Critical Review:
The Effectiveness of Hearing Conservation Initiatives on the Incidence of Noise Induced Hearing Loss Amongst Industrial Workers

Rhys Kooistra
M.Cl.Sc (AUD) Candidate
University of Western Ontario: School of Communication Sciences and Disorders

Noise exposed industrial workers are at a constant risk of noise-induced hearing loss (NIHL) but the effectiveness of hearing conservation programs (HCPs) is often difficult to evaluate. The large variety that exists amongst industrial settings and HCPs calls for objective outcome measures that can be compared across programs. The most common method of evaluation of these programs at present is the measurement of workers' audiometric thresholds over time. Such evaluations are valuable in that the results may be useful as support for current practices or as evidence that a new approach is necessary in regards to HCPs. In light of these challenges, this critical appraisal reviews several studies published over the last decade with the aim of evaluating the effectiveness of hearing conservation initiatives on the incidence of noise induced hearing loss (NIHL) amongst industrial workers.

Introduction

It is estimated that nearly 30 million American workers are at risk of noise-induced hearing loss (Rogers et al., 2009). The World Health Organization reports that occupational noise induced hearing loss (NIHL) is second only to accidental injury in terms of years of healthy life lost (Concha-Barrientos et al., 2004). Furthermore, the cost of NIHL in the United States is estimated in the billions of dollars (Rabinowitz, 2000). Whereas legislation in Canada and the United States has established standards for allowable noise exposure and hearing protection requirements in most areas, issues regarding adherence (Horie, 2002), enforcement (Daniell et al., 2006), effectiveness (Rogers et al., 2009), and implementation (Brink et al. 2002) result in continued risk of occupational NIHL for noise exposed workers. The effectiveness of hearing conservation programs (HCPs) is an ongoing topic of research across a broad range of industries and strategies. So far the evidence for the effectiveness of such interventions is lacking (Rabinowitz et al., 2010) or contradictory (Verbeek et al., 2009). The large variety that exists amongst industrial settings and HCPs calls for objective outcome measures that can be compared across programs. While there are promising new possibilities in regards to such measures (Miller et al., 2004), the measurement of workers' audiometric thresholds over time remains the most important outcome measure at present. This measure is not perfect. Neither the research community nor organizations such as the American National Standards Institute (ANSI), despite their efforts, have been able to produce an effective method for evaluating HCPs based on audiometric data which has been consistently adopted (Davies et al. 2008). Nonetheless, considering the implications of occupational NIHL, it is worthwhile to review the existing outcome-based evidence with the aim of either lobbying for these programs or calling for a restructuring of our approach. In light of these challenges, this appraisal reviews studies conducted over the last decade with the aim of evaluating the effectiveness of hearing conservation initiatives on the incidence of NIHL amongst industrial workers. The implications of this type of evaluation will speak to the cost-effectiveness of HCPs in terms of the health of industrial workers as well as the financial considerations to the employer. Additionally, researchers may benefit from the data by borrowing and improving research designs and methods as well as by attaining a body of literature which can be referenced and compared to future studies. Finally, audiologists stand to benefit from the information presented here by providing better counseling to their clients on issues surrounding HCPs and personal hearing protection (PHP).

Objectives

This paper aims to provide a critical review of several independent studies as they pertain to the effectiveness of HCPs on the incidence of NIHL amongst industrial workers.

Methods

Search Strategy

Scopus, PubMed, CINAHL, Web of Science, and Google Scholar were the primary databases used in this literature search. The following search terms were used:

- (hearing conservation) AND (hearing loss) AND (noise-induced)
- (hearing conservation) AND (effectiveness)
- (hearing conservation) AND (threshold shift)
- (hearing conservation) AND (industrial) AND (hearing loss)

The following terms were excluded:

- (veteran) AND (military) AND (child) AND (agriculture) AND (education) AND (construction) AND (mining)

Results were limited by date to include only those articles published in or since the year 2000.

Selection Criteria

Only papers presenting evidence of the effect of an HCP on the long term audiometric thresholds of noise exposed workers in an industrial setting were included in this review. Although various HCP methodologies are represented in this review in regards to their effect on audiometric thresholds, articles relating to the effectiveness of novel technologies not yet widely used in HCPs were excluded. Sources discussing the background issues relating to this topic were included throughout the review.

Data Collection

The results of this literature search produced 4 longitudinal cohort studies (Adera et al., 2000, Brink et al., 2002, Davies et al., 2008 and Rabinowitz et al., 2011). The focus of three of these articles is the effectiveness of HCPs and/or specific components of HCPs in regards to the long term preservation of audiometric thresholds of noise exposed industrial workers (Brink et al., 2002, Davies et al., 2008 and Rabinowitz et al., 2011). One of the articles focuses the use of a reference population in the evaluation of HCPs, and in the process reports on the effectiveness of a certain industrial HCP (Adera et al., 2002).

Results and Critical Analysis

Davies et al. (2008)

This study is a response to the need for a standard approach to assessing the effectiveness of regulatory HCPs. Specifically, it addresses the effectiveness of British Columbia's provincial hearing conservation initiative by focusing on the audiometric threshold shifts of lumber mill workers over a 17 year period (1979-1996). In this retrospective, longitudinal cohort study, the study group's permanent threshold shifts (PTSs) were compared to a control group consisting of workers from the same cohort who were subjected to a lower cumulative noise exposure. The sample size was n=16,374 for the study group and n=6002 for the control group. All of the participants were male. The mean time between initial and final hearing tests was 7.1 years. Audiometric data was provided by the Workman's Compensation Board (WCB) of British Colombia. Univariate analysis revealed that the consistent use of PHP delayed the median age of threshold shift by 2.4 years. Additionally, multivariate survival analysis (Cox modeling) was used to account for a variety of variables including cumulative noise exposure, pre-existing hearing ability, year of baseline test, and PHP use. This analysis revealed that the use of PHP was responsible for a 30% decrease in the risk of threshold shift. This was not the case, however, for workers who had elevated risk levels due to exposure to very high levels of noise. Additionally, individuals who entered the study at a later date, well after the commencement of the HCP, had a further 30% reduction in their risk of a threshold shift. These results suggest that the implementation of a hearing conservation program has a negative effect on the incidence in PTS amongst noise-exposed workers.

Do to the presence of several potentially confounding variables, the use of survival statistical analysis is appropriate. This analysis allows for the estimation of hazard ratios which can be used as a gage of the effectiveness of HCPs (Adera et al., 2000). The same analysis is used by Adera et al. (2000) who conducted a similar study, suggesting that the procedure is a valid one for such designs. The validity of this study is fairly good since many of the confounding variables are accounted for and the study and reference group populations are large. The large sample sizes also lends power to the study. Additionally, the methods and procedures are very well presented and explained.

Rabinowitz et al. (2011)

The authors of this study recognized the need for strong evidence for the effectiveness of specific interventions for occupational NIHL. This study measures the effectiveness of a HCP that employs noise exposure monitoring as an intervention strategy. To accomplish this, the researchers used a mixed longitudinal cohort design with a matched control group. A study group of 78 aluminum smelter workers were provided with daily monitoring of at-ear noise levels and were given regular feedback on noise exposure from their supervisors. An internal control group of 234 was established and matched for age, gender, and high frequency audiometric thresholds. This group was selected from workers of the same company but at different smelter locations and did not have access to noise monitoring technologies during the course of the study. Three control subjects were matched to each individual study subject. Data collection was done retrospectively for the four years before the commencement of the intervention and continued for four years afterwards. Results showed a deceleration in the rate of hearing loss for both groups when the pre and post-intervention time periods were compared. However, the deceleration was significantly greater for the study group ($p<0.0001$). These results led the researchers to conclude that the evidence supports the use of noise monitoring as a effective strategy in slowing rates of NIHL in an industrial setting. Mandatory noise monitoring that regularly alerts workers to their moment to moment exposure may result in more consistent use of PHP as well as increased efforts to reduce excessive exposure. These factors likely contribute to the significance of the intervention effect.

This rational for this study is uniquely compelling in that is supports a HCP intervention strategy other then the mandatory use of PHP. An over-reliance on PHP, often unenforced and improperly worn, is a well recognized barrier to the effectiveness of a HCP (Davies et al., 2009). The measures in this study were administered independently. The careful matching of the control group and the consistent measurement of at-ear noise levels for each group across both pre and post-intervention time periods adds to the validity of the study. This being said, the study can only speak to the effect of a mandatory intervention, which is not always the case for intervention strategies beyond the use of PHP. The power of the study was good but could have been improved by a larger sample size. The statistical analysis was performed using SAS v 9.01 but is not discussed in detail.

Brink et al. (2002)
Citing issues with a lack of adherence amongst workers to mandatory use of PHP, along with suspect effectiveness of such equipment when in use, the authors of this study attempt to evaluate the effectiveness of PHP in the context of a HCP. The study is a longitudinal, repeated measures cohort design with no control group. The study group consisted of 301 automobile stamping and assembly workers with an average tenure of 14.3 years. All participants had a normal initial audiogram measured at the beginning of their tenure with the company. The main focus of the study was the effect of PHP on the threshold shift of the workers. A significant correlation was found between the percentage of time the participants wore PHP during their tenure and their total hearing loss experienced ($p<0.0001$). It was found that as the use of PHP increased, total hearing loss decreased, providing evidence for the effectiveness of PHP in the preservation of the workers' hearing sensitivity. This effect was linear and did not have a threshold.

Multiple linear regression, done in a cross-sectional fashion, was the main statistical method utilized in this study. The variables included in this analysis were age, cumulative noise exposure, gender, race, tenure, transfer status, and percentage of time wearing PHP. By accounting for these variables, the study remained relatively unbiased by exclusion criteria. In turn, this level of control strengthens the internal validity of the study as do certain precautions taken in the measurement of the participants' audiometric thresholds. For instance, the audiometers used were calibrated to ANSI standards and, in order to prevent the effects of temporary threshold shifts, the workers did not have exposure to noise in the 14 hours prior to their audiological assessments. The estimate of the use of PHP amongst the study group during the time period of interest was based on a point estimate for each year, as were estimates of noise exposure. Confidence intervals would have provided a better estimate of the reliability of such measures. The power of this study is good due to an adequate sample size, although a larger study would be advantageous.

Adera et al. (2000)
Although this article's research question is not directly related to this review, the subsequent design incorporates an evaluation of the effectiveness of a HCP. Historically, the lack of adequate control groups with the necessary audiometric data has limited such evaluations. This study aims to demonstrate a new methodology in the evaluation of HCPs using a large external reference population. To accomplish this, a longitudinal, between groups cohort design was used comparing a study group (n=14,900) from a single large industrial company with an in-place HCP to a reference population from various diverse industrial companies across the United States and Canada. Less than 2% of the reference population members were part of a HCP. Baseline audiometric data was collected for both groups along with follow-up assessment data after five years. Information on race, age, and gender was also attained and accounted for in the analysis. Data for the reference population was provided by the ANSI S12.13 Working Group under the sponsorship of the National Institute for Occupational Safety and Health (NIOSH). Results indicate that the study group males were 2.1 to 3.9 times more likely to incur hearing loss compared to the reference population. Likewise, females of the same group were 1.8-5.1 times more likely to experience a PTS. This suggests that the HCP under question is performing poorly and is in need of improvement.

The Cox proportional hazards model was used here and, as in the case of Davis et al. (2008), the use of survival analysis is appropriate for this design. Additionally, 95% confidence intervals were calculated for each hazard ratio and are sufficiently narrow, suggesting good reliability. The large sample sizes lends power to the study and the validity is fair-to-good due to the control of confounding variables. The researchers admit, however, that certain confounding variables could not be controlled for due to a lack of subject data, which compromises the validity to some extent.

Limitations

The studies reviewed above have many similarities in their design, which are to some extent dictated by the nature of the research, and therefore have several overlapping limitations. All four of the studies employed a longitudinal cohort design and represent a 2b level of evidence. As a general limitation to such a design, the study group, and control group if there is one, is not randomized. Additionally, the list of confounding variables is long, and not all of these variables can be easily controlled. For example, factors like smoking, alcohol use, and ototoxic medication (Davies et al., 2008), as well as a history of chronic ear disease, brain trauma, hereditary history of hearing loss, and non-occupational noise exposures (Adera et al., 2000, Brink et al., 2002), cannot necessarily be controlled for. Additionally, much of data relating to these variables is self-reported, as is the use of PHP (Davies et al., 2008, Brink, 2002). Since it is subject to peer pressure, concealment, and inaccuracy, this type of data collection may compromise validity to some extent. For example, in the case of Davies et al. (2008), 35% of the data regarding previous noise exposure was missing. Although these individuals were not included in the multivariate analysis, some amount of inaccurate information, which is much harder to detect then missing information, is likely to have been included in the study.

In their study, Rabinowitz et al. (2011) warn of potential confounding variables that may lead to a type I error in their evaluation of noise monitoring intervention. In their case, the specific aspect of the HCP they were evaluating was not the only strategy in place designed to prevent or reduce the progression of NIHL. As with almost all HCPs, this cohort was also required to wear PHP, and the counseling, retraining, and fitting of such devices could potentially obscure the beneficial effect of the intervention of interest. The fact that PHP in and of itself can be a confounding variable in studies of this kind has been acknowledged (Rabinowitz et al., 2007). Additionally, the researchers point out that falsely elevated audiograms due to measurement error at the time of the initial assessment may further obscure the intervention effect due to the phenomenon of regression towards the mean. This being said, the strong statistical significance in support of the effectiveness of the intervention, along with the careful selection of the control group, argues strongly for the effectiveness of the intervention in this case. Given that NIHL most often develops gradually over time, follow-up measures involving this cohort may be warranted to further support the significance of this intervention effect (Rabinowitz et al., 2011).

Two of the above studies made use of internal control groups (Davies et al., 2008, Rabinowitz et al., 2011). Since an internal control is part of the cohort in these cases, there is no gold standard outside the HCP to which the study group can be compared. This limits the extent to which the results can be extrapolated to other populations. This also limits the studies' ability to measure the effect of changes with time on hearing sensitivity that are unrelated to occupational noise exposure (Davies et al., 2008). Brink et al. (2002), although not including a control group in their study, express the importance and difficulty of establishing a true control population which has not been exposed to noise in the past. Unfortunately, this is not always possible in retrospective cohort designs.

Discussion

Generally speaking, the articles reviewed above incorporated designs with good to excellent sample sizes and sufficient control of potential confounding variables. In regard to the effectiveness of HCPs the results of the articles in this review are not unanimous. Adera et al. (2000) were condemning of the HCP they evaluated using their large reference population, while the other studies (Davies et al., 2008, Rabinowitz et al., 2011, Brink et al., 2002) found statistically significant evidence in support of the effectiveness of HCPs in the reduction of audiometric threshold shifts over time. This evidence suggests that HCPs can be effective in the prevention of hearing loss amongst noise exposed industrial workers but are not universally so. Evaluations such as these are informative in regards to cost-benefit to the company as well as the personal well-being of the employees. Adera et al. (2000) describe evaluation as an essential component to any HCP. The information gained from the regular evaluation of HCPs may lead to improved implementation and increased adherence. This may be accomplished through the advocating of new strategies, as is the case with noise monitoring (Rabinowitz et al., 2011), or by providing evidence for lack of effectiveness (Adera et al., 2000). Due to these implications, the importance of all of the studies reviewed is compelling.

Brink et al. (2002) reported an increase in the use of PHP amongst the participants of the study group during the duration of the study. If this trend is still at work in a more broad sense in noisy industrial work places, this data may also be useful in suggesting that the effectiveness of HCPs would be expected to improve simply by an increase in adherence to the PHP requirements.

The specific knowledge gained by these studies must be viewed in light of the inherent limitations of this type of research as discussed above. Most notably, retrospective cohort studies of this kind have many confounding variables to account for and seem to rely on self-reported data for a number of these variables (Davies et al., 2008, Brink et al., 2002). These difficulties may be offset in some cases by the use of very large sample sizes made possible by archived audiometric data (Davies et al., 2008, Adera et al., 2000). One further difficulty in regards to the beneficial effects of HCP on hearing preservation has to do with the quantitative nature of the results and their subsequent interpretation. An evaluation of this type may suggest a significant reduction in the rate of hearing loss but it is up to the researcher or employer to determine if this reduction is acceptable. For example, Brink et al. (2002) found that over the course of their tenures the mean hearing loss of the study group increased by over 10 dB at 1, 2, and 3 kHz, but not enough to meet the NIOSH definition for NIHL. Despite the success of these results, these may not be acceptable figures as the use of PHP increases and HCP intervention strategies evolve and improve. The use of Cox modeling is one answer to this issue since the calculation of hazard ratios for hearing loss provides numerical vales by which a HCP can be judged. Adera et al. (2000) outlined a rating system based on such hazard ratios using 95% confidence intervals. Nonetheless, the need for comparison between HCPs calls for further research in this area.

Finally, there are several negative consequences associated with the type of evidence reviewed above, in particular regarding its support for the effectiveness of HCPs. First, the overall reduction of NHIL as measured in PTS may be misleading if certain subgroups within the cohort are exposed to higher or lower levels of noise. This measure can be controlled for (Davies et al., 2008) but should be differentiated from long term estimates of accumulated noise exposure such as those calculated by Brink et al. (2002). The latter does not take into account the relationship between noise exposures associated with specific tasks and PTS. It has been shown that in some HCPs it is possible for workers exposed to more intense noise to display lower rates of hearing loss than workers in exposed to less intense noise, perhaps due to the more diligent use of PHP in bothersome levels of noise (Rabinowitz et al., 2007). This in turn may lead to erroneous predictions based on long term estimates that associate a higher risk of hearing loss with more intense noise exposure. Second, the dependence on PHP by some HCPs, effective or not, has prevented the implementation of more salient solutions such as engineered noise control (Davies et al., 2009, Suter, 2009). A HCP should not be used as a substitute for reducing noise emissions in the work place.

Conclusion

In light of the evidence presented by the studies reviewed in this appraisal, it appears that HCPs can play a significant role in the prevention of NIHL in industrial workers. Furthermore, the evaluation of the effectiveness of HCPs provides critical information regarding the cost-effectiveness and performance of the initiatives. Specifically, these evaluations provide data that may lead to the advocacy and/or improvement of HCPs which will ultimately better preserve the workers' quality of life. In regards to the implications for audiologists, the knowledge acquired for these studies may prove useful when counseling a client on the importance of PHP and HCPs or when engaging in practice in the field of hearing conservation.

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