Gender differences in a longitudinal study of age-associated hearing loss

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Current studies are inconclusive regarding specific patterns of gender differences in age-associated hearing loss. This paper presents results from the largest and longest longitudinal study reported to date of changes in pure-tone hearing thresholds in men and women screened for otological disorders and noise-induced hearing loss. Since 1965, the Baltimore Longitudinal Study of Aging has collected hearing thresholds from 500 to 8000 Hz using a pulsed-tone tracking procedure. Mixed-effects regression models were used to estimate longitudinal patterns of change in hearing thresholds in 681 men and 416 women with no evidence of otological disease, unilateral hearing loss, or noise-induced hearing loss. The results show (1) hearing sensitivity declines more than twice as fast in men as in women at most ages and frequencies, (2) longitudinal declines in hearing sensitivity are detectable at all frequencies among men by age 30, but the age of onset of decline is later in women at most frequencies and varies by frequency in women, (3) women have more sensitive hearing than men at frequencies above 1000 Hz but men have more sensitive hearing than women at lower frequencies, (4) learning effects bias cross-sectional and short-term longitudinal studies, and (5) hearing levels and longitudinal patterns of change are highly variable, even in this highly selected group. These longitudinal findings document gender differences in hearing levels and show that age-associated hearing loss occurs even in a group with relatively low-noise occupations and with no evidence of noise-induced hearing loss.

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INTRODUCTION

An age-associated decline in hearing sensitivity in the absence of known otological disorders or noise-induced hearing loss is extremely common. However, our knowledge of the natural history of age-associated hearing loss is limited, particularly among women. Current knowledge of gender differences in hearing sensitivity is based primarily on cross-sectional studies (e.g., Corso, 1963; Kell *et al.*, 1970; Moscicki *et al.*, 1985). These studies have consistently reported that women have better pure-tone thresholds than men at frequencies above 1000–2000 Hz. However, some studies suggest that the gender differences may be reversed below 1000–2000 Hz (Eisdorfer and Wilkie, 1972; Royster and Thomas, 1979; Driscoll and Royster, 1984; Gates *et al.*, 1990; Jerger *et al.*, 1993; Lindenberger and Baltes, in press).

Gender differences in rates of change in hearing thresholds are less clearly documented across the adult lifespan. One study of 70- to 75-year-olds found almost no change in the pure-tone thresholds of men over 5 years of follow-up but found approximately a 2- to 12-dB deterioration in hearing levels in women (Møller, 1981). In contrast, a large study of pure-tone thresholds in the Framingham cohort found that "the rate of change with age did not differ by gender" (Gates *et al.*, 1990). However, all previously published longitudinal analyses of age-associated change in hearing thresholds which have included both men and women have had less than 10 years of follow-up, had a maximum of only two or three repeated observations, and have not included individuals younger than 60 years of age (Eisdorfer and Wilkie, 1972; Møller, 1981; Gates *et al.*, 1990). Longitudinal studies with a maximum of only two or three repeated observations are potentially biased by learning effects that may occur during the first few audiometric tests (Royster and Royster, 1986). Since hearing sensitivity begins to decline before age 60, it is also desirable to examine gender differences in longitudinal rates of change in hearing sensitivity throughout the lifespan in order to determine when the differences begin to appear.

The purposes of this paper are to describe long-term longitudinal changes in hearing thresholds as an individual ages and to allow examination of gender differences at different points in the lifespan. We do not attempt to investigate "pure presbycusis" (i.e., age-related loss of hearing sensitivity which cannot be attributed to otological disorders, noise, or other ototoxic factors) since the current state of knowledge regarding risk factors for hearing loss is still limited. However, we do attempt to examine gender differences in rates of change in hearing thresholds after minimizing the effects of factors such as overt noise-induced hearing loss and otological disorders. Specifically, this study describes longitudinal patterns of change in pulsed pure-tone thresholds from age 20 to 90 in 681 men followed for up to 23

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TABLE I. Characteristics of longitudinal follow-up [mean, (range)].

	Age at first visit							
	<30	30–39.9	40–49.9	50–59.9	60–69.9	70–79.9	80+	Total
Men								
n	126	112	78	90	111	127	37	681
Years of follow-up	9.2	10.4	15.2	12.1	7.7	5.2	2.9	9.1
	(0, 22.0)	(0, 22.1)	(0, 22.9)	(0, 21.6)	(0, 21.4)	(0, 19.6)	(0, 12.1)	(0, 22.9)
Number of visits	4.2	4.7	7.0	5.9	4.6	3.7	2.3	4.7
	(1,15)	(1,12)	(1,13)	(1,14)	(1,14)	(1,12)	(1,5)	(1,15)
Interval between visits	2.8	2.8	2.5	2.5	2.2	1.9	2.2	2.5
	(0.9, 14.3)	(0.9, 14.1)	(0.9, 14.7)	(0.5, 15.8)	(0.7, 14.5)	(0.7, 9.3)	(0.6, 12.1)	(0.5, 15.8)
Women								
n	64	85	43	62	74	69	19	416
Years of follow-up	3.9	5.5	7.5	6.4	5.6	3.7	2.0	5.2
	(0, 12.3)	(0, 12.3)	(0, 12.9)	(0, 12.5)	(0, 12.0)	(0, 12.5)	(0, 7.6)	(0, 12.9)
Number of visits	2.5	3.3	4.1	3.7	3.6	2.7	1.9	3.2
	(1,7)	(1,7)	(1,7)	(1,8)	(1,7)	(1,7)	(1,5)	(1,8)
Interval between visits	2.6	2.4	2.4	2.3	2.2	2.2	2.1	2.3
	(1.8, 7.2)	(1.2, 8.4)	(1.0, 7.8)	(0.9, 7.1)	(0.9, 9.0)	(0.9, 6.5)	(1.3, 4.0)	(0.9, 9.0)

years, and 416 women followed for up to 13 years, who have been screened for otological disorders, unilateral hearing loss, and evidence of noise-induced hearing loss. The nearly 4500 audiometric tests over a period of up to 23 years represent the largest and longest longitudinal study of hearing thresholds in men and women yet reported. This study extends a previous report on longitudinal changes in continuous pure-tone thresholds in BLSA men (Brant and Fozard, 1990; Morrell and Brant, 1991) by (1) using pulsed pure-tone stimuli, (2) reporting the data as dB HL rather than dB SPL, (3) reporting thresholds for both men and women, and (4) screening more rigorously for otologic disorders, unilateral hearing loss, and evidence of noise-induced hearing loss.

I. METHOD

A. Study population

Participants are male and female volunteers in the Baltimore Longitudinal Study of Aging (BLSA), an open-panel multidisciplinary study of normal human aging which began in 1958 and which is conducted by the intramural research program of the National Institute on Aging (Shock *et al.*, 1984). Participants in the study are predominantly white (95%), well-educated (over 75% have a bachelor's degree or higher), and financially comfortable (82%) volunteers. The participants are scheduled to visit the Gerontology Research Center in Baltimore at approximately 2-year intervals where they stay for 2 1/2 days of evaluation and testing.

Data are excluded from the present analyses for participants with otologic disease, unilateral hearing loss, or evidence of noise-induced hearing loss. Of the 1247 men and 588 women who have had audiometric tests in the BLSA, 161 men (13%) and 57 women (10%) are excluded due to otological disorders (i.e., Meniere's disease, cholesteatoma, perforation of the tympanic membrane, congenital hearing loss, otosclerosis, ototoxicity, stroke-induced hearing loss, middle ear effusion, impacted cerumen, or chronic middle ear infections) on the basis of information from the medical histories obtained at each BLSA visit, or as determined from otoscopic inspection combined with shifts in hearing sensitivity at the time of the visit. Another 159 men (13%) and 38 women (6%) are excluded due to unilateral hearing loss (i.e., the mean hearing level at 500, 1000, 2000, and 4000 Hz differed between the ears by more than 10 dB at one or more visits) which presumably reflects the presence of an unidentified pathology. A criterion for evidence of noise-induced hearing loss was developed based on the fact that noise exposure produces the greatest permanent threshold shift near 4000 Hz (Ward, 1980; Kryter, 1985). Evidence of noise-induced hearing loss is defined here as a notch in an audiogram of either ear where the hearing level at 3000, 4000, or 6000 Hz is more than 15 dB worse than the hearing level at both 2000 and 8000 Hz for at least one visit (Ward, 1980; Kryter, 1985). This criterion excludes 189 men (15%) and 17 women (3%) because of evidence of noise-induced hearing loss. An additional 57 men (5%) and 60 women (10%) with only one visit are excluded because missing data in the 2000- to 8000-Hz region of their audiograms made it impossible to screen for noise-induced hearing loss.

The final male study group consists of 681 men (55% of the original group) whose beginning age in the study is between 17 and 90 years and who entered the study between 1965 and 1991 (Table I). The male data set has 3200 audiograms with a mean of 4.7 visits and 9.1 years of follow up (maximum of 22.9 years). Approximately 60% of the men have 5 or more years of follow-up and 43% have 10 or more years of follow-up. The final female study group consists of data collected on 416 participants (71% of the original group) between 1978 and 1991 with age at entry between 18 and 86 years. The women have a total of 1331 audiograms with a mean of 3.2 visits and 5.2 years of follow up (maximum of 12.9 years). Approximately 48% of the women have 5 or more years of follow-up and 17% have 10 or more years of follow-up.

Participants in this study group have typically been employed in occupations generally believed to have relatively little noise exposure (Table II). Only 8.1% of the men and

TABLE II. Occupation distribution of the participants in the study.

	Men		Women	
Occupation	Number	%	Number	%
Professional/technical	469	68.9	211	50.7
Managerial/proprietor	95	14.0	36	8.7
Clerical/sales	49	7.2	127	30.5
Skilled/craft	44	6.5	10	2.4
Semiskilled/labor	10	1.5	5	1.2
Farmer	1	0.1	0	0
Student	11	1.6	3	0.7
Other	2	0.3	24	5.8

3.6% of the women were employed in skilled/craft, semiskilled labor, or farming occupations.

B. Apparatus and procedures

As part of the BLSA testing, participants completed continuous pure-tone audiologic testing followed by pulsed pure-tone testing. The hearing threshold levels reported in this paper are determined for nine frequencies (500, 750, 1000, 1500, 2000, 3000, 4000, 6000, 8000 Hz) from a Bekesy audiogram obtained using a pulsed pure tone generated by a Grason–Stadler audiometer. The pulses are 200 ms on and 200 ms off with a rise/fall time of 25 ms. Participants are instructed to press a hand-held response key upon hearing a tone, to hold the key down as long as they hear the tone, and to release it when they no longer hear the tone. Frequencies are swept continuously from 100–10 000 Hz. Each ear is tested individually with pulsed tones presented through Telephonics earphones (TDH-49P) with cushions (MX-41/AR). Testing for each ear takes 7 min with a 15-s pause between ears. The selection of the first ear tested is randomized during each testing period. During the audiometric tests, participants are seated in a sound-treated chamber manufactured by the Industrial Acoustics Company (model 400-A) which met the prevailing standards for maximum permissible ambient noise levels during air conduction audiometry (ANSI, 1977) at 500 to 8000 Hz. Data are not presented for 250 Hz because of excess ambient noise levels at that frequency.

Threshold levels are determined from the audiogram at 1 dB steps at each of the ten frequencies by linear interpolation between the midpoints of the tracking excursions, as suggested by Reger (1952) and used by Burns and Hinchcliffe (1957). All thresholds are expressed in dB HL using the ANSI (1989) standards. Three audiometers were used over the 28-year course of the study. Before 1979, the audiometers were calibrated to audiometric zero in accordance with the standards set by the International Standards Organization (ISO, 1964), and later were calibrated in accordance with standards set by the American National Standards Institute (ANSI, 1969; ANSI, 1989). As in Brant and Fozard (1990), minor correction factors were developed using longitudinal regression techniques to account for small systematic differences between audiometers used from 1975 to 1980.

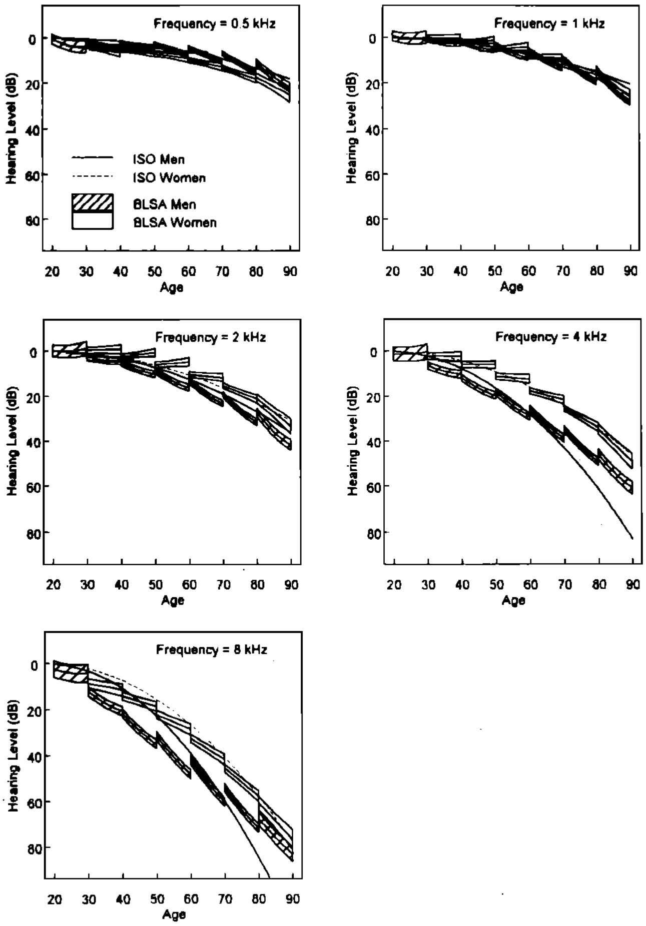

FIG. 1. Average (±95% confidence intervals) longitudinal changes in hearing levels at selected frequencies in BLSA men and women as estimated by mixed-effects regression models. Note that the ISO 7029-1984 standards are identical for men and women at 0.5 and 1 kHz.

C. Statistical methods

Linear mixed-effects regression models are used to analyze these longitudinal data (Laird and Ware, 1982; Lindstrom and Bates, 1988). Mixed-effects models allow estimation of the average hearing level curve for the population and also allow each subject's estimated longitudinal change and audiometric curve to deviate from the group average.

In the mixed-effects model, the fixed effects estimate the average intercept and rates of change for the independent variables, while the random effects represent the deviation for each individual from the average intercept and slope terms. Thus the random effects account for natural heterogeneity in initial level, ear, patterns of longitudinal change, and audiometric shape among the individuals in the study. Mixed-effects models account for the autocorrelation among repeated measures within individuals and allow the analysis of unbalanced data where individuals have differing numbers of observations taken at varying intervals between the observations.

Arranging the terms in the mixed-effects model to see how the longitudinal change depends upon first age and frequency, the full model for a hearing level observation on the ith person at time j and frequency k is

$$y_{ijk}=(\beta_0+b_{i0})+(\beta_1+b_{i1})\mathrm{ear}_i+(\beta_2+b_{i2})\mathrm{time}_{ij}+(\beta_3+b_{i3})\mathrm{time}_{ij}^2+(\beta_4+b_{i4})\ln(\mathrm{freq})_{ik}+(\beta_5+b_{i5})\ln^2(\mathrm{freq})_{ik}+(\beta_6$$
$$+b_{i6})\ln^3(\mathrm{freq})_{ik}+\beta_7\mathrm{fage}_i+\beta_8\mathrm{fage}_i^2+\beta_9\mathrm{fage}_i^3+\beta_{10}\mathrm{visit1}_i+[\beta_{11}\mathrm{fage}_i+\beta_{12}\mathrm{fage}_i^2+\beta_{13}\mathrm{fage}_i^3+(\beta_{14}+\beta_{15}\mathrm{fage}_i$$
$$+\beta_{16}\mathrm{fage}_i^2)\ln(\mathrm{freq})_{ik}+(\beta_{17}+\beta_{18}\mathrm{fage}_i+\beta_{19}\mathrm{fage}_i^2)\ln^2(\mathrm{freq})_{ik}+\beta_{20}\ \ln^3(\mathrm{freq})_i]\mathrm{time}_{ij}+[\beta_{21}\mathrm{fage}_i+\beta_{22}\mathrm{fage}_i^2$$
$$+\beta_{23}\mathrm{fage}_i^3+(\beta_{24}+\beta_{25}\mathrm{fage}_i+\beta_{26}\mathrm{fage}_i^2)\ln(\mathrm{freq})_{ik}+(\beta_{27}+\beta_{28}\mathrm{fage}_i+\beta_{29}\mathrm{fage}_i^2)\ln^2(\mathrm{freq})_{ik}+\beta_{30}\ \ln^3(\mathrm{freq})_{ik}]\mathrm{time}_{ij}^2$$
$$+[\beta_{31}\mathrm{fage}_i+\beta_{32}\mathrm{fage}_i^2+\beta_{33}\mathrm{fage}_i^3+\beta_{34}\mathrm{visit1}_i]\ln(\mathrm{freq})_{ik}+[\beta_{35}\mathrm{fage}_i+\beta_{36}\mathrm{fage}_i^2+\beta_{37}\mathrm{fage}_i^3+\beta_{38}\mathrm{visit1}_i]\ln^2(\mathrm{freq})_{ik}$$
$$+[\beta_{39}\mathrm{fage}_i+\beta_{40}\mathrm{fage}_i^2+\beta_{41}\mathrm{fage}_i^3]\ln^3(\mathrm{freq})_{ik}+\epsilon_{ijk},$$

TABLE III. Hearing levels (dB) at selected frequencies for various ages and amounts of longitudinal follow-up for BLSA men and women as estimated by the mixed-effects model.

		Frequency						
Age	Follow-up	500	1000	2000	3000	4000	6000	8000
Men								
20	0	0.6	−0.7	−0.2	0.6	1.2	2.0	2.3
	5	3.3	0.5	−0.0	0.6	1.3	2.8	4.0
	10	4.0	−0.1	−1.3	−0.7	0.2	2.2	4.0
30	0	1.5	0.5	2.3	4.4	6.3	9.5	12.0
	5	3.7	2.2	4.0	6.5	8.9	13.3	17.0
	10	4.7	2.6	4.4	7.4	10.3	15.7	20.5
40	0	2.2	1.7	5.0	8.6	11.8	17.2	21.5
	5	4.2	4.1	8.2	12.5	16.5	23.3	29.0
	10	5.7	5.5	10.1	15.1	19.8	28.0	35.0
50	0	3.0	3.2	8.4	13.6	18.1	25.4	31.3
	5	5.3	6.6	13.0	19.1	24.3	33.2	40.4
	10	7.4	9.0	16.2	23.1	29.2	39.5	48.1
60	0	4.4	5.5	13.0	19.8	25.5	34.8	42.0
	5	7.5	10.2	19.0	26.6	33.0	43.5	51.7
	10	10.4	13.6	23.2	31.7	38.9	50.7	60.1
70	0	6.9	9.0	19.1	27.7	34.7	45.6	53.8
	5	11.3	15.3	26.4	35.6	43.0	54.5	63.4
	10	15.1	19.7	31.6	41.3	49.3	61.9	71.6
80	0	10.8	14.3	27.2	37.7	46.0	58.4	67.3
	5	17.0	22.4	35.9	46.4	54.7	66.9	75.8
	10	21.9	27.9	41.8	52.5	61.0	73.7	83.0
Women								
20	0	...	...	...	...	...	...	...
	5	...	...	...	...	...	...	...
	10	...	...	...	...	...	...	...
30	0	3.4	0.2	−0.4	0.7	2.3	5.5	8.5
	5	4.9	0.4	−0.6	0.6	2.4	6.2	9.9
	10	6.5	0.6	−0.9	0.4	2.5	7.0	11.3
40	0	5.0	2.4	2.5	4.1	6.0	10.1	14.0
	5	6.0	1.8	1.5	3.5	6.0	11.2	16.2
	10	7.0	1.2	0.5	2.9	6.0	12.3	18.4
50	0	7.2	5.1	6.0	8.4	11.2	16.7	22.0
	5	8.1	4.6	5.4	8.3	11.8	18.7	25.2
	10	9.1	4.1	4.7	8.3	12.4	20.7	28.4
60	0	9.9	8.3	10.3	13.8	17.7	25.3	32.4
	5	11.4	8.7	10.9	15.2	19.7	28.7	36.9
	10	12.9	9.2	11.6	16.5	21.7	32.0	41.5
70	0	13.3	11.9	15.2	20.3	25.6	35.8	45.2
	5	15.8	14.3	18.2	23.9	29.8	41.1	51.4
	10	18.3	16.6	21.1	27.5	34.0	46.3	57.5
80	0	17.4	15.9	20.9	27.8	34.9	48.3	60.5
	5	21.3	21.1	27.1	34.6	42.1	56.0	68.5
	10	25.3	26.3	33.4	41.4	49.3	63.7	76.5

Note: Hearing levels were not estimated for 20-yr-old women because of small sample size and extremely wide confidence intervals.

TABLE IV. Ten-year longitudinal change in hearing level (dB/decade) in men and women as estimated by the mixed-effects model.

		Frequency						
Age	Sex	500	1000	2000	3000	4000	6000	8000
20	♂	3.4^{a}	0.7	−1.1	−1.3	−1.0	0.2	1.7
	♀	...	...	...	...	...	...	...
30	♂	3.1^{a}	2.1^{a}	$2.1^{a,b}$	$2.9^{a,b}$	$4.0^{a,b}$	$6.2^{a,b}$	$8.5^{a,b}$
	♀	3.1^{a}	0.4	−0.6	−0.3	0.2	1.5	2.8^{a}
40	♂	3.5^{a}	$3.8^{a,b}$	$5.0^{a,b}$	$6.5^{a,b}$	$8.0^{a,b}$	$10.9^{a,b}$	$13.5^{a,b}$
	♀	2.0^{a}	−1.2	-1.9^{a}	−1.1	−0.1	2.2^{a}	4.4^{a}
50	♂	$4.4^{a,b}$	$5.8^{a,b}$	$7.8^{a,b}$	$9.5^{a,b}$	$11.1^{a,b}$	$14.1^{a,b}$	$16.7^{a,b}$
	♀	2.0^{a}	−1.0	−1.3	−0.2	1.2	4.0^{a}	6.5^{a}
60	♂	$6.0^{a,b}$	$8.1^{a,b}$	$10.3^{a,b}$	$11.9^{a,b}$	$13.3^{a,b}$	$15.9^{a,b}$	$18.2^{a,b}$
	♀	3.0^{a}	1.0	1.3	2.6^{a}	4.0^{a}	6.7^{a}	9.1^{a}
70	♂	$8.2^{a,b}$	$10.7^{a,b}$	$12.5^{a,b}$	$13.7^{a,b}$	$14.6^{a,b}$	$16.3^{a,b}$	$17.8^{a,b}$
	♀	5.0^{a}	4.8^{a}	5.9^{a}	7.2^{a}	8.4^{a}	10.5^{a}	12.3^{a}
80	♂	11.1^{a}	13.5^{a}	14.6^{a}	14.8^{a}	15.0^{a}	15.3^{a}	15.6^{a}
	♀	8.0^{a}	10.3^{a}	12.5^{a}	13.6^{a}	14.4^{a}	15.4^{a}	16.0^{a}

[a] Longitudinal change over ten years is significant at the 5% level of significance.

[b] Men and women are statistically different at the 5% level of significance.

Note: Longitudinal change was not estimated for 20-yr-old women because of small sample size and extremely wide confidence intervals.

where longitudinal change is represented by follow-up time (time and time^2), cross-sectional age differences are represented by polynomial terms for age at first visit (fage, fage^2, and fage^3), audiogram shape is represented by polynomial terms for the natural logarithm of the frequency in kHz [ln(freq), ln^2(freq), and ln^3(freq)], interaural differences are represented by ear, learning effects are represented by a contrast between first visit and subsequent visits (visit1), and ϵ represents the statistical error term. Previous analyses have shown that polynomials of ln(freq) are an efficient and flexible method of modeling the audiogram frequency-intensity function (Brant and Fozard, 1990; Morrell and Brant, 1991). Interaction terms are included that allow the longitudinal patterns of change to differ with age at entry (fage*time), allow the audiogram shape to change longitudinally [ln(freq)*time] and with age at entry [ln(freq)*fage]. Three-way interactions between fage, time, and ln(freq) are included to test for differences in rate of change in thresholds at different ages and frequencies.

Seven random-effect terms (b_{i0}, b_{i1}, b_{i2}, b_{i3}, b_{i4}, b_{i5}, and b_{i6}) are included in the full model to account for natural heterogeneity among individuals with respect to hearing level (intercept), interaural difference (ear), longitudinal pattern of change (time and time^2), and audiogram shape [ln (frequency), ln^2 (frequency), and ln^3 (frequency)]. Thus, each person's hearing thresholds may have a level and audiometric shape that deviates from the overall average, each person's longitudinal pattern of change may deviate from the overall average, and there is a difference between the ears that may vary from subject to subject.

In order to reduce the multicollinearity among the polynomial terms, the follow-up time and first age variables are

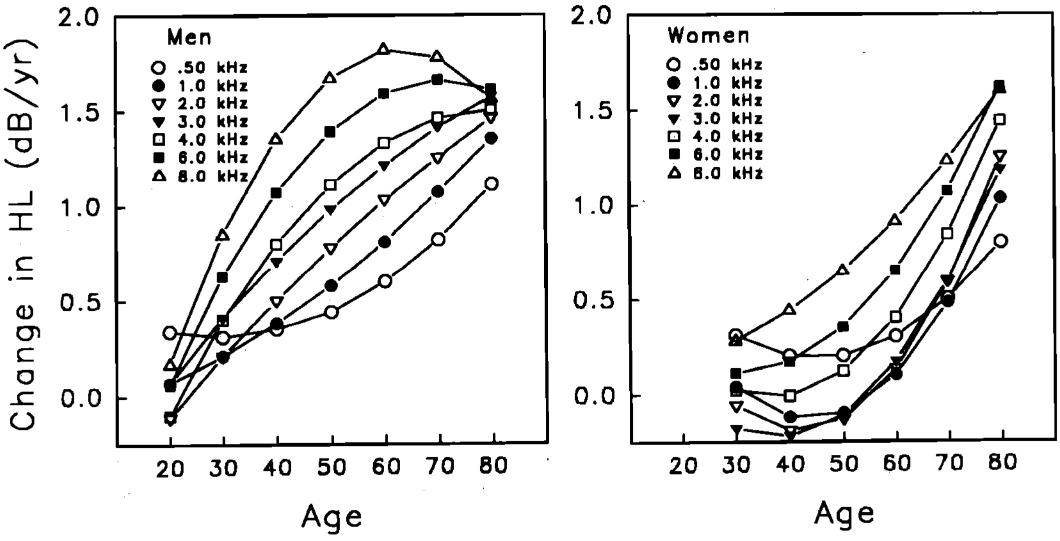

FIG. 2. Average 10-year changes in hearing levels (dB/yr) for men and women at selected frequencies and ages as estimated by mixed-effects regression models.

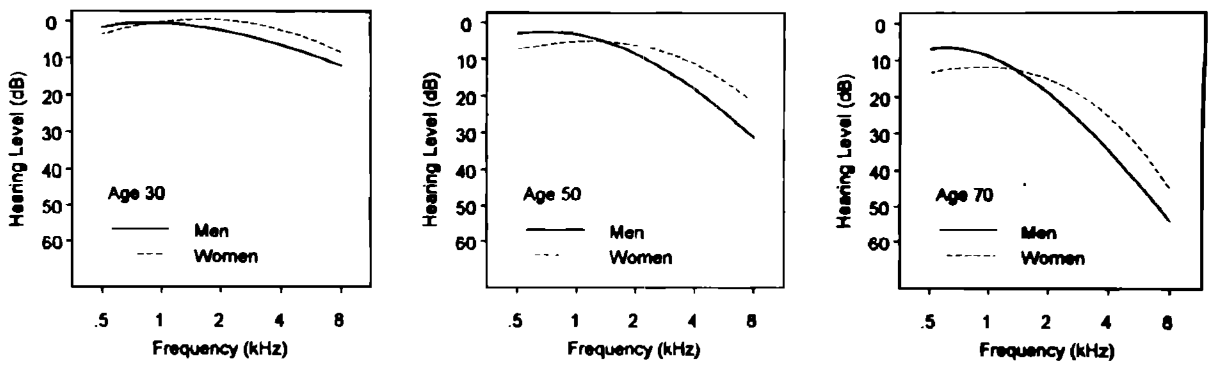

FIG. 3. Gender differences in audiometric shape at age 30, 50, and 70 as estimated from the mixed-effects model.

centered on the mean follow-up time and age at first visit by subtracting 9 and 53 years respectively from time and fage for men and by 5 and 53 years, respectively, for women (Draper and Smith, 1981). The most parsimonious well-formulated models (Peixoto, 1990) are obtained by backward elimination of the highest-order nonsignificant polynomial and cross-product terms.

II. RESULTS

The final mixed-effects model for the men reduced to 36 fixed-effects variables (excluding the terms subscripted as 13, 23, 33, 37, 38, and 41). Since only 38.5% of the women had more than three visits, the only longitudinal terms included in the women's model were time and visit1 (i.e., no time^2 terms were included). The final model for women had 24 variables (excluding the terms subscripted as 3, 9, 13, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 33, 37, 40, and 41). The men's model contained all seven random factors in the final reduced model, whereas the women's model included all the random effects except for time^2 (b_{i3}). Comparison of the observed data and predicted curves for each individual confirmed that the model fit the data adequately and that the changes in hearing levels were gradual and progressive rather than abrupt threshold shifts.

Figure 1 shows the hearing levels and longitudinal changes in hearing level over ten years of follow-up as estimated by the mixed-effects regression models for subjects beginning the study at 20, 30, 40, 50, 60, 70, and 80 years of age. Table III also shows the estimated hearing levels at 0, 5, and 10 years of longitudinal follow-up. Estimates for 20-year-old women are not shown because the number of women starting the study aged 17–25 was very small and the confidence intervals for the estimates were extremely wide. The hearing levels shown at the beginning of each ten-year longitudinal curve represent the cross-sectional estimates for different ages at entry into the BLSA. Cross-sectionally, hearing sensitivity in men declines after age 20 at all frequencies above 500 Hz. After age 30, hearing sensitivity in women declines cross-sectionally at all frequencies.

Longitudinally, hearing sensitivity declines among both men and women, although hearing levels at 1000, 2000, and 4000 Hz improve slightly (<2.0 dB per decade) for women under age 60 (Fig. 1, Table IV). At most ages and frequencies, the amount of longitudinal change in hearing level over ten years is more than twice as fast in men than in women, although the rate of change in men and women begins to converge after age 60 (Fig. 2, Table IV). The greatest gender difference in longitudinal rates of hearing loss occurs in 50-year-olds at 3000 to 8000 Hz where the change is approximately 10 dB/decade faster in men than women.

Among men, hearing sensitivity declines significantly at age 20 and beyond for 500 Hz, and at age 30 and beyond for all other frequencies (Table IV). However, the rate of decline is greater in older men than in younger men and is greater at higher frequencies (Fig. 2). Among women, hearing levels worsen at all ages for 500 Hz, after age 50 for 1000 to 3000 Hz, after age 40 for 4000 Hz, and by age 30 for 6000 and 8000 Hz (Table IV). The longitudinal rate of change in hearing level at 6000 and 8000 Hz plateaus after age 60 in men, but continues to accelerate in women (Fig. 2). The decline in hearing sensitivity accelerates at approximately age 20–30 in men and age 40–50 in women.

Both men and women exhibited a statistically significant learning effect from the first visit to subsequent visits. The estimated improvement in hearing levels ranges from 1.0 dB at 3000 Hz to 1.9 dB at 500 Hz in men and from 0.1 dB at 500 Hz to 1.6 dB at 8000 Hz for women. Thus, there was little meaningful difference in the magnitude of the learning effect at different frequencies.

There are significant gender differences in hearing thresholds. At age 30 and above, men have significantly better hearing thresholds than women at 500 Hz (Figs. 1 and 3). At 1000 Hz, the hearing levels of men and women are not significantly different. However, women have significantly better hearing thresholds than men at all frequencies above 1000 Hz. The gender difference also changes with age (Fig. 3). At 500 Hz, the gender difference in hearing thresholds in favor of men increases from approximately 2 dB at age 30 to approximately 6 dB at age 70. Above 1000 Hz, the gender difference in favor of women increases from approximately 2–4 dB at age 30 to approximately 4–10 dB at age 70.

As has been found in previous studies (e.g., Kannan and Lipscomb, 1974; Chung *et al.*, 1983), hearing levels are slightly poorer on average for the left ear compared to the right ear (0.7 dB poorer for men and 0.4 dB poorer for women).

There is a significant degree of between-subjects variability in hearing levels (likelihood ratio test for the inclusion

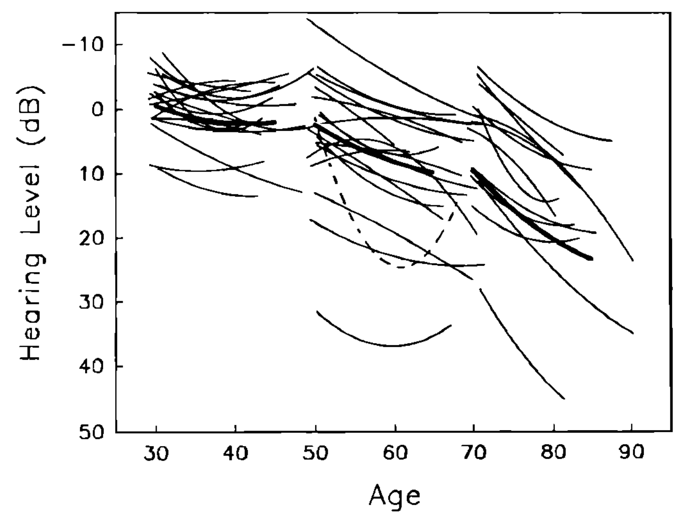

FIG. 4. Variability in initial hearing levels at 1000 Hz and subsequent longitudinal change among 30-yr-old ($n=19$), 50-yr-old ($n=19$), and 70-yr-old ($n=13$) men with 10 or more years of follow-up and at least three visits. The thick line represents the average threshold level estimated from the mixed-effects model and the thin lines represent predicted threshold levels for each individual as estimated from the mixed-effects model. The dashed line indicates an individual with an unusual pattern of change.

of random effect b_{i0}:$p<0.0001$) and in the longitudinal pattern of change in hearing levels over time (likelihood ratio test for the inclusion of random effects b_{i1} and b_{i2}:$p<0.0001$) at any given age, although the variability increases with age. The between-subjects variability in hearing levels is significantly greater among men than women ($\sigma_{b_{i0}}$ = 9.8 and 8.1 dB for men and women respectively, $p<0.001$).

Figure 4 illustrates the variability in initial hearing levels at 1000 Hz and subsequent longitudinal change among 30-, 50-, and 70-yr-old men with ten or more years of follow-up and at least three visits. The random effects in the mixed-effects model allow estimation of each individual's longitudinal pattern of change and can reveal unusual cases which may be of interest. For example, one individual in Fig. 4 (dashed line) exhibits an unusual "U-shaped" longitudinal pattern of change in hearing thresholds at 1000 Hz. Subsequent review of this participant's audiograms and medical records revealed that at the visit when his thresholds were the worst, he complained of postural dizziness and hearing loss. At the visits preceding and following that visit, there were no complaints of dizziness or hearing loss. No otological diagnosis was made at the suspect visit, but the medical history suggests that an acute or subacute, but limited, process was occurring which temporarily affected the individual's hearing sensitivity.

III. DISCUSSION

Age-associated hearing loss has been reported consistently in many cross-sectional, and a few longitudinal, studies conducted primarily in industrialized societies (e.g., Glorig and Nixon, 1962; Corso, 1963; Kell *et al.*, 1970; Royster and Thomas, 1979; Royster *et al.*, 1980; Driscoll and Royster, 1984; ISO, 1984; Brant and Fozard, 1990; Davis *et al.*, 1991; Ostri and Parving, 1991). The age-associated reduction in hearing sensitivity is particularly pronounced at high frequencies and is generally greater in men than in women, although the few longitudinal studies have been inconclusive regarding gender differences in rates of change in hearing sensitivity (Møller, 1981; Gates *et al.*, 1990). Cross-sectional studies also tend to indicate that women have better hearing thresholds than men at frequencies above 1000 or 2000 Hz, although some studies suggest that men may have better hearing thresholds below 1000 or 2000 Hz (e.g., Gates *et al.*, 1990; Jerger *et al.*, 1993).

These studies have varied in the degree to which subjects have been screened for otological disorders and noise-induced hearing loss. As a consequence of the longitudinal nature of the Baltimore Longitudinal Study of Aging, information from repeated clinical examinations was available to screen our study group for otological disorders. Furthermore, the effects of noise exposure were minimized by the relatively low-noise occupations of the participants and by the screening of audiograms for evidence of noise-induced hearing loss, although it is possible that our criteria for noise-induced hearing loss may have missed some individuals with actual noise-induced hearing loss. Figure 1 shows that the BLSA findings are in substantial accord with previous findings in screened samples such as ISO 7029-1984 (ISO, 1984). The ISO 7029-1984 standard represents a meta-analysis of studies of individuals with no known ear pathology and with no history of undue exposure to noise, although not all of the studies performed otological examinations or rigorous noise-exposure screening. The BLSA results do differ in some respects from the ISO (1984) standard: 1) the ISO (1984) standard did not indicate a gender difference in hearing thresholds at 1000 Hz or lower and 2) the BLSA estimates at 3000 to 8000 Hz are 4–9 dB better than the ISO (1984) values for men age 70 and older. The better thresholds at 3000 to 8000 Hz for men may be the result of the more rigorous screening for exogenous causes of hearing loss in the BLSA study compared to the studies in the ISO standard.

After screening for otological disorders and apparent noise-induced hearing loss, our findings indicate an age-associated longitudinal decline in hearing thresholds on the order of 2.5 to 18 dB per decade in men and from -2 to $+19$ dB per decade in women. Although the mixed-effects model estimates indicate longitudinal improvements in the hearing thresholds of women between ages 30 and 50 at 2000–4000 Hz, these apparent improvements are small and most are not statistically significant.

There is a small learning effect on the order of 0.1- to 1.9-dB improvement in thresholds from the first to subsequent visits in both men and women. Although we attempted to control for this learning effect in the mixed-effects regression model, we believe that the small improvements in hearing thresholds at 2000 and 4000 Hz exhibited by younger women represent a residual bias from learning effects. Given the smaller number of visits in women, there is a greater degree of confounding between the learning-effect term (visit1) and the estimates of longitudinal change which makes it more difficult to statistically separate the two effects in women than in men. Other studies have reported learning effects on the order of 4–9 dB for tests conducted over a period of several weeks or years (Stephens, 1971; Robinson and Whittle, 1973; Robinson *et al.*, 1975; Thomas *et al.*, 1975; Berger *et al.*, 1977; Royster and Thomas, 1979; Royster and Royster, 1986). These learning effects compromise the results from cross-sectional studies which may report artificially poorer hearing sensitivity because the subjects are unpracticed. Learning effects can also bias longitudinal studies with only two or three repeated measurements because the improvement in thresholds with practice will mask some of the age changes.

The rate of decline in hearing sensitivity accelerates with age in both men and women, but men decline more than twice as fast as women at most ages and frequencies. It is interesting to note that the largest gender differences in longitudinal rates of hearing loss occur at 3000 and 4000 Hz which are the frequencies most affected by noise exposure. The rates of change at 3000 and 4000 Hz are approximately 10 dB/decade faster in 50-year-old men than in comparably aged women. In contrast, women have significantly faster rates of hearing loss than men only at low frequencies and younger ages. By age 80, the rates of hearing loss are no longer significantly different in men and women. The long period of follow-up in our study also confirms that over periods of up to 23 years, the age-associated changes in hearing thresholds tend to be gradual and progressive rather than abrupt (Møller, 1981; Ostri and Parving, 1991).

The findings also reinforce the observation that age-associated hearing loss is not restricted to the elderly. Among men, the decline in hearing sensitivity is detectable by age 30 for all frequencies. Corso (1963) also reported that the decline in hearing sensitivity began between the ages of 26 and 32 in men. Among women, the age of onset of hearing decline is frequency dependent. In women, longitudinal changes in thresholds begin by age 30 at 500 and 8000 Hz and by age 60–70 at the other frequencies. Thus the initial detectable declines in BLSA women for frequencies other than 500 and 8000 Hz are later than in Corso's data where the decline in hearing sensitivity in women began at age 37.

Our findings confirm earlier BLSA findings which indicated that age-associated hearing loss is not confined to high frequencies (Brant and Fozard, 1990). In fact, the longitudinal declines in hearing thresholds are detectable earlier at 500 Hz than at the middle or high frequencies. The findings also confirm previous BLSA findings that the longitudinal rate of change in hearing thresholds in men is relatively constant at 8000 Hz after age 50 but that the rates of change in other frequencies continue to increase with age until they begin to catch up to 8000 Hz (Brant and Fozard, 1990). However, our current findings show no evidence of a slowing in the rate of change at 8000 Hz among women. The plateau in rate of loss at 8000 Hz may be a ceiling effect due to the limits of the audiometer to measure hearing thresholds beyond 90 dB HL or may indicate that once thresholds have deteriorated to a certain level, there is little residual hearing sensitivity left to lose.

The cross-sectional and longitudinal results in this study do not differ appreciably. The absolute value of the difference between the cross-sectional and longitudinal hearing levels after ten years is approximately 3.5 dB (median 3.5, range 0.2–8.0 dB). Since the measurement error in an audiometric test is approximately 5 dB, the difference between cross-sectional and longitudinal estimates in this study group appears to be negligible. These findings are in contrast to findings previously reported for BLSA men which suggested that hearing thresholds deteriorated more rapidly longitudinally than cross sectionally, particularly in younger men (Brant and Fozard, 1990). However, the previous BLSA studies examined continuous pure-tone thresholds rather than pulsed pure tones. Pulsed-tone thresholds are preferable since they minimize the effects of auditory adaptation (Jerger *et al.*, 1958). Furthermore, the previous BLSA studies did not exclude individuals with otologic problems or noise-induced hearing loss. Therefore, the rapid longitudinal declines in hearing thresholds observed by Brant and Fozard (1990) may reflect the development of otologic problems or noise-induced hearing loss in some subjects in that study.

Our findings confirm the "gender reversal" in pure-tone thresholds noted in several previous studies (e.g., Corso, 1963; Royster and Thomas, 1979; Chung *et al.*, 1983; and Jerger *et al.*, 1993). At lower frequencies, hearing levels tend to be better in men than in women, at about 1000 Hz the levels are similar, while at frequencies above 1000 Hz hearing levels in women are better than in men with the difference becoming larger at the higher frequencies and older ages. It has been speculated that the gender reversal may represent the greater influence of noise exposure on high frequency hearing loss in men and the greater influence of atrophy of the stria vascularis on low frequency hearing loss in elderly women (Gates *et al.*, 1992; Jerger *et al.*, 1993). An alternative explanation, postulated by Shaw (1993), is that the gender differences in the low-frequency region could be associated with measurement artifacts that occur when measuring hearing threshold levels with supra-aural earphones. Two measurement artifacts may operate individually or in combination to produce the observed gender differences: (1) Masking noise of physiological origin generated in the ear canal when an earphone is coupled to the ear (Rudmose, 1962); and (2) variations in signal sound pressure, generated in the ear canal by the earphone, due to variations in air leakage and in the effective volume enclosed by the earphone (Shaw, 1974). Shaw and Piercy (1962b) reported that the $\frac{1}{3}$-oct band levels of physiological noise produced in the external ear when an earphone is tightly sealed to the ear are inversely proportional to signal frequency below 1000 Hz. Moreover, the acoustic pressure of physiological noise at the ear varies inversely with the effective enclosed volume (Shaw and Piercy, 1962a). The mean linear dimensions of the female pinna and ear canal are about 10% smaller than the average values for male ears and the volume about 30% smaller (Stinson and Lawton, 1989). Thus females may produce greater physiological masking noise levels in the low frequencies compared to males, which would yield the observed gender differences in low-frequency thresholds. The second hypothesis suggests that there may be more loss of signal sound pressure due to air leakage and pinna compliance in females than in males. Shaw (1974) has noted that there is considerable variation in the coupling between an earphone and an individual ear below 300 Hz and above 3000 Hz, which in turn alters the acoustic pressure distribution in the ear (Villchur, 1969). Differences in the size, shape, and compliance properties of the concha and pinna extension between males and females may alter this coupling systematically, thereby producing the gender differences in low-frequency hearing sensitivity observed in this report. Although our study does not permit any definitive conclusions regarding the source of the gender reversal, these factors warrant careful evaluation in future studies. Specifically, a comparison of free-field thresholds obtained from males and females would resolve questions about the extent to which earphone coupling artifacts contribute to gender differences in low-frequency thresholds.

Although it is widely recognized that there is substantial variability in hearing levels, even in screened populations, our findings also show that individuals do not necessarily track at the same hearing level over time (Fig. 4). Since it is difficult to identify a "normal" pattern of hearing loss with age, one must be cautious in attempting to generalize from the average hearing level curves to the longitudinal pattern of change expected for an individual.

IV. CONCLUSIONS

Our findings demonstrate that there are gender differences in hearing levels and in rate of change in hearing level, and that hearing sensitivity declines gradually and progressively with aging, even in screened samples. The longitudinal rate of hearing loss is more than twice as rapid in men as in women at most frequencies and ages. Among men, hearing decline begins by age 30 at all frequencies whereas among women the age of onset of hearing decline is frequency dependent. Our findings benefit from the longer follow-up, greater number of repeat visits, and better control for learning effects compared to previous short-term longitudinal analyses which have not consistently detected a difference between men and women in rate of decline in hearing thresholds. This study does not identify the cause of gender differences in hearing sensitivity or of age-associated hearing loss. The gender difference in hearing thresholds has generally been attributed to greater noise exposure to men in occupational, military, and leisure settings. However, our findings are unlikely to be the result of extreme noise exposure because of the select nature of the study group and the method of screening for noise-induced hearing loss. Further studies will be necessary to determine if other specific risk factors can be identified (e.g., vascular factors, medication use, osteoblastic activity) that may allow the prevention of progressive hearing loss over the lifespan of men and women. The current findings indicate that women, as well as men, are at risk for age-associated hearing loss, and that prevention programs will have to begin in early adulthood or earlier and continue over a large portion of the lifespan.

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