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# Using software to predict occupational hearing loss in the mining industry

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## Abstract

Powerful mining systems typically generate high-level noise that can damage the hearing ability of miners. Engineering noise controls are the most desirable and effective control for overexposure to noise. However, the effects of these noise controls on the actual hearing status of workers are not easily measured. A tool that can provide guidance in assigning workers to jobs based on the noise levels to which they will be exposed is highly desirable. Therefore, the Pittsburgh Mining Research Division (PMRD) of the U.S. National Institute for Occupational Safety and Health (NIOSH) developed a tool to estimate in a systematic way the hearing loss due to occupational noise exposure and to evaluate the effectiveness of developed engineering controls. This computer program is based on the ISO 1999 standard and can be used to estimate the loss of hearing ability caused by occupational noise exposures. In this paper, the functionalities of this software are discussed and several case studies related to mining machinery are presented to demonstrate the functionalities of this software.

### Keywords

Noise control; Hearing loss prediction; Software; Hearing threshold level 3

## Introduction

People regularly exposed to noise can develop hearing loss at different levels of severity depending on a number of factors. The resultant hearing loss can affect a person's ability to

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understand speech, ability to learn, acoustic signal perception and appreciation of music. Hearing loss caused by overexposure to noise has long been recognized in literature (Anonymous, 1989; Rosenwinkel and Stewart, 1959; Henderson and Subramaniam, 1996). However, those working in noisy environments still do not pay serious attention to it because the loss of hearing ability is a gradual process and workers are often unaware of it until the damage becomes an apparent problem.

In the United States, occupational hearing loss is one of the most common work-related illnesses. Depending on the definition of exposure and impairment, in 2012 the U.S. National Institute for Occupational Safety and Health (NIOSH) estimated there are between 5 million and 30 million workers in the United States who are exposed to noise levels at work that put them at risk of hearing loss (NIOSH, 2012). In the mining industry, noise-induced hearing loss (NIHL) is particularly severe due to the fact that heavy-duty machinery is widely used to improve production efficiency, and this machinery can generate much higher noise levels than the permissible level defined by regulation (Masterson et al., 2013; McBride, 2004). As a result, the mining sector has the highest prevalence, at 76 percent, of hazardous workplaces with high noise exposures among all industrial sectors (Tak, Davis and Calvert, 2009).

Noise-induced temporary threshold shift (TTS) is a reversible temporary effect on hearing. However, if one continues to be exposed to the noisy environment, the damage will become permanent and irreversible, resulting in noise-induced permanent threshold shift (NIPTS). Because the loss of hearing is a gradual process, people do not typically notice any hearing deficit until their hearing ability has dropped to a certain level. Often, the hearing loss is rather substantial before a person seeks medical attention (Sataloff and Sataloff, 2006). Hence, predicting hearing loss due to noise exposure ahead of its actual occurrence would greatly benefit both workers and their employers. With a tool that can predict hearing loss due to noise exposure, employers could prevent further hearing damage to their workers through administrative efforts such as assigning the worker at risk to a different job.

This approach requires a model that represents the relationship between hearing threshold level and the contributing factors, such as the noise exposure level and the exposure duration. Rosenwinkel and Stewart (1959) studied hearing loss related to nonsteady noise exposure and concluded that the hearing loss appeared to be a function of time, rate and an interaction between the two, although the actual relationship between hearing loss and noise exposure could not be derived. Later, Gallo and Glorig (1964) published their research results on the permanent hearing threshold shift produced by noise exposure and aging. They took their data from a high-noise-level industrial environment and presented their results in terms of frequency of noise and exposure time. Schneider et al. (1970) then demonstrated how to obtain hearing loss trends resulting from various industrial noise exposures. All of these studies laid the foundation for predicting hearing loss due to occupational noise and resulted in ISO 1999, which provides a fundamental procedure to estimate hearing threshold level considering noise exposure and other factors, and ISO 7029, which provides statistical distributions of hearing thresholds as a function of age (International Organization for Standardization, 1990, 2000).

Many noise controls have been developed to reduce machinery noise. To evaluate the effectiveness of the developed noise control techniques on hearing loss, an effective and convenient tool is highly desirable.

To address this need to reduce NIHL in the mining industry, the Hearing Loss Prevention Branch of NIOSH's Pittsburgh Mining Research Division (PMRD) developed noise controls for various mining machines, including continuous mining machines, roof bolting machines and longwall mining systems. However, the effect on the actual hearing status of workers who benefit from these noise controls is not easily measured. To completely realize the benefit of these noise controls as long-term protection, an understanding of how a reduction in worker noise exposure translates into a reduction in the risk of acquiring NIHL is required. NIOSH's Office of Mine Safety and Health Research (OMSHR) therefore developed a software tool to estimate hearing loss due to occupational noise and connect the engineering noise control approach to estimated hearing loss in a systematic way. In addition, this program can be integrated into a company's existing hearing loss prevention program as a training tool, giving the trainer great flexibility to demonstrate the progression of hearing loss given individualized examples of noise exposure.

In this paper, a detailed discussion of the functionality of the software developed by PMRD is presented. Several case studies related to the application of noise controls to mining machines are provided to demonstrate the functionalities of the developed program.

## Background

Hearing loss is a complex problem caused by many factors. Normally, hearing ability will degrade with the advancing of age even without exposure to noise. The hearing ability of a person can be represented as the hearing threshold level (HTL). The part of the HTL due to aging can be termed the HTL associated with age (HTLA). However, noise exposure will also affect the HTL, resulting in a shift toward poorer hearing. This part of the HTL can be termed the noise-induced permanent threshold shift (NIPTS). Hence, when evaluating the hearing loss based on the actual HTL caused by all effects, the shift due to noise exposure as well as any shift due to age should be considered.

Different persons will generally have different actual HTLs even when they are at the same age and have the same noise exposures. For a specific population, the HTLs will show a variation and a range of values. Hence, the best way to describe the hearing loss is to calculate the HTL for a certain population percentage. Different population percentages will have different HTLs. In other words, we can only statistically estimate a person's HTL. A detailed statistical model for this purpose can be found in ISO 1999. In this paper, for simplification, only the calculation of the median value of HTL will be discussed theoretically. The calculations for other distribution percentages are based on the median value and will not be discussed here.

## Methods

As defined in ISO 1999, the median value of actual HTL can be expressed as

$$H'_{50}=H_{50}+N_{50}-\frac{H_{50}\times N_{50}}{120} \quad (1)$$

where $H_{50}{}'$ is the median value of actual HTL, $H_{50}$ is the median value of HTLA, and $N_{50}$ is the median value of NIPTS. The median value of HTLA, $H_{50}$, and the median value of NIPTS, $N_{50}$, can be calculated in the following manner:

### Hearing threshold level associated with age (HTLA)

ISO 7029 provides a formula for calculating hearing threshold level as a function of age for the various ranges of percentages. As defined in ISO 7029, the median value of hearing threshold level can be calculated using:

$$H_{50,Y}=\alpha(Y-18)^2+H_{50,18} \quad (2)$$

where α is a parameter depending on sex and sound frequency, and $Y$ is the age. The value can be found in ISO 7029. $H_{50,\,18}$ is the median value of the hearing threshold at the age of 18, which can be set to zero for practical use.

### Noise-induced permanent hearing threshold shift (NIPTS)

The calculation of NIPTS is defined in ISO 1999. For exposure durations between 10 and 40 years, the median value of NIPTS, $N_{50}$, can be calculated by:

$$N_{50}=\left[u+v\lg(\frac{t}{t0})\right]\left(L_{EX,8h}-L_0\right)^2 \quad (3)$$

where lg($t/t_0$) is the logarithmic function of $t/t_0$, $L_{EX,\,8h}$ is the noise exposure level normalized to an eight-hour working day, $L_0$ is the sound pressure level defined as a function of frequency below which the effect on hearing is negligible, $t$ is the exposure duration in years, $t_0$ is 1 year, and $u$ and $v$ are frequency-dependent parameters of the statistical hearing loss model that can be found in ISO 1999. Note that in cases where $L_{EX,8h}$ is *less* than $L_0$, it is set to $L_0$. Hence, in these cases, $N_{50}$ is zero. Furthermore, the $N_{50}$ value for exposure duration less than 10 years can be extrapolated from the value of $N_{50}$ for 10-year exposure duration using:

$$N_{50,t<10}=\frac{\lg(t+1)}{\lg(11)}N_{50,t=10} \quad (4)$$

### Consideration of changes of exposure level

For a number of reasons, a miner's noise exposure may change over time. There may be relevant changes to the machine or the worker's job assignment, or the worker may change careers. In this situation, the effects of the different exposure levels over time must be considered. However, this situation is not considered in the ISO 1999 standard. In this paper, three different strategies that can be used to consider the transition of exposure levels will be discussed:

**NIPTS-based strategy—**The first strategy, the NIPTS-based strategy, considers each current exposure as a new start from year 0 but based on the resultant NIPTS value at the end of the previous exposure, ${N_{50}}^{n-1}$, as the bias value. The median value of the NIPTS of current exposure, ${N_{50}}^{n}$, can be expressed:

$$N_{50}^{n}=\left[u+v\lg(\frac{t}{t_0})\right]\left(L_{EX,8h}-L_0\right)^2+N_{50}^{n-1} \quad (5)$$

Equation (5) is a revision of Eq. (3) where the second term on the right-hand side of the equation is equal to zero. Hence, when multiple exposures are considered, Eq. (3) is used for the first exposure, and Eq. (5) is used for the following exposures.

Figure 1 shows an example using this strategy. In this case, two noise exposures were assumed. For this discussion, a miner is employed from time 0 to $t_1$, during which he is exposed to 90 dB(A) of noise. At time $t_1$ he is reassigned to a new job where he is exposed to 100 dB(A) of noise. For the first exposure, the duration is $t_1$ years and the equivalent daily exposure level is 90 dB(A). The duration of the second exposure is $t_2$ years. The equivalent daily exposure level is 100 dB(A). The median values of NIPTS of the two different exposure levels are represented by the black curves. (Note that they all start at zero.) The first segment of the first exposure is shown by the red curve from year 0 to year $t_1$. This segment represents the NIPTS for 90 dB(A) exposure and $t_1$ duration from Eq. (3). The first segment of the second exposure is shown by the red dashed curve from year 0 to year $t_2$. This segment represents the NIPTS for 100 dB(A) exposure and $t_2$ duration from Eq. (3). The final estimated median value of the NIPTS for this particular case is shown as a red solid curve from year 0 to year $t_1 + t_2$, which is composed of two segments. The first segment is the first $t_1$ years of the NIPTS of 90 dB(A) exposure level. The second segment is the first $t_2$ years of NIPTS of 100 dB(A) exposure level. Figure 1 shows the red dashed curve, which is the first $t_2$ years of NIPTS of 100 dB(A) exposure level, moved to the position labeled by the arrow lines to become the final NIPTS of the second exposure.

**Change-based strategy—**In the second strategy, called the change-based strategy, the NIPTS values for different exposure levels are calculated starting at year 0 up to the maximum exposure time in the analysis, and the estimated result is then amended using the change of NIPTS value due to the different exposure levels. Similar to the first strategy, the median value of the NIPTS of current exposure, ${N_{50}}^{n}$, can be expressed as:

$$N_{50}^{n}=\left[u+v\lg(\frac{t}{t_0})\right]\left(L_{EX,8h}-L_0\right)^2-\delta_{50}^{n} \quad (6)$$

where the second term on the right-hand side of the equation is the bias value that represents the difference between the NIPTS of the previous exposure level and the NIPTS of the current exposure level at the starting time of the current exposure level.

An example using this strategy is shown in Fig. 2. As in the above case, two noise exposures were assumed. For the first exposure, the duration is $t_1$ years and the equivalent daily exposure level is 90 dB(A). The duration of the second exposure is $t_2$ years. The equivalent daily exposure level is 100 dB(A). The median values of NIPTS of the two different exposure levels are represented by the black curves, and the final estimated median value of the NIPTS for this particular case is shown as a thick red solid curve from year 0 to year $t_1+t_2$ , which is composed of two segments. As in the above case, the first segment is the first $t_1$ years of the NIPTS of 90 dB(A) exposure level. However, the second segment is no longer the first $t_2$ years of the NIPTS of 100 dB(A) exposure level but is actually the biased version of the NIPTS for 100 dB(A) exposure level from year $t_1$ to year $t_1 + t_2$, shown as a red dashed curve. The second segment of the red solid curve is the red dashed curve moved down by the amount indicated by the arrow lines to represent the median value of NIPTS of the second exposure. The bias is the difference between the NIPTSs of 90 dB(A) and 100 dB(A) exposure levels at year $t_1$.

**Equivalent value strategy—**The third strategy is called the equivalent value strategy. This strategy determines the equivalent exposure year, $t_e$, of the new exposure level for the same NIPTS resulting from the previous exposure. The equivalent exposure year, $t_e$, is given by:

$$t_e=t_0\cdot 10^{\frac{1}{v}\left[\frac{N_{50}^{n-1}}{\left(L_{EX,8h}-L_0\right)^2}-u\right]} \quad (7)$$

The actual NIPTSs will copy the NIPTSs of the new exposure starting from the equivalent year, $t_e$, instead of starting from year 0 as in the first strategy or year $t_1$ as in the second strategy. An example using this strategy is shown in Fig. 3. As in the first two cases, two noise exposures were assumed. The first exposure is 90 dB(A) with duration of $t_1$ years. The second exposure is 100 dB(A) with duration of $t_2$ years. The median values of NIPTS of the two different exposure levels are represented by the black curves, and the final estimated result for this particular case is shown as a thick red solid curve from year 0 to year $t_1 + t_2$, which is composed of two segments. As in the above case, the first segment is the first $t_1$ years of the NIPTS of 90 dB(A) exposure level. The second segment of the red solid curve is the red dashed curve moved from exposure time $t_e$ to the time $t_1$, which is the end of the first exposure and start of the second exposure. (Note that the NIPTS of the first exposure level at time $t_1$ is the same as that of the second exposure at time $t_e$.)

## Demonstration and discussions

Four different types of analyses can be performed in the developed software: (1) computing hearing loss based on assignment, (2) evaluating the effectiveness of the control, (3 predicting future damage based on measured HTL, and (4) correlation between actual test and prediction. The user can pick any one task to perform from the above choices. For each analysis, the software will instruct the user to input the parameters, then calculate and show the results accordingly.

### Computing hearing loss based on work assignment

**Input parameter settings—**The first analysis can estimate the hearing loss based on the exposure histories of the work assignments. In this analysis, the user can add multiple "tasks" into the analysis. Each task contains a particular career course that is the work assignments for the worker with the corresponding exposure levels. Hence, the user can compare the results among many tasks. For each task, as shown in Fig. 4, the user can insert, modify or delete a work assignment in the table by clicking the "Insert," "Edit" or "Delete" button for a specific worker. The worker's sex can also be set on this page. For each work assignment, four parameters — start age, end age, job and daily exposure level — are entered. The user can add any number of assignments throughout a worker's career, which is set as starting at age 18 and ending at age 60 as the default. Hence, the start age of the first exposure cannot be less than 18 and the end age of the last exposure cannot be greater than 60. The user can also set the job and corresponding exposure level for that specific exposure. For example, in this case, the work assignment is the operator of the longwall machine. The default noise exposure is set at 95 dB(A). A collection of jobs with the corresponding default exposure levels has been stored in a job profile, which can also be created by the user. Once the job profile is ready, the user can select a particular job for the exposure assessment from the created job profile database.

**Results display—**Three different displays can be shown in the software: (1) HTL versus hearing impairment risk, (2) HTL versus age, and (3) hearing impairment risk versus age. These displays are shown in Figs. 5a-5c. Note that the values of HTL are actually the average over several critical frequencies. According to ISO 1999, there are nine different average options (International Organization for Standardization, 1990). In Figs. 5a and 5b, the horizontal line represents the fence value. The fence value is used to identify the hearing impairment. Once the HTL value exceeds the fence value, the hearing impairment will be identified. In the software, this value is set at 25 dB as the default. However, this fence value can be user-defined. The risk of hearing impairment can be obtained using the results shown in Fig. 5a by locating the intersection points. The risk analysis result for a particular age is shown as a percentage at the lower right corner of the screen. Changing the age and average option can change the result. From Fig. 5b, one can see the relation between HTL and age for different distributions. Figure 5c shows that the hearing impairment risk increases as age increase.

**Guidance for reducing the risk of hearing loss—**Normally, a company will change a worker's work assignment if the worker experiences excessive hearing loss based on his or her Leq (equivalent continuous sound level), dose or other noise exposure and hearing test results. However, it is unclear how the noise exposure of a new assignment will affect the worker's hearing loss, which may be the concern of the company and worker. This analysis can be an analysis of changing work assignments based on predicted hearing threshold level. Assuming that in the worker's original plan of work assignment, the worker will be the operator of a continuous miner from age 20 to age 60. The exposure level for the operator of a continuous miner is about 102 dB(A) without any hearing protection. Through a hearing test at age 25 and performing the analysis, the worker is expected to experience about 12 dB of hearing loss after five years of noise exposure as a continuous miner operator, as shown by the red curve in Fig. 6, and the hearing loss is projected to reach 25 dB, defined as hearing impairment, at the age of 39. Hence, the supervisor decides to change the worker's job duty to a new one where the noise exposure level is 90 dB(A). The problem now is whether this level of noise exposure is low enough to protect the worker's hearing. The estimated results from this analysis, shown by the black curve in Fig. 6, tell us that the hearing loss will be greatly reduced. The hearing loss would be 25 dB at age 39 if the work assignment isn't changed. With the change in work assignement, the hearing loss will be only 15 dB at age 39 and will not reach 25 dB until the age of 60.

## Evaluating the effectiveness of the control

**Input parameter settings—**Another use of this tool is to analyze the effectiveness of noise controls in reducing hearing loss. There are only two ways to objectively relate the impact in terms of hearing loss changes with the implementation of controls that make a finite reduction in noise emission:

- Conduct a long-term — lasting at least 10 years — audiological study of a statistically significant-sized group of miners where noise controls are and are not applied to compute the difference in hearing loss.
- Use this tool to estimate the impact of the noise control on predicted hearing loss.

Using this software to express the effectiveness of noise controls in terms of the risk of hearing impairment caused by noise exposures can give a better index of the effectiveness of the control. In this case, unlike the earlier case, the system will not only ask for the exposure history but also the noise levels of future job assignments for comparison to the baseline exposure and after applying the noise control, as shown in Fig. 7. The lower table on the screen asks the user to input the parameters of the future exposure, the baseline exposure, and the exposure after applying noise controls. In this case, the worker works as a roof bolting machine operator from year 20 to year 30 and as the operator of a longwall machine from year 30 onward. In this example, we assume that the noise control can reduce the exposure level from 95 dB to 90 dB with a 5-dB reduction.

**Results display—**These results can also be displayed in three different ways as in Figs. 5a-5c for the previous analysis. Because the first and third types of displays — HTL versus risk, and risk versus age — are the same as in Figs. 5a and 5c, they will not be discussed in detail again here. On the other hand, the second type of results display, HTL versus age, is slightly different from that of the earlier analysis. As shown in Fig. 8, this result can be a bounded result describing the entire ranges of responses for subjects. This option can help users understand the effectiveness of noise controls for different distributions of hearing ability and susceptibility to hearing loss. The red curve is baseline exposure, and the black curve is exposure with the noise control treatment applied. The difference in estimated hearing loss between baseline exposure and exposure with the noise control treatment applied can be clearly seen after age 30. This is because we assume that two different exposures happen after age 30 of the worker.

## Predicting future damage based on the measured HTLs

**Input parameter settings—**In some cases, previous exposures are unknown, but if measured HTLs are available, it is still possible to predict the future hearing impairment. The third type of analysis is capable of performing such a task. For this analysis, the input parameters include the previously measured HTLs, as shown in Fig. 9. Only the data at frequencies 500 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz and 6 kHz are required for the analysis because the hearing impairment determination is based on the values at these frequencies. In this case, the analysis is similar to that for the case used to evaluate the effectiveness of noise controls.

**Results display—**Again, because the first and third type of results displays for this analysis are very similar to those of the first analysis, which were discussed in detail, only the difference in the second type of display will be discussed here. As shown in Fig. 10, the measured data are plotted with rectangular markers. The dotted red curve is the results estimated from the measured data. The prediction — represented by the solid red curve for baseline exposure and solid black curve for exposure after the noise treatment is applied — of the future HTL begins at year 33 in this case because the exposure begins at year 33 as shown in Fig. 9.

## Correlation between actual test and prediction

**Input parameter settings—**The fourth analysis is to perform a correlation study between actual HTLs from the test and the predicted results based on exposure histories. The input page is shown in Fig. 11. There should be multiple data sets of the measured HTLs at different ages. Also, the exposure data are needed for this analysis. Based on the exposure data, the predicted results of the hearing loss can be calculated for different statistical distributions of hearing ability. This analysis will give the difference between the measured hearing test results and the predicted results in terms of the standard deviation. Also, it will give the best match of the percentage of distribution that yields the least standard deviation.

**Results display—**Only the second type of display, HTL versus age, for the results of this analysis will be discussed here, because the other two types of displays are very similar to those of the first analysis. As shown in Fig. 12, the measured data are plotted with rectangular markers. The red curve represents the results estimated from the exposure data for the selected percentage of distribution. The error between the measured data and the prediction is presented as the standard deviation and shown in the center top area of the figure.

## Conclusion

A detailed procedure based on ISO 1999 and ISO 7029 to estimate hearing threshold level due to age and noise exposure is presented. Three special strategies — the NIPTS-based strategy, change-based strategy and equivalent value strategy — were proposed to address the transition of different exposures occurring over the course of a worker's career. Three strategies for the calculation of NIPTS were implemented using Visual Basic programming language (Microsoft Corp., Redmond, WA), and the software was demonstrated using noise data from mining machines. The program is capable of estimating the risk of hearing impairment due to occupational noise exposure. Furthermore, the program is a tool to connect the engineering noise control approach to estimated hearing loss in a systematic way, providing guidance for operators to reduce the risk of hearing loss through changing work assignments. This software is expected to be released as a NIOSH product in the coming months and will then be available for use by the general public.

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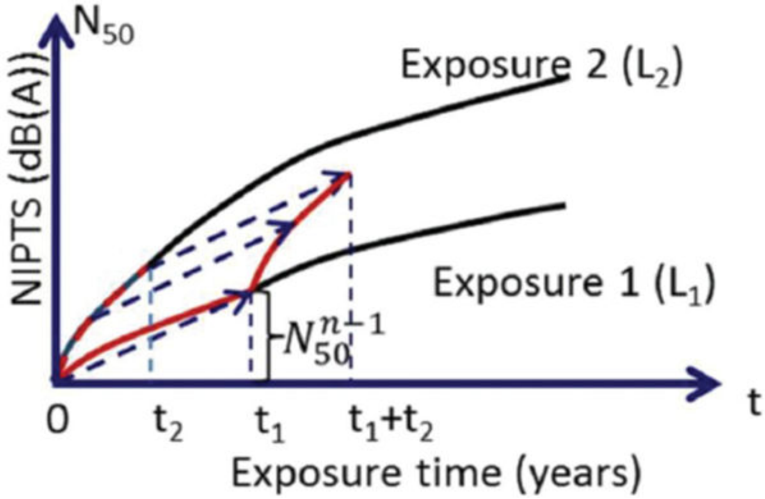


**Figure 1.**
NIPTS-based strategy for exposure change.

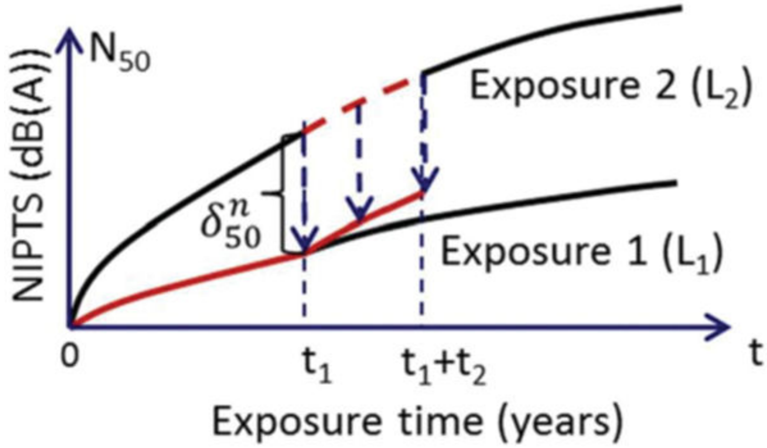


**Figure 2.**
Change-based strategy for exposure change.

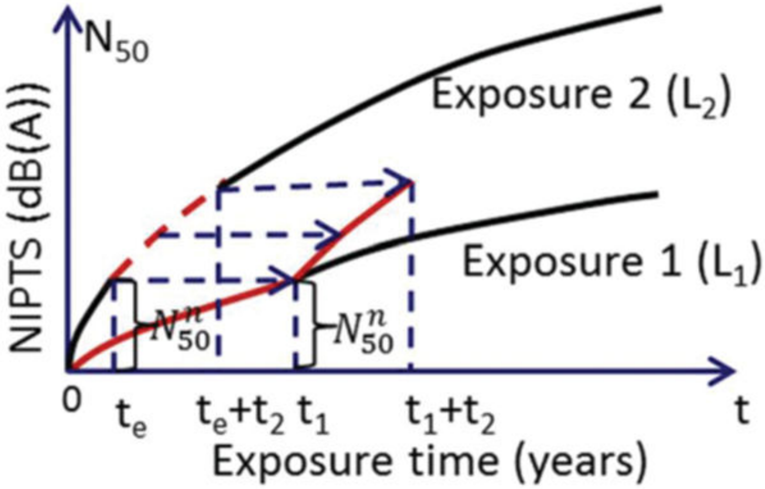


**Figure 3.**

Equivalent value strategy for exposure change.

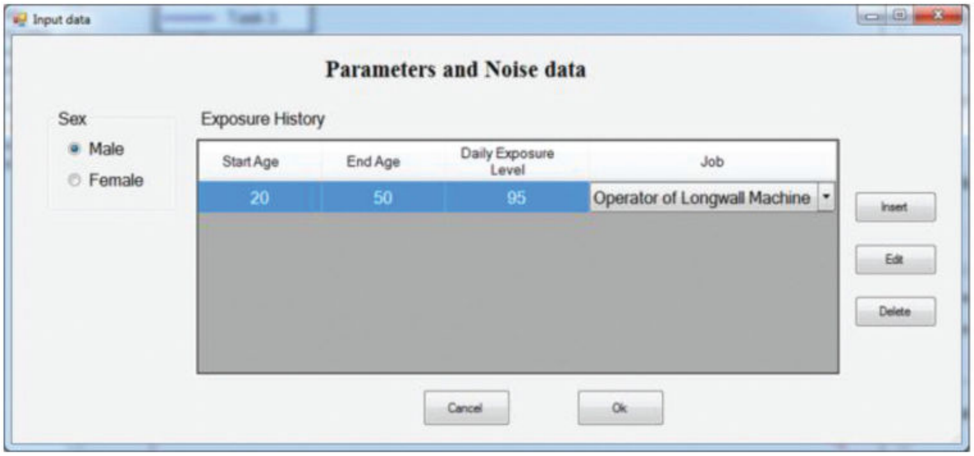


**Figure 4.**
Input parameters for the first type of analysis.

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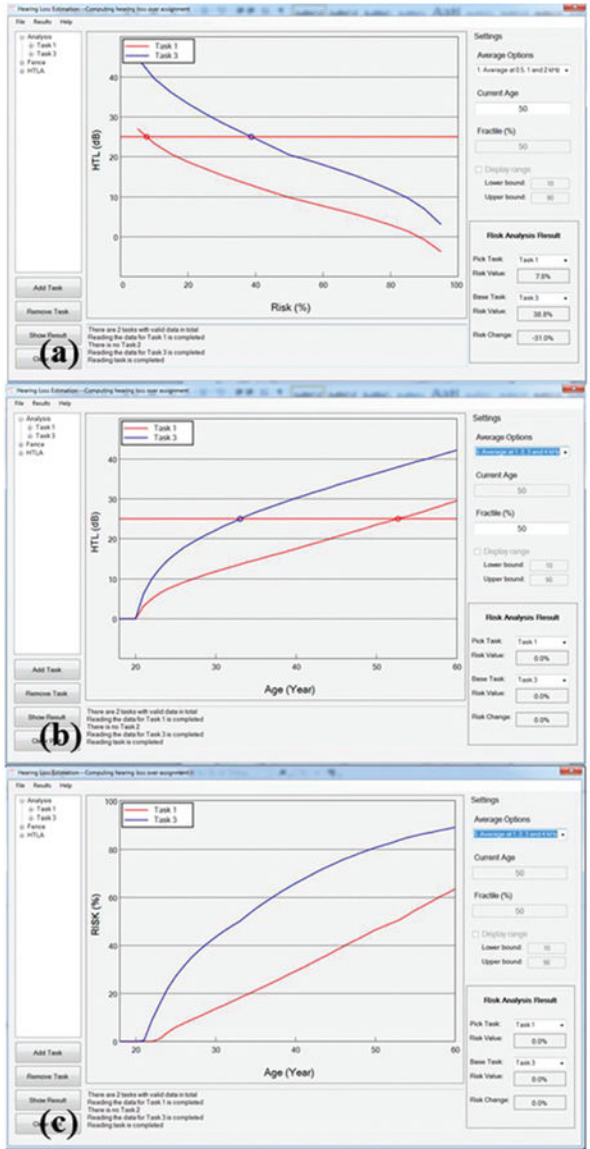


**Figure 5.**

Three different displays of the analysis results: (1) HTL versus hearing impairment risk, (2) HTL versus age, and (3) hearing impairment risk versus age.

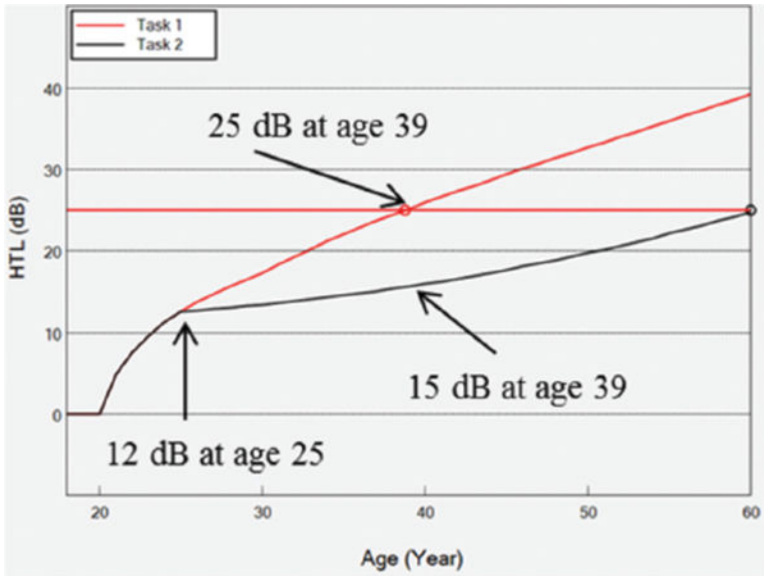


**Figure 6.**
Work assignment comparison through risk analysis. (red curve = original work assignment, black curve = revised work assignment.)

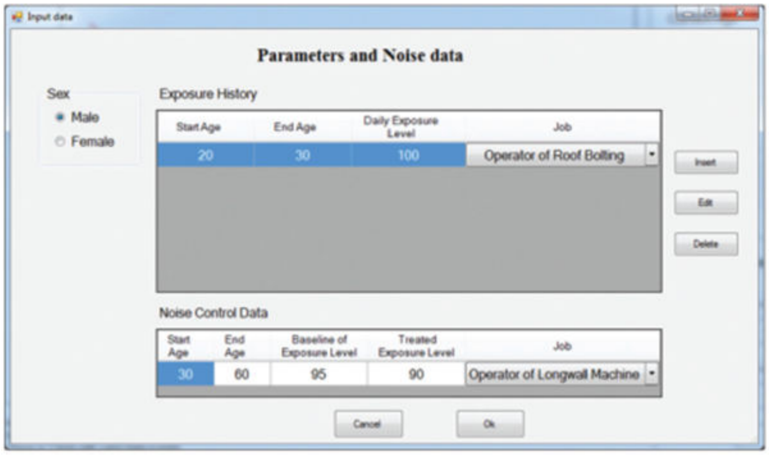


**Figure 7.**

Input parameters for the second type of analysis.

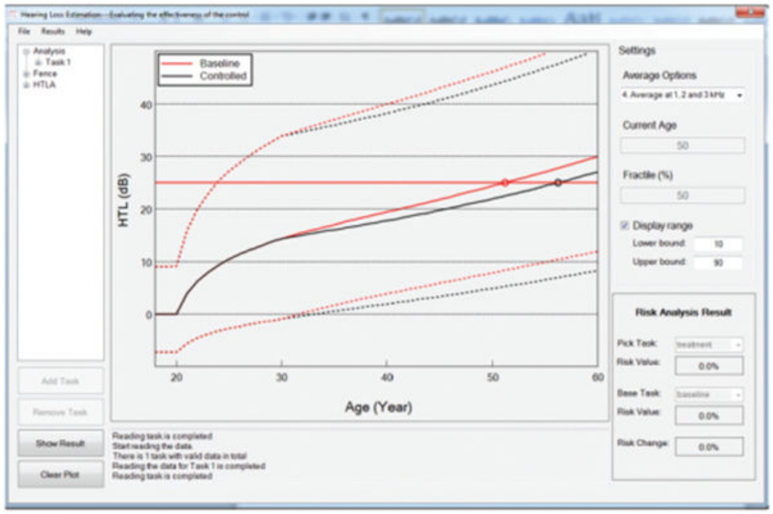


**Figure 8.**
HTL versus age for the second type of analysis.

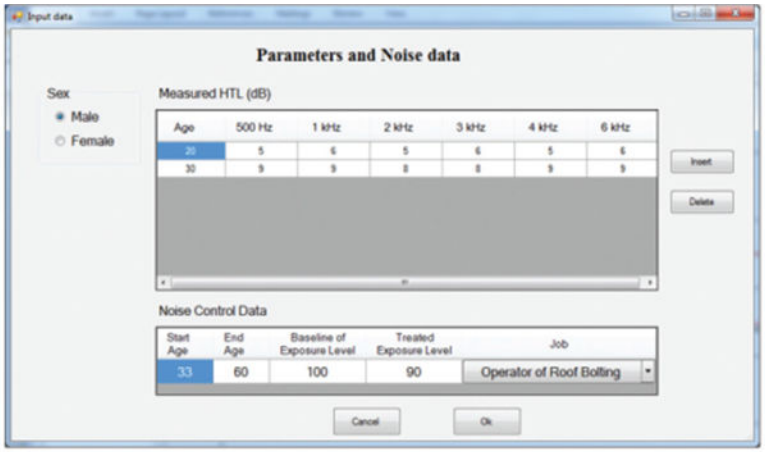


**Figure 9.**
Input parameters for the third type of analysis.

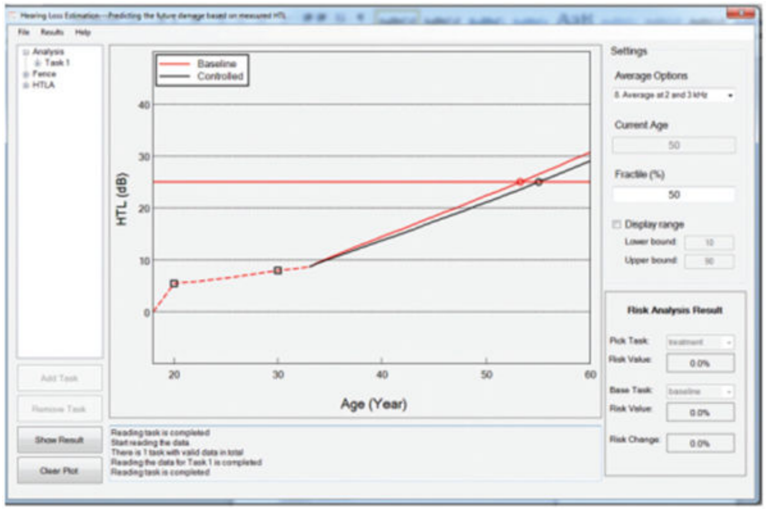


**Figure 10.**

HTL versus age for the third type of analysis.

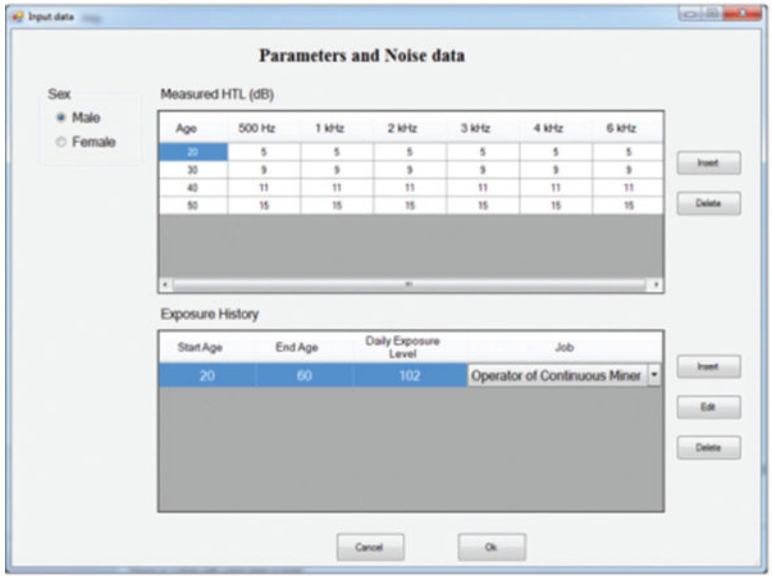


**Figure 11.**

Input parameters for the fourth type of analysis.

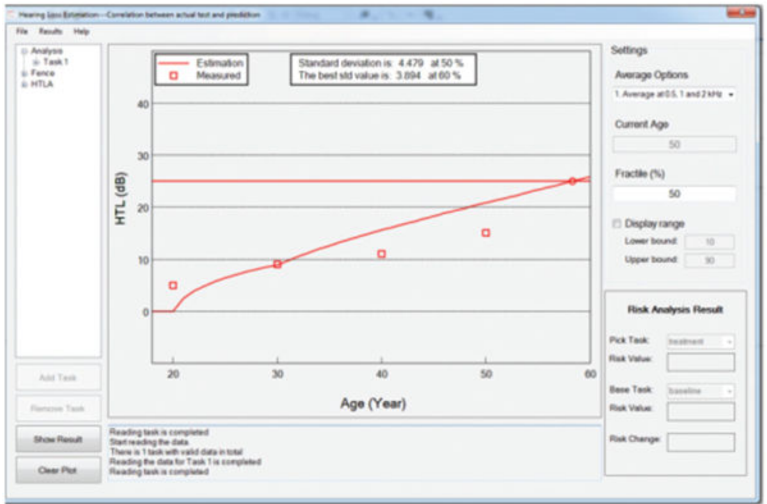


**Figure 12.**
HTL versus age for the fourth type of analysis.