on age and sex, were calculated using the cumulative threshold distributions (see below). Percentiles were estimated by linear interpolation.

For comparability with the current version of Annex B, we defined "better ear" as described earlier and divided the NHANES sample into four age groups: 25 to 34, 35 to 44, 45 to 54, and 55 to 64 yrs of age (nominally 30, 40, 50, and 60 yrs). In the NHES I dataset, both men and women aged 25 to 34 yrs displayed distributions at 1000 Hz that were extremely truncated, with >40% of thresholds at the lowest presentation level (−10 dB HL by the old calibration standard, 0 dB HL by the current standard). To estimate medians (50th percentiles) and their confidence intervals (CIs), which include both higher and lower percentiles, for example 42nd to 58th, it was therefore necessary to assume that no subject would have responded at the next lower level (−5 dB HL by the current standard); that assumption may of course be incorrect, in which case the confidence limits for the medians for these two subgroups could have been wider.

The NHANES dataset presented very mild truncation problems, only for the youngest group of women, at 3000 and 4000 Hz, and only for the 5th percentile values (for the 5% with the lowest thresholds). This was handled as described earlier, by assuming that no subject would have responded at a level below the lowest presentation level.

In reporting the NHANES 1999–2004 and NHES I data, we considered a measured threshold of "x" dB HL to be the midpoint of the interval from $x - 2.5$ to $x + 2.5$ dB HL. This "midpoint" convention has the desirable property that percentiles estimated by linear interpolation correspond closely and without bias to those estimated by simply counting cases, by using a spreadsheet such as MS Excel™, or by using the grouped-data method (Dobie 2006). For example, consider this distribution of 100 thresholds:

Threshold (dB HL)	Interval	No. of cases	Cumulative proportion
5	2.5–7.5	10	0.10
10	7.5–12.5	24	0.34
15	12.5–17.5	32	0.66
20	17.5–22.5	24	0.90
25	22.5–27.5	10	1.00

The simple median (50th percentile) is obviously 15 dB HL. The same median is obtained by interpolation when cumulative proportions are plotted against the interval boundaries above (Fig. 1, solid line).

In contrast, some statistical programs (including SUDAAN) allow the specification that the measured value is the upper limit of a 5-dB range; this approach leads to estimates of medians and other percentiles that are exactly 2.5 dB lower than those obtained with the midpoint convention (e.g., the median of the distribution shown above would be reported as 12.5 dB HL). If the cumulative proportions are plotted against measured thresholds and one looks for the point in which the curve intersects the 50th percentile (this is the graphical

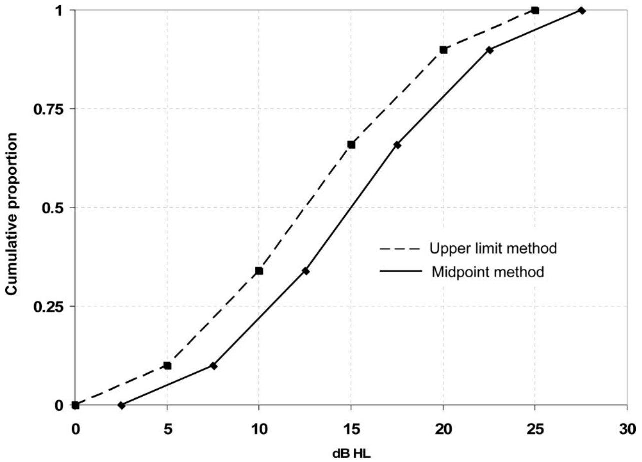

Fig. 1. Cumulative distributions for a hypothetical set of hearing thresholds (see text). Medians can be estimated by interpolation at the points where cumulative proportion = 0.5. The solid curve is based on the convention that a threshold estimate of "x dB" is the midpoint of a range from $x - 2.5$ to $x + 2.5$ dB (median = 15 dB HL). The dashed curve is based on the convention that the threshold estimate is the upper limit of a range from $x - 5$ to x dB (median = 12.5 dB HL).

method used by Johnson to estimate the percentiles in Annex B) the result is again 12.5 dB HL, because the upper limit assumption was used (Fig. 1, dashed line). Interpolation yields the correct answer (15 dB HL) only when each measured threshold is considered to be the midpoint of a 5-dB-wide interval (Fig. 1, solid line).

In addition to the 10th, 50th, and 90th percentile values presented in Annex B, the 5th and 95th percentiles were estimated from the NHANES 1999–2004 data. All tabled threshold estimates are rounded to the nearest integer.

Ninety-five percent confidence intervals (95% CI) for percentile estimates were obtained using two methods. SUDAAN uses a linear interpolation method, based on normal approximation, as described by Altman et al. (2000). For example, the standard error (SE) of the median, expressed in terms of proportions (at the 50th percentile, $p = q = 0.5$), is estimated to be $\sqrt{\frac{pq}{N}} = \frac{0.5}{\sqrt{N}}$; for a sample of 100 cases, the SE would be 0.05 or 5 percentile units, and the 95% CI of the median (±2 SEs) would thus extend from the 40th to the 60th percentile (13.5 to 16.5 dB HL, for the data tabulated above). Although these 95% CIs are symmetrical in percentile terms, they are generally not symmetrical in terms of decibels, especially at the tails of the distributions. Interpolated confidence limits, even for the 5th and 95th percentiles, never exceeded the range of presentation levels (-10 to 110 dB HL for 8 kHz, -10 to 120 dB HL for all other frequencies). We also used a resampling (bootstrap) method, as described by Korn and Graubard (1999). The widths of the 95% CIs using the two methods were very highly correlated ($R^2 = 0.997$), but the resampling method yielded 95% CI widths that were always slightly narrower (by 8% on average) than those obtained with linear interpolation. The figures in this report are based on the more conservative interpolation estimates of 95% CIs; both these and the bootstrap estimates are available on request.

In addition to the frequency by frequency analyses described above, we compared the number of subjects with hearing thresholds >25 dB HL at each of four frequencies, 500, 1000, 2000, and 4000 Hz, and for the four-frequency averages (4FAs) of thresholds at these frequencies, for each subject's better ear for NHANES 1999–2004 versus NHES I. A better-ear 4FA exceeding 25 dB HL has been used as a criterion for hearing impairment that is mild or worse in other surveys (Davis 1989). The odds ratios were calculated for prevalence at each frequency of hearing threshold >25 dB HL and of better-ear 4FA >25 dB HL for NHANES 1999–2004 men and women across the age range 25 to 64 yrs, using the NHES I subgroups of the same sex and age range as reference groups.

RESULTS

Table 1 shows the better-ear values in Annex B (ISO-1999, 1990), based on the 1959–1962 NHES I data, as corrected by Clark and Bohl (1992). When the source data were reanalyzed using the same assumption that had been used in creating Annex B (recorded threshold as the upper limit of the range in which the true threshold resides), all but seven of the recalculated medians, 10th, and 90th percentiles were within 1 dB HL of the Annex B values in Table 1, with a mean difference of only 0.2 dB HL. Because the two sets of estimates were obtained using different methods (linear interpolation versus hand-drawn "best-fit" lines, as described in the Materials and Methods section), these small differences were not considered of material importance.

Table 2 shows the NHANES 1999–2004 threshold distributions in the same format. These estimates are based on the midpoint convention. Thus, they are 2.5 dB higher than if the "upper limit" convention had been used. As mentioned in the Materials and Methods section, the 5th percentile values may not be accurately estimated for women aged 25 to 34 yrs, at 3000 and 4000 Hz, because of truncation of the data.

To compare the 1959–1962 NHES I data with the 1999–2004 NHANES data, the 95% CIs for the medians of both datasets, using the midpoint convention for both, are plotted according to decibel hearing level and log frequency in Figures 2a–d (for men) and 3a–d (for women). Therefore, the plotted NHES I thresholds are 2.5 dB higher than those in Annex B. Each figure has four curves: the solid lines indicate the upper and lower 95% confidence limits for NHANES 1999–2004 and the dashed lines show the same limits for NHES I. When the 95% CIs fail to overlap, it is reasonable to conclude that there are significant differences between the two populations. On inspection, it is clear that for each age group, median thresholds at 1000 and 2000 Hz for men and women in 1999–2004 are very similar to those seen in 1959–1962. Equally clearly, the median thresholds are better (lower) at 500, 3000, 4000, and 6000 Hz in the NHANES 1999–2004 results. For these frequencies, most age/sex groups show no overlap between the NHANES 1999–2004 and NHES I CIs. The median differences are largest at 6000 Hz, up to 11 dB HL for men aged 30 yrs (25 to 34 yrs) and 9 dB HL for women aged 60 yrs (55 to 64 yrs).

It is apparent from the figures that although most of the 95% CIs were <5 dB wide, the CI widths were larger when the estimated medians were larger. This was true for all percentiles (5th, 10th, 50th, 90th, and 95th); the CI width was systematically related to the percentile estimate in decibels. When that

TABLE 1. Annex B percentile distribution of hearing threshold levels according to frequency by age group and gender, U.S. National Health Examination Survey I, 1959–1962 (ISO-1999, 1990; Clark & Bohl 1992)

	Hearing Threshold Level (dB HL) Age*											
	30			40			50			60		
	Percentiles											
Frequency (Hz)	10	50	90	10	50	90	10	50	90	10	50	90
Men												
500	−1	7	15	0	8	19	1	10	21	2	12	26
1000	−5	0	10	−4	3	15	−3	5	16	−2	6	21
2000	−4	2	13	−3	4	19	−2	8	28	0	10	43
3000	−1	9	30	2	13	41	5	19	51	9	30	62
4000	−1	10	38	4	17	50	8	26	54	12	36	68
6000	8	18	48	11	24	62	17	31	62	22	46	80
Women												
500	−1	6	15	0	7	19	1	10	23	4	14	29
1000	−6	1	9	−5	2	13	−4	4	16	−2	7	21
2000	−6	0	10	−4	2	13	−2	6	23	0	8	29
3000	−4	4	13	−2	6	18	0	9	26	6	16	37
4000	−5	4	16	−4	6	18	−1	9	26	4	17	43
6000	3	12	25	5	15	31	8	20	45	15	29	57

Age is grouped in 10-yr intervals, that is, "30" represents ages 25–34 yrs, etc.

estimate was 10 dB HL or less, the CIs were always <6-dB wide. When percentile estimates were 20 dB HL or less, CIs were <9 dB wide. For percentile estimates of 30 dB HL or less, CIs were <13 dB wide. When percentile estimates exceeded 30 dB HL, most CIs were 10 to 15 dB wide, with only one CI width exceeding 20 dB.

Table 3 shows the odds ratios for the prevalence of 4FA >25 dB HL in the NHANES 1999–2004 data, compared with NHES I. For both men and women, the prevalence of hearing loss of mild or worse degree, defined as thresholds >25 dB HL, is lower for NHANES 1999–2004 compared with NHES I, which is indicated in the table by odds ratios <1.00. The odds ratio estimate for the better-ear 4FA is 0.56 for men and 0.66 for women, both of which indicate significantly lower prevalence of hearing loss for NHANES 1999–2004 as compared with NHES I. Similarly, each of the individual frequencies studied had significantly reduced odds ratios, except at 1000 Hz. At this frequency, although the odds ratio was <1.00 (0.81 and 0.91, for men and women, respectively), the 95% CIs included 1.00 and the corresponding *p* values were not signif-

TABLE 2. Proposed new Annex B; percentile distribution of hearing threshold levels according to frequency by age group and gender, U.S. National Health and Nutrition Examination Survey, 1999–2004

	Hearing Threshold Level (dB HL) Age*																			
	30					40					50					60				
	Percentiles																			
Frequency (Hz)	5	10	50	90	95	5	10	50	90	95	5	10	50	90	95	5	10	50	90	95
Men																				
500	−2	−1	7	16	20	−2	−1	8	19	22	−1	1	10	20	24	−1	2	11	23	29
1000	−5	−2	4	14	17	−2	−1	6	17	21	−1	1	9	18	24	−2	1	11	23	32
2000	−7	−5	4	14	19	−6	−3	6	20	24	−2	0	10	24	34	−1	3	14	38	50
3000	−6	−5	4	17	23	−4	−1	9	29	39	0	3	15	45	56	4	7	25	57	65
4000	−5	−2	7	23	34	−1	2	13	39	53	3	6	22	57	67	9	13	35	65	72
6000	−3	0	11	27	34	2	4	17	41	57	6	9	25	64	75	13	16	40	74	79
8000	−5	−2	8	21	30	−1	2	14	41	57	4	7	23	61	74	8	13	42	78	84
Women																				
500	−2	0	7	17	20	−2	−1	7	19	24	−1	1	9	21	26	3	4	13	27	35
1000	−5	−3	4	12	15	−4	−2	5	15	20	−2	−1	7	19	23	−1	1	10	26	34
2000	−7	−4	4	12	14	−5	−2	5	16	21	−4	−1	7	21	27	−1	1	11	28	37
3000	−8	−6	2	11	14	−6	−2	4	15	21	−4	−2	7	21	27	−1	2	12	33	43
4000	−8	−5	4	14	16	−5	−2	7	19	25	−2	0	10	26	32	1	4	16	40	51
6000	−3	0	10	22	26	0	3	12	27	31	1	4	17	34	40	7	9	24	49	58
8000	−5	−2	7	17	22	−2	1	10	25	31	1	4	16	39	48	7	10	26	58	66

Age is grouped in 10-yr intervals, that is, "30" represents ages 25–34 yrs, etc.

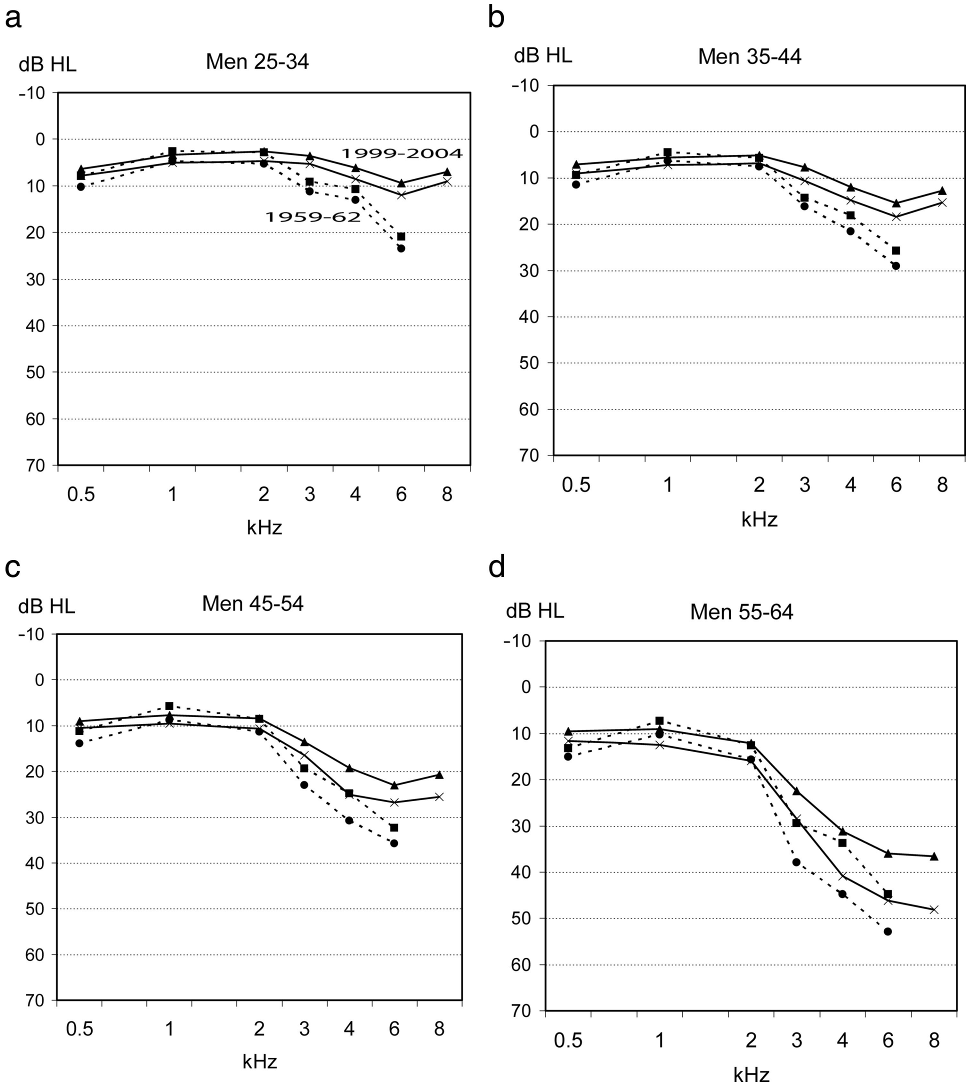

Fig. 2. For the better ears of men in each of four age groups (25 to 34, 35 to 44, 45 to 54, and 55 to 64 yrs), the 95% confidence intervals for medians are shown in audiometric format (threshold in dB HL vs. frequency in kHz). The solid curves represent NHANES 1999–2004 and the dashed curves represent NHES I 1959–1962.

icant. Hence, there was no statistical difference in the prevalence of hearing impairment, that is, hearing thresholds >25 dB HL, only at 1000 Hz.

DISCUSSION

Both the NHANES 1999–2004 and NHES I datasets show the typical features of age-related hearing loss: hearing thresholds increasing with age, with a generally downsloping configuration, in an accelerating fashion (i.e., thresholds increase faster in middle age than in young adulthood). In middle age, men hear much worse than women in the high frequencies, but slightly better than women at 500 Hz.

Comparison of the two datasets shows that median thresholds, for men and women of all ages, have improved at several frequencies: 500, 3000, 4000, and 6000 Hz. Changes at 500 Hz may be attributable, at least in part, to changes in ambient noise standards for audiometry. The test booths in the NHES I were not always able to meet even the relatively lenient standards of 1960 (e.g., 40 dB SPL for the 500 Hz octave band; Glorig & Roberts 1965), whereas NHANES 1999–2004 booths were required to meet stricter standards (19.5 dB SPL for the 500 Hz octave band; ANSI S3.1-1991). Excessive low-frequency ambient noise will falsely increase the thresholds of people with very low thresholds and could therefore have spuriously increased the NHES I medians at 500 Hz. However, if ambient noise was the only cause of the apparent improvement at 500 Hz, one might expect to see the effect at the median (for all age/sex groups, medians were <17 dB HL) but not at the 90th percentile. Contrary to that expectation, 90th percentile thresholds at 500 Hz were also lower (better) for NHANES 1999–2004 than for NHES I for all but one of the age/sex groups. For 60-yr-old women, the worst-hearing group at 500 Hz, the NHANES 1999–2004 and NHES I 90th percentiles were 27 and 32 dB HL, respectively; it seems unlikely that ambient noise could be solely responsible for population differences at these presentation levels. Therefore, a genuine improvement at 500 Hz cannot be ruled out. One possible explanation could be a reduction in conductive hearing loss, attributable to better medical management of middle-ear disease in childhood (antibiotics were not widely available until the 1950s). It is difficult to test this hypothesis because neither survey included bone conduction testing and only NHANES 1999–2004 included tympanometry.

Median thresholds were consistently lower (improved) in the 3000 to 6000 Hz region, with the largest specific reductions

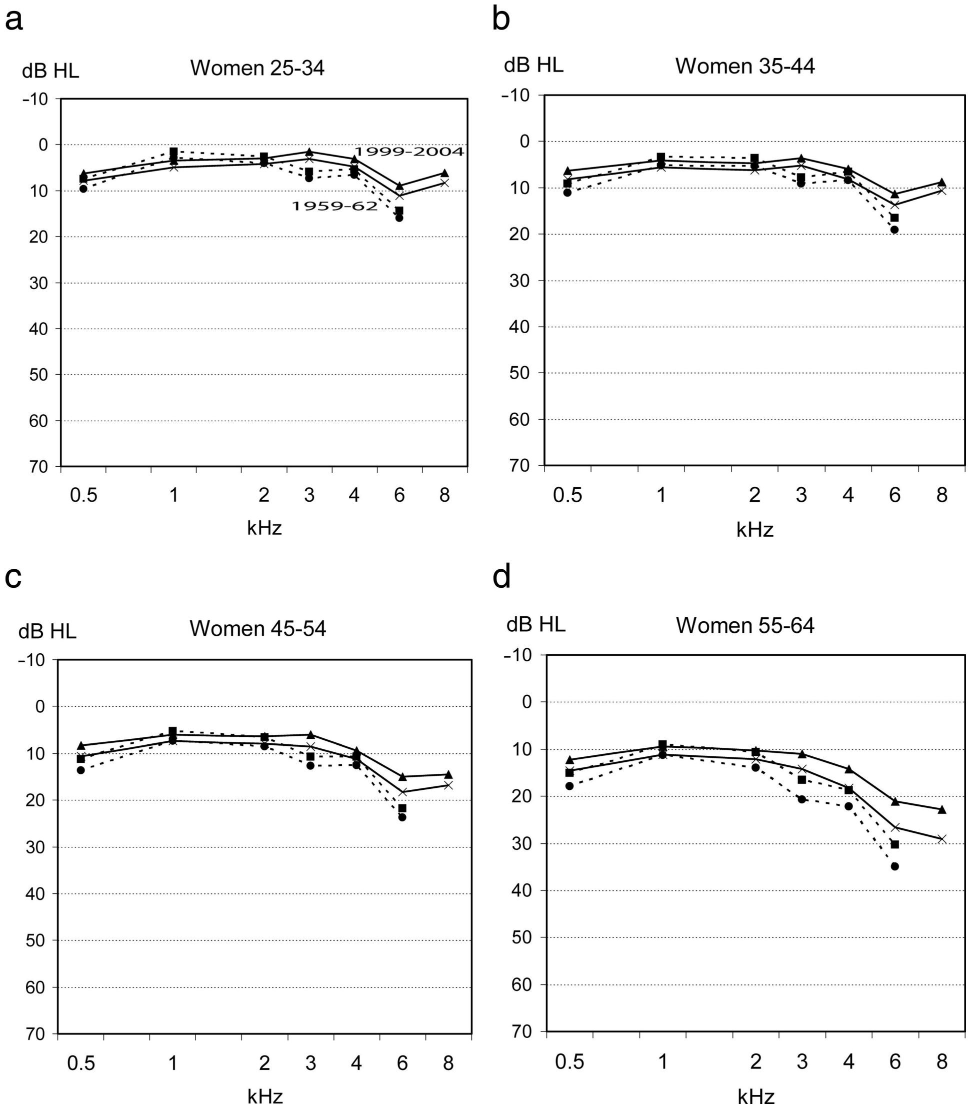

Fig. 3. For the better ears of women in each of four age groups (25 to 34, 35 to 44, 45 to 54, and 55 to 64 yrs), the 95% confidence intervals for medians are shown in audiometric format (threshold in dB HL vs. frequency in kHz). The solid curves represent NHANES 1999–2004 and the dashed curves represent NHES I 1959–1962.

at 6000 Hz, where the differences between NHANES 1999–2004 and NHES I ranged from 5 to 11 dB HL across age/sex groups. Because noise-induced hearing loss (NIHL) preferentially affects the 3000 to 6000 Hz region, one plausible explanation is a reduction in NIHL. The United States has only half as many manufacturing jobs now compared with 30 yrs ago (Dietz & Orr 2006). Also, since 1983, most noise-exposed workers have been required to be enrolled in hearing conservation programs. It is unfortunate that 8000 Hz was not tested in the NHES I; a finding of improvements that were greater in the 3000 to 6000 Hz range than at 8000 Hz might have helped to support the "less NIHL" hypothesis.

Since the racial-ethnic composition of the U.S. population has changed during the past half century, we performed additional analyses restricted to white race in NHES I and non-Hispanic whites in NHANES 1999–2004. The median hearing threshold levels in NHES I and NHANES 1999–2004 were minimally affected by this restriction, although the "whites only" median thresholds were slightly higher (worse) compared with the total race-ethnicity median thresholds. Nevertheless, the white-only median thresholds were always within the 95% CIs shown in Figures 2 and 3.

Other factors that affect high-frequency thresholds may also have changed since 1962. Recent analyses of the NHANES 1999–2004 dataset showed that diabetes and heavy smoking were associated with increased hearing loss (Agrawal et al. 2008; Bainbridge et al. 2008). Although diabetes is probably not less prevalent, its management may be more effective today. Unquestionably, our population smokes far less today than in 1962.

Figures 2 and 3 show a small "notch" at 6 kHz for both men and women at younger ages (25 to 34 and 35 to 44 yrs) in the NHANES data, which generally persists even at the lower and upper percentiles. The NHES I data show a similar drop (worsening) in threshold at 6 kHz in the younger age groups, but it is impossible to tell whether this drop forms a notch, because 8 kHz was not tested in the earlier survey. This effect has been seen in other studies (Arlinger 1991; Lutman & Davis 1994) and has been attributed to an error in the reference value for audiometric zero when calibrating TDH-39 headphones on an NBS-9A (6 cm^3) acoustic coupler (Robinson et al. 1981; Lutman & Qasem 1998; Lawton 2005). Lutman and Davis (1994) raised concerns about 6 kHz calibration bias in the current audiometric standards (ISO 389-1, 1998) after finding

TABLE 3. Odds ratio estimates for risk of hearing impairment (air conduction threshold > 25 dB HL) for "better" ear, comparing NHANES 1999–2004 adults with the reference population, the U.S. National Health Examination Survey (NHES), Cycle 1, 1959–1962

		Ages 25–64 yrs		
Gender	Frequency (Hz)	Odds Ratio	95% Confidence Interval	*p*
Men	500	0.50	0.32–0.79	0.003
	1000	0.81	0.50–1.30	0.378; NS*
	2000	0.46	0.33–0.66	0.000
	4000	0.57	0.43–0.76	0.000
	Better-ear 4FA	0.56	0.43–0.73	0.000
Women	500	0.37	0.27–0.50	0.000
	1000	0.91	0.62–1.34	0.637; NS*
	2000	0.60	0.37–0.98	0.003
	4000	0.48	0.36–0.64	0.000
	Better-ear 4FA	0.66	0.48–0.90	0.010

The better-ear four frequency average (4 FA) is the average of thresholds at these frequencies for either left or right ear, whichever is lower (better).
**NS, not statistically significant, $p > 0.05$.*

that their young subjects, whether or not screened for noise exposure, had unusually increased thresholds at this frequency. Lutman and Qasem (1998) reported that this bias—causing thresholds to appear too high by an average of 6 dB—was seen when audiometer calibration was performed with TDH-39 earphones with NBS-9A couplers, as in both NHES I and NHANES. If the apparent notch is an artifact of calibration, it would affect both the NHES I and NHANES data equally. Thus, although 6-kHz thresholds could be spuriously increased, the differences between surveys shown in Figures 2 and 3 should be free of bias.

There were many minor methodological differences between NHES I and NHANES: manual versus microprocessor, steady tones versus pulsed tones, descending versus ascending series for threshold estimation, number of series required to establish threshold, and use of insert phones when large interaural asymmetries were present. None of these should have caused substantial differences in better-ear threshold distributions.

We have used two different methods to compare hearing thresholds across frequencies in the NHES I and NHANES 1999–2004 data. The first method compared distributions of hearing thresholds at each frequency based on medians and other percentile measures within 10-yr age groups for men and women separately. The second method was based on the prevalence (relative numbers of subjects) who had "impaired" hearing, defined as better-ear thresholds >25 dB HL, at each of four frequencies and also for better-ear 4FA of 500, 1000, 2000, and 4000 Hz. With both methods, we found that hearing thresholds at 1000 Hz were not statistically different between the NHANES 1999–2004 and NHES I. For most of the other frequencies and for the 4FA, we found that hearing thresholds were significantly lower (better) in NHANES 1999–2004 compared with NHES I.

After our article was submitted, a report by Zhan et al. (2010) was published, showing an improvement in hearing across generations of subjects in the Beaver Dam, WI cohort study. They reported less hearing impairment, based on a 4FA in either ear >25 dB HL, in more recent birth cohorts, especially within the age range from 45 to 69 yrs (the original Beaver Dam Hearing Loss Study did not include individuals younger than 48 yrs of age). This report estimated a reduction in hearing impairment with every 5-yr increase in birth years that was larger in men (odds ratio was 13% lower) compared with women (odds ratio was 6% lower). The authors concluded—consistent with our findings—that Americans in their study were retaining good hearing longer than previous generations and that modifiable factors contribute to hearing impairment in adults.

Although men and women of a given age may hear better today than their parents and grandparents did, the U.S. population is far larger now and is aging rapidly; the net effect is that the number of hearing-impaired persons is also growing rapidly.

Table 2 may be appropriate as a replacement for Table 1 as Annex B when ISO-1999 and ANSI S3.44 are revised, for several reasons:

1. The 1999–2004 NHANES data, similar to those in the current Annex B, reflect a sampling and weighting strategy that ensures results are from a contemporary, nationally representative sample of the entire civilian, noninstitutionalized U.S. population.
2. Distributions based on large samples are available for each separate age/sex subgroup, permitting the estimation of both percentiles and their 95% CIs for each subgroup, without the need to fit the data to a regression model of threshold growth with age (although such models, as in Johansson & Arlinger 2002, can be useful, e.g., in estimating thresholds for intermediate ages).
3. The total sample size is very large (4218 between ages 25 and 64 yrs), with the result that 95% CI widths for medians are relatively small, as seen in Figures 2 and 3: always 6 dB or less, except for men aged 55 to 64 yrs at higher frequencies (for this subgroup, the widest CI was 12 dB wide, at 8 kHz).
4. The participation rate is high (73%), minimizing the risk of nonresponse bias. In other mail or telephone health surveys, nonresponders were disproportionately smokers, severe diabetics, of low socioeconomic status, and in generally poor health (Etter & Perneger 1997; Hill et al. 1997; Melton et al. 1993; Søgaard et al. 2004), and thus can be expected to have worse hearing (Agrawal et al. 2008).
5. The data are presented in the same format as the current Annex B (better-ear thresholds, for age groups centered on 30, 40, 50, and 60 yrs), but with extensions to include 8 kHz and additional percentiles (5th and 95th).

The current Annex B was based on the "upper limit" convention (see Materials and Methods) to estimate percentiles. Table 2 used the midpoint convention (which yields results that are 2.5 dB higher). Any new Annex B should clearly indicate which convention was chosen so that end users can appropriately compare their study populations with these population standards.

The percentiles in Table 2 agree very well with the unscreened data from another recent large population-based survey, with a relatively high response rate (55%) in a Western industrialized country. Engdahl et al. (2005) used different age groups, but comparable median thresholds could be obtained by interpolation; for example, their age 20 to 29 yrs and age 30 to 39 medians were averaged for comparison with the age 25 to 34 medians in Table 2. When this was done, median thresholds for the two surveys were always within 6 dB, across sex, age, and frequency. In all cases in which differences were >2 dB, median thresholds were lower in Table 2, which may be explained by the fact that better-ear thresholds (as in Table 2) are by definition the same or lower than binaural average thresholds (as in Engdahl et al. 2005).

The British National Study of Hearing (NSH), another large population-based audiometric survey, collected data in the early 1980s (Davis 1989, 1995; Lutman & Davis 1994). At 0.5, 1, and 2 kHz, binaural median thresholds for unscreened men aged 18 to 30 yrs in the NSH (Lutman & Davis, 1994) were within 1 dB of better-ear medians for men aged 25 to 34 yrs in Table 2, but were 1 to 5 dB worse at 3 to 6 kHz. Because the age ranges are not precisely comparable, because binaural thresholds are on average worse than better-ear thresholds, and because it is unclear which of the conventions described in this article were used to estimate the NSH medians, it is difficult to know whether there are substantial differences between the NSH data and those from the U.S. surveys we describe in this article.

Nevertheless, it would not be surprising to find differences in age-related threshold distributions in different countries, whose populations may differ in genetic composition, health habits (diet, smoking, etc.), occupational noise exposure, leisure noise exposure such as use of firearms, and access to medical care, to mention only the most obvious. ISO-1999 recognizes this, stating that Annex B is merely an example of a typical control population, and recommending that each country compile its own data base for prediction of NIHL. Our aims for this article are to present the recent U.S. data and to compare them with much older U.S. data. Detailed comparisons of U.S. data with data of other countries would be a worthy undertaking for a future study, one best accomplished by reanalysis of original data (the NHANES original data are publicly available).

Datasets such as NHANES 1999–2004 can be subdivided to produce subgroups such as those in Annex B (based on age and sex), and other subgroups such as African Americans, diabetics, nonsmokers. In doing so, it is important to remember that differences between pairs of subgroups may reflect more than the effects of the single variable that defines them. For example, men aged 55 to 64 yrs hear worse than women of the same age, but they differ in more than just sex; the men are more likely to have been exposed to gunfire, to have had noisy jobs, and perhaps to have been heavy smokers. Estimates of the independent effect of male sex, taking into account these other variables, requires multivariate analysis, which is beyond the scope of this study.

A special case of this problem is found in ANSI S3.44, which in addition to Annex A and Annex B offers a third aging database: Annex C gives threshold distributions for people who have never had noisy jobs, based on Royster and Thomas (1979) and Royster et al. (1980). Annex C is suggested as an appropriate comparison standard for study populations with occupational noise exposure, with the implicit assumption that any differences that are found could be attributed to the noisy jobs. But people who have never had noisy jobs are also less likely to be smokers or diabetics, and less likely to have had nonoccupational noise exposure, compared with people who have had noisy jobs (Agrawal et al. 2009). Thus, differences in threshold distributions between Annex C and an occupationally noise-exposed study population could be due to any or all these factors. Theoretically, the most appropriate population standard for such comparisons would be one that is similar to the study population in every respect except occupational noise. The thresholds in such a standard would be higher (worse) than in an Annex C—created by simply excluding occupationally noise-exposed people—and might even be worse than Annex B (Agrawal et al. 2009). In the absence of such standards, unscreened population-based data, as in Annex B, remain the most practical basis for comparison with study populations drawn from developed, industrialized countries.

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The authors prepared this report in their roles as U.S. Federal employees, except for one (Dobie), who is a member of the faculties of The University of Texas Health Science Center at San Antonio and the University of California at Davis, and also has a private consulting practice in otology. The authors have no other financial or potential conflicts of interest to declare. The views expressed are solely those of the authors and do not necessarily represent the agencies or institutions for which they work.

The order of the authors is intended to reflect the relative contributions each author made to the article. Hoffman and Themann participated in the design and oversight of the NHANES audiometry and can vouch for the acquisition and quality control of the data. Hoffman, Dobie, and Ko participated in the conceptual design of the article and the statistical analysis. Dobie and Hoffman were the primary drafters. Each of the authors participated in the interpretation of the data and the preparation of the final manuscript.

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