Tracking occupational hearing loss across global industries: A comparative analysis of metrics

Peter M. Rabinowitz¹, Deron Galusha¹, Michael F. McTague¹, Martin D. Slade¹, James C. Wesdock², and Christine Dixon-Ernst²
¹Yale Occupational and Environmental Medicine Program, Yale University School of Medicine, New Haven, CT
²Alcoa Inc, Pittsburgh, PA, USA

Abstract

Occupational hearing loss is one of the most prevalent occupational conditions; yet, there is no acknowledged international metric to allow comparisons of risk between different industries and regions. In order to make recommendations for an international standard of occupational hearing loss, members of an international industry group (the International Aluminium Association) submitted details of different hearing loss metrics currently in use by members. We compared the performance of these metrics using an audiometric data set for over 6000 individuals working in 10 locations of one member company. We calculated rates for each metric at each location from 2002 to 2006. For comparison, we calculated the difference of observed–expected (for age) binaural high frequency hearing loss (in dB/year) for each location over the same time period. We performed linear regression to determine the correlation between each metric and the observed–expected rate of hearing loss. The different metrics produced discrepant results, with annual rates ranging from 0.0% for a less-sensitive metric to more than 10% for a highly sensitive metric. At least two metrics, a 10 dB age-corrected threshold shift from baseline and a 15 dB nonage-corrected shift metric, correlated well with the difference of observed–expected high-frequency hearing loss. This study suggests that it is feasible to develop an international standard for tracking occupational hearing loss in industrial working populations.

Keywords

Hearing conservation; hearing loss; noise induced; standards

Introduction

Occupational hearing loss is one of the most prevalent occupational medicine conditions, and is a major contributor to the global burden of illness due to hearing loss.¹ As the bulk of industry transitions from more developed nations to other parts of the world, multinational corporations increasingly find themselves in the situation of tracking rates of hearing loss across diverse geographic and political boundaries. One consequence of this is

Address for correspondence: Mr. Peter M. Rabinowitz, 135 College St, Suite 366, New Haven, CT 06510, USA.
peter.rabinowitz@yale.edu.

Source(s) of Support: None

Conflict of Interest: Several of the authors (PMR, DG, and MDS) provide consulting services to Alcoa Inc., and performed some of the work under contract to Alcoa. JW serves as a representative of Alcoa to the International Aluminium Institute Health Committee. Ms. Dixon-Ernst is employed by Alcoa as a corporate audiologist.
that the metrics mandated by various local regulatory authorities may differ between countries, or even between administrative divisions of a single country such as Canada.

Hearing conservation programs rely upon audiometric surveillance, with (usually) annual audiograms as an important component. While determination of hearing loss in an individual worker is important, it is also important for a professional supervisor of such a program to review the hearing loss rates for the entire population and to determine whether such rates indicate that an unacceptable degree of hearing loss is occurring in the workforce and that the program is less than maximally effective.[2] It can also be useful for different industries to compare rates of occupational hearing loss to determine whether noise and ototoxic exposures can be better controlled in a certain sector of the industry.

Audiometric surveillance of noise-exposed workers is generally performed using air conduction audiometry at a range of frequencies that is similar throughout the world. The analysis of these audiograms, however, may vary greatly between countries and between and within industries. For example, while the US criterion for a “standard threshold shift” from baseline is a 10 decibel change in the average of 2, 3 and 4 KHz in either ear, with age correction allowed,[3] the regulations used in the United Kingdom base their audiometric classification on the total of recorded hearing levels obtained at 1, 2, 3, 4, 5 and 6 kHz. This process is done for each ear, and then a reference table (that takes age and gender into account) is checked to determine whether the relevant warning and referral thresholds have been met.[4] The Australian Standard for Auditory Assessment defines a significant threshold shift as:

- a threshold shift greater than or equal to 15 dB at 500, 1000, 1500 or 2000 Hz or greater or equal to 20 dB at 8000 Hz in either ear; a change in mean threshold greater than or equal to 10 dB at 3000 and 4000 Hz or greater than or equal to 15 dB at 6000 Hz in either ear; or a change in average threshold at 3000, 4000 and 6000 Hz greater than or equal to 5 dB in either ear.[5]

The lack of uniformity in metrics used for audiometric surveillance highlights the need for an international standard.

As part of a larger effort to track health and safety across the worldwide aluminum industry, a sector that includes mining and heavy industrial operations, the International Aluminium Institute (IAI) has expressed interest in defining a metric for comparison of hearing loss rates and hearing conservation program quality across its member companies. Developing such a uniform metric could allow the IAI to benchmark companies in other sectors doing a particularly good job with hearing conservation and facilitate information sharing that could lead to more effective prevention measures across the industry. We therefore performed a comparative analysis of a variety of different metrics for tracking occupational hearing loss.

**Materials and Methods**

The IAI is the Global Forum of the world’s Aluminium Producers, and is comprised of 27 member companies, most of them multinational, who account for the majority of the aluminum production in the world. The Health Committee of the IAI meets regularly and shares information on a variety of issues pertaining to the aluminum industry. As part of a current initiative to track occupational safety and health metrics across the industry, the IAI Health Committee members expressed interest in determining a common metric for tracking hearing loss. Members discussed the metrics that they were currently using, and found that they differed. They agreed to submit their current company criteria and allow these criteria to be applied to a common database for analysis. Table 1 lists the criteria supplied by IAI members for analysis as well as a 15 dB shift metric recommended by NIOSH.[6]
Where company criteria overlapped, they were collapsed into a single metric for purposes of this analysis. In addition to the criteria that IAI members supplied, we also included for comparison the 15 dB significant threshold shift criteria recommended by the National Institute for Occupational Safety and Health (NIOSH), which requires a confirmed shift in hearing threshold of 15 dB or greater at 0.5, 1, 2, 3, 4 or 6 KHz in either ear.[6]

As Table 1 shows, all of the candidate metrics involved calculations of “shift” from an audiometric baseline. However, they differed from each other in both the degree of shift required to meet the metric criteria as well as the frequencies used for shift calculations. Some metrics involved using an age correction method to calculate the shift and some, but not all, involved a resetting of the baseline after criteria had been met (baseline revision). The criteria for each metric was required to be present on two consecutive audiograms.

**Audiometric Data Set**

Alcoa, an IAI member company, maintains an electronic data set of surveillance audiograms for current and former employees in US locations. The Yale School of Medicine Human Investigation Committee has approved a protocol for research in an anonymous manner on this data set.[7] Alcoa routinely performs surveillance audiograms annually on employees who work in areas where at least 5% of the current noise measurements are equal to or greater than 85 dBA for an 8-h time-weighted average (TWA), and every 3 years where exposures fall between 82 and 85 dBA.

**Study Population**

We chose for this analysis to study the audiograms of a number of workers at 10 US Alcoa locations where consistent audiometric data were available for at least 10 years on a large group of noise-exposed workers. To be in the data set for analysis, workers must have had at least three audiograms performed between 1982 and 2005, with no gap between audiograms of greater than 2 years. Six thousand six hundred and two individuals met these inclusion criteria, and their audiograms were analyzed according to the different metrics provided by IAI member companies as well as the NIOSH shift criteria.

**Calculation of Metrics**

Different shift criteria as listed in Table 1 were applied to the audiometric data set using SAS v 9.1 (SAS Institute, Cary, NC, USA). The annual rates of hearing loss were determined for each set of criteria for each year from 2002 to 2006, and the rates for these years were also averaged in order to assess year-to-year variability of the different metrics. When age correction was required, we used the tables in appendix F-1 of the OSHA Hearing Conservation standard[3] to perform such correction.

**Calculation of Observed and Expected Rates of High-Frequency Loss**

As a comparison standard across the different Alcoa locations included in the study sample, we calculated, using American National Standards Institute (ANSI) 3.44 formulae, the predicted age-related hearing loss (as dB/year) in the binaural average of both 2, 3 and 4 KHz as well as 3, 4 and 6 KHz for individuals in the study sample at each location over the time period of 2002–2006 based on their age and gender. These calculations were based on hearing levels appearing in Annex A of the ANSI 3.44 standard. However, the yearly rates of change (as opposed to the absolute hearing levels) are similar between Annex A and Annex B. We then calculated the observed rate of hearing loss (dB/year) over the same audiometric frequencies for the same individuals over the same time period. We used both sets of frequencies in order to detect hearing loss in both older and younger individuals.
Noise-induced hearing loss (NIHL) typically first appears at 4000 Hz and adjacent frequencies.[8] However, in older workers, there can be extension of the loss to lower frequencies including 2000 Hz. Finally, we used the difference of the two rates (observed–expected) to define the excess of high-frequency hearing loss occurring in the study population at each of the 10 locations over the 5-year period from 2002 to 2006.

Comparison of Observed and Expected Hearing Loss Rates with Individual Metrics for Occupational Hearing Loss

Using linear regression, we then compared the average annual rate of each of the proposed tracking metrics listed in Table 1 over the same time period (2002–2006) to the difference between observed and expected hearing loss for each location in order to determine the statistical correlation between each tracking metric and the calculated actual excess of high-frequency hearing loss among workers, in particular the company location’s hearing conservation program.

Results

Table 2 shows the demographics of the study populations by study location and the mean number of years of surveillance and number of surveillance audiograms occurring in the data set for each individual.

As the table demonstrates, individuals in the sample were predominantly white and male, and as a group had been under audiometric surveillance for more than 15 years.

Table 3 displays the mean and ranges for the rates, over a 5-year period, of the different hearing loss metrics at each study location. This table also shows the difference, over the same 5-year period, of observed–expected high-frequency hearing loss (for the average of 2, 3 and 4 KHz as well as the average of 3, 4 and 6 KHz) for each of the 10 locations.

As shown in the table, the annual rates for different metrics varied from each other by up to two orders of magnitude. Criteria that did not allow for age correction, such as metrics # 4, 5a and 6, exhibited higher absolute rates than metrics that age-corrected (metrics #1, 2 and 3). Metrics that required a greater degree of audiometric shift from baseline, such as #2, 3 and 5b and c, showed the lowest absolute rates, often 0 or close to 0. The 10 dB age-corrected shift at 2, 3, 4 KHz (#1) displayed an amount of yearly hearing loss that was intermediate between the two above extremes, with a relatively small range over the 5-year period at a particular location. In addition to discrepant results between different metrics, some individual metrics showed considerable year-to-year variability. There was also a range of values for the observed–expected rates of high-frequency hearing loss for the different locations.

Table 4 shows the statistical correlation between the different metrics (average value over the study period) and the observed–expected hearing loss 2002–2006 for both 2, 3 and 4 KHz and 3, 4 and 6 KHz. Table 4 shows that for the 5-year average metrics, a number of metrics (1, 2, 4 and 6) appear to correlate well with the observed–expected hearing loss, whereas metrics 3 and 5a–c did not show a good correlation with the observed–expected loss.

Figures 1–8 graphically show these correlations between average metric values and observed–expected hearing loss for each plant location [2002–2006 (for average of 2, 3 and 4 KHz)].
Table 5 shows the statistical correlation between the average annual rates of the different hearing loss metrics for the 10 locations. As shown in the table, Metrics 1, 2, 4 and 6 were highly correlated with each other.

**Discussion**

Our analysis found that different metrics for occupational hearing loss currently employed in the aluminum industry lead to markedly different estimates of the burden of disease when applied to the same set of industrial audiograms. At the same time, a number of metrics, including an age-corrected 10 dB threshold shift criteria and a 15 dB shift criteria, showed good correlation with the observed–expected rate of high-frequency hearing loss occurring at each study location over the 5-year period of observation. These metrics demonstrate potential for providing a reasonable “signal” of hearing loss occurrence that could serve as an international standard for comparison of occupational hearing loss across countries and industries.

The variation in absolute rates between different metrics implies differences in sensitivity of the measures. Certain metrics appeared to be “highly sensitive,” as exemplified by metrics #4 and 6. Approximately 10% of the population or more met these metrics’ criteria for hearing loss each year of the study period. Our previous analysis of metric 6 as a candidate “early flag” for detecting cases of early hearing loss in individuals found that the high number of individuals flagged by such sensitive metrics on annual screening may limit its clinical usefulness due to the requirement for greater resources for follow-up of many individuals who may not go on to develop significant hearing loss during employment.[9] At the same time, such sensitive measures may be useful when assessing overall program quality, and the lack of age correction may limit the usefulness of such measures, as explained below.

Other metrics appeared to be relatively insensitive, with lower annual rates, as demonstrated by metrics 2 and 3. For metric 3, the criteria requiring a significant shift from baseline (25 dB age-corrected shift in the average of 2, 3 and 4 KHz) means that only a few individuals who work at a location for many years will be identified. By that time, it will be too late to salvage much of their hearing, and the noise problem of the company will also have gone undetected for a prolonged period. Such measures, because they produce low annual rates of loss, are likely, in a smaller worker population, to spuriously produce rates of 0 due to their inability to detect small hearing changes in the population.

Whether or not to adjust a baseline following the occurrence of a hearing shift is another important consideration in developing an international standard. If no baseline revision takes place, sensitive metrics such as #4 would produce results several-fold higher (data not shown) and be less likely to detect recent trends, as much of the annual hearing loss reported would be cumulative from previous years.

For valid comparison of rates of health outcomes across different at-risk populations, the methods of analysis need to reduce possible biases that could lead to erroneous conclusions about where unacceptable rates of occupational hearing loss are occurring. A particular problem arises in comparing rates of diseases that are more common in different age groups across populations with varying age structures. To account for this, methods of age standardization have been developed. Hearing loss risk (due to presbycusis) increases markedly with age. The age correction of surveillance audiograms is a form of age standardization, whereby each individual audiogram is “adjusted” for the expected amount of hearing loss due to normal aging (using standard tables such as appendix F of the OSHA hearing conservation standard).[3] The hearing loss metric is then applied in the setting of
this age correction. While age correction may have some disadvantages when applied to an individual audiogram,\textsuperscript{[6]} age correction does allow the hearing loss experience in an industry where the workers are older, to be compared with the hearing loss occurring in an industry where the workers are relatively younger, without as much bias due to a differential effect of age. One key potential problem with this type of age standardization of hearing loss as an international standard is that rates of hearing loss with normal aging may vary across different populations and countries. Little is known about this, and if subsequent studies confirm such variability, development of country- or population-specific age adjustment tables would be indicated. At the same time that age correction appears to be intuitively important, our finding that the 15 dB shift metric (with no age correction) demonstrated a similar degree of correlation with the observed–expected hearing loss as the age-corrected 10 dB shift suggests that age correction may not be critical for the purposes of comparing occupational hearing loss across locations or countries. In fact, the two measures (10 dB age-corrected shift and 15 dB nonage-corrected shift) showed a high degree of correlation between the measures. Further study of these metrics in populations that diverge in their age structure more than the locations studied here is necessary to determine whether age correction is necessary for comparing hearing loss rates between occupational populations.

One finding of this study was that at approximately half of the study locations, we observed less hearing loss over the study period than would be expected by aging alone (observed–expected <1). The prevalence of this finding suggests that the aging formulae in the ANSI 3.44 standard may not accurately reflect the aging rates of current populations, as the U.S. population today may be losing less hearing as they age compared with previous generations. This finding is consistent with other recent reports that suggest that Americans hear as well or better than 40 years ago, and that the age correction tables in current use may need to be updated.\textsuperscript{[10]} Whether this same trend for improving hearing holds true in other countries remains unclear.

While this study reports promising results for at least two of the candidate metrics, we recommend further studies before setting an international standard. The population of workers used to validate these metrics was based in the US, and further development of an international standard should involve analysis of databases from other countries as well to ensure that the metrics perform well in a number of settings.

The study was also limited by the small number of locations used for the comparison (10). As a result, although the correlations between certain metrics and the difference of observed and expected hearing loss were statistically significant, and the R\textsuperscript{2} values for some metrics appeared much larger than others, a larger sample should be used to assess the statistical significance of the differences between the performance of individual metrics.

This study used the observed–expected rate of high-frequency hearing loss (either at 2, 3 and 4 KHz or 3, 4 and 6 KHz) as a comparison standard to approximate the actual degree of high-frequency hearing loss occurring in each location. One could argue that this type of measure would be even better than the other proposed metrics that are based on either shifts from baseline or absolute values of hearing loss at particular frequencies. Calculating observed and expected rates of loss, however, requires more sophisticated computing that is beyond the capabilities of many industrial settings, and an approach that is unfamiliar to many hearing conservation professionals. The good correlation between metrics 1 and 6 and the observed–expected hearing loss argues that existing methods such as age-corrected shift rates or the 15 dB shift criteria that we used could provide useful comparison metrics for assessing the relative burden of NIHL in different industrial settings across countries.
Acknowledgments

The members of the International Aluminium Institute are greatly acknowledged.

References

1. Nelson DI, Nelson RY, Concha-Barrientos M, Fingerhut M. The global burden of occupational noise-induced hearing loss. Am J Ind Med. 2005; 48:446–58. [PubMed: 16299704]

2. Rabinowitz, P. [February 2011] ACOEM position statement. The role of the professional supervisor in the audiometric testing component of the hearing conservation program. 2007. Available at: www.acoem.org/ProfessionalSupervisor_ConservationPrograms.aspx.

3. OSHA. 1910.95 CFR Occupational Noise Exposure: Hearing Conservation Amendment (Final Rule). Federal Register. 1983; 48:9738–9785.

4. United Kingdom Health and Safety Executive. [February 2011] Proposals for new Control of Noise at Work Regulations Implementing the Physical Agents (Noise) Directive (2003/10/EC). Available at: http://www.hse.gov.uk/consult/condocs/cd196.pdf.

5. Australian/New Zealand Standard AS/NZS 1269.4: 2005 Occupational noise management, Part 4: Auditory assessment. Standards Australia; Sydney: 2005.

6. NIOSH. Criteria for a Recommended Standard: Occupational Noise Exposure Revised Criteria 1998. DHHS; Cincinnati: 1998. p. 105

7. Rabinowitz PM, Slade M, Dixon-Ernst C, Sircar K, Cullen M. Impact of OSHA final rule—recording hearing loss: an analysis of an industrial audiometric dataset. J Occup Environ Med. 2003; 45:1274–80. [PubMed: 14665813]

8. ACOEM Noise and Hearing Conservation Committee. ACOEM evidence-based statement: noise-induced hearing loss. J Occup Environ Med. 2003; 45:579–81. [PubMed: 12802210]

9. Dobie RA. Audiometric threshold shift definitions: simulations and suggestions. Ear Hear. 2005; 26:62–77. [PubMed: 15692305]

10. Hoffman HJ, Dobie RA, Ko CW, Themann CL, Murphy WJ. Americans hear as well or better today compared with 40 years ago: hearing threshold levels in the unscreened adult population of the United States, 1959-1962 and 1999-2004. Ear Hear. 2010; 31:725–34. [PubMed: 20683190]
Figure 1.
Average annual percent of workers with hearing loss by metric 1 versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
Figure 2.
Average annual percent of workers with hearing loss by metric 2 versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
**Figure 3.**
Average annual percent of workers with hearing loss by metric 3 versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
Figure 4.
Average annual percent of workers with hearing loss by metric 4 versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
Figure 5.
Average annual percent of workers with hearing loss by metric 5a versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
Figure 6.
Average annual percent of workers with hearing loss by metric 5b versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
Figure 7.
Average annual percent of workers with hearing loss by metric 5c versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
Figure 8.
Average annual percent of workers with hearing loss by metric 6 versus observed–expected hearing loss at 2, 3 and 4 KHz by plant location (2002–2006)
### Table 1

Metrics for tracking occupational hearing loss analyzed in this study

| Metric | Metric criteria (present on two consecutive audiograms) | Frequencies used | Age correction | Baseline revision |
|--------|--------------------------------------------------------|------------------|----------------|------------------|
| 1      | 10 dB shift in either ear                               | Average 2, 3, 4 kHz | Yes            | Yes              |
| 2      | 25 dB shift in either ear                               | Average 2, 3, 4 kHz | Yes            | Yes              |
| 3      | 25 dB shift in both ears                                | Average 1, 2, 3 kHz | Yes            | Yes              |
| 4      | 15 dB shift in both ears                                | 3, 4 or 6 kHz    | No             | Yes              |
| 5a-c   | (a) 11–20 dB shift                                      | Average 0.5, 1, 2 kHz | No             | No               |
| 6      | 15 dB shift in either ear (NIOSH)                       | 0.5, 1, 2, 3, 4 or 6 kHz | No             | Yes              |
Table 2

Demographics of individuals in hearing conservation programs at 10 Alcoa locations (n = 6602)

| Location | Total | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|          | n     | %   | n   | %   | n   | %   | n   | %   | n   | %   | n   | %   |
| Age      |       |     |     |     |     |     |     |     |     |     |     |     |
|          | 47.8  | 8.5 | 50.4| 8.9 | 48.6| 8.7 | 46.4| 8.1 | 47.4| 7.6 | 48.5| 8.1 |
| Male     | 5917  | 89.6| 776 | 90.9| 169 | 87.1| 666 | 90.4| 1301| 86.9| 449 | 86.3|
| Race     |       |     |     |     |     |     |     |     |     |     |     |     |
| white    | 9979  | 90.6| 745 | 87.2| 179 | 92.3| 551 | 74.8| 1411| 94.3| 510 | 98.1|
| black    | 556   | 8.4 | 99  | 11.6| 8   | 4.1 | 176 | 23.9| 75  | 5.0 | 9   | 1.7 |
| other race| 67   | 1.0 | 10  | 1.2 | 7   | 3.6 | 10  | 1.4 | 11  | 0.7 | 1   | 0.2 |
| Salary   | 1020  | 15.4| 42  | 4.9 | 188 | 96.9| 85  | 11.5| 205 | 13.7| 30  | 5.8 |
| # of audiograms - mean, sd | 14.4 | 6.1 | 14.2| 5.7 | 12.8| 5.9 | 13.0| 5.9 | 15.5| 6.1 | 15.8| 6.6 |
| Years of surveillance - mean, sd | 16.7 | 7.2 | 19.0| 7.9 | 17.2| 7.0 | 15.0| 7.0 | 16.7| 6.8 | 17.1| 6.8 |

*Age as of 1/1/2006
Rate of each hearing loss metric (mean, range) and observed–expected rate of hearing loss at 2, 3, 4 KHz and 3, 4, 6 KHz, 2002–2006, for 10 locations

| Loc | N   | OBS-EXP (3A,6) | OBS-EXP (2,3,4) | Metric 1          | Metric 2          | Metric 3          | Metric 4          | Metric 5a        | Metric 5b        | Metric 5c        | Metric 6          |
|-----|-----|----------------|-----------------|-------------------|-------------------|-------------------|-------------------|-----------------|-----------------|-----------------|-----------------|
| 1   | 854 | 0.05           | -0.07           | 1.9 (1.2-3.2)     | 0.2 (0.1-0.4)     | 0.0 (0.0-0.1)     | 12.2 (7.7-16.5)  | 3.0 (1.5-5.4)   | 0.6 (0.0-1.3)   | 0.1 (0.0-0.2)   | 10.8 (7.8-14.6) |
| 2   | 194 | -0.42          | -0.43           | 1.3 (0.5-2.1)     | 0.0 (0.0-0.0)     | 0.1 (0.0-0.5)     | 10.2 (8.8-14.4)  | 2.6 (1.0-6.6)   | 0.7 (0.5-1.0)   | 0.2 (0.0-0.5)   | 9.0 (7.7-10.8)  |
| 3   | 737 | -0.48          | -0.34           | 1.3 (0.8-2.0)     | 0.1 (0.0-0.3)     | 0.0 (0.0-0.0)     | 10.6 (8.5-11.5)  | 1.8 (1.1-2.4)   | 0.2 (0.1-0.4)   | 0.5 (0.3-0.7)   | 10.1 (8.3-12.3) |
| 4   | 1497| 0.01           | 0.04            | 1.6 (1.1-2.2)     | 0.3 (0.1-0.6)     | 0.0 (0.0-0.1)     | 9.3 (5.2-12.6)   | 4.6 (2.9-6.4)   | 0.3 (0.1-0.6)   | 0.3 (0.2-0.3)   | 9.0 (5.9-11.1)  |
| 5   | 520 | 0.14           | -0.05           | 2.3 (1.3-4.0)     | 0.3 (0.0-0.6)     | 0.1 (0.0-0.2)     | 14.0 (9.8-18.7)  | 3.2 (2.1-4.4)   | 1.0 (0.4-1.3)   | 0.6 (0.0-1.2)   | 12.3 (9.2-16.2) |
| 6   | 425 | -0.12          | -0.18           | 1.6 (0.5-2.8)     | 0.3 (0.0-0.5)     | 0.0 (0.0-0.0)     | 10.2 (6.6-13.6)  | 4.2 (2.1-6.4)   | 0.4 (0.0-0.7)   | 0.2 (0.2-0.2)   | 10.0 (5.6-13.9) |
| 7   | 275 | -0.21          | 0.08            | 1.7 (0.7-3.6)     | 0.3 (0.0-0.7)     | 0.2 (0.0-0.7)     | 10.9 (7.6-13.8)  | 2.4 (1.1-5.1)   | 0.1 (0.0-0.4)   | 0.4 (0.0-0.7)   | 11.3 (8.0-14.9) |
| 8   | 356 | -0.54          | -0.43           | 2.0 (0.6-3.4)     | 0.3 (0.0-0.8)     | 0.0 (0.0-0.0)     | 10.6 (1.4-15.2)  | 3.8 (1.1-5.1)   | 0.4 (0.0-0.8)   | 0.0 (0.0-0.0)   | 9.4 (0.6-14.6)  |
| 9   | 1545| -0.69          | -0.62           | 1.3 (0.8-1.7)     | 0.1 (0.0-0.3)     | 0.0 (0.0-0.1)     | 9.2 (7.9-10.0)   | 2.1 (1.2-2.6)   | 0.5 (0.3-0.7)   | 0.3 (0.3-0.4)   | 8.8 (6.9-9.8)   |
| 10  | 199 | 0.43           | 0.45            | 2.8 (0.5-6.5)     | 0.5 (0.0-2.0)     | 0.0 (0.0-0.0)     | 14.3 (8.0-20.1)  | 3.8 (2.0-5.5)   | 0.4 (0.0-1.1)   | 0.1 (0.0-0.5)   | 12.9 (7.0-20.6) |
Table 4
Correlation between average metric values (2002–2006) and observed–expected rate of hearing loss

| Metric | OBS-EXP (3,4,6) | OBS-EXP (2,3,4) |
|--------|-----------------|-----------------|
|        | R²   | p-value | R²   | p-value |
| Metric 1 | 0.6061 | 0.0080 | 0.5266 | 0.0175 |
| Metric 2 | 0.5141 | 0.0196 | 0.6098 | 0.0077 |
| Metric 3 | 0.0000 | 0.9974 | 0.0320 | 0.6210 |
| Metric 4 | 0.5558 | 0.0133 | 0.4257 | 0.0409 |
| Metric 5a | 0.3058 | 0.0973 | 0.2092 | 0.1838 |
| Metric 5b | 0.0427 | 0.5669 | 0.0178 | 0.7133 |
| Metric 5c | 0.0008 | 0.9373 | 0.0025 | 0.8915 |
| Metric 6 | 0.5993 | 0.0086 | 0.6206 | 0.0068 |
Table 5

Correlation between different hearing loss metrics

| Metric   | Metric 1 | Metric 2 | Metric 3 | Metric 4 | Metric 5a | Metric 5b | Metric 5c | Metric 6 |
|----------|----------|----------|----------|----------|-----------|-----------|-----------|----------|
| Metric 1 |          | 0.810    |          |          | 0.44      | 0.29      |          | 0.81     |
| Metric 2 |          |          |          | 0.88     | 0.53      | 0.7       |          | 0.61     |
| Metric 3 |          |          |          |          |          |          | 0.34      | 0.17     |
| Metric 4 |          |          |          |          |          |          | 0.04      | 0.18     |
| Metric 5a|          |          |          |          |          |          |          | 0.21     |
| Metric 5b|          |          |          |          |          |          |          |          |
| Metric 5c|          |          |          |          |          |          |          |          |
| Metric 6 |          |          |          |          |          |          |          |          |