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MODEL FOR ESTIMATING NOISE-INDUCED HEARING LOSS ASSOCIATED WITH OCCUPATIONAL NOISE EXPOSURE IN A SPECIFIED U.S. NAVY POPULATION

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This report details the initial steps in the development of a method for modeling the noise-induced hearing loss accrued by a population of Sailors exposed to high-level, steady-state occupational noise. The model is based on the predictive algorithm described in ANSI S3.44-1996, "Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment." For the purpose of developing the model, a specific population of Sailors is described which meets many of the criteria for the application of the S3.44 algorithm. Next, the predicted distributions of hearing threshold levels associated with age and noise for this population are calculated using the S3.44 algorithm, and these predicted distributions are compared with the distributions of actual hearing threshold levels of the group. Corrections to the input values of the S3.44 algorithm are proposed based on a maximum likelihood curve-fitting procedure. Finally, recommendations are provided for the purposes of refining the model and improving its generalizability to other noise-exposed populations.

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EXECUTIVE SUMMARY

In the acquisition of a military system, total life-cycle costs associated with the system, including personnel, can be included in trade-off decisions. Currently, the cash outlays by the U.S. government for noise-induced hearing loss (NIHL) caused to service personnel by noisy systems and spaces are unaccounted for in estimates of life-cycle costs. This pilot study explored whether a NIHL prediction algorithm from the American National Standards Institute (ANSI S3.44-1996) could be quantitatively applied to a specific population of U.S. Navy sailors. A companion report estimates the Navy and Veterans Affairs outlays for the medical and compensation costs of NIHL in this population.

This population of Sailors has a "simple" exposure in that the main career-long noise exposure is in a single machinery space in an aircraft carrier. Many, but not all, of the standard assumptions for the application of ANSI S3.44-1996 are satisfied by this group. Predicted distributions of hearing loss from both noise and aging did not initially agree with data for this population taken from a Navy Environmental Health Center database. A –5 dBA correction to the presumed machinery room ambient noise level (likely due to several factors, including the wearing of hearing protection) produced maximum likelihood agreement between prediction and the data. Extension of these results to prediction of other Navy populations' hearing losses is not yet justifiable. Recommendations are made for further work to strengthen the generality of hearing loss predictions in military populations.

ADMINISTRATIVE INFORMATION

This work was conducted under NSMRL Work Unit(s) 50518, entitled: Life Cycle Cost Evaluation Tool for Weapons System Noise Exposure. The views expressed in this article/report are those of the author and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the United States Government. This Technical Report was approved on 10 January 2007, and designated as NSMRL/50518/T--2007-1247.

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1. ABSTRACT

This report details the initial steps in the development of a method for modeling the noise-induced hearing loss accrued by a population of Sailors exposed to high-level, steady-state occupational noise. The model is based on the predictive algorithm described in ANSI S3.44-1996, "Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment." For the purpose of developing the model, a specific population of Sailors is described which meets many of the criteria for the application of the S3.44 algorithm. Next, the predicted distributions of hearing threshold levels associated with age and noise for this population are calculated using the S3.44 algorithm, and these predicted distributions are compared with the distributions of actual hearing threshold levels of the group. Corrections to the input values of the S3.44 algorithm are proposed based on a maximum likelihood curve-fitting procedure. Finally, recommendations are provided for the purposes of refining the model and improving its generalizability to other noise-exposed populations.

2. BACKGROUND

a. Department of Defense and Navy regulations require that noise and other hazards be identified in the development process for a new military system, and abated in the original systems engineering and design process. However, cost is always a consideration, and cheaper components and processes are frequently noisier. Additionally, many designs reflect repeated modifications of earlier systems and do not address noise control as an element of design. Thus, aircraft carriers continue to have some very noisy spaces as do other new surface ships, despite the available quieter technologies applied for tactical reasons to submarines and anti-submarine warfare platforms[1]. Protection of sailors' hearing then depends less upon effective engineering and administrative controls and more on the use of individual hearing protection devices, whose effectiveness and use are commonly overestimated. Communications, military performance, and quality of life suffer as a result. Inevitably, thousands of service people incur permanent noise-induced hearing loss (NIHL) and tinnitus (ringing in the ears) (Veterans Benefit Administration, 2005), now the two biggest disability categories for VA compensation and medical care.

b. Life-cycle costs, or the total costs of system design, construction, operation, and eventual disposal, are a visible item in the systems acquisition process. However, there is a natural tendency for systems acquisitions to focus upon procurement cost rather than on investments that will reduce life-cycle costs. Currently, the cash outlays by the government for NIHL caused to service personnel by noisy systems and spaces are un-accounted for during the acquisition process. A methodology to tie anticipated system noise levels to projected NIHL costs could allow hearing loss to become a cost "trade-off" factor in military acquisition and engineering decisions and reviews. The present project is an initial attempt to (1) relate the NIHL of a specific occupational group in the U.S. Navy to the source of their greatest noise exposure, and (2) account for the associated economic costs of the NIHL incurred by this population.

c. This report is the first of two. This report describes the adjustment of the ANSI S3.44-1996 algorithm for predicting hearing loss due to age and noise in an effort to relate the

[1] Yankaskas K. (2005). System safety implications and applications of noise evaluation and control in military ships. Proceedings of 23rd Int. System Safety Conference.

NIHL of a specific U.S. Navy occupational group to the source of their greatest noise exposure. The companion report, “Model for estimating life-cycle costs associated with noise-induced hearing loss,” describes the development of a model to predict associated economic costs of hearing loss incurred by this U.S. Navy population (Sachs, Weathersby, Marshall, and Tufts, 2006).

3. DEVELOPMENT APPROACH

a. This report draws heavily on prior research on the effect of noise exposure on human hearing levels. Specifically, ANSI standard S3.44-1996, “Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment,”[2] is used to predict the hearing threshold levels associated with age and noise (HTLAN) of a specific population of Sailors.

(1) ANSI S3.44-1996 (hereafter referred to as S3.44) provides an algorithm for calculating the predicted noise-induced permanent threshold shifts (NIPTS) of a population exposed to noise of a specified intensity and duration. For each of the audiometric frequencies of 500, 1000, 2000, 3000, 4000, and 6000 Hz, the algorithm outputs a probability distribution of predicted NIPTS based on the given inputs. Probability distributions of hearing threshold levels associated with age only (HTLA) and hearing threshold levels associated with age and noise (HTLAN) may also be calculated at these frequencies.

b. A population of specially qualified machinists’ mates (MMs) assigned to large Machinery Rooms of US Navy nuclear-powered aircraft carriers (CVNs) was chosen for the development of the model. Retrospective data were accessed to provide the hearing levels and noise exposures of this group. The types and sources of these data are listed in Table 3.1.

(1) These data meet several, though not all, of the criteria for the application of the S3.44 algorithm. Table 3.2 lists the criteria for application of S3.44 with respect to the MMs. Data whose parameters fall outside the intended scope of S3.44 may produce distributions of HTLA, NIPTS, or HTLAN that contain unrealistically high or low values.

(2) Table 3.3 lists additional assumptions in the development of the model.

(3) The original database from which the population of MMs was culled contained 87,001 records. A search for the specific Navy enlisted classification of these MMs yielded 380 records. Of these records, 130 were removed, leaving a total of 250 records. Table 3.4 lists the reasons for removing records, and the number of records removed in each category.

c. As a result of the assumptions made in the development of this model, potential sources of error exist in the prediction of HTLAN for this population. See Section 6 for further discussion.

d. The remaining sections of this report describe the calculation of predicted HTLAN of the MMs using the S3.44 algorithm; the comparison of predicted HTLAN to actual hearing levels of the MMs; and a maximum likelihood procedure to improve the match between prediction and data.

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[2] ANSI (1996). “Determination of occupational noise exposure and estimation of noise-induced hearing impairment,” ANSI S3.44-1996, Acoustical Society of America, New York, NY.

Table 3.1. Data on Selected MMs

Data	Source
Dates of birth, dates and results of reference* and current* audiograms, and right- and left-ear threshold shifts (i.e., current audiogram minus reference audiogram) for male Sailors with specific MM Navy enlisted classifications [N=250 out of approximately 4000 total in the US Navy] **Reference and current audiograms refer to the earliest and most recent audiograms, respectively, in the database.*	Navy Environmental Health Center (NEHC) database for 1996-1999[3]
Estimated length of training tour for MM is 2 years following enlistment	Appendix C
For each year of sea duty, it is estimated that the "typical" MM works in the Machinery Room for approximately 12 hrs/day for 7 days/week for 0.5 years. The Machinery Room noise has an estimated Leq = 95 dBA.	Appendix C

Table 3.2. Criteria for the Application of ANSI S3.44-1996 to Selected MMs (SPL = sound pressure level)

Criterion	Comment re: MMs
For use with population data, not individual data	Condition met
Period of noise exposure lasts from 0 to 40 years (Note: ANSI S3.44 sometimes gives unusable predictions for exposures under 5 years)	Condition met
Noise is essentially steady, broadband, non-tonal, <10kHz	Condition may not be met; some strong tonal components may exist in the noise
Equivalent continuous A-weighted SPLs for a normal 8-hour working day fall between 75 and 100 dB inclusive (or an equivalent effective level)	Condition met
Instantaneous SPLs do not exceed 140 dB	Assumed
Daily equivalent continuous A-weighted SPL on the "worst" day does not exceed, by >10 dB, the equivalent continuous A-weighted SPL averaged over a longer period (not to exceed 1 year)	Condition may not be met
Instrumentation, microphone positions, and methods of measurement meet requirements in S3.44 Section 4	Assumed
A typical career profile, including typical noise exposure patterns and levels, applies to everyone in the population	Condition likely not met; see Appendix C
Non-occupational exposure is negligible compared with the occupational exposure under consideration	Assumed
Daily noise exposure duration $\leq$ 12 hours	Assumed
Exposure to hazardous occupational noise occurs on a reasonably regular and predictable basis (e.g., a given number of days/week for most weeks during each year of service)	Condition not met

[3] Bohnker, B.K., Page, J.C., Rovig, G.W., Betts, L.S., Muller, J.G., and Sacks, D.M. (2002). U.S. Navy and Marine Corps hearing conservation program. Mean thresholds for enlisted personnel by gender and age groups. Milit Med, 167,132-135.

Table 3.3. Additional Assumptions in the Model

Assumption	Comment
A sailor was assumed to enlist at age 20 unless the data indicated an earlier age. If the Sailor's age at the time of the reference audiogram was >20 years, then length of Naval service (LOS) is assumed to be equal to the Sailor's age at the time of the current audiogram minus 20 years; otherwise, LOS is equal to the Sailor's age at the time of the current audiogram minus his age at the time of the reference audiogram. [*For example, the LOS of a Sailor with a reference audiogram that was obtained at age 19, and a current audiogram that was obtained at age 24, would be estimated at 24 - 19 = 5 years. The LOS of a Sailor with a reference audiogram that was obtained at age 30, and a current audiogram that was obtained at age 35, would be estimated at 35 - 20 = 15 years.*]	In the NEHC database, reference audiograms are not coded as to whether they are original or revised baseline audiograms. Therefore, the Sailor's age at the time of the reference audiogram may not be his age at enlistment. In those cases where the age at the reference audiogram is >20 years, it is assumed that the age at enlistment was 20 years. This definition of LOS was applied to 110 individuals (44% of the population of MMs); the LOS of 140 individuals (56% of the population of MMs) was calculated directly.
Number of years as a qualified MM is equal to LOS minus two years.	The date that each Sailor began working in the Machinery Room is not available in the NEHC database. Two years typically elapse between enlistment and assignment to the Machinery Room, during which time a Sailor completes basic and specialized training (Appendix C). Note: Table 4.2 shows the MMs grouped by number of years as a qualified MM. The median age minus the median number of years as an MM ranges from 21.3 to 21.8 from the youngest to the oldest group, suggesting that the ad hoc definitions of LOS and number of years as a qualified MM are reasonable.
Race will not be taken into account in calculation of HTLAN	Data on race of MMs not available
Data from female Sailors will not be used in the development of the model	N=3; too small to permit evaluation of sex as a predictor of HTLAN
Time/intensity trading relation of 3 dB assumed (see Glossary, Appendix D)	As per S3.44

Table 3.4 Data Editing Steps

Reason for removing records in original database	**Number of records removed**
Records for Navy enlisted classifications other than the specified fields	86,621
Female Sailors	3
Apparent age of the Sailor at the time of the reference audiogram was 16 years	1
Length of service was negative (see Table 3.3 for an explanation of how length of service is calculated)	1
Grade incompatible with length of service: in this case, the length of service of one individual with a grade of E-1 was 11.5 years (taking the high-year tenure service limit for a grade of E-1 to be 10 years; see http://www.mediacen.navy.mil/pubs/allhands/feb01/pg6f.htm for high-year tenure service limits, which designate whether poorly advancing sailors are allowed to continue in the Navy)	1
Number of years as a qualified MM was <1 (N=42) or >21 (N=1); see Table 3.3 for an explanation of how number of years as an MM was calculated	43
Multiple records of same individual (criterion for removal: if multiple records listed identical dates of birth AND identical dates for the reference audiogram, only the record with the most recent current audiogram was kept)	81

4. USE OF ANSI S3.44-1996 TO CALCULATE DISTRIBUTIONS OF PREDICTED HEARING THRESHOLD LEVELS ASSOCIATED WITH AGE AND NOISE

a. The required inputs to the S3.44 algorithm for prediction of HTLAN are the noise exposure level normalized to a nominal 8-hour working day (L_{A8hn}), the years of noise exposure, and age. For each audiometric frequency, probability distributions of predicted noise-induced permanent threshold shifts (NIPTS) and of predicted hearing threshold levels associated with age (HTLA) are the outputs. HTLAN is then equal to HTLA + NIPTS – ((HTLA*NIPTS)/120). The equation applies to corresponding fractiles of the probability distributions of HTLA and NIPTS (ANSI S3.44-1996, p. 9).

b. Appendix C outlines the typical sequence and duration of training, sea, and shore tours for MMs. As described in Appendix C, the exposure patterns of MMs do not follow a civilian industrial noise exposure pattern of 8 hrs/day for 5 days/week for a number of consecutive years. Therefore, finding appropriate values for L_{A8hn} and years of noise exposure for input to S3.44 is not straightforward. In the development of this model, a simplifying approach was taken. In this approach, L_{A8hn} and years of noise exposure are based on exposure to noise in the Machinery Room only; other occupational noise exposure is not taken into account. This approach does not require the averaging of several values of L_{A8hn}, as would be the case if several occupational noise sources were taken into account; it recognizes the Machinery Room as the source of noise of greatest potential for causing NIPTS (because its level is at least 5 dB greater than that of other noise sources typically encountered by the MM) and as the source that distinguishes this population from other noise-exposed populations in the US Navy; it also recognizes that other noise exposures (such as might occur during flight operations on the CVN) may vary considerably from person to person. This approach also recognizes the relative paucity of data available for characterizing noise exposures and assumes that many of the remaining variables will be accounted for by the adjustment of the algorithm.

(1) In order to plot the predicted HTLAN of the population of MMs and compare them to the actual thresholds, the MMs were "binned" into four groups according to years as a qualified MM. Bin widths were chosen as a compromise between maximizing the N in each group while at the same time producing values for median age and median years as a qualified MM that were reasonably representative of all members of the group. See Table 4.2.

(2) L_{A8hn}: From Table 3.1, the Leq in the Machinery Room is estimated at 95 dBA, and the length of the work shift is estimated at 12 hours. From Equation (6) in Section 3.6 of S3.44, the corresponding L_{A8hn} is 96.76 dBA. (L_{A8hn}= Leq + 10log(12/8) = Leq + 1.76). This L_{A8hn} is then normalized from a seven-day working week to a five-day working week. From Equation (8) in Section 3.6 of S3.44, the normalized L_{A8hn} is approximately equal to 98 dBA (normalized L_{A8hn} = $10\log[(1/5)*7*10^{(0.1*96.76)}]$). Therefore, the L_{A8hn} input to S3.44 is 98 dBA.

(3) Years of noise exposure: Consistent with Appendix C and the simplifying assumptions discussed previously, years of noise exposure are assumed to commence with the first sea tour and accumulate at a rate of 0.5 years for each year of sea duty. This is shown in Table 4.1. Figure 4.1 shows the estimated cumulative years of Machinery Room noise exposure (from the last column of Table 4.1) plotted as a function of LOS (from the first column of Table 4.1). A quadratic curve, shown as the curved dotted line in Figure 4.1, was fitted to these points. This smooth trend curve, noise exposure = $-0.0062*(LOS)^2 + 0.4472*(LOS) - 0.6461$, was used to calculate the estimated cumulative years of noise exposure for each group. For example, from Table 4.2, the median years as a qualified MM for Group IV is 14.1. Assuming a training tour of two years, the median LOS is 16.1 years. Then, $-0.0062*(16.1)^2 + 0.4472*(16.1) - 0.6461 = 4.95$, the estimated cumulative years of noise exposure for Group IV.

(4) Age: The median age was calculated in each group. See Table 4.2.

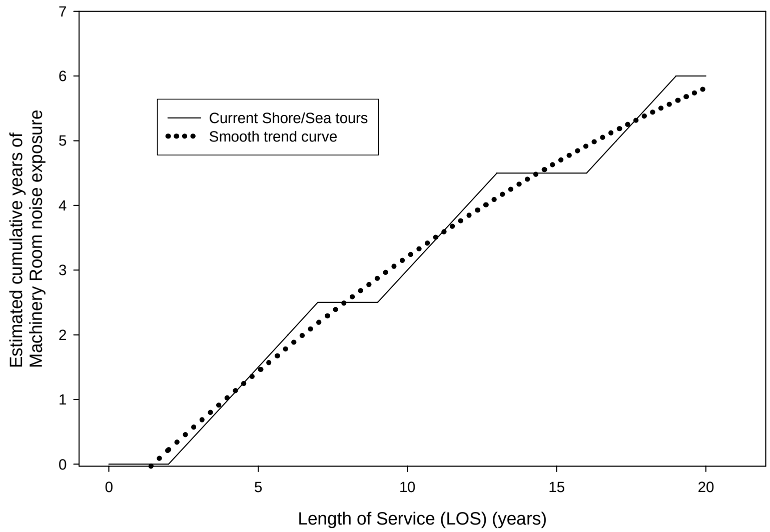

Figure 4.1. Estimated Cumulative Years of Machinery Room Noise Exposure as a Function of Length of Service

Table 4.1. Cumulative Noise Exposure
Note: see Appendix C for more information.

LOS	**Tour**	**Years as a qualified MM**	**Estimated cumulative years of Machinery Room noise exposure**
1	Training	0	0.0
2	Training	0	0.0
3	Sea	1	0.5
4	“	2	1.0
5	“	3	1.5
6	“	4	2.0
7	“	5	2.5
8	Shore	6	2.5
9	“	7	2.5
10	Sea	8	3.0
11	“	9	3.5
12	“	10	4.0
13	“	11	4.5
14	Shore	12	4.5
15	“	13	4.5
16	“	14	4.5
17	Sea	15	5.0
18	“	16	5.5
19	“	17	6.0
20	Shore	18	6.0
21	“	19	6.0
22	“	20	6.0

Table 4.2. Grouping of the MMs by Years as a Qualified MM

	Bin width	**N**	**Age (median and range)**	**Years as a qualified MM (median and range)**	**Cumulative years of noise exposure**
Group I	1 to 4 years	121	23.7 (21.0-25.9)	2.4 (1.0 - 3.9)	1.20
Group II	4 to 7 years	64	26.6 (26.0-28.9)	5.3 (4.0 - 6.9)	2.29
Group III	7 to 11 years	32	30.0 (27.0-32.9)	8.6 (7.0 - 10.9)	3.40
Group IV	11 to 20 years	33	35.9 (31.3-42.2)	14.1 (11.0 – 20.2)	4.95

5. COMPARISON BETWEEN OUTPUT OF ANSI S3.44-1996 ALGORITHM AND HEARING LEVEL DATA ON THE MACHINIST'S MATES

a. In this section, the predicted distributions of HTLA and HTLAN are compared with the distributions of actual hearing levels of the MMs at the audiometric frequencies of 1000, 2000, 3000, and 4000 Hz. No distributions were calculated for the audiometric frequencies of 500 Hz and 6000 Hz because these frequencies are not used in the calculation of significant threshold shift. The hearing threshold level at 500 Hz is not considered indicative of an individual's noise exposure history because NIPTS is typically seen in the frequencies above 500 Hz. In addition, thresholds at 500 Hz are subject to masking by ambient noise in field testing conditions. Thresholds at 6000 Hz are sensitive to variability in earphone placement.

(1) For each group of MMs, the inputs to the S3.44 algorithm were the estimated cumulative years of noise exposure, the median age, and the L_{A8hn} of 98 dBA (from Table 4.2 and section 4a(1) of this report).

(2) For the calculation of HTLA, ANSI S3.44-1996 offers the choice of two databases, Annex A (representing a highly screened population) and Annex B (representing an unscreened population assumed to be free from occupational noise exposure). (Alternatively, a database may be specified by the user.) In this report, all calculations of HTLA are based on Annex A. This database was compiled from a larger and more geographically diverse sample than Annex B and is parameterized for ease of use. The Institute of Medicine has recently concluded that military populations should not be considered to be as highly screened as the Annex A population[4]. However, parameterizing Annex B or finding a different database was outside the scope of this report. See Section 6 for further discussion on the consequences of the choice of Annex A.

(3) The hearing levels from the current audiograms of the MMs were binaurally averaged and then converted into distributions for comparison with the predicted distributions. Binaural averages were used instead of individual-ear data because among the current audiograms in the dataset, 95% of the right ear/left ear threshold pairs were no more than 10 dB different from one another. For reference purposes, Figure 5.1 plots the median thresholds of each group of MMs at 1000, 2000, 3000, and 4000 Hz. All plotted values fall within the range of

[4] Humes, L.E., Joellenbeck, L.M., Durch, J.S., eds. (2005). Noise and military service: Implications for hearing loss and tinnitus. Medical Follow-Up Agency. Washington DC: Institute of Medicine.

normal hearing (i.e., thresholds at or below 20 dB HL). This finding is not unexpected, given the relatively youthful population and the small number of years of cumulative noise exposure. Because of these characteristics, as well as the small sample size, it is difficult to draw conclusions about how the hearing status of the population changes with increasing length of service. Nevertheless, it is of interest to note that Groups III and IV have slightly higher median thresholds than Groups I and II at the more age- and noise-sensitive frequencies of 3000 and 4000 Hz.

b. Plots of the predicted distributions of HTLA and HTLAN for L_{A8hn} = 98 dBA (HTLAN-98) and the distributions of actual hearing levels of the MMs are shown in Figures A1-A16 of Appendix A. Although all of the data are shown in these plots, only the left side of the distributions (i.e., fractiles <0.50) is considered in the following discussion. This half of the population incurs the greater hearing loss and associated economic costs. (Note that in many cases, the right side of the distribution shows predicted HLs due to the combination of aging and noise that are better than predicted HLs due to aging alone. This is an artifact of the S3.44 algorithm. It makes sense to us that the developers of the algorithm were focused on the hearing loss side of the population and were less bothered by artifacts at the better hearing extremes).

(1) HTLA predicted by the S3.44 algorithm slightly underestimated actual hearing levels for all groups at all frequencies with the exception of group IV at 2000 Hz. Therefore, it appears likely that there is a noise exposure component in the actual hearing thresholds.

(2) HTLAN-98 overestimated the actual hearing levels for all groups at 2000, 3000, and 4000 Hz. At 1000 Hz, where noise-induced hearing loss is typically minimal, HTLAN-98 slightly underestimated actual hearing levels for Group I, and nearly overlapped the actual hearing levels for Groups II, III, and IV.

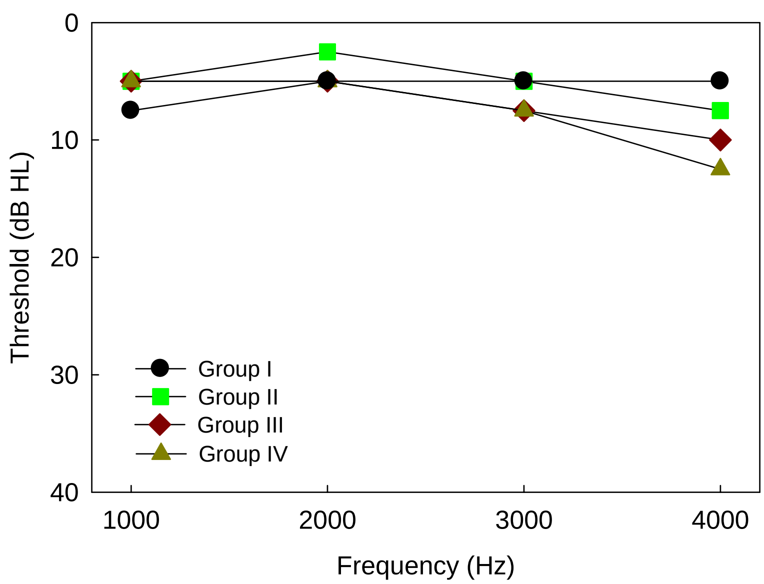

Figure 5.1. Median Hearing Thresholds at 1000, 2000, 3000, and 4000 Hz for each Group of MMs

6. POSSIBLE SOURCES OF ERROR IN PREDICTION OF HTLAN

a. Using available (albeit simplified) estimates of the L_{A8hn} and duration of noise exposure, the S3.44 algorithm overestimated the hearing thresholds of the MMs at 2000, 3000, and 4000 Hz, and either underestimated or nearly overlapped their hearing thresholds at 1000 Hz. Table 6.1 lists possible sources of error that may have contributed to this finding. As an example, if workers consistently use hearing protection devices (HPDs), then the noise level measured in the Machinery Room will be higher than the effective level reaching the workers' ears. It should be noted that the amount of attenuation that HPDs provide in the "real world" is consistently lower than that obtained under optimal conditions. However, HPDs that provide modest amounts of attenuation and that are worn for most, but not all, of the work shift (as might occur in an optimistic, yet real-world scenario) may reduce the effective noise level by an amount that could account for the discrepancies between observed and predicted HLs (Mr. Elliott Berger; personal communication, June 2006). As another example, exposure to hazardous levels of noise for the last four hours of a 12-hour shift may not incur additional risk to hearing beyond that incurred during the first eight hours of exposure (Dr. Donald Henderson; personal communication, June 2006). In that case, the normalization of the 12-hour work shift required by S3.44 would produce an overestimation of the effective noise level and an over prediction of HTLAN.

Table 6.1. Possible Sources of Error in Predicting HTLAN of MMs

Possible source of error	**Comment**
Incomplete characterization of noise exposure and its effects: • Use of HPDs; • Parameters of noise exposure do not meet criteria for application of S3.44 (e.g., some MMs do work shifts >12 hours for more than 5 days/week, possibly with noisy sleep environment); • Noise intensity based on unverified reports; • Years of occupational noise exposure are estimated, not known; • Assumed exposure time patterns account only superficially for differences in noise exposure during training, sea, and shore duty, and not at all for differences in length of training, sea, and shore duty across individuals • Nonoccupational noise exposure	(1) Limited data available; (2) S3.44 assumes exposure to hazardous noise on a regular basis and is based on data obtained for noise exposures <12 hours/day for 5 days/week, not 7 days/week; (3) Risk of hearing loss due to noise exposure for work shifts > 12 hours may not differ significantly from risk due to 8-hour work shifts (4) Noise level input to algorithm assumes an unprotected ear; consistent use of HPDs that provide modest amounts of attenuation may account for discrepancies between predicted and observed HLs
Small N	(5) Bias in available database (<10% of target population)
Choice of Annex A instead of Annex B to characterize HTLA	If Annex B had been used instead of Annex A, that part of the MMs' thresholds due to aging would be assumed to be greater, and that part due to NIPTS would be assumed to be smaller. In that case, it is possible that the HLs at 1000 Hz would be shown to be a consequence of aging only, with no NIPTS component.
Invalid audiometric data	Due to data entry errors; faulty calibration or equipment; high ambient noise levels; improperly positioned headphones; inattention; other
Threshold shifts may be due to other causes besides noise exposure and age	Pathology, genetic disorder, other
Additional, unknown error sources	--

7. PROCEDURE FOR MODIFYING ANSI S3.44 ALGORITHM TO IMPROVE AGREEMENT BETWEEN PREDICTED AND ACTUAL HEARING THRESHOLD LEVELS

a. The ANSI S3.44 algorithm predicts that NIPTS follows a set of normal distributions (one per audiometric frequency), whose parameters of mean and standard deviation are entirely determined by L_{A8hn} and duration of noise exposure in years. Rather than change distribution shape or adjust any of the S3.44 algorithm's internal frequency-dependent parameters, we chose to treat L_{A8hn} as an unknown variable, and allow it to be estimated by the data.

(1) L_{A8hn} is considered a better choice of parameter for adjustment than years of noise exposure for the following reasons. First, we wish to predict changes in the HTLAN of a population due to changes in the noise exposure level, regardless of years of noise exposure, making L_{A8hn} the more attractive candidate for adjustment. Second, the years of noise exposure will change from person to person, while the estimated value of L_{A8hn} will not. In this context, finding a single value for years of noise exposure that characterizes the entire dataset does not make sense.

b. A maximum likelihood (ML) procedure was used to find the value of L_{A8hn} that yielded the best agreement between predicted and actual HTLAN for the MMs. This procedure does not require binning; it uses each Sailor’s age, duration of noise exposure, and hearing thresholds in its calculation. See Appendix B for a description of the principles of ML and details regarding its implementation in the development of the current model.

c. The ML procedure described in Appendix B was applied with the assumption that the noise exposure duration was equivalent to the estimated cumulative years of Machinery Room noise exposure (as estimated for each Sailor by using the smooth trend curve from Figure 4.1 of this report). By defining the duration of noise exposure in this way, any discrepancy between the original, assumed L_{A8hn} of 98 dBA and the L_{A8hn} determined by the ML procedure would presumably stem primarily from error sources related to actual environment and population characteristics (e.g., HPD use), rather than from a gross overestimate of the duration of noise exposure. In turn, this would perhaps allow better insight into the true exposure levels and risk to MMs.

d. The ML procedure produced a best-fitting value of L_{A8hn} of approximately 93 dBA, with a standard error of approximately 0.3. Compared to the original estimate of L_{A8hn} = 98 dBA, this value is approximately 5 dB lower.

(1) The curves for HTLAN-93 are shown in Appendix A, Figures A1-A16. Visual inspection of Figures A1-A16 supports the following general conclusions:

(2) At 1000 Hz, the curves for HTLA and HTLAN-93 nearly overlap, and underestimate actual HLs for all Groups;

(3) At 2000, 3000, and 4000 Hz, the curves for HTLAN-93 provide better agreement with actual HLs than HTLAN-98 for all Groups; and

(4) For Group IV at 3000 and 4000 Hz, HTLAN-93 substantially overestimates actual HLs, though to a lesser degree than HTLAN-98.

e. In light of these general conclusions, and the results of the ML procedure, a correction of -5 dB to the L_{A8hn} is recommended to best approximate the HLs of this population at 2000, 3000, and 4000 Hz, when noise exposure duration is estimated using the quadratic equation derived from Table 4.1. This correction will produce an under prediction of the HLs at 1000 Hz.

f. The noise exposure level of a population may decrease due to the implementation of noise control methods or may increase due to the introduction of new noise sources, with concomitant changes in the distribution of HTLAN. To predict changes in HTLAN due to a change in exposure level (assuming no changes to the demographics or exposure pattern of the population), the new L_{A8hn} may be corrected by -5 dB, and a new distribution of HTLAN calculated. The changes in predicted HTLAN can then be used to calculate cost increases or cost savings due to changes in noise exposure levels.

(1) As an example, the Leq in the Machinery Room of a newer aircraft carrier is expected to be approximately 86 dBA (Dr. Lynne Marshall; personal communication, May 2006). Following paragraph 4c(1) in this report, this Leq translates to an L_{A8hn} of 89 dBA. From paragraph 7g, a correction of -5 dB is applied to the L_{A8hn} of 89 dBA, yielding an L_{A8hn} of 84 dBA for input to S3.44. At this low exposure level, no NIPTS is predicted at 1000 Hz for any duration of noise exposure (i.e., HTLAN-84 is simply equal to HTLA). At 2000, 3000 and 4000 Hz, minimal NIPTS is expected. In Figures A17-A28 in Appendix A, HTLA, HTLAN-84, and HTLAN-93 are plotted for each Group at 2000, 3000 and 4000 Hz. (Recall that HTLAN-93 reflects the best fit to the actual HLs of the MMs). Differences between HTLAN-93 and HTLAN-84 show the improvement in HLs to be expected if this population of MMs were working in the quieter Machinery Room.

g. The conclusions in this report should be interpreted with caution, due to limitations in the dataset on which they are based. These limitations include the following: small N; incomplete characterization of the 24-hour noise exposures of MMs at sea; and incomplete characterization of career-long noise exposure. Additionally, these conclusions are based on the assumption of a “typical” pattern of noise exposure in the Machinery Room only.

(1) The description of the MM’s noise exposure is relatively simple. In reality, the noise exposures are more complicated -- within the day, within the week, within the year, across years, and across individuals. Obtaining the desired level of precision in describing the noise exposure of a population is time-consuming and oftentimes impractical. With our approach of adjusting the input parameter L_{A8hn} in the S3.44 algorithm in order to match predicted to actual HTLAN, the more complicated descriptions of noise exposure history are unnecessary.

h. The correction of -5 dB to the L_{A8hn} for this population may not be generalizable to similar populations with initial estimates of L_{A8hn} that differ greatly from the original estimate of 98 dBA used in this report. Furthermore, the correction may not be generalizable to non-MM populations with other patterns and levels of noise exposure. To more accurately predict changes in HTLAN due to changes in noise exposure levels, the procedure described in this report should be repeated for multiple populations with various noise exposure levels and histories in order to discern the underlying correction pattern.

(1) In particular, this correction should be validated on populations whose noise exposure falls well outside the scope of S3.44 (e.g., Leq much higher than 100 dBA, impulse noise exposure, etc.)

8. SUMMARY AND CONCLUSIONS

a. The purpose of this report was to relate the hearing losses of a specific occupational group in the U.S. Navy to the source of their greatest noise exposure.

b. The predictive algorithm in ANSI S3.44-1996 was already available for this purpose. This algorithm provides the distribution of hearing thresholds that are expected in a population due to aging, noise exposure, and their combined effects. However, the algorithm is based on data from industrial noise exposures, which may be very different from military noise exposures. For this reason, it was necessary to validate the S3.44 algorithm on an occupational group in the U.S. Navy.

c. A population of machinist mates (MMs) was chosen to validate the S3.44 algorithm. This group was chosen because the major source of their occupational noise exposure is broadband, steady-state noise originating from a single location (i.e., the Machinery Room), thus simplifying the validation process.

d. The S3.44 algorithm was applied using the ages of the MMs as well as best estimates of the level and duration of their noise exposure. The hearing thresholds of the MMs were found to be worse than predicted from aging effects alone. Therefore, it appears likely that there is a noise exposure component in the actual hearing thresholds of the MMs.

e. The hearing thresholds of the MMs at the audiometric frequencies of 2000, 3000, and 4000 Hz were found to be better than predicted from the combined effects of aging and occupational noise exposure. The better-than-predicted hearing thresholds of the MMs suggest exposure to a lower effective noise level than originally estimated.

f. To find the effective noise level that would produce the best match to the distribution of actual hearing thresholds, a maximum likelihood procedure was implemented. In this procedure, the presumed noise level was allowed to vary in the S3.44 algorithm until the best-fitting noise level was found. The duration of noise exposure was estimated as the cumulative years of noise exposure in the Machinery Room.

g. Based on the results of the maximum likelihood procedure, it is recommended that -5 dB be subtracted from the presumed noise level when the S3.44 algorithm is applied to this population of MMs. By adjusting the presumed noise level in the ANSI algorithm by this amount, better agreement between predicted and actual hearing thresholds is obtained at the audiometric frequencies of 2000, 3000, and 4000 Hz.

h. Correction to the presumed noise level did not produce better agreement between predicted and actual hearing thresholds at the audiometric frequency of 1000 Hz. However, correction will not produce large discrepancies between predicted and actual hearing thresholds at this frequency.

i. Although this adjustment approach may be considered a successful proof of concept, it is not yet sufficiently mature for general application to other systems and populations.

9. RECOMMENDATIONS FOR FUTURE WORK

a. The approach taken in this report to reconcile predicted hearing loss with actual hearing loss in a specific U.S. Navy occupational group may be considered a successful proof of concept. However, further work is required before this approach may be generally applied.

b. A number of steps are foreseeable to move this approach forward to a broadly useful predictor of hearing loss in military service:

(1) Confirm the present results with a larger, more up-to-date sample of the target population. The present sample comprised approximately 5% of all U.S. Navy machinist mates. The database itself was over five years old.

(2) Perform sensitivity calculations to see which of the assumptions in the present analysis made an important difference in the outcome, and which were of lesser importance.

(3) Concentrate future data-gathering efforts on strengthening the validity of the assumptions that were shown to be most critical in the sensitivity calculations.

(4) Repeat the analysis with another Navy population having career-long exposures to broadband noise. Either confirm the present corrections to S3.44, if warranted, or seek to understand how the correction factors change with population and noise.

(5) Extend the analysis to a Navy population with exposures to steady noise over 100 dBA (e.g., CVN flight deck, many other ships' engine rooms). Noise levels over 100 dBA fall outside the scope of ANSI S3.44.

(6) Extend the analysis to Navy populations with occupational exposures from multiple systems and places. Such a research effort may require a valid means of apportioning hearing loss to segments of a career. The possible effects of the order of occupational exposures on risk to hearing should be considered.

(7) Extend the analysis to include exposures to impulse noise sources, which are common in U.S. Army and U.S. Marine Corps careers. Such a research effort may require the development of a predictive algorithm for hearing loss due to impulse noise, analogous to the ANSI S3.44 algorithm for predicting hearing loss due to steady-state noise exposures.

(8) Extend the analysis to include the prediction of severity of tinnitus resulting from noise exposure. Monetary compensation for tinnitus is a growing area of concern. Such a research effort may require the development of a predictive algorithm for the presence/absence or severity of tinnitus due to noise exposure, analogous to the ANSI S3.44 algorithm for predicting hearing loss.

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APPENDIX A: GRAPHS SHOWING DISTRIBUTIONS OF PREDICTED HTLA AND HTLAN AND DISTRIBUTIONS OF ACTUAL HEARING LEVELS FROM CURRENT AUDIOGRAMS

Figures A1-A16: Predicted vs. Actual HLs
These figures show the relationships between HLs predicted by ANSI S3.44-1996 and the actual HLs of the MMs for the audiometric frequencies of 1000, 2000, 3000, and 4000 Hz. The population of MMs was divided into Groups I, II, III, and IV based on length of service, with Group I representing the least experienced MMs, and Group IV representing the most experienced MMs. Each figure depicts hearing threshold levels (HLs) of a specific Group at a specific audiometric frequency (e.g., Group II at 4000 Hz) as a function of population fractile.

Four cases are shown in each figure:
Actual HLs = the HLs of the population of MMs (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line). This case represents the original estimated noise exposure of the MMs.
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line). This case represents a better fit between predicted and actual HLs than the original estimate.

Visual inspection of these figures supports the following general conclusions: 1) at 1000 Hz, the curves for HTLA and HTLAN-93 nearly overlap, and underestimate actual HLs for all Groups; 2) at 2000, 3000, and 4000 Hz, the curves for HTLAN-93 provide better agreement with actual HLs than HTLAN-98 for all Groups; and 3) for Group IV at 3000 and 4000 Hz, HTLAN-93 substantially overestimates actual HLs, though to a lesser degree than HTLAN-98.

Note: In many cases, for higher fractiles of the population, predicted HLs due to the combination of aging and noise are better than predicted HLs due to aging alone. This is an artifact of the S3.44 algorithm and may be ignored.

Figures A17-A28: Predicted HLs for two values of LA8hn
These figures show the predicted effect of reducing the noise level to which the population of MMs is exposed. The population of MMs was divided into Groups I, II, III, and IV based on length of service, with Group I representing the least experienced MMs, and Group IV representing the most experienced MMs. Each figure depicts hearing threshold levels (HLs) of a specific Group at a specific audiometric frequency (e.g., Group II at 4000 Hz) as a function of population fractile.

Three cases are shown in each figure:
HTLA = predicted HLs due to aging effects (long-dashed red line).
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line). This case represents the best fit to the distribution of actual HLs of the MM.

HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line). This case represents the predicted HLs due to a plausible reduction in the noise level to which the MMs are exposed.

Visual inspection of these figures supports the following conclusions: 1) reducing the noise level from 93 dBA to 84 dBA leads to better predicted HLs for all Groups at 2000, 3000 and 4000 Hz; and 2) at the relatively low noise level of 84 dBA, minimal noise-induced hearing loss is predicted, even for low fractiles of the population (representing greater susceptibility).

Note: Figures are not shown for the audiometric frequency of 1000 Hz because no noise-induced hearing loss is predicted for exposure to the lower noise level [i.e., HTLAN (84 dBA)].

Predicted vs. Actual HLs
Group I: 1000 Hz

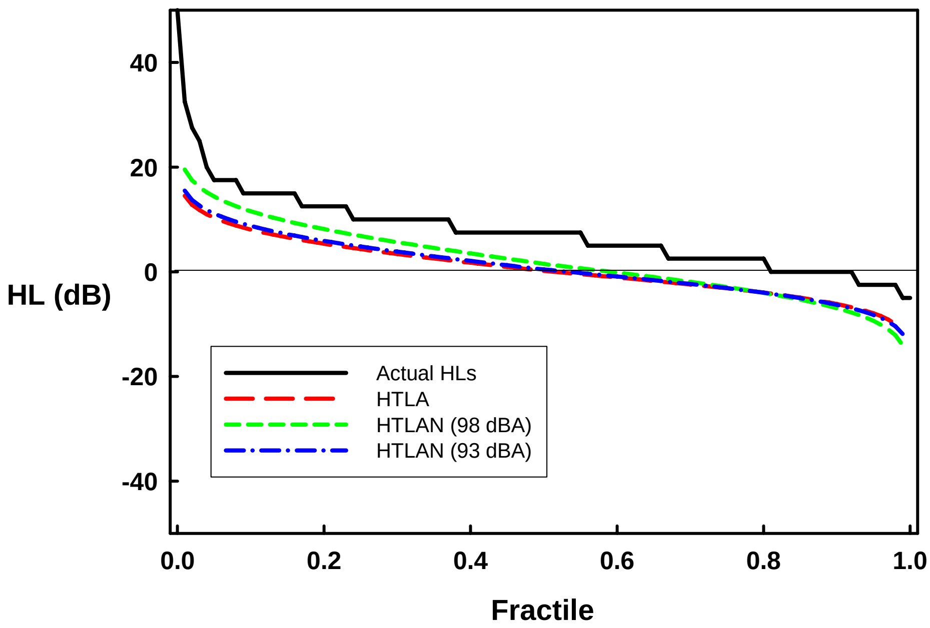

Figure A1. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

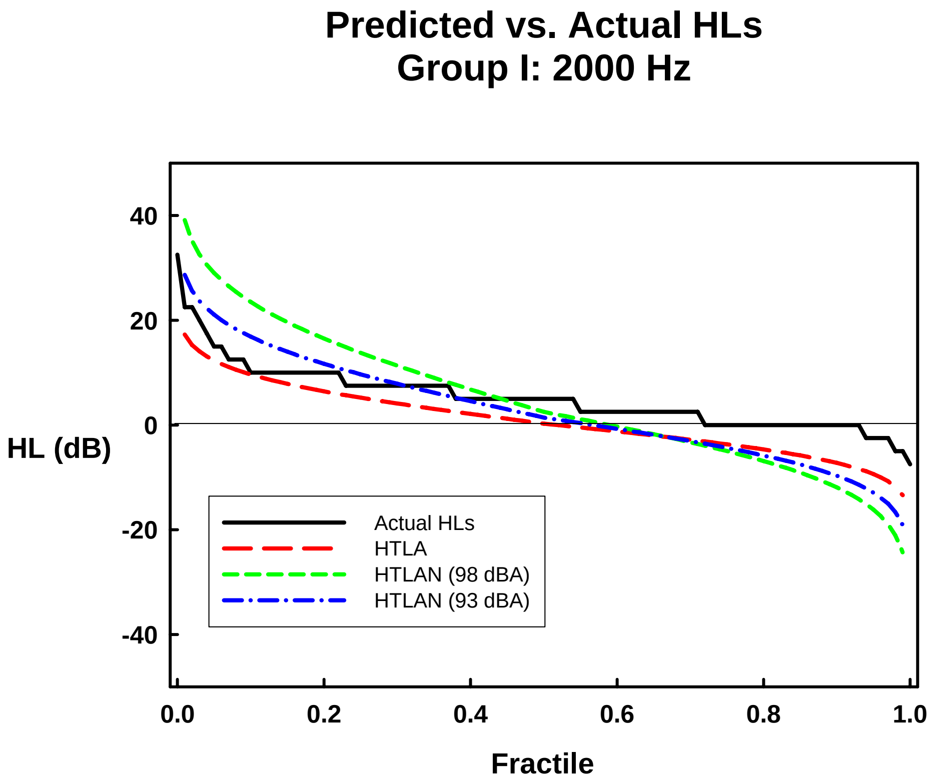

Figure A2. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

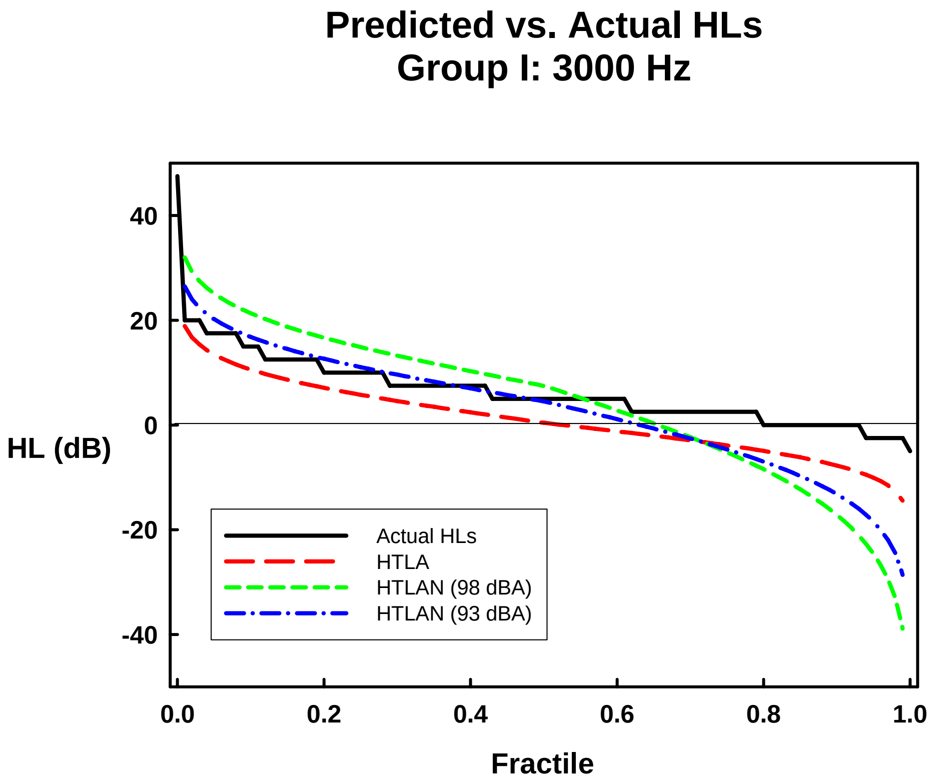

Figure A3. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

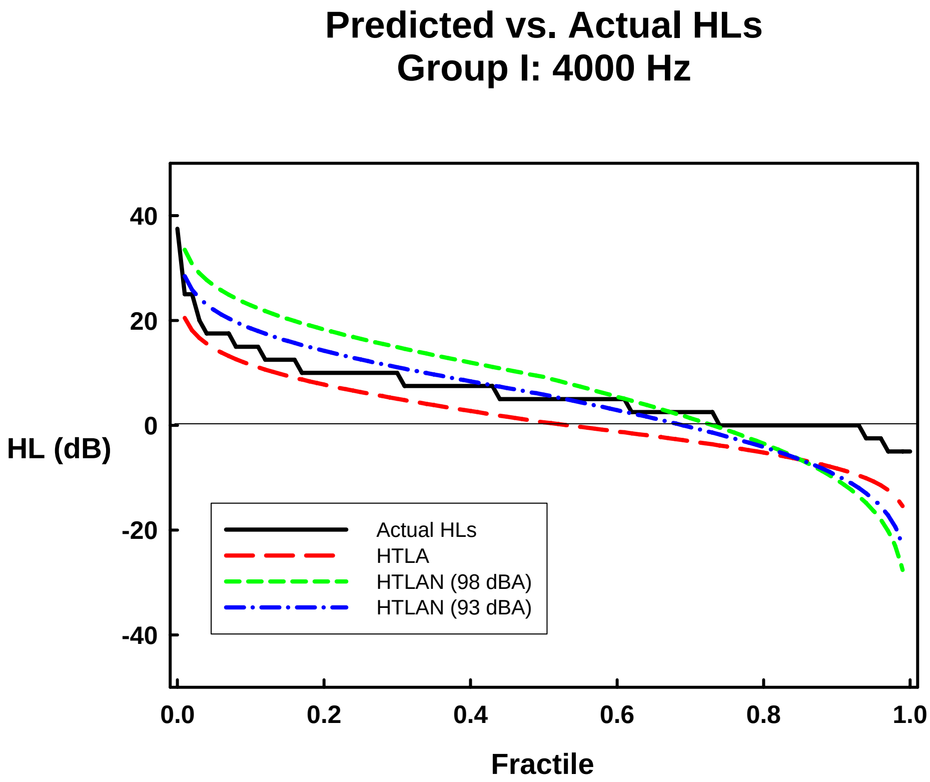

Figure A4. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

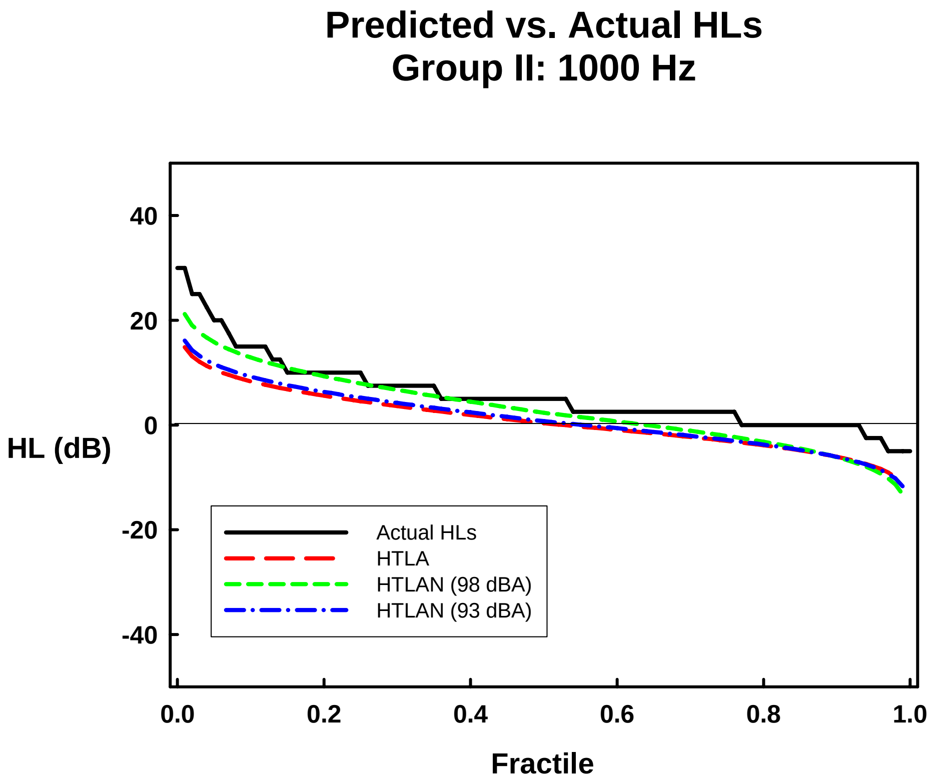

Figure A5. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

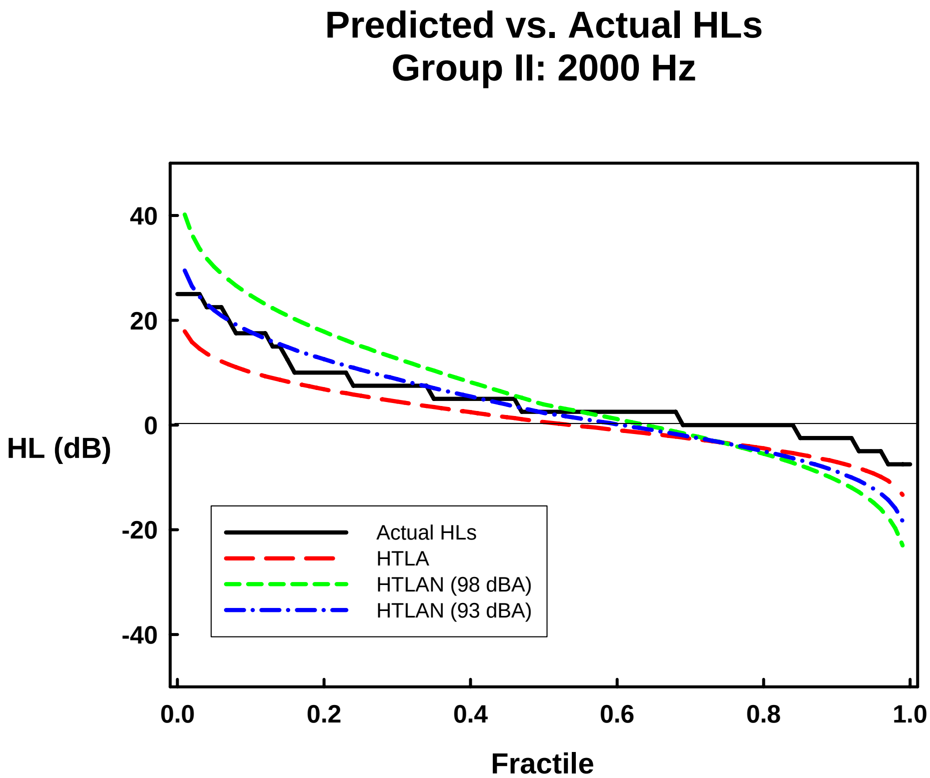

Figure A6. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

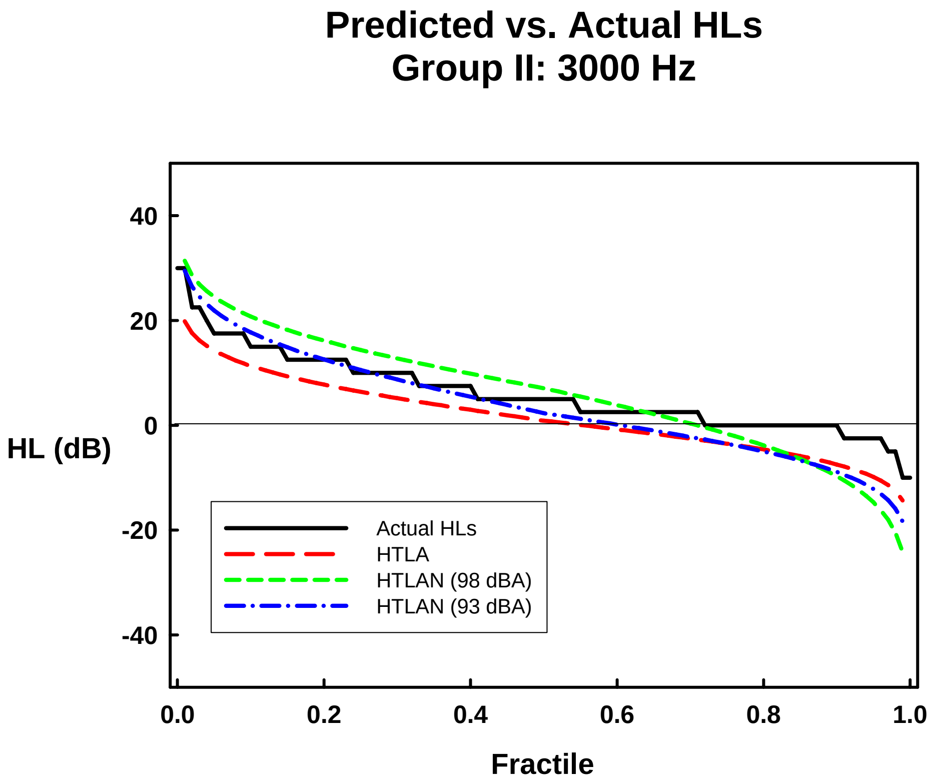

Figure A7. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

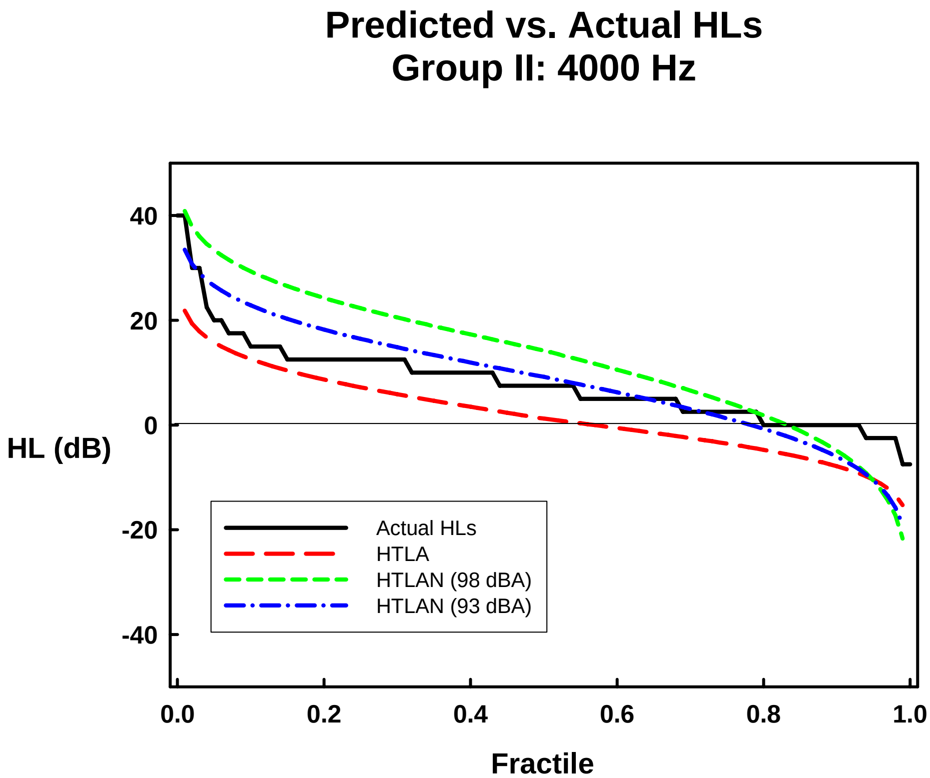

Figure A8. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

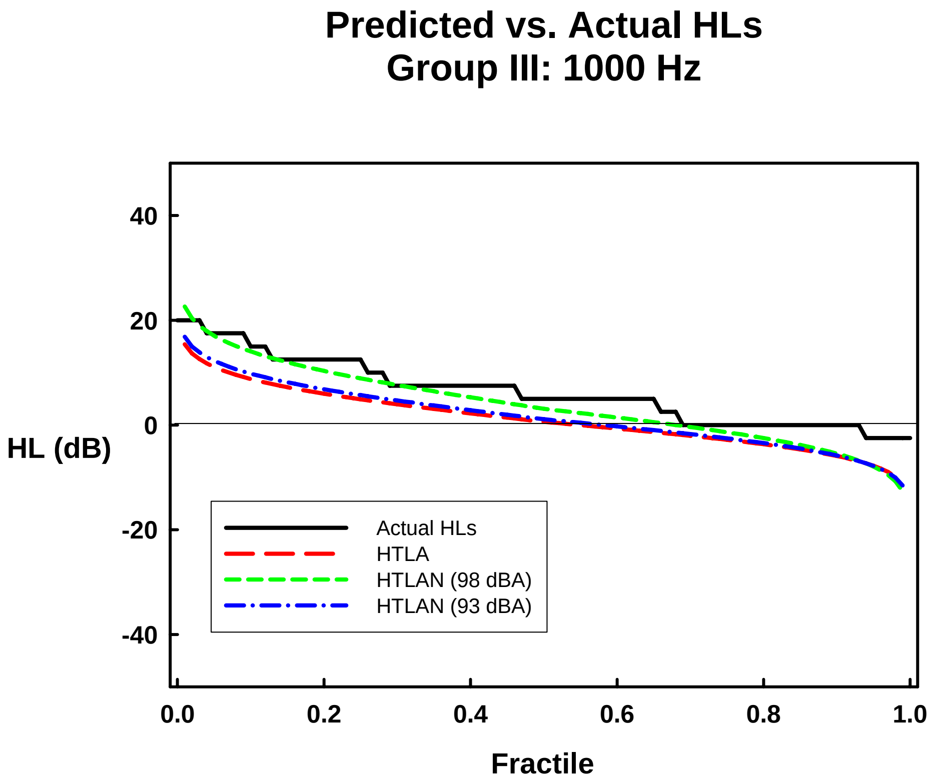

Figure A9. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

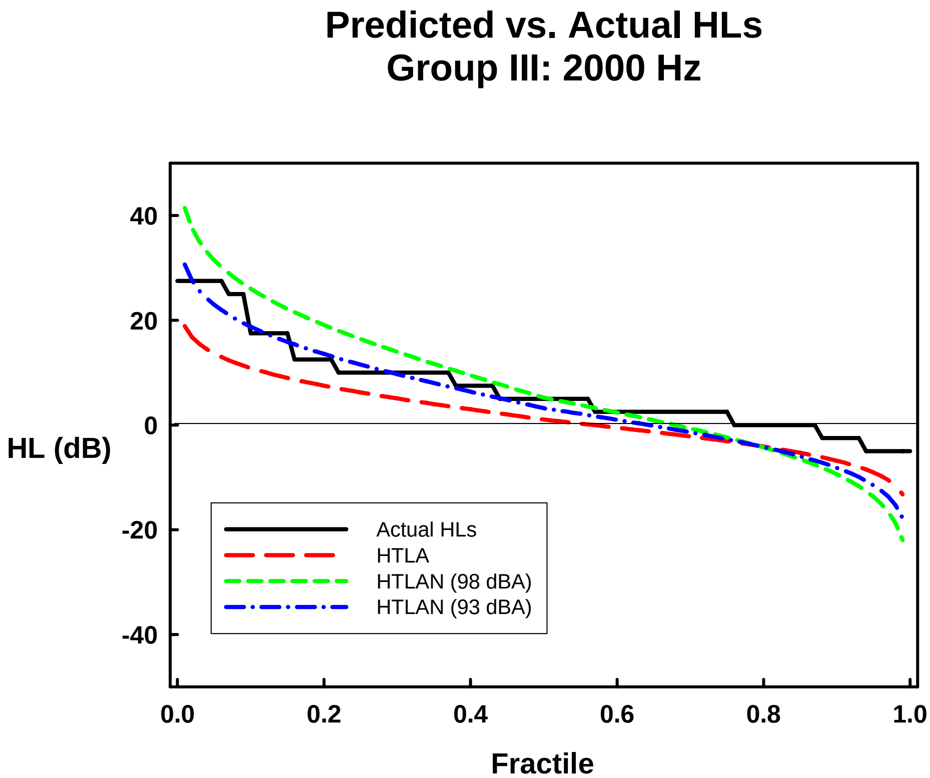

Figure A10. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

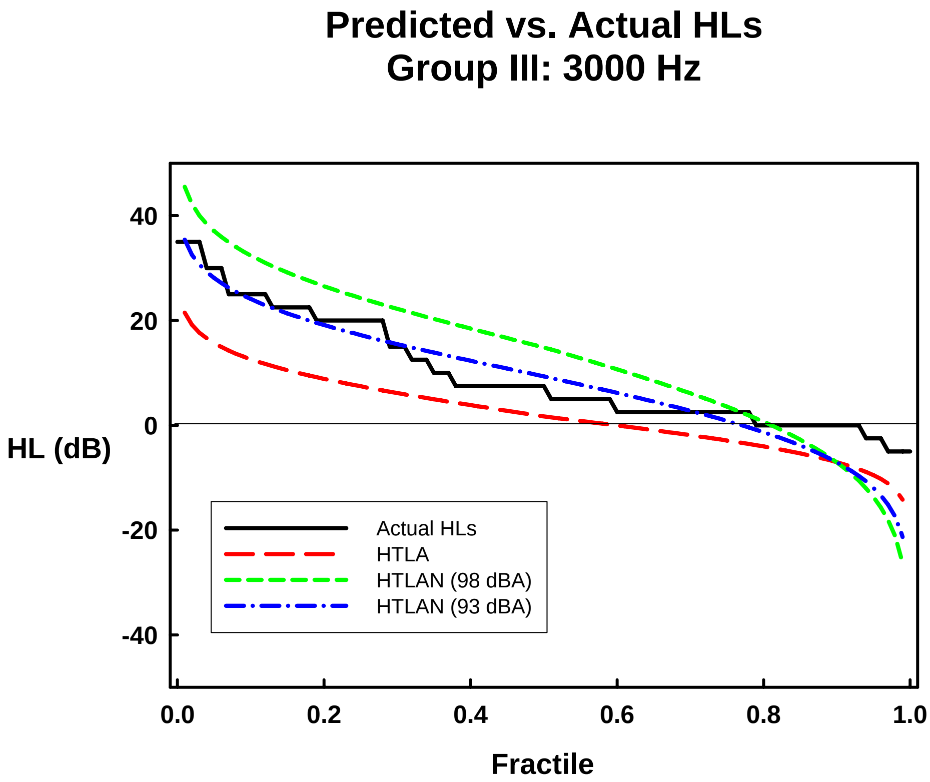

Figure A11. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

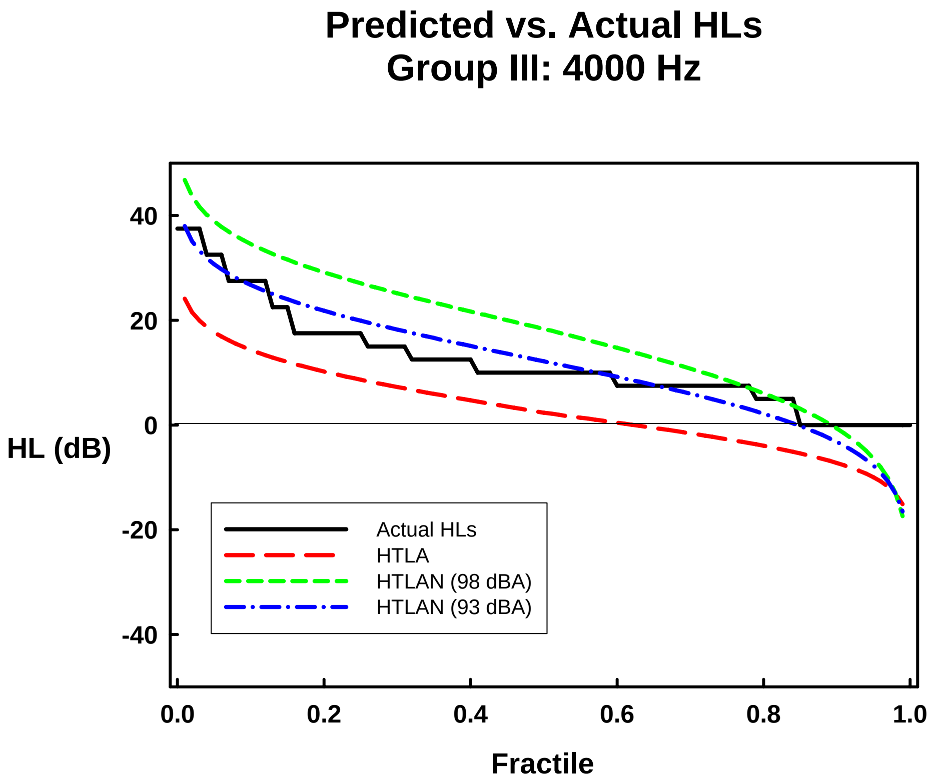

Figure A12. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

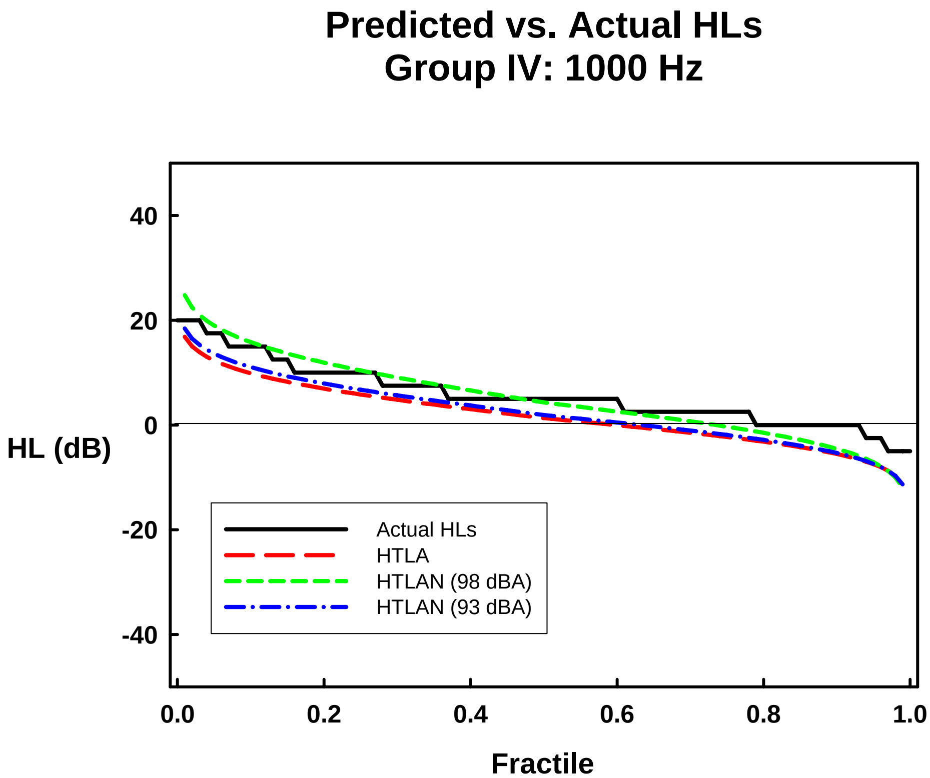

Figure A13. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

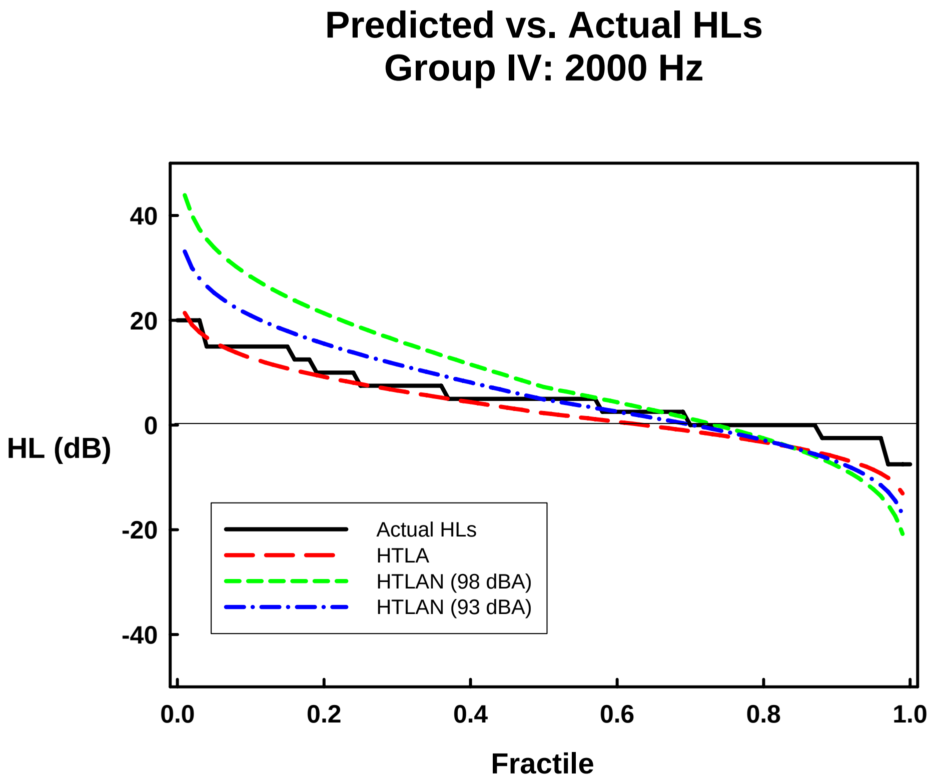

Figure A14. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

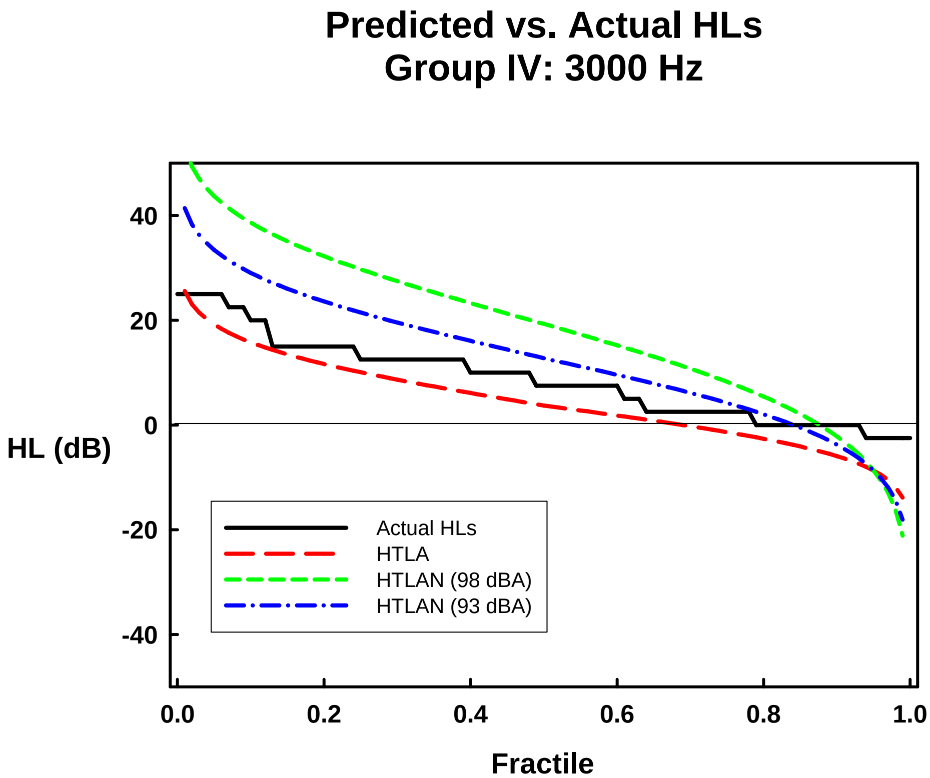

Figure A15. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

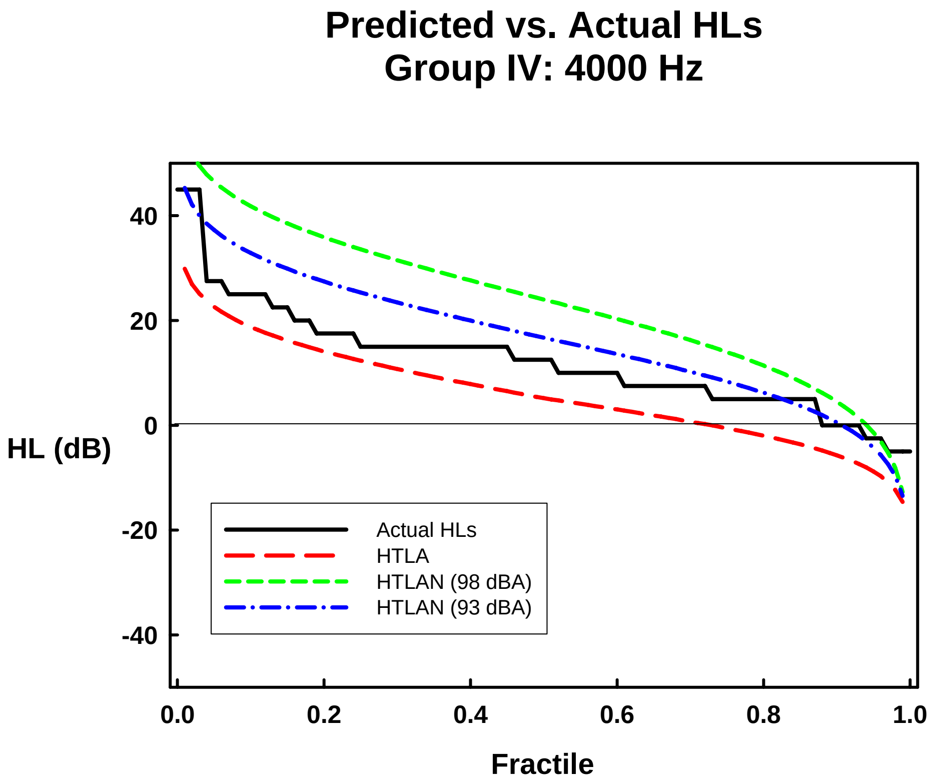

Figure A16. Hearing threshold levels (HLs) as a function of population fractile for four cases:
Actual HLs = the HLs of the population (solid black line)
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (98 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 98 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (short-dashed green line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA, and noise exposure duration equal to estimated cumulative years of Machinery Room noise exposure (dash-dot blue line)

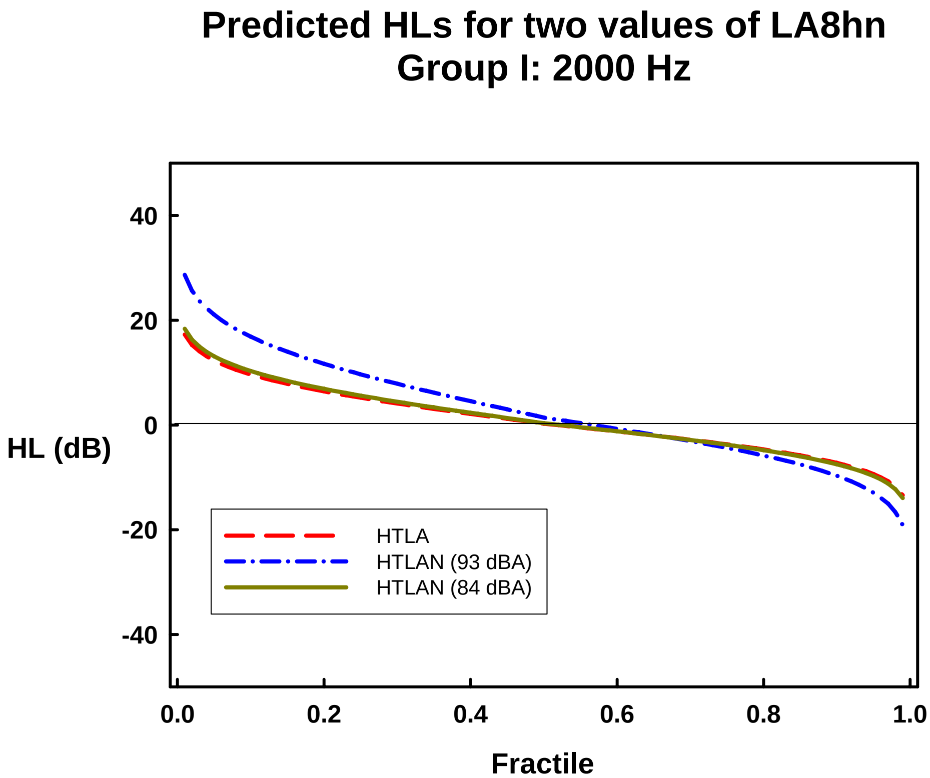

Figure A17. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

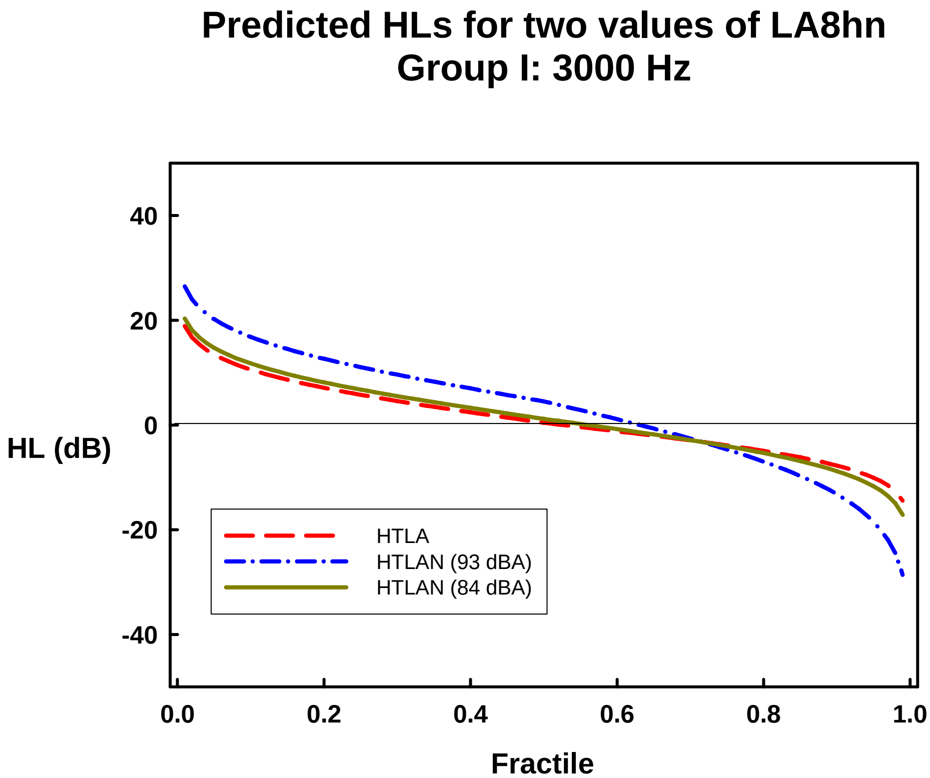

Figure A18. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

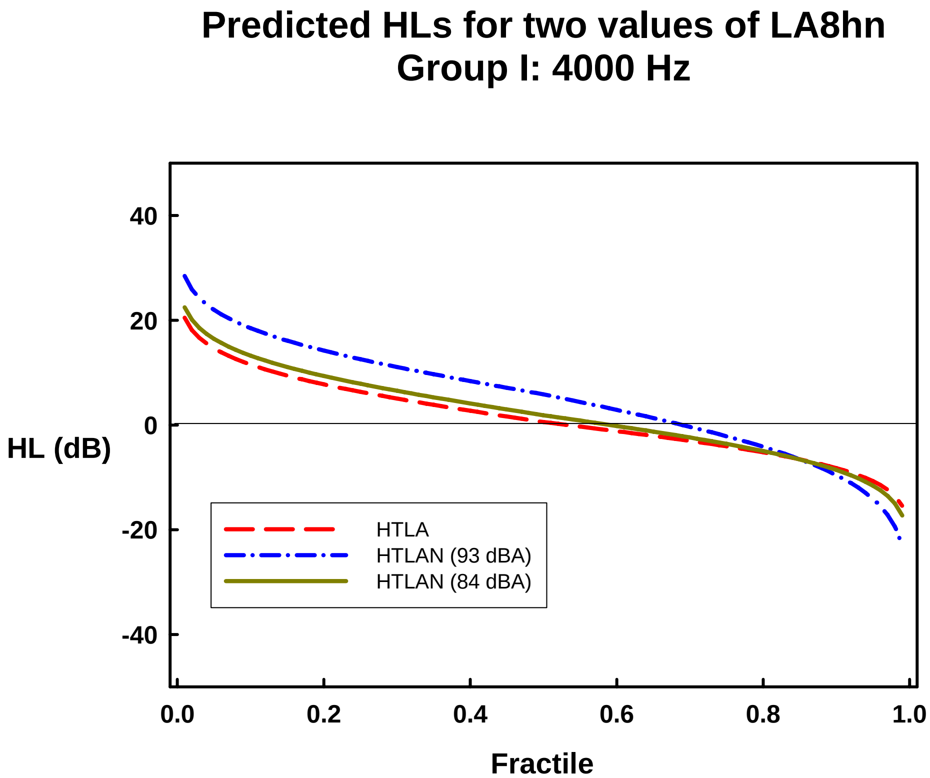

Figure A19. Hearing threshold levels (HLs) as a function of population fractile for three cases:
<u>HTLA</u> = predicted HLs due to aging effects (long-dashed red line)
<u>HTLAN (93 dBA</u>) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
<u>HTLAN (84 dBA</u>) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

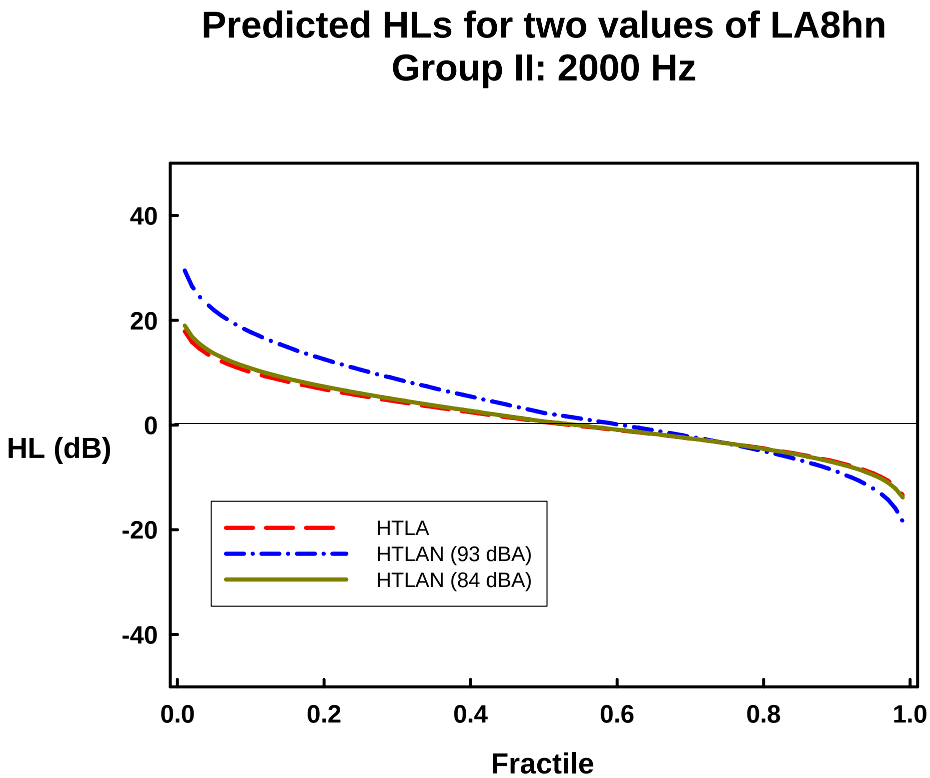

Figure A20. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

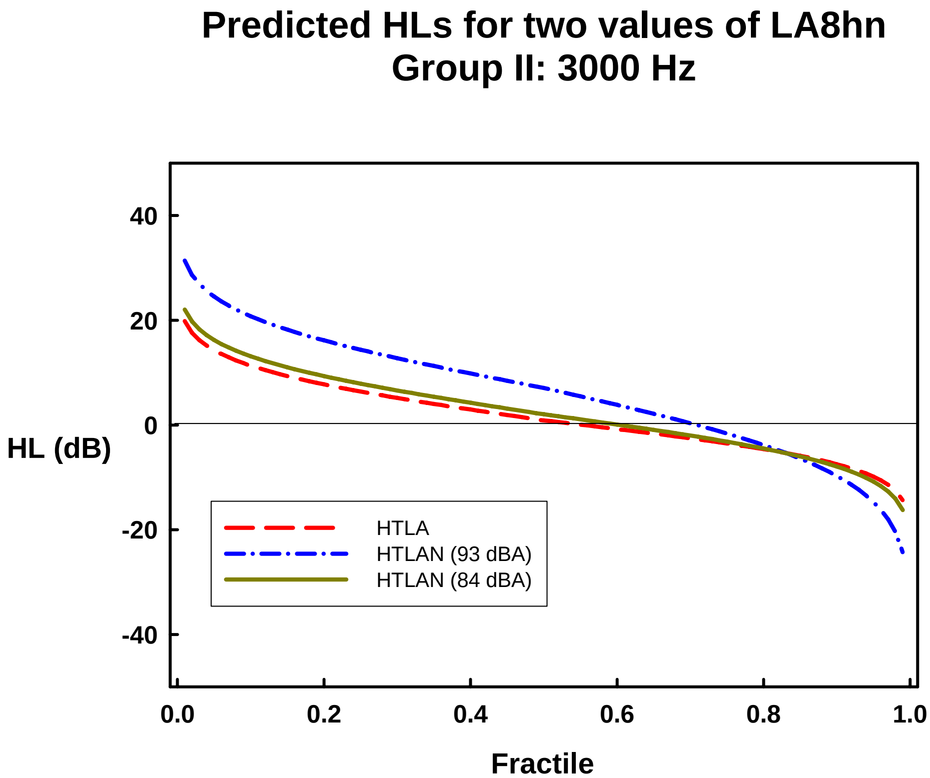

Figure A21. Hearing threshold levels (HLs) as a function of population fractile for three cases:
<u>HTLA</u> = predicted HLs due to aging effects (long-dashed red line)
<u>HTLAN (93 dBA)</u> = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
<u>HTLAN (84 dBA)</u> = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

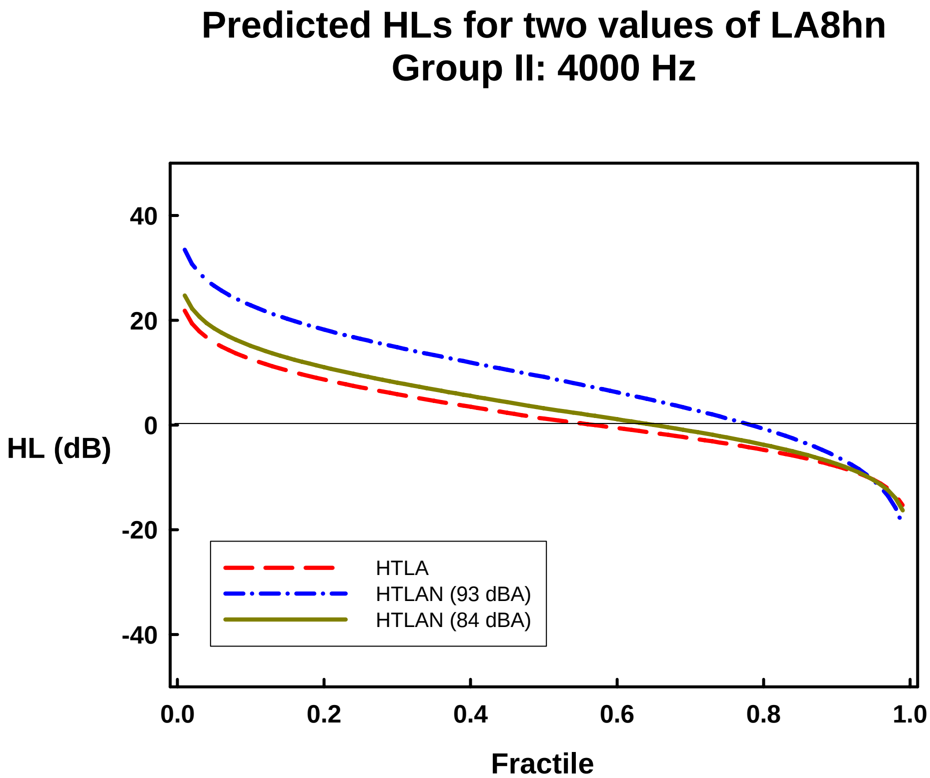

Figure A22. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

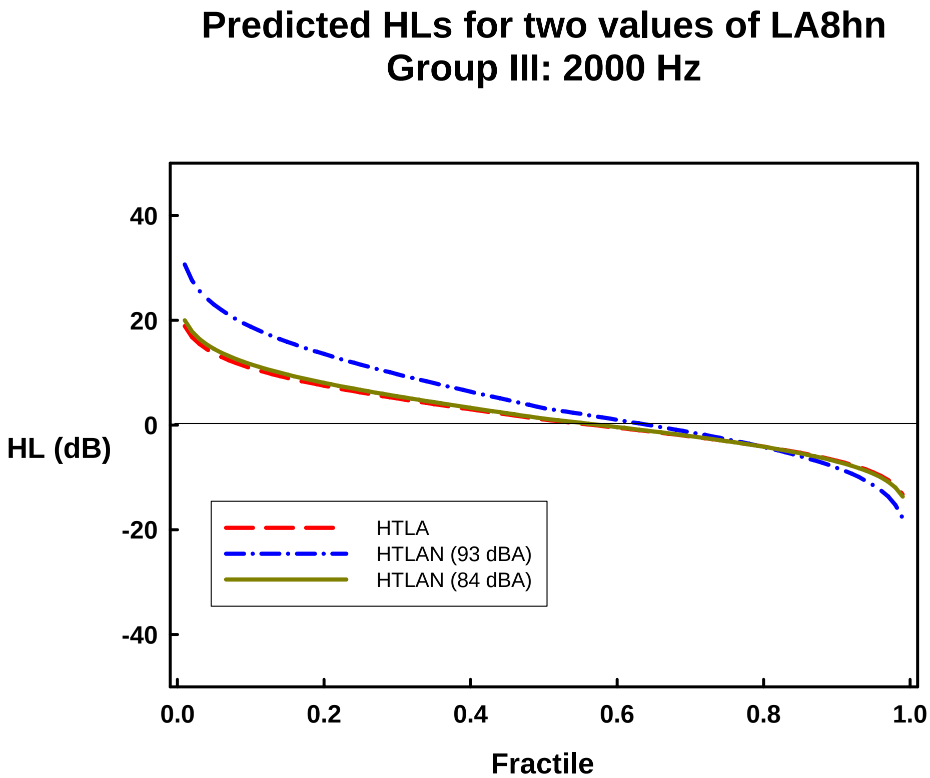

Figure A23. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

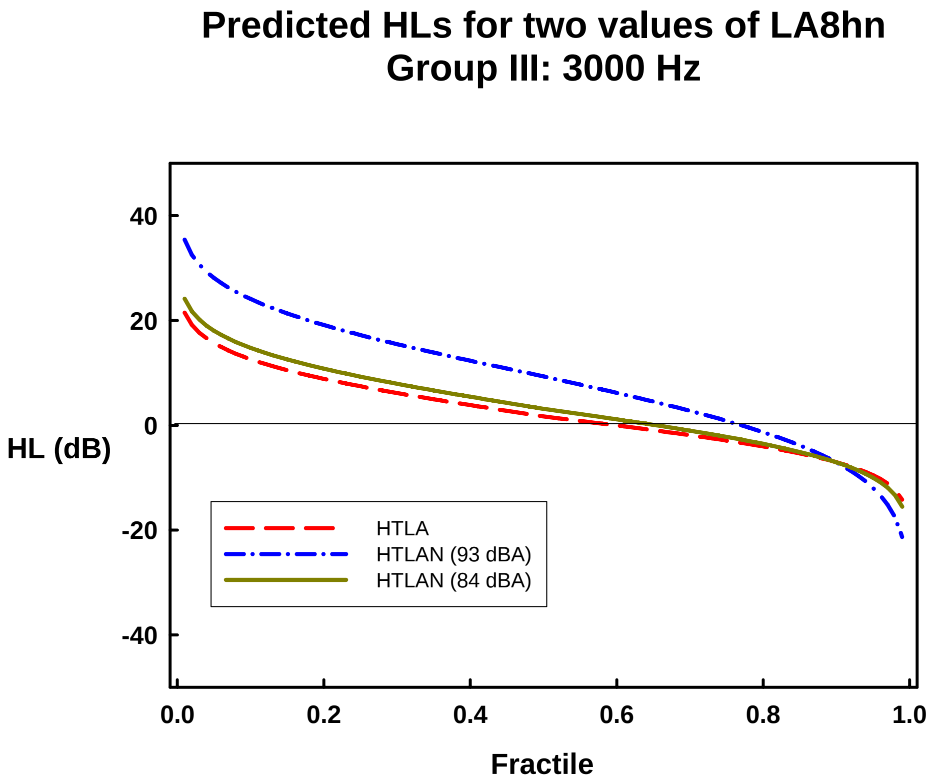

Figure A24. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

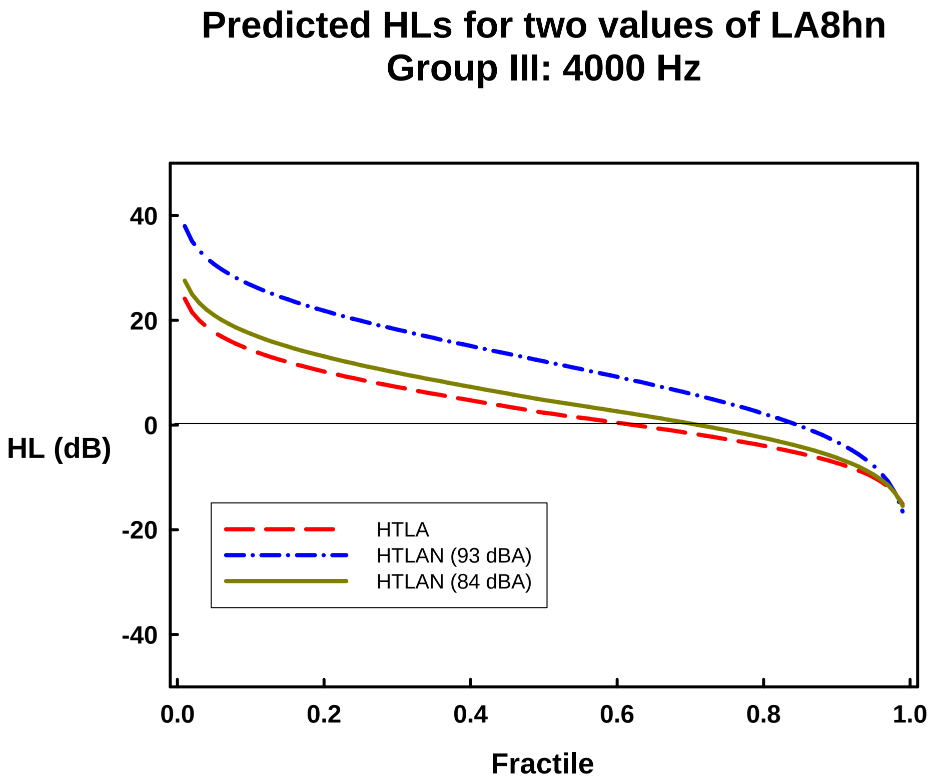

Figure A25. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

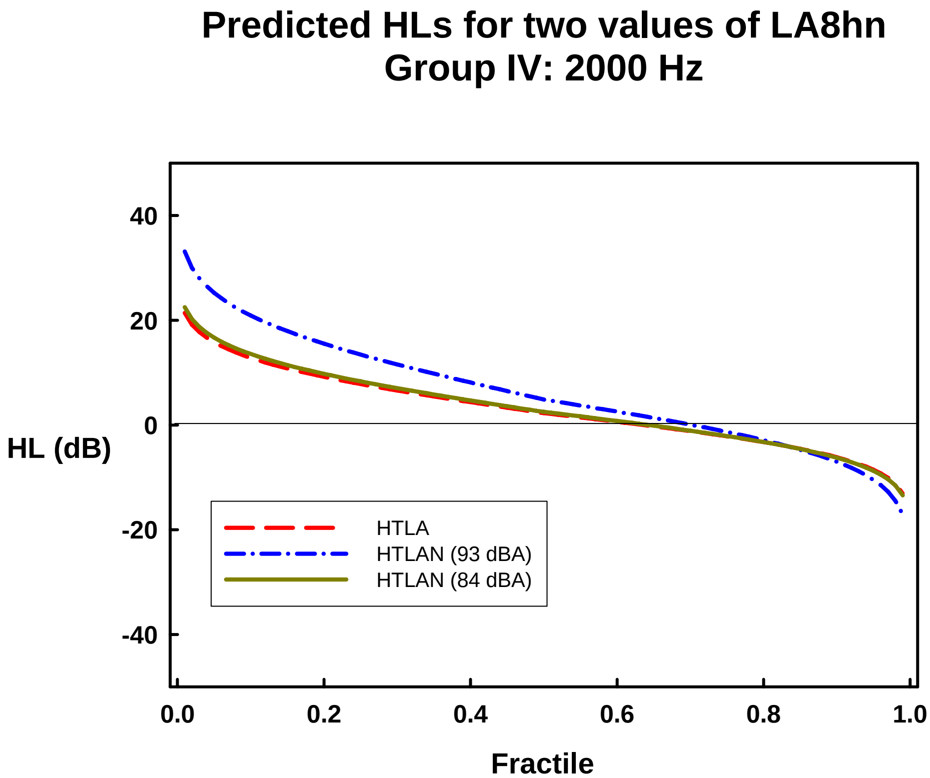

Figure A26. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

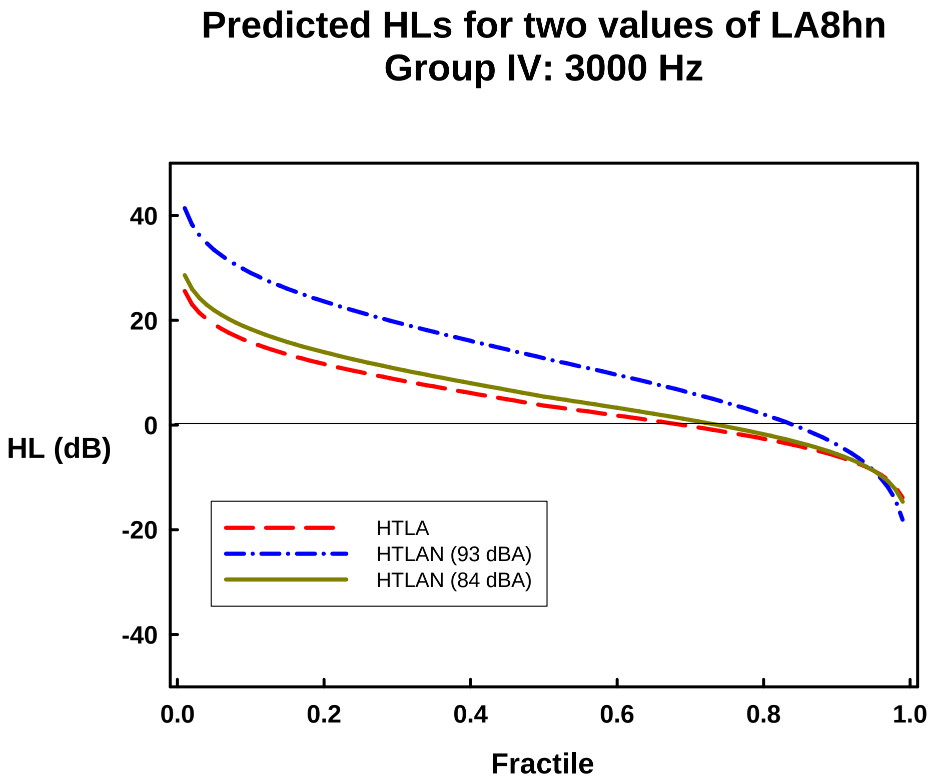

Figure A27. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

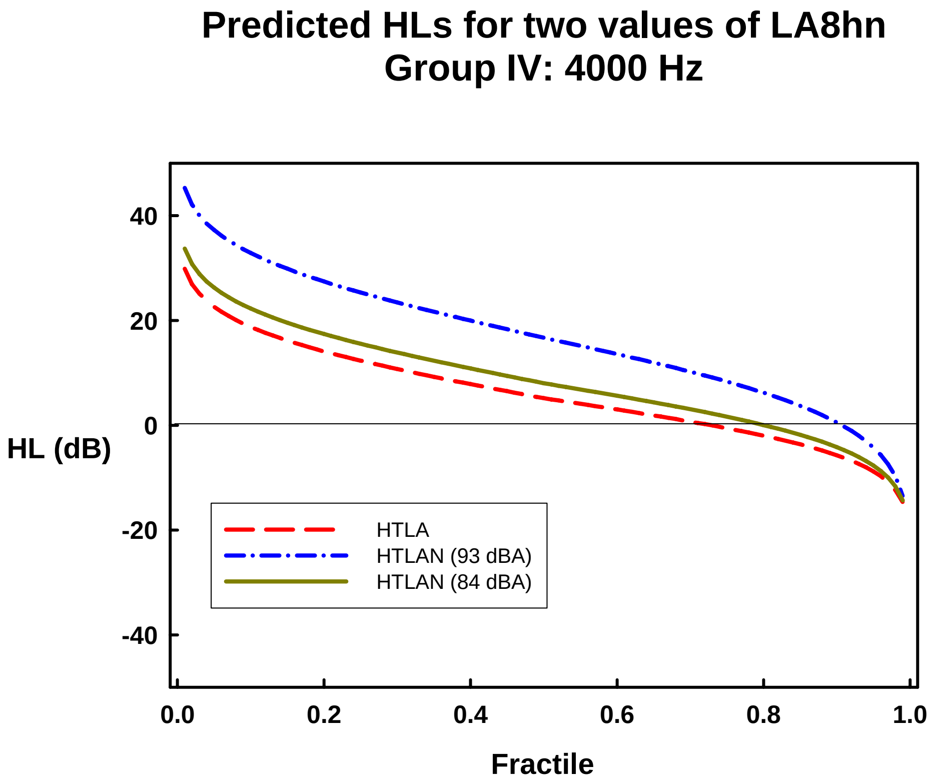

Figure A28. Hearing threshold levels (HLs) as a function of population fractile for three cases:
HTLA = predicted HLs due to aging effects (long-dashed red line)
HTLAN (93 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 93 dBA (dash-dot blue line)
HTLAN (84 dBA) = predicted HLs due to the combined effects of age and noise, assuming L_{A8hn} of 84 dBA (solid dark yellow line)

APPENDIX B: DESCRIPTION OF MAXIMUM LIKELIHOOD PROCEDURE USED TO DETERMINE BEST VALUE OF LA8HN

The data available for calibration are the hearing threshold levels (HLs) of 250 Sailors at the audiometric frequencies of 1000, 2000, 3000, and 4000 Hz. In ANSI S3.44-1996, age and noise exposure do not uniquely determine a HL, but rather specify a probability distribution for the possible values of HL. We begin by defining that probability.

Consider each individual HL measurement at a particular audiometric frequency to be a single observation. Then, for each observation *i*,

$$p\,(HL)_i = \left[1 / (2\pi\, s_i) \right]^{1/2} \cdot \exp\left[-\frac{1}{2} \left(\frac{HL_i - N_{0.50,i}}{s_i} \right)^2 \right] \qquad \text{(B1)}$$

Equation (B1) describes the Normal probability density function with parameters of mean or median $N_{0.50,i}$ and standard deviation s_i. There is no need for the median or the standard deviation to be identical for any two or more observations. In the present case, both parameters are uniquely predicted at each audiometric frequency by age, noise level, and length of exposure to the noise.

To achieve agreement of the entire collection of measured HLs with the predictions of any algorithm, we introduce the likelihood function. It states that the joint probability of all the observations **together** is the product of the individual probabilities of each observation:

$$\text{Likelihood} = p(HL_{i=1}) * p(HL_{i=2}) * \ldots * p(HL_{i=n}) \qquad \text{(B2)}$$

where ***n*** is the total number of observations in the data set. For the present case, ***n*** is the number of audiometric frequencies (4) **x** number of subjects (250) = 1000.

The agreement of probabilities from an algorithm with the full set of observed HLs is greatest when the value of the Likelihood function is at its maximum possible value. Hence, this fitting procedure is called the Principle of Maximum Likelihood (ML).

Since each individual probability p in equation (B2) is a very small number, it is more convenient to take the (natural) logarithm of each probability. This yields

$$LL = \log [\, p(HL_{i=1}) \,] + \log [\, p(HL_{i=2}) \,] + \ldots + \log [\, p(HL_{i=n}) \,] \qquad \text{(B3)}$$

where LL is the Log Likelihood function. The maximum LL will occur at precisely the same parameter values as the ML.

For a Normal probability function (B1), the log-probability of each HL is

$$\text{Log} [\, p(HL_i) \,] = -\tfrac{1}{2} \log (2\pi) - \log (s_i) - [\, (HL_i - N_{0.50,i})^2 / 2 \cdot s_i^{\,2} \,] \qquad \text{(B4)}$$

The term containing π is a constant, which, being the same for all measurements, does not influence the result. The effect of L_{A8hn} is contained in the Normal distribution parameters $N_{0.50,i}$ and standard deviation s_i, which will vary during the fitting process until a maximum LL is achieved.

What values of $N_{0.50,i}$ and standard deviation s_i should be applied to each measurement? The measured values of HL are subject to the effects of both noise and aging. S3.44 provides the normal distribution parameters of each effect, taken separately. Equation (14) of S3.44 states that corresponding fractiles of the noise and aging threshold shifts can be added (with a small correction). We generalize that statement to say that the full distributions simply add (with the small correction given in S3.44):

$$HL_i = HTLAN_i = NIPTS_i + HTLA_i - (HTLA_i * NIPTS_i /120) \qquad (B5)$$

The distribution that results from the sum of two independent normal distributions is also normal, but while the means simply add, the standard deviations add in root-mean-square:

$$N_{0.50\text{-}HTLAN} = N_{0.50\text{-}NIPTS} + N_{0.50\text{-}HTLA} \qquad (B6)$$

$$s_{HTLAN} = [\, s^2_{NIPTS} + s^2_{HTLA} \,]^{1/2}$$

The procedures to calculate values of the median $N_{0.50,i}$ and the standard deviation s_i for $NIPTS_i$ are found in Section 6.3 of S3.44. Two values of the standard deviation (denoted d, not *s*, in that Section) are provided. Parameter d_u applies when HL_i is above the median of HTLAN, while parameter d_l applies when HL_i is below the median of HTLAN. The procedures to calculate values of the median $N_{0.50,i}$ and the standard deviation s_i for $HTLA_i$ are found in Annex A. Two values of the standard deviation are provided. Standard deviation s_u applies when HL_i is above the median of HTLAN, while s_l applies when HL_i is below the median of HTLAN.

We used a MATLAB routine[5] written to implement the non-linear optimization method of Marquardt[6] for the ML fitting. To that general fitting algorithm, we provided equations B4, B5, and B6 as well as the S3.44 algorithm for determining normal distribution parameters based on age, noise level, and noise duration. Multiple runs with different starting guesses at L_{A8hn} were performed to achieve a global ML.

[5] Fahlman, A. (2001). A modified Marquardt-Levenberg parameter estimation routine for MATLAB. Naval Medical Research Center, Technical Report No. 01-02, Silver Spring, MD.

[6] Marquardt, D.W. (1963). An algorithm for least-squares estimation of nonlinear parameters. J Soc Indust Appl Math, 11, 431-441.

APPENDIX C: DESCRIPTION OF NOISE EXPOSURES OF MACHINIST'S MATES DURING TRAINING, SEA, AND SHORE TOURS

C.1 Tours

The major division of time in a naval career is the two-to-five-year slot in a particular assignment, called a "tour". Our population of MMs starts with a set of basic and specific training blocks we call the initial Training tour. Thereafter, the MMs alternately rotate between a Sea duty tour and a Shore duty tour.

Navy policy in November 2005 stipulates that these MMs, following their training tour, are to strictly alternate between Sea and Shore duty tours. The standard tour durations as of that time are:
1^{st} sea tour = 5 years; 1^{st} shore tour = 2 years
2^{nd} sea tour = 4 years; 2^{nd} shore tour = 3 years
3^{rd} sea tour = 3 years; 3^{rd} shore tour = 3 years

These standard tour durations are assumed for everyone in this report. We are not aware of any variation in the tour duration policy during the historical period when the HL data were obtained. However, variations from the standard tour durations are not uncommon for individuals. For example, a sailor could elect to stay on Sea duty for 10 years.

(a) Training tour

From enlistment to full qualification, the training period requires 18-24 months. A total training period of 24 months is assumed for all in this Report. The total time is segmented among several different courses, with different noise exposures.

Recruit training	9 weeks	low noise
MM "A school"	5 weeks	occupational noise
Power School	6 months	low noise
Prototype	7 months	occupational noise
Other schools	lengths vary	noise varies

MM "A" School. This is an entry-level course on the basic skills expected of a machinist. It is assumed that the noise in the shops is at 90 dBA Leq.

Prototype: This is a permanent installation of reactor, power plant, and auxiliary equipment used specifically for high fidelity training. Noise levels 5 dBA lower than the noise levels of aircraft carrier machinery are assumed, since the Navy's present prototypes are of the submarine machinery type (rather than those of an aircraft carrier), and submarines are quiet vessels relative to carriers. The level assumed is 90 dBA Leq.

(b) **Sea duty tour**

The sea tour is the only duty when significant Machinery Room exposure actually occurs. We do not have actual noise exposure data from the Machinery Room, but based on many fragmentary conversations, we assume an Leq of 95 dBA.

Aircraft carriers go to sea regularly for a deployment of typical length 6 months. Prior to that time, the ship spends 4-5 months at sea in a workup phase. Subsequent to the 6-month deployment, the ship enters a shipyard for about 6 months of intense maintenance. For the balance of a full ship cycle (which resets every 18 to 24 months), the ship is at a pier, and the crew is either on leave, in training, or performing minor maintenance (with assumed low noise exposure). For an average exposure, we take the ratio of time spent at sea (i.e., 6 month deployment + 4.5 months workup = 10.5 months) to the length of an average ship cycle (i.e., 21 months). This gives 10.5/21 = 0.50 as the fraction of time that Machinery Room exposure occurs during a ship cycle. Although ship cycles and tour lengths may not naturally coincide, we use this ratio to describe average exposures for a sea duty tour. Thus, for this report, it is assumed that MMs are exposed to Machinery Room noise for 6 months out of every year of a sea tour.

During the 21-month average ship cycle, 6 months or 6/21 = 0.29 of the time is spent in the shipyard. Several times during its ~ 40 year life, each CVN will enter the shipyard for a multiyear overhaul. Crews are reduced, but only partially, during that overhaul.

(c) **Shore duty tour**

Many Navy enlisted job specialties disperse to a wide variety of assignments during shore duty; these MMs typically do not. Most return as instructors at Power School or as staff at the Prototype, where they had previously trained. Their occupational noise exposure is assumed to be similar to that received by students at the same facility. Some senior people may be placed in administrative posts in various headquarters, though those assignments may require some time spent back at sea and in the Machinery Room.

C.2 Time within tours

Sea duty does not follow a 40-hour work week. While at sea, most watchstanding is performed on the same rotation 7 days a week. These MMs usually split into 3 sections, with a section rotating at 5 hours *on* watch followed by 10 hours *off*. On-site turnover of the watch, requiring both the new and old watchstander to be present, is quite time consuming. Off-watch activities such as maintenance frequently occur in the Machinery Room as well. It is estimated that while at sea, these sailors are in the Machinery Room for 10-12 hours per day typically, with a common surge of 12-14 hours/day.

Not every moment of an MM’s watch is spent in the Machinery Room. It is estimated that about 90% of the watch is spent in the Machinery Room and a nearby auxiliary room. Other possible locations during watchstanding are in the shaft alley, the reboiler room, and at chow. The noise levels at these other locations are not known. In this report, it is assumed that all MMs are exposed to Machinery Room noise for 12 hours/day, 7 days/week.

Even during free time, non-Machinery Room noise exposure may be important. On these aircraft carriers, crew sleeping quarters and the ship’s library on the level immediately below the flight deck need to be considered. During flight operations, aircraft and catapult sounds propagate into the spaces below, creating noise transients of 90 to over 110 dB. In high-tempo operations (an aircraft launch or recovery every minute), these sounds can disrupt communications (and sleep) for many minutes at a time. Such a condition would also violate the implicit ANSI S3.44 assumption of a daily 8-12 hour quiet recovery time before the next occupational exposure to hazardous noise.

Some crewmembers go to outside areas of the ship regardless of whether flight operations are happening or not. Watching the sea is a common recreation while on sea duty. Smoking is not allowed inside. This source of non-Machinery Room exposure can be estimated using crude numbers. Rough estimates are that flight operations occur about 10% of the week, crewmembers spend about 1 hour per day outside, randomly, and flight noise at the designated smoking location is 110 dBA during operations.

NOTE: Most of the information (with the exception of noise levels) in this Appendix was taken from notes of a telephone call between Drs. Lynne Marshall and Paul Weathersby (Naval Submarine Medical Research Lab), and MMCM (SW) David Renn (Naval Manpower Analysis Center), November 2005, after referral from Ms. Nancy Dolan (OPNAV N125).

GLOSSARY

Audiogram- a graphic representation of hearing thresholds as a function of frequency

Current audiogram- the most recent audiogram available for an individual in the NEHC database

Original baseline audiogram- the initial audiogram obtained for an individual, against which future audiograms are compared (see revised baseline audiogram)

Reference audiogram- the earliest audiogram available for an individual in the NEHC database; may be an original or revised baseline audiogram

Revised baseline audiogram- an audiogram that reflects a change in hearing for better or worse relative to the original baseline audiogram and that is now used as the baseline against which future audiograms are compared

A-weighted- refers to a standard weighting of the audible frequencies that reflects the response of the human ear to noise

Binaural- involving both ears

CVN- nuclear-powered aircraft carrier

Equivalent continuous sound pressure level (Leq)– the sound pressure level of a hypothetical steady sound that, within a given time interval, has the same mean-square sound pressure as the sound being measured; expressed in dB

HPDs- hearing protection devices

HTLA- hearing threshold level associated with age

HTLAN- hearing threshold level associated with age and noise

Hz- Hertz, or cycles per second; the unit of frequency

Intensity- energy per unit area

kHz- kilohertz; see Hertz

L_{A8hn}- noise exposure level normalized to an 8-hour working day

Leq- see Equivalent sound pressure level

LOS- length of service

MM- machinists' mate

NEHC- Navy Environmental Health Center

NIPTS- noise-induced permanent threshold shift

Non-tonal- non-periodic; noise-like

S3.44- ANSI S3.44-1996, “Determination of occupational noise exposure and estimation of noise-induced hearing impairment”; provides an algorithm for calculating the predicted noise-induced permanent threshold shifts of a population exposed to noise of a specified intensity and duration

SPL- sound pressure level

Threshold- the level at which a stimulus is detectable 50% of the time (i.e., barely perceptible)

Time/intensity trading relation- the number of decibels permitted for each doubling or halving of exposure duration (e.g., a trading relation of 3 dB means that exposure duration must be halved if the exposure level increases by 3 dB)