Estimation of Equivalent Noise Exposure Level Using Hearing Threshold Levels of a Population

Jennifer B. Tufts,¹ Paul K. Weathersby,² and Lynne Marshall²

Objectives: Noise-induced hearing loss (NIHL) is costly in both human and economic terms. One means of reducing NIHL is to apply engineering controls to hazardous noise sources. To trade off the cost of engineering controls against the total direct monetary costs incurred by NIHL, a means of predicting the amount of NIHL that will be incurred over the life-cycle of a hazardous noise source is necessary. A widely known algorithm for the prediction of NIHL is published in ANSI S3.44-1996. However, the algorithm inputs, noise exposure level and duration, may be difficult to determine in some cases. This paper describes the conceptual basis of an approach for using ANSI S3.44-1996 to predict hearing thresholds in a population even when noise exposure levels and durations are not precisely known, and demonstrates the initial application of this approach to a single military population.

Design: Retrospective data were obtained on the hearing-threshold levels, demographic characteristics, and noise exposure history of 250 male U.S. Navy machinists’ mates. A maximum-likelihood fitting procedure was developed in which the noise level input to the ANSI S3.44-1996 algorithm was varied in order to determine the noise level that best accounted for all of the data.

Results: The maximum likelihood fitting produced a value for the noise level input of approximately 93 dBA, with a standard error of approximately 0.3. The low standard error virtually eliminates any estimate above 94 or below 92 dBA, and indicates that a good fit to the data was achieved.

Conclusions: This research demonstrates the feasibility of calibrating the ANSI S3.44-1996 algorithm to an individual population, even when noise exposure level or duration is not precisely known. Future work will focus on validating and generalizing this approach so that it may be used to predict hearing-threshold levels in various populations. Such an approach may be used in calculating potential cost savings in compensable hearing loss due to the application of noise control solutions.

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INTRODUCTION

The prevalence of noise-induced hearing loss (NIHL) among personnel serving in the U.S. military continues to be high (Henselman et al. 1995; Humes et al. 2005). In fiscal year 2005, auditory disorders, including NIHL and tinnitus, were the most common disabilities for which veterans received compensation from the Veterans Administration (VA), with total VA compensation exceeding $1 billion (Veterans Benefit Administration 2005). From an economic standpoint alone, a reduction in the prevalence of NIHL in the U.S. military would be clearly desirable.

Hearing protection devices (HPDs) are currently the primary means by which noise exposure is controlled, albeit with limited success (Bjorn et al. 2006; Humes et al. 2005). In some circumstances, a better approach to reducing exposure to hazardous noise is to deploy “quieter” systems. However, the design and purchase of quieter systems often involve increased financial costs. For military systems-acquisition personnel, the extra expenditure may not seem to be fiscally justifiable. If it could be shown that the greater costs of quieter systems would be offset in the long term by decreases in government costs from NIHL, then noise-control solutions might become more attractive. To project the potential cost savings of “buying quiet,” a means of predicting the amount of NIHL that will be incurred over the life cycle of a new system is required. Predicted NIHL must then be translated into dollars, according to the medical and compensation policies of the U.S. military and the VA.

A widely known algorithm for the prediction of NIHL is published in ISO 1999 (1990) and adapted in ANSI S3.44-1996 (1996). This algorithm predicts the amount of noise-induced permanent threshold shift (NIPTS) to be expected in a population exposed to broadband occupational noise of specified intensity and duration. Because a range of NIPTS will occur in any noise-exposed population, even if the individuals in that population have identical noise exposure histories, the ANSI S3.44 algorithm provides a series of probability distributions of NIPTS instead of single values. Each probability distribution shows the amount of NIPTS as a function of population fractile for a single audiometric frequency. For example, assuming a standard 40 hr work week, exposure to noise at 95 dBA for 15 yr will result in a median NIPTS at 2000 Hz of 7.3 dB for the population. At the 0.10 and 0.90 population fractiles, NIPTS at 2000 Hz is predicted to be 15.6 and 2.7 dB, respectively.

Annex A of ANSI S3.44-1996 (1996) provides an algorithm for predicting the amount of hearing loss caused by aging only. Analogous to the NIPTS algorithm, the Annex A algorithm produces probability distributions showing hearing-threshold levels associated with aging only (HTLA) as a function of population fractile for each audiometric frequency. To obtain hearing-threshold levels associated with both age and noise (HTLAN), corresponding fractiles of the NIPTS and HTLA distributions are added, with a small correction factor (HTLAN − NIPTS)/120 subtracted from the sum.

To apply the ANSI S3.44-1996 (1996) algorithm, the noise exposure level and duration must be known. However, determining these values for military populations can be problematic. Access to work spaces for noise level measurements may be restricted for security reasons. Exposure durations may be difficult to quantify because of irregular or changing work hours. Exposure to noise sources besides the main occupational source (if one exists) may vary from person to person. Taking HPD use into account directly may not be feasible. Individual personnel records often are incomplete. The logistical and security-related obstacles to obtaining accurate estimates of noise exposure level and duration for many military popula-
tions would seem to render ANSI S3.44-1996 (1996) unusable for predicting NIHL in these personnel.

This article describes the conceptual basis of an approach for using ANSI S3.44-1996 (1996) to predict hearing thresholds in a population, even when noise exposure levels and durations are not precisely known, and to demonstrate the initial application of this approach to a single military population. This approach uses hearing threshold data in a population to calibrate the ANSI S3.44-1996 (1996) algorithm, thereby circumventing the need for precise estimates of noise exposure level and duration.

MATERIALS AND METHODS

Conceptual Approach

The conceptual basis for using ANSI S3.44-1996 (1996) even when noise exposure levels and durations are not precisely known relies on the existence of a large data base of hearing thresholds from a population exposed to the same conditions as the population whose hearing losses are to be predicted. This data base should contain thresholds from individuals of various ages and lengths of service. A reference population of non-noise-exposed individuals is also required.

Estimates of noise exposure duration are obtained. In some cases, these estimates may be little more than informed guesses; in other cases, the exposure times can be reconstructed rather well. Next, a maximum-likelihood (ML) fitting procedure is used in conjunction with the ANSI S3.44 algorithm to determine the noise level most likely to have produced the collection of observed hearing-threshold levels of the population. Once the algorithm is “calibrated,” the estimated effective exposure level may be used to predict the future hearing-threshold levels of populations with the same demographics and noise exposure conditions as the original population, provided the calibration has been shown to be reliable and exposure durations are estimated in the same way. In the remainder of this article, we demonstrate an application of this method to a single military population.

Population

The method described in the previous section was applied to a population of specially trained U.S. Navy machinists’ mates (MMs) working in the main machinery room of Nimitz-class aircraft carriers. All were men. Retrospective data on the hearing-threshold levels and demographic characteristics of 250 of these MMs were obtained from a data base maintained by the Navy Environmental Health Center (Bohnker et al. 2002). These data were gathered in the years 1996–1999. Limited data were available to characterize the noise exposure history of this population. Information about the noise exposure of these MMs was obtained largely through consultation with a senior MM at the Navy Manpower Analysis Center.

With this information, a function was developed relating cumulative years of noise exposure (Nexp) in the main machinery room to length of service (LOS) in years (equation 1).

\[
\text{Nexp} = -0.0062 \times (\text{LOS})^2 + 0.4472 \times (\text{LOS}) - 0.6461 \tag{1}
\]

In equation 1, Nexp refers to equivalent years of 40 hr work weeks, not equivalent years of continuous, 24 hr noise exposure.

No data were available on HPD usage by the MMs. Very limited information was available regarding noise exposure outside the main machinery room.

Calibration Procedure

In the calibration procedure, noise exposure level normalized to an 8-hour work day (LA8hn) was treated as an unknown parameter to be estimated by the data themselves. A ML fitting procedure (Marquardt 1963) was used to find the value of LA8hn that yielded the best agreement between predicted and observed hearing thresholds. First, an arbitrary starting value of LA8hn was chosen. Next, the probability of observing each individual hearing threshold was calculated with the ANSI algorithm, given the chosen LA8hn, the individual’s age, his cumulative years of noise exposure (from equation 1), and the particular audiometric frequency. In all, 1000 probabilities were calculated, one for each hearing threshold (250 MMs \( \times 4 \) audiometric frequencies). The common logarithms of these 1000 individual probabilities were added together to give the joint log probability of the entire dataset for that value of LA8hn. LA8hn was then incremented, and a new joint probability was obtained in the same way. The value of LA8hn at convergence (the ML estimate) represented the noise level most likely to have produced all of the hearing thresholds in the dataset. Multiple runs with different starting guesses at LA8hn were performed to assure that a global ML was achieved. The entire ML fitting process was conducted by a routine written in MATLAB (Fahlman 2001), specifically modified to accommodate the ANSI S3.44-1996 (1996) algorithm.

RESULTS

The ML fitting produced a value for LA8hn of approximately 93 dBA, with a standard error of approximately 0.3. The low standard error virtually eliminates any estimate greater than 94 or less than 92 dBA and indicates that a good fit to the data was achieved.

To visualize the results of the ML fitting, the population of MMs was split into four groups, I to IV, based on number of years as a qualified MM. The range of years in each group was arbitrarily chosen both to maximize the number of years as a qualified MM, median age, and median cumulative years of noise exposure.

### TABLE 1. Grouping of the machinists’ mates (MMs) by number of years as a qualified MM

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Age (median and range)</th>
<th>Years as a qualified MM (median and range)</th>
<th>Cumulative years of noise exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>121</td>
<td>23.7 (21.0–25.9)</td>
<td>2.4 (1.0–3.9)</td>
<td>1.20</td>
</tr>
<tr>
<td>II</td>
<td>64</td>
<td>26.6 (26.0–28.9)</td>
<td>5.3 (4.0–6.9)</td>
<td>2.29</td>
</tr>
<tr>
<td>III</td>
<td>32</td>
<td>30.0 (27.0–32.9)</td>
<td>8.6 (7.0–10.9)</td>
<td>3.40</td>
</tr>
<tr>
<td>IV</td>
<td>33</td>
<td>35.9 (31.3–42.2)</td>
<td>14.1 (11.0–20.2)</td>
<td>4.95</td>
</tr>
</tbody>
</table>
noise exposure. The latter value was obtained by entering the median LOS (i.e., “years as a qualified MM” + 2 years of training) into equation 1.

For each group of MMs, predicted distributions of HTLA and HTLAN were obtained for the audiometric frequencies of 1000, 2000, 3000, and 4000 Hz, using information from Table 1 and an LA8hn of 93 dBA. The observed hearing-threshold levels of the MMs were converted into distributions for comparison with the predicted distributions.

Several general trends emerged across the four groups. To reduce redundancy, only group III is shown.* Group III’s results most clearly illustrate all of the trends observed across the groups. This may be because of the slightly greater hearing loss and longer duration of noise exposure of group III compared with groups I and II and the greater homogeneity of group III with respect to age and years on the job compared with group IV.

Figure 1 (panels A–D) shows the distribution of actual hearing-threshold levels of the MMs in group III as a function of population fractile, along with the distributions of predicted hearing-threshold levels associated with age and noise (HTLAN) and hearing-threshold levels associated with age (HTLA) from ANSI S3.44-1996 (1996). The HTLAN distribution corresponds to an input noise level of 93 dBA. Each panel (A–D) shows thresholds at a single audiometric frequency.

As shown in Figure 1, HTLA underestimated the observed hearing-threshold levels of group III at all audiometric frequencies (panels A–D). At 1000 Hz, HTLAN also underestimated the observed thresholds. Differences between the HTLA and HTLAN distributions were relatively small at this frequency because the ANSI S3.44 algorithm predicts minimal NIPTS at 1000 Hz. At 2000, 3000, and 4000 Hz, predicted HTLAN provided a reasonably good fit to the observed hearing thresholds of group III. Recall that the ML-fitting procedure took into account the hearing thresholds of all four groups (and actually calculated the probabilities of each individual’s hearing thresholds separately). If only group III’s thresholds had been considered, the fit likely would have been even better.

DISCUSSION AND CONCLUSIONS

The purpose of this study was to describe the conceptual basis of an approach for using ANSI S3.44-1996 (1996) to predict hearing thresholds in a population even when noise exposure levels and durations are not precisely known. The population chosen to demonstrate this approach comprised 250 male U.S. Navy MMs. A means of calibrating the ANSI S3.44-1996 (1996) algorithm was implemented to match as closely as possible the predicted and observed hearing-threshold levels. The noise level input to the algorithm was allowed to vary, and an ML fitting procedure was used to find the value

*Interested readers who wish to view the graphs for groups I, II, and IV are encouraged to contact the first author.

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that best accounted for all of the hearing threshold data. In this particular example, the fitting process produced a value of 93 dBA with a low standard error of 0.3.

The hearing thresholds of the MMs at 1000, 2000, 3000, and 4000 Hz were generally worse than expected from aging alone, according to Annex A of ANSI S3.44-1996 (1996). Because the MMs were noise-exposed, this finding suggests that they had suffered some NIPTS. However, this finding may have been influenced by the choice of Annex A to predict the effects of aging. Annex A is based on data from a highly screened, non-noise–exposed population free of otologic disease. According to an Institute of Medicine report (Humes et al. 2005), military recruit populations should not be considered highly screened; even in the absence of any noise exposure, the hearing thresholds of service personnel would likely be somewhat worse than those predicted by Annex A. If this was true for the MMs in the present study, then any presumed NIPTS component in their hearing thresholds would be smaller or perhaps even nonexistent.

Annex B of ANSI S3.44-1996 (1996) is an alternative data base representing a non-noise–exposed population unscreened for other causes of hearing loss. Annex B hearing thresholds at 1000, 2000, 3000, and 4000 Hz are generally worse than Annex A thresholds. Several authors, notably Clark and Bohl (2005) and Dobie (2006), have argued that Annex B is a more appropriate choice of control group with which to compare the thresholds of a presumably unscreened population. However, we chose to use Annex A because it is fully parameterized, thereby facilitating the ML fitting procedure. Parameterizing Annex B for use in the ML fitting procedure was outside the scope of this study. If Annex B had been used instead, then the effective exposure level determined by the ML fitting procedure would have been smaller (because the presumed NIPTS component would have been smaller). In turn, a smaller exposure level would suggest reduced cost savings with the application of noise-control solutions. To lend greater confidence to the estimate of the effective exposure level, and to the estimates of cost savings that might result from noise-control solutions, future refinements of the model should use a fully parameterized reference data base similar in most demographic respects to the population under study. In the current state of development of the model, the effective exposure level of 93 dBA should be considered a likely upper bound of exposure.

This work demonstrates the feasibility of reconciling the observed hearing thresholds of a population with those predicted by ANSI S3.44-1996 (1996). If a reliable estimate of exposure duration is available, the ML procedure will determine the noise level that best matches predicted with actual hearing thresholds, regardless of the true noise level in the work space. The effective exposure level determined by this method will be a result of all of the unknown variables associated with the population’s noise exposure, including effectiveness and rate of HPD use, off-the-job noise exposure (including lack of recovery time because of noisy living conditions), and other factors.

Several steps remain before this approach can be used to predict future hearing-threshold levels of any population with confidence. First, a reference data base demographically similar to the population under study should be established. Second, the generalizability of the approach should be extended to other populations, whose hearing protector use rates and length of work shift may vary. Third, the flexibility of the approach should be improved for application to populations with more complex noise exposure histories. Fourth, the predictions that are generated should be verified by longitudinal examination of prospective hearing-threshold data. Eventually, this approach may be developed for use by military and industrial systems-acquisition personnel. Such a tool could assist them in making sound economical and health-promoting decisions regarding the design and purchase of noisy machinery and weapons systems.

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