CHAPTER 30

# Noise Exposure and Control

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## 30.1 INTRODUCTION

For centuries, the ill effects of noise exposure in the workplace have been recognized as a principal cause of hearing loss. Evidence of hearing impairment in workers involved in, for example, blacksmithing and mining, has been documented in the Middle Ages (Berger, 2000) and cited in the medical literature of the nineteenth century (Fosboke, 1831). The problem of occupational hearing loss has been recognized as one of the most common work-related diseases in the United States. In 1998, the National Institute for Occupational Safety and Health (NIOSH) estimated approximately 5 million workers had daily time-weighted average (TWA) exposures in excess of 85 dBA (NIOSH, 1998). More recent estimates place this figure at 24 million workers based upon the National Health and Nutrition Examination Survey data (Tak et al., 2009). Using the National Occupational Exposure Health Survey data (NIOSH, 1988) as well as reports issued by the Booz-Allen Hamilton (1983) and the Bolt et al. (1976), Franks (1988) estimated that 95% of daily TWA exposures were less than 95 dBA. Although the TWA exposures represent an average over a day and are not necessarily indicative of instantaneous noise levels, such a statistic suggests that noise exposures can be reduced to a safe level.

In the 1970s, the U.S. Environmental Protection Agency (EPA) published the “levels” document (EPA, 1978), wherein they concluded that the safe level of exposure representing 1% risk of incurring a significant threshold shift was 70 dBA for 8 h a day for 40 years. The U.S. Occupational Safety and Health Administration (OSHA) concluded from a similar risk analysis that 20% of workers would incur a significant change in hearing at an exposure of 90 dBA for 8 h per day for 40 years. NIOSH conducted two separate analyses of the excess risk of material hearing impairment for an 8 h exposure per day for 40 years. The earlier analysis (NIOSH, 1972) suggested that 85 dBA represented a 15% risk. Later, this estimate was revised to 17% (Prince et al., 1997; NIOSH, 1998). NIOSH’s earlier recommendation for a criterion for noise exposure was modified from 85 dBA with a 5 dB exchange rate to 85 dBA with a 3 dB exchange rate. Currently the OSHA regulation enforces a 90 dBA PEL and a 5 dB exchange rate. The exchange rate dictates the trading relationship between exposure time and level, for example, 90 dBA for 8 h, 95 dBA for 4 h, 100 dB for 2 h.

The problem of occupational hearing loss is multifaceted. Hearing loss is often identified through an employer's audiometric monitoring but can be caused by both occupational and recreational exposures. Noise-induced hearing loss (NIHL) may result from a single intense exposure or from prolonged exposure to lower levels of sound. Noise may be continuous and vary little with respect to time, or it may be intermittent and have large fluctuations in the instantaneous level. Exposure to intermittent and fluctuating noise may present a greater risk of producing hearing loss than the same equivalent levels of continuous noise (Dunn et al., 1991). Occupational hearing loss may also result from exposure to ototoxic chemicals, heavy metal contaminants, asphyxiants such as carbon monoxide, heat, and other physical or chemical agents (Morata, 2003; Sliwinska-Kowalska et al., 2007; Johnson and Morata, 2010).

Extensive research conducted during the last several decades has considerably enhanced our knowledge about noise-induced damage mechanisms of the inner ear. Efficient engineering and administrative control measures for reducing the noise exposure have been developed and widely implemented in industry. Various personal hearing protection devices (HPDs) are now available. Hearing conservation programs have been implemented widely in many countries, including a NIOSH-defined "hearing loss prevention program" in the United States (NIOSH, 1998), a "noise management program" in Australia, and others. Sophisticated sound monitoring devices such as sound level meters (SLMs) and sound dosimeters are at our disposal and are extensively used in occupational environments as critical tools for determining the workers' noise exposure.

The first part of this chapter introduces the fundamentals of sound propagation, description, and measurement. Subsequently, exposure- and health-related issues are discussed following by the determination of the allowable dose. The OSHA standard is described, including the elements of a hearing loss prevention program. Functional descriptions of the auditory system, measurement equipment, and noise control techniques are also provided.

## 30.2 FUNDAMENTALS

### 30.2.1 Generation and Propagation of Sound

Sound is a disturbance in an elastic medium that propagates through the medium at a speed that is a characteristic of the medium. The speed of sound in air at 20°C and 1 atm is approximately 343.1 m/s. Sound in air can be generated by vibration or impact of bodies, unsteady motion of air, or interaction of flow and structures. Sound pressure is measured as the variation relative to the static atmospheric pressure at sea level, $1.013 \times 10^5$ Pa (N/m$^2$). Sound pressures are generally much smaller than the static atmospheric pressure. For example, the sound pressure of 100 dB noise is only 0.002% of the atmospheric pressure.

Figure 30.1 illustrates how sound propagates in a one-dimensional (1D) duct of infinite length. The speaker attached to the left end of the duct induces a rarefaction or compression of air, which propagates along the duct with the speed of sound. Figure 30.1 can be considered as a snapshot of the pressure in the duct in a grayscale map (top) and by a transverse wave (bottom). Darker and lighter areas, respectively, represent compression and rarefaction. The pressure field is often depicted as a transverse wave because it is easier to show. Wavelength is the distance between the points of same pressure of adjacent cycles.

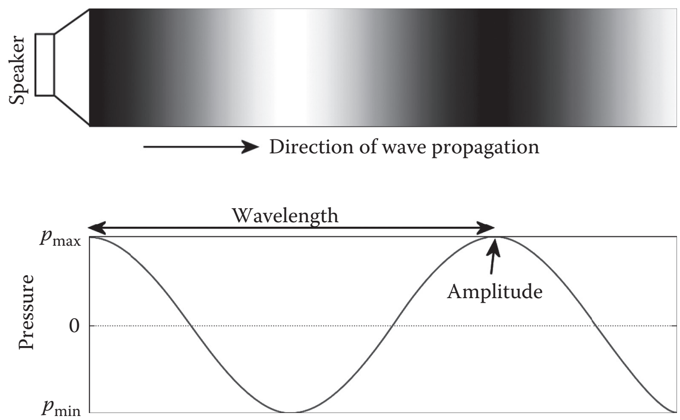


FIGURE 30.1 Sound propagation in a lossless 1D semi-infinite duct. Sound generated by the speaker at left travels to right. The degree of darkness (shown on the top figure) as well as the deviation from the background pressure (shown relative to $p = 0$ on the bottom figure) is proportional to the sound pressure. Wavelength is the distance between two adjacent points of the same magnitude of pressure.

While the wave shown in Figure 30.1 travels at the speed of sound, the sound pressure measured at any given point changes as a function of time. Figure 30.2 demonstrates how the pressure at point A in Figure 30.1 changes with the time. The frequency $f$, wavelength $\lambda$, and speed of sound $c$ are related as follows:

$$\lambda = \frac{c}{f} \tag{30.1}$$

The speed of sound in a gas is expressed as

$$c = \sqrt{\gamma RT} \tag{30.2}$$

where
- $\gamma$ is the ratio of specific heats
- $R$ is the ideal gas constant
- $T$ is the absolute temperature (K)

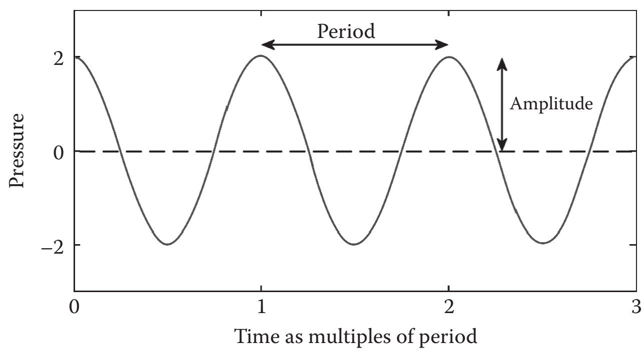


FIGURE 30.2 Variation of sound pressure as a function of time measured at a single point for the speaker operating in the duct at a single frequency.

Through substituting variables with numerical data as follows, $\gamma = 1.4$, $R = 287$ N-m/(kg-K), and $T = 293$ °K, the speed of sound in air under the standard atmospheric conditions is calculated as $c = 343.1$ m/s (or 1130 ft/s).

To calculate the speed of sound in air at different temperatures, the following approximations can be adopted (in metric and English systems, respectively):

$$c = 331.5 + 0.58 \cdot (T, °\text{C})\ (\text{m/s}) \tag{30.2a}$$

$$c = 1054 + 1.07 \cdot (T, °\text{F})\ (\text{ft/s}) \tag{30.2b}$$

For example, according to this approximation, at 40°C (313 °K, or 104°F), $c$ = 354.7 m/s = 1165.3 ft/s.

In media of higher density, such as liquids and solids, the speed of sound is much higher, for example, approximately 1500 m/s in water, 4000 m/s in solid oak wood, and >5000 m/s in steel.

Using the speed of sound in air, the wavelength of sound wave of a specific frequency can be calculated.

Sample calculation 1:

Question: The frequency range of human hearing varies from one individual to another. The typically referred frequency range is $f$ = 20–20,000 Hz. What is the corresponding wavelength range under the standard atmospheric conditions?

Answer: According to Equation 30.1, the shortest wavelength corresponds to the highest frequency so that

$$\lambda = \frac{c}{f} = \frac{343.1\,\text{m/s}}{20{,}000\,\text{Hz}} \approx 0.0172\,\text{m} \approx 1.72\,\text{cm}$$

The longest one corresponding to the lowest frequency is

$$\lambda = \frac{c}{f} = \frac{343.2\,\text{m/s}}{20\,\text{Hz}} \approx 17.16\,\text{m}$$

In addition to the frequency, the amplitude of sound pressure (Figure 30.2) is a key characteristic representing the acoustic output. However, the maximum value of the oscillating quantity is generally not a good measure of its significance (except for a transient impulsive sound). An average value of sound pressure is zero, which itself is a useless quantitative characteristic of the sound source. An alternative—and useful—descriptor of the effective sound pressure is the root-mean-square (rms) value of the time-varying sound pressure. It is defined as a time-averaged magnitude of the pressure:

$$p_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T p^2(t)\,dt} \tag{30.3}$$

The sound power ($W$) of a source is the acoustic energy generated and propagated per second by the source. This quantity is a constant unless some attribute of the source is changed. The sound power is measured in watts (W).

The sound intensity ($I$) is defined as the time-averaged rate of energy transmission flowing through a surface of unit area:

$$I = \frac{1}{T}\int_0^T pu\,dt \tag{30.4}$$

where
$p$ is the instantaneous pressure
$u$ is the particle velocity normal to the unit surface

If the direction of the outward normal of a surface and the direction of the intensity flowing through that surface are the same, then the intensity is positive. If they are oppositely directed, then the intensity is negative. The sound intensity is measured in $W/m^2$.

For a point source operating in a free field (i.e., sound travels only in one direction without reflected waves), the intensity and rms pressure are related as follows:

$$I = \frac{p_{rms}^2}{\rho c} \tag{30.5}$$

where $\rho$ is the density of air. Assuming omnidirectional wave propagation, the sound intensity at a distance $r$ from the source relates to the sound power as follows:

$$I = \frac{W}{4\pi r^2} \tag{30.6}$$

In a typical noise environment, sources have directional properties and there are reflections. To consider these effects, Equation 30.6 is modified as follows:

$$I = \frac{WQ}{4\pi r^2} \tag{30.7}$$

where $Q$ is the directivity factor which is dependent on the source property as well as reflections from surfaces. If the acoustic wave from a point source located in free space propagates omnidirectionally, the radiation pattern is spatially uniform and $Q = 1$ (denoted as spherical radiation). If an ideal sound source is located on a floor in the center of a large room or at ground level outdoor, $Q = 2$ (hemispherical radiation). In this case the sound intensity at distance $r$ would be twice as great as that for spherical radiation because the surface area, over which the sound is spread, is reduced by a factor of 2. If the sound source is located at the intersection of the floor and a room wall, the radiation area is one-quarter of a sphere and $Q = 4$, reflecting that the spherical area is reduced by a factor of 4.

If the source is placed on the floor in a corner at an intersection of two walls, then $Q = 8$. In addition to the sound source location, directivity is influenced by the directional characteristics of the source itself.

### 30.2.2 Levels in Decibel: Sound Intensity, Power, and Pressure

In acoustics, most quantities are expressed in decibels (dB). The decibel is a logarithmic unit of measurement that expresses the magnitude of a physical quantity A (e.g., power or intensity) relative to a specified or implied reference level $A_0$:

$$L = 10 \cdot \log_{10} \frac{A}{A_0} \tag{30.8}$$

Since it expresses a ratio of two quantities with the same unit, it is a dimensionless characteristic.

The acoustic intensity can be expressed as a level above or below reference intensity:

$$L_I = 10 \cdot \log_{10} \frac{I}{I_0} \tag{30.9}$$

where
- $L_I$ is the sound intensity level in dB
- $I$ is the sound intensity in W/m$^2$
- $I_0$ = 10–12 W/m$^2$ is the reference intensity

For example, the intensity of 1 W/m$^2$, based on Equation 30.9, corresponds to the intensity level of 120 dB, which represents relatively loud industrial noise. According to the definition, Equation 30.8, every increase in sound intensity by a factor of 10 results in an increase of 10 dB in the intensity level.

The sound power level is defined in a similar way as

$$L_W = 10 \cdot \log_{10} \frac{W}{W_0} \tag{30.10}$$

where
- $W$ is the sound power in W
- $W_0$ = 10–12 W is the reference power

The sound pressure level (SPL) is derived from the intensity of a plane wave (Equation 30.5) where the pressure is substituted for intensity and reference pressure is approximated as 20 μPa ($2 \times 10^{-5}$ N/m$^2$). The resulting equation for SPL is

$$L_p = 10 \cdot \log_{10} \left( \frac{p_{\text{rms}}}{p_0} \right)^2 = 20 \cdot \log_{10} \left( \frac{p_{\text{rms}}}{p_0} \right) \tag{30.11}$$

Note that the multiplier here is 20 and not 10 as with the sound intensity and power. According to Equation 30.11, doubling the sound pressure increases the SPL by 6 dB. The sound pressure increase by a factor of 10 results in a 20 dB increase of SPL.

The following examples are worth noticing: the sound pressure of $p = 1$ Pa corresponds to SPL = 94 dB; for $p = 1$ lb/ft$^2$, SPL = 128 dB; for $p = 1$ lb/in.$^2$, SPL = 171 dB; and for $p = 1$ atm, SPL = 194 dB.

The decibel scale is convenient for expressing sound intensity, power, and pressure over a very wide range. For example, exposures to noise ranging from 0 dB (below the threshold of a healthy human ear) to 140 dB (maximum impact noise allowable by OSHA) correspond to sound pressures covering seven decades: from 20 μPa to 200 Pa.

### 30.2.3 Decibel Multiplications

Decibel addition and subtraction is used when several independent and uncorrelated sound sources are considered. Examples of addition are (a) the estimation of the total SPL produced by several machines and (b) the estimation of the total SPL from a multifrequency source by adding frequency-band SPLs. Subtraction may be used to correct for the background noise that contaminates the field measurement. The equation for the total sound levels produced by $n$ random, uncorrelated independent sounds is

$$L_{\text{Total}} = 10 \cdot \log_{10}\left(10^{L_1/10} + 10^{L_2/10} + 10^{L_3/10} + \cdots + 10^{L_n/10}\right) \tag{30.12}$$

Sample calculation 2:

Question: Each of two machines produces SPL of 93 dB at the measuring location. What is SPL measured at this location if both machines are turned on?

Answer: According to Equation 30.10,

$$L_p = 10 \cdot \log_{10}(2 \times 10^{9.3}) \approx 96\,\text{dB}$$

that is, adding the second machine increased the pressure level only by 3 dB.

Sample calculation 3:

Question: Two different machines produce considerably different SPLs at the measuring location: 110 and 90 dB. What is SPL measured at this location if both machines are turned on?

Answer: According to Equation 30.12,

$$L_p = 10 \cdot \log_{10}(10^{11} + 10^{9}) \approx 110.04\,\text{dB} \approx 110\,\text{dB}$$

The example mentioned earlier shows that if two machines produce SPLs of significantly different level, their combined SPL is approximately equal to the higher SPL of the two. In other words, the lower one has little effect on the total (but increases in relative significance if the higher SPL source is quieted). Commonly one finds that changes in level of less than

TABLE 30.1 Combining Levels of Uncorrelated Sounds

| Numerical Difference between $SPL_1$ and $SPL_2$ (dB) | Amount to Be Added to the Higher SPL (dB) |
|---|---|
| 0.0–0.6 | 3.0 |
| 0.7–1.6 | 2.5 |
| 1.7–3.1 | 2.0 |
| 3.2–4.7 | 1.5 |
| 4.8–7.2 | 1.0 |
| 7.3–13.9 | 0.5 |
| >13.0 | 0.0 |

0.1 dB are insignificant. In addition to Equation 30.11, there is a "rule of thumb" for decibel addition, presented in Table 30.1.

### 30.2.4 Relationships between Sound Power and Sound Pressure Levels

In free-field environment, assuming propagation of a spherical wave of a specific frequency and no sound reflection, the following relationship exists between the sound power and pressure levels:

$$L_W = L_p + 10 \cdot \log_{10} r^2 + k - CF(T, P) \tag{30.13}$$

where

*r* is the distance from the source in meters or feet

*k* is a constant accounting for the unit system ($k = 11$ dB for metric units [with *r* expressed in meter], and $k = 0.5$ dB for English units [with *r* expressed in feet])

*CF* (*T*, *P*) is a correction factor, in decibels, accounting for atmospheric temperature and pressure

For most industrial noise situations involving steady-state sources, *CF* is negligible. Given that $L_W$ is constant for a given source, the SPLs measured in two locations from the source, SPL ($r_1$) and SPL ($r_2$), can be related as follows:

$$L_W = L_{p1} + 10 \cdot \log_{10} r_1^2 = L_{p2} + 10 \cdot \log_{10} r_2^2 \tag{30.14}$$

Equation 30.13 yields

$$L_{p2} = L_{p1} - 20 \cdot \log_{10}\left(\frac{r_2}{r_1}\right) \tag{30.15}$$

Equation 30.15 is known as the inverse-square law; it allows determining SPL at any distance ($r_2$) based on a single measurement performed at a specific distance ($r_1$). The equation produces an important "rule of thumb": each doubling of distance from the source results in a 6 dB loss of SPL.

Sample calculation 4:

Question: SPL = 100 dB is measured at 3 ft from the source. What is SPL measured at 12 ft from the source?

Answer: According to Equation 30.15,

$$L_{p2} = L_{p1} - 20 \cdot \log_{10}\left(\frac{12}{3}\right) \approx 100\,\text{dB} - 12\,\text{dB} = 88\,\text{dB}$$

Reflecting different conditions of the sound wave propagation, the directivity factor affects the relationship between sound power and pressure levels. Equation 30.13, derived from the omnidirectional propagation condition, can be modified to account for the directivity factor:

$$L_W = L_p + 10 \cdot \log_{10}\left(\frac{r^2}{Q}\right) + k - CF(T, P) \tag{30.16}$$

Sample calculation 5:

Question: A machine producing sound of a specific frequency is mounted on a steel floor in the center of a large room. SPL = 90 dB at 6 ft from the source. What would be SPL at 6 ft if the machine was moved into a reflecting corner?

Answer: According to Equation 30.16, first convert the SPL to sound power level using $r$ = 6 ft, $Q$ = 2, and $k$ = 0.5:

$$L_W = L_p + 10 \cdot \log_{10}\left(\frac{6^2}{2}\right) + 0.5 \approx 103\,\text{dB}$$

For $Q$ = 8, $r$ = 6 ft, and $L_W$ = 103 dB, solve for $L_p$ in Equation 30.16:

$$L_p = L_W - 10 \cdot \log_{10}\left(\frac{6^2}{8}\right) - 0.5 \approx 96\,\text{dB}$$

Note that the noise exposure at the same distance from the source increases once it is moved from the room center to a corner.

### 30.2.5 Bandwidth: Octave Band Principles

The acoustic energy is usually widely distributed over a range of frequencies. The frequency spectrum, or contents, can be expressed with frequency bands of fixed or proportional bandwidth. The spectrum with fixed band utilizes a constant frequency band of relatively narrow width for the entire frequency range. The most common proportional bands are the octave and one-third octave band. The octave band is such that the upper limit frequency ($f_2$) is twice of the lower limit frequency ($f_1$). The one-third octave band is such that the upper limit frequency ($f_2$) is $2^{1/3}$ times of the lower limit frequency ($f_1$). The center frequency ($f_c$) for a specific band is defined as the geometric mean of the lower and upper limit frequencies:

$$f_c = \sqrt{f_1 f_2} \tag{30.17}$$

Sample calculation 6:

Question: For the octave band centered at 1 kHz, find the lower and upper edge frequencies.

Answer: $f_2 = 2f_1$. According to Equation 30.17,

$$f_c = \sqrt{f_1 f_2} = \sqrt{2f_1^2} = f_1\sqrt{2}, \quad \text{that is,} \quad f_1 = \frac{f_c}{\sqrt{2}} \approx 707\,\text{Hz}, \quad \text{and} \quad f_2 = \sqrt{2}f_c \approx 1414\,\text{Hz}.$$

## 30.3 MEASUREMENT AND INSTRUMENTATION

### 30.3.1 General

Measurement is an essential step in assessing the risk of an acoustic environment and developing exposure control measures. The sound measurements are conducted to generate information for predicting the impact of sound on humans as well as for mitigating this impact. A wide range of instruments are available today for acoustic measurement, including SLMs and sound dosimeters.

Performance of acoustic instrumentation is generally characterized by factors such as frequency response, dynamic range, crest factor capability, and response time (Lord et al., 1980). *Frequency response* refers to the range of frequencies that an instrument can accurately measure. *Dynamic range* refers to the range of amplitudes of the signal that can be measured by the instrument. For example, typical SLMs have a dynamic range of 60–80 dB. The *crest factor* is the ratio of the peak value to the rms value of the signal. *Crest factor capability* refers to the capacity of an instrument that can measure signals of high crest factor without overloading the instrument, which is important for measuring an impulsive sound. *Response time* refers to the time for an instrument to respond to a sudden change of the input signal.

### 30.3.2 Microphones

A microphone is an acoustic sensor that converts acoustic pressure variations into corresponding voltages. Dynamic, ceramic, electret, and condenser microphones are used; condenser and ceramic types are used most commonly (Lord et al., 1980). While high-precision SLMs (type 1, see the following text) use condenser microphones, conventional, general-purpose SLMs (type 2, see the following text) use ceramic ones.

Microphones are designed for optimum performance in specific sound fields (Wong and Embleton, 1994; Raichel, 2006). A free-field microphone is designed to be used whenever the sound comes mainly from one direction in a reflection-free field such as an open space or in an anechoic chamber. The free-field microphone should be pointed directly at the noise source for maximum accuracy. The diffuse field occurs when sound reflects multiple times in random directions, which is typical of a reverberant factory environment. A random-incidence microphone, also called omnidirectional microphone, provides better accuracy at the high frequencies in the diffuse field. When random-incidence microphones are used in a diffuse field, no corrections need to be made because the microphone response is designed to correct for the effects of sound arriving from all directions. However, if the source is known to exhibit primarily a single direction, correction curves are usually provided to allow the spectral measurements to be corrected for the angle of incidence. Microphones have to be calibrated along with the measurement instrumentation, for example, SLM should be calibrated by using an acoustic calibrator prior to and after a series of measurements.

### 30.3.3 Sound Level Meters

A typical SLM consists of a microphone, a preamplifier, a network of frequency filters, and a display. Modern SLMs used in the field are portable and battery operated. Figure 30.3 shows a commonly used handheld SLM. The current standard defines type 0, 1, and 2 SLMs, according to the American National Standard Institute (ANSI) and the International Electrotechnical Commission (IEC), respectively, referring to "laboratory standard," "precision," and "general purpose." Type 0 SLM is intended for use in the laboratory as a high-precision reference standard (error < 0.1 dB). Type 1 is intended for measurements in the field and laboratory; it is characterized by a relatively low error of ±1 dB or below. Type 2 is designed for a routine field use, particularly in applications where a high-frequency (>10 kHz) sound component is not dominant; its estimated error does not exceed ±2 dB. In addition, type S is defined as a "special purpose" SLM designed for operating in under special conditions (e.g., under water). Also, some documents refer to "type 3" SLMs, which are considerably less expensive and less accurate and used sometimes for rough survey work or for making preliminary measurements before more accurate surveys are initiated. Either type 1 or 2 is acceptable for enforcement of noise regulations. SLMs often come with A-, B-, or C-frequency weighting capabilities (explained in the following) and a setting for "fast" and "slow" response. A-weighting is the most commonly used as it reflects sensitivity of human ears for noises of 40 phon loudness. The "fast" setting responds more quickly to transient noises, but the setting makes it difficult to read the rapidly changing SPL. The "slow" setting reduces the response time; thus, the SPL of rapidly fluctuating sounds can be read more easily. Many modern SLMs come with capabilities to display one-third and

FIGURE 30.3 A handheld SLM. (Courtesy of Larson-Davis.)

full octave frequency spectra, a computer interface that enables downloading additional software and more sophisticated postprocessing.

### 30.3.4 Weighting Filters

Sound measuring instruments often employ frequency-selective weighting filters so that the data reflect how sound is actually perceived and how it can damage human hearing. The A-weighted filter is commonly used to emphasize frequencies around 3–6 kHz where the human ear is most sensitive, while attenuating very high and very low frequencies to which the ear is less sensitive. While A-weighting derives its shape from the 40 phon Fletcher-Munson equal-loudness contour (Fletcher and Munson, 1933), it is more useful to consider it as the transfer function of sound frequencies reaching the cochlea. The outer and middle ears provide amplification in the middle frequencies and enhance the amount of energy around 3–6 kHz. The B and C curves were intended for louder sounds (70 and 100 dB at 1000 Hz, respectively). The B-weighting is not extensively used in industrial hygiene monitoring. The C-weighting is utilized in applications that involve blast-type waveforms and often deployed for evaluating HPDs when considering the effects of predominantly low- or high-frequency environments. Table 30.2 shows the spectral corrections for estimating A- and C-weighted SPLs, dBA and dBC (Royster and Royster, 2002).

TABLE 30.2 A and C Frequency Weighting Curves

| Octave Band Center Frequency (Hz) | A-Weighted Correction (dB) | C-Weighted Correction, (dB) |
|---|---|---|
| 16 | −56.7 | −8.5 |
| 31.5 | −31.4 | −3.0 |
| 63 | −26.2 | −0.8 |
| 125 | −16.1 | −0.2 |
| 250 | −8.6 | 0.0 |
| 500 | −3.2 | 0.0 |
| 1,000 | 0.0 | 0.0 |
| 2,000 | 1.2 | −0.2 |
| 4,000 | 1.0 | −0.8 |
| 8,000 | −1.1 | −3.0 |
| 16,000 | −6.6 | −8.5 |
| 20.000 | −9.3 | −11.2 |

Question: The octave band survey revealed SPL values listed in the following table. What is the total SPL of the source (all bands)?

| Center frequency (Hz) | 31.5 | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|---|
| Octave-band SPLs (dB) | 85 | 86 | 90 | 94 | 98 | 101 | 102 | 104 | 105 |

Answer: First, the measured SPL are corrected as follows:

| Center frequency (Hz) | 31.5 | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|---|
| Octave-band SPLs (dB) | 85 | 86 | 90 | 94 | 98 | 101 | 102 | 104 | 105 |
| A-weighted correction (dB) | −39.4 | −26.2 | −16.1 | −8.6 | −3.2 | 0 | +1.2 | +1 | −1.1 |
| A-weighted octave-band SPL (dBA) | 45.6 | 59.8 | 73.9 | 85.4 | 94.8 | 101 | 103.2 | 105 | 103.9 |

### 30.3.5 Acoustical Calibrator

Acoustic calibrators are used to check that an SLM or microphone is in proper working condition. The acoustic calibrator produces a single tone sound of a precise reference sound level and fits over the microphone. One typical calibration frequency and SPL level are 1 kHz with 94 dB (rms pressure of 1 Pa). SPLs of 124 and 114 dB are also used for calibration, as well as a frequency of 250 Hz. When using a pistonphone to calibrate a microphone, an adjustment must be made for the barometric pressure.

Sample calculation 7:

Question: The octave band survey revealed SPL values listed in the table in the following. What is the total SPL of the source (all bands)?

Second, the total is calculated according to Equation 30.12:

$$L_{\text{Total}} = 10 \cdot \log_{10}\left(10^{45.6/10} + 10^{59.8/10} + 10^{73.9/10} + \cdots + 10^{103.9/10}\right) \approx 109.7\,\text{dBA}$$

### 30.3.6 Dosimeters

A noise dosimeter is a body-worn, battery-powered instrument designed to measure the percentage of the worker's noise exposure compared to the maximum allowable daily noise dose. A dosimeter essentially operates as an SLM but, in addition, utilizes software to express the measured exposure dose in percent. A typical dosimeter consists of a small microphone, a small amplifier and A-weighting filter, and a circuit that squares and integrates the signal in time (Equation 30.4) to obtain the cumulative exposure. An overload indicator is incorporated to indicate if the sound level exceeds the range of the meter. More sophisticated dosimeters are capable of tracking A- and C-weighted exposure levels and other characteristics.

### 30.3.7 Frequency Analyzers

Frequency analyzers are common tools to understand the spectral content of acoustic signals. A sound signal is measured with a microphone and preamplifier assembly and digitally sampled to represent the electrical signal. Different systems utilize a range of sampling rates and resolutions. These sampling rates and resolutions are sufficient to characterize the range of frequencies and levels that are typical of human hearing (Oppenheim et al., 1999; Bosi and Goldberg, 2003). Once the acoustic signal is digitally sampled, the available analyses are numerous. Fourier spectral analysis is a common means to understand the tonal content of a signal. Analyzers will provide a wide range of time window functions (e.g., Hanning, Blackman, flat-top, rectangular) to minimize the effects of sampling a limited portion of a long signal and to minimize signal processing errors. Octave band analysis can be done through the implementation of digital filters to condense the frequency information into a limited number of values typically used in room acoustics and industrial hygiene. Numbers such as equivalent level, A-weighted equivalent level, and other metrics can be computed from the same digitally sampled waveform.

Frequency analyzers are increasingly implemented in software applications that are used with data acquisition systems. Postprocessing of the digital waveforms allows analysis to be tailored to specific questions that may not be available with standard commercial instruments. Regardless of the analysis, frequency analyzers provide output to a visual display to represent the acoustic data. An acoustical consultant is often equipped with an analyzer or SLM that provides a real-time representation of the acoustic environment. Whether it is tethered to an AC electrical power outlet or runs on batteries, analyzers provide the frequency-related information and help identify critical acoustic components.

## 30.4 BASIC ANATOMY OF EAR AND CAUSES OF HEARING LOSS

### 30.4.1 Anatomy of Ear

Figure 30.4 schematically shows the human ear, comprising the outer, middle, and inner parts. The outer ear funnels the sound collected by the pinna through the ear canal to the ear drum (tympanic membrane). Vibration of the tympanic membrane induced by the incident sound is transmitted through three small bones (ossicles)—the malleus, incus, and stapes—to the oval window. The inner ear has two parts: the vestibular system including the semicircular canals, and the cochlea. The semicircular canals provide a sense of balance. The cochlea is the organ that senses the magnitude

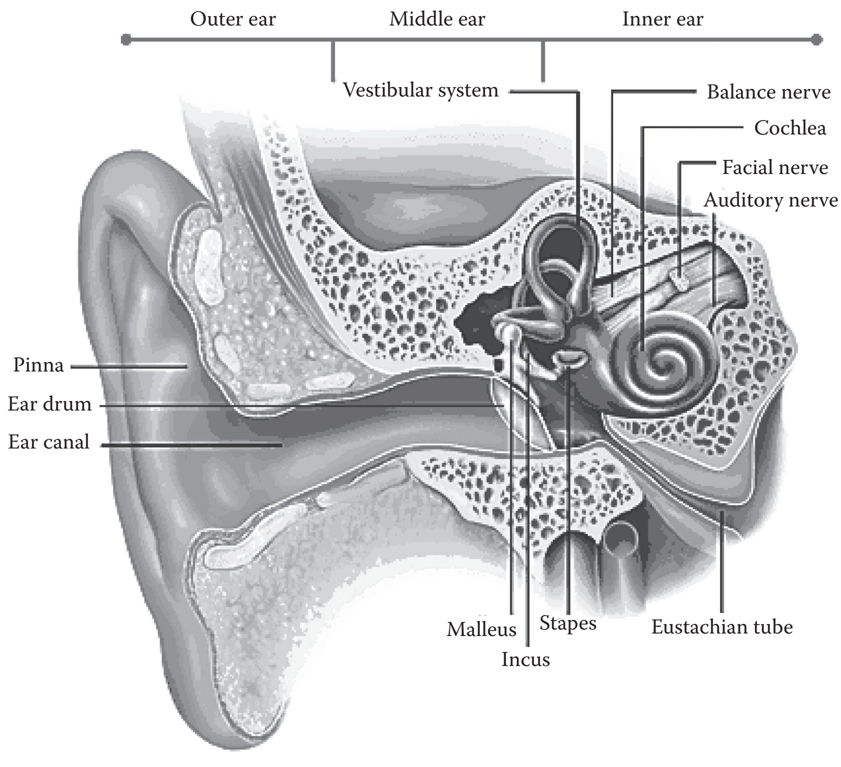


FIGURE 30.4 Anatomy of the ear. (Reproduced with permission from MED-EL Corporation.)

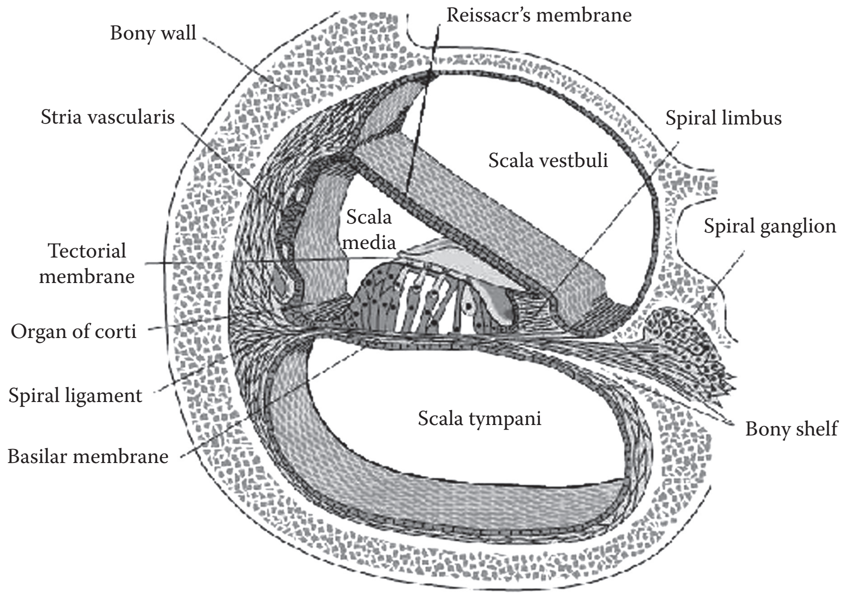


FIGURE 30.5 Structure of the cochlea. (Reprinted with permission from Richard, K., *Tissues and Organs: A Text-Atlas of Scanning Electron Microscopy*, W. H. Freeman & Co., New York, 1979.)

and frequency of sound. The cochlea is a tube-like structure wound about 2.7 turns in the shape of a snail shell and filled with fluid.

Figure 30.5 shows a cross section of the cochlea. The upper and lower scalae of the cochlea are connected by a small opening at the apex of the cochlea called the helicotrema (Durrant and Lovrinic, 1995). The ossicles maximize sound transmission to the inner ear by transforming air to fluid vibrations and minimize the impedance mismatch between the air in the outer ear and fluid in the inner ear. The disturbance of the fluid in the upper gallery induced by the stapes motion excites the motion of the basilar membrane while traveling along the cochlea. The basilar membrane has varying width and thickness, thus exhibiting the highest stiffness at the stapes side and the lowest stiffness at the apex of the cochlea. Due to this arrangement, the sound of a given frequency deflects the basilar membrane the most at a location uniquely corresponding to the frequency. A high-frequency sound deflects the basilar membrane close to the stapes and a low-frequency sound close to the apex of the cochlea. This frequency of sound is sensed accordingly.

The organ of Corti attached to the top of the basilar membrane contains four rows of hair cells spanning the entire length of the membrane. Cilia at the top of the hair cells are embedded in the bottom of the tectorial membrane. The displacement of the basilar membrane generates shearing force on the cilia that creates electrical potential that triggers electrical impulses in the neurons. The auditory nerve innervates the hair cells in the basilar membrane and transmits the afferent neural impulses toward the brain, which makes sound audible. Efferent neural impulses from the brain activate reflex responses of the middle ear and suppress hair cell responses in the cochlea.

TABLE 30.3 Definition of Hearing Losses

| Degree of Hearing Loss | Range of Hearing Loss (dB HL) |
|---|---|
| Normal | −10 to 15 |
| Slight | 16–25 |
| Mild | 26–40 |
| Moderate | 41–55 |
| Moderately severe | 56–70 |
| Severe | 71–90 |
| Profound | 91+ |

*Source:* Clark, J.G., *ASHA*, 23, 493, 1981.

### 30.4.2 Causes of Hearing Loss

There are three types of hearing loss: conductive hearing loss, sensorineural hearing loss, and mixed loss (Yost, 2006; Pickles, 2008). The first one is caused by damage in the transmission path in the outer and middle ear, which can often be repaired through surgery. The second one is due to damage to the inner ear or the neural pathway to the brain. Most occupational noise exposure results in sensorineural hearing loss, preceded by the metabolic failure of hair cells due to overloading of the hair cells for a prolonged period of time. Sensorineural hearing loss can also be caused by diseases, birth defects, ototoxic chemicals, ototoxic pharmaceuticals, and aging. Sensorineural hearing loss is a permanent loss that cannot be medically repaired. Mixed hearing loss is conductive hearing loss occurring in combination with sensorineural hearing loss.

Hearing loss is defined relative to the lowest SPL (dBA) that normal hearing persons can hear. Hearing threshold levels (HTLs) are defined for a highly screened population with no known abnormalities at each octave frequency 125–8000 Hz relative to the average hearing. For thresholds at 1000 Hz, 0 dB HTL = 0 dB SPL. Reference thresholds expressed as SPLs (decibel reference, 20 μPa) can be found in ANSI S3.6-1999. For example, an individual who has 30 dB hearing threshold at 1000 Hz is considered to have 30 dB hearing loss. Table 30.3 lists the ranges representing specific degrees of hearing loss defined by the American Speech-Language-Hearing Association (Clark, 1981).

## 30.5 ALLOWABLE EXPOSURE LIMITS

Existing regulations and guidelines concerning the noise exposure establish specific thresholds and relationships between the allowable sound level (an A-weighted $SPL_{exp}$) and the permitted exposure time ($T_{exp}$):

$$T_{exp} = \frac{8}{2^{\left(\left(SPL_{exp} - SPL_0\right)/R_0\right)}} \tag{30.18}$$

Here $SPL_0$ is the criterion level representing a specific A-weighted threshold that corresponds to an 8 h permissible exposure, and $R_0$ is the exchange rate—the quantitative measure of the SPL change that allows for doubling the exposure time.

The OSHA guidelines (OSHA, 1983) specify $SPL_0$ = 90 dBA [defined as the permissible exposure limit (PEL)] and $R_0$ = 5 dBA so that

$$T_{exp} = \frac{8}{2^{\left(\left(SPL_{exp}-90\right)/5\right)}} \tag{30.19}$$

Thus, OSHA guidelines allow for a maximum 8 h exposure of an unprotected worker to a 90 dBA noise. A louder noise leads to lower permitted exposure time intervals, for example, 4 h to SPL = 95 dBA, 2 h to SPL = 100 dBA, 1 h to SPL = 105 dBA, and 30 min to SPL = 110 dBA ($T_{exp}$ is reduced by a factor of 2 for every 5 dBA increase in SPL). The OSHA guidelines recognize a ceiling exposure level of 115 dBA, although there is evidence that this ceiling level is not being enforced (Suter, 2000). A much higher level of 140 dB of intermittent or impulsive noise is usually referred to as the upper limit of human exposure during any time duration (NIOSH, 1998).

The American Conference of Governmental Industrial Hygienists (ACGIH) adopted the threshold limit values (TLVs) for noise by utilizing the general form of Equation 30.18 but lowering $SPL_0$ to 85 dBA and changing $R_0$ from 5 to 3 dB. This resulted in the following relationship (ACGIH, 1994):

$$T_{exp} = \frac{8}{2^{\left(\left(SPL_{exp}-85\right)/3\right)}} \tag{30.20}$$

Thus, one can calculate the allowable exposure times for a worker not wearing hearing protection for an 8 h work shift (85 dBA), 4 h shift (88 dBA), 30 min work (97 dBA), and so on. For an unprotected exposure of 139 dBA, the allowable exposure time is 0.11 s.

By comparing Equations 30.19 and 30.20, one would conclude that ACGIH allows a shorter exposure to the same noise level as compared to OSHA. Although the ACGIH recommendations do not directly affect the U.S. government regulations, they carry considerable weight in the scientific community and are adopted by some large companies (Suter, 2000). The ACGIH TLVs also match better the standards of exposure allowed outside the United States.

Although many agencies in the United States promulgating noise regulations primarily rely on OSHA guidelines, some variations exist. For instance, the U.S. Department of Transportation used the noise standard that calls for a maximum noise level of 90 dB at the driver's position (required to be measured with a 2 dB tolerance), that is, does not allow the driver exposure in excess of 90 dBA for any period of time (DOT, 1973). The U.S. Department of Defense's safety and health instructions are consistent with the ACGIH-recommended PEL and require an exchange rate at least as protective as 4 dB with a strong recommendation to use $R_0$ = 3 dB. Some variations take place in implementing the DoD instructions by the U.S. Army, Navy, and Air Force (Suter, 2000). Different countries use different standards and regulations for occupational exposure to noise. Most European counties have adopted PEL = 85 dBA and a 3 dB exchange rate.

The amount of actual exposure relative to the amount of allowable exposure is defined as dose. The dose of 100% and above represents exposures that are hazardous. For a specific SPL, the noise dose is calculated as the ratio of the actual exposure time ($T_{actual}$) to the permitted exposure time ($T_{exp}$ determined from Equation 30.18):

$$D = \frac{T}{T_{exp}} \times 100\% \tag{30.21}$$

If an individual is exposed to $n$ different noise levels ($SPL_1$, $SPL_2$,…, $SPL_n$) throughout the observation period (typically one day) during respective time intervals of $T_1$, $T_2$,…, $T_n$, the dose is calculated as follows:

$$D = \left( \frac{T_1}{T_{exp\,1}} + \frac{T_2}{T_{exp\,2}} + \cdots + \frac{T_n}{T_{exp\,n}} \right) \times 100\% \tag{30.22}$$

where $T_{exp\,1}$, $T_{exp\,2}$,…, $T_{exp\,n}$ are the permissible exposure times from Equation 30.18.

Sample calculation 8:

Question: The following worker's exposures were measured during the 8 h shift: $SPL_1$ = 90 dBA over the first 4 h, then 100 dBA over the next hour, 95 dBA over the next 2 h, and 110 dBA in the last hour. What is the noise dose assuming (a) the OSHA rules and (b) ACGIH TLV?

Answer:

(a) From Equation 30.20, the $T_{exp}$ values are 8, 2, 4, and 0.5 h, respectively. Thus, according to Equation. 30.22,

$$D_{OSHA} = \left( \frac{4}{8} + \frac{1}{2} + \frac{2}{4} + \frac{1}{0.5} \right) \times 100\% = 350\%$$

(b) From Equation 30.21, the $T_{exp}$ values are approximately 2.52, 0.25, 0.8, and 0.025 h, respectively. Thus, according to Equation 30.22,

$$D_{ACGIH} = \left( \frac{4}{2.52} + \frac{1}{0.25} + \frac{2}{0.8} + \frac{1}{0.025} \right) \times 100\% = 4808\%$$

As expected, the ACGIH-calculated dose is much greater than the one obtained based on the OSHA rules. Both are excessive (>100%).

A special cutoff level of 80 dBA is defined so that any noise exposure below this level is considered nonhazardous. This level corresponds to the risk of incurring a material hearing impairment of less than 3% for a 40 year occupational exposure. In assessing the dose, all SPL values below the referenced cutoff are replaced by zero.

The averaging of different noise exposure levels during an exposure period (an 8 h work shift) produces the TWA value defined as the constant sound level that would generate the same dosimeter reading over this exposure period as would the nonsteady noise. This sound level is also referred to as the dose-equivalent level ($L_{eq}$). Derived from the OSHA guidelines,

$$L_{eq} = 90 + \frac{5}{\log_{10} 2}\log_{10}\left(\frac{D}{100}\right) = 90 + 16.61 \times \log_{10}\left(\frac{D}{100}\right) \quad (30.23)$$

From the ACGIH TLVs,

$$L_{eq} = 85 + \frac{3}{\log_{10} 2}\log_{10}\left(\frac{D}{100}\right) = 85 + 9.67 \times \log_{10}\left(\frac{D}{100}\right) \quad (30.24)$$

The TWA values are calculated for nonsteady noise and compared to specific levels such the OSHA-defined action level (85 dBA) or PEL (90 dBA) in order to determine the course of action. Once TWA reaches the action level (dose = 50%), the hearing conservation ("hearing loss prevention") program must be established as explained in Section 30.6 in the following text. A higher TWA of 90 dBA (PEL, dose = 100%) requires establishing a hearing protection program. However, given the tolerance of measurement (±2 dB), the latter is enforced only if the measured value is equal to (or in excess of) 92 dBA (the corresponding dose is 132%).

## 30.6 ELEMENTS OF HEARING LOSS PREVENTION PROGRAM

### 30.6.1 Background

The Occupational Safety and Health Act and the Noise Control Act were passed by Congress and signed into law by President Nixon (U.S. Public Law 91–596, 1970; U.S. Public Law 92–574, 1972). In 1981, OSHA promulgated the Hearing Conservation Amendment to define the requirements of implementing a hearing conservation program within general industry (OSHA, 1981, 1983). In 1996, NIOSH published its recommendations for implementing a hearing conservation program (NIOSH, 1996). The NIOSH Practical Guide is available from the NIOSH web site (http://www.cdc.gov/niosh). The principal elements of a hearing conservation program are described in this section.

Since 2004, the U.S. Bureau of Labor Statistics (BLS) has been summarizing the number of recordable hearing loss injuries reported from the OSHA Form 300 for a sampling of industries in the United States. Hearing loss has consistently ranked as the second most prevalent nonfatal injury or illness with approximately 22,000 cases reported in 2007 (Hager, 2009). Although the specific cause of the cases reported is not provided within the BLS data, one may safely assume the primary cause to be noise exposure. Thus, the first element of a successful hearing conservation program is the protection against noise.

### 30.6.2 Monitoring Hearing Hazards

In addition to the classical risk of induced hearing loss, other less obvious issues that present safety hazards include the ability to communicate, to hear warning signals, or to identify auditory cues while operating machinery. Occupational exposures to solvents, chemicals, heavy metals, and even temperature extremes can contribute to worker hearing problems.

Noise exposure is the principal cause of hearing loss in most cases. Employers need to classify noise sources in the workplace through area noise surveys, personal dosimetry, or engineering surveys. Area surveys use an SLM to plot out the levels of noise within a workplace. A simple map of the factory and color-coded noise levels identifying different exposure levels (e.g., green for TWA < 85 dBA, yellow for TWA < 88 dBA, orange for TWA < 91 dBA, and red for TWA < 94 dBA) would inform workers of the risk of exposure. Areas with high exposures should be identified as mandatory use of hearing protection.

Personal dosimetry is important when the work force is mobile or the noise exposures during the workday vary. Mobile workers may be operating in several areas with a combination of high, moderate, or no exposure risk. For construction workers, the noise exposures vary considerably with the job task on a daily basis (Nietzel and Seixas, 2005). Workers should be monitored with personal noise dosimeters to determine their individual exposure. Two elements are critical to effective dosimetry: identification of job tasks and worker participation to record the exposures. Exposure levels are determined automatically in many dosimeters. Threshold levels within the dosimeter set the effective level above which the noise exposure is integrated into the dose. Typically, the threshold is set to the cutoff level (80 dBA) when estimating a noise dose. If workers spend significant time in quiet areas, the threshold can be set to zero to accurately assess the exposure.

Engineering surveys are typically more concerned with identifying particular features of a noise exposure that may be controlled. To accomplish these surveys, more sophisticated analysis of the spectral content may require octave band analyzers, sound level recorders, in situ analysis of sound power or sound intensity measurements, and vibration measurements with accelerometers to assess particular pieces of machinery that are targeted for engineering noise control.

### 30.6.3 Engineering and Administrative Controls

Engineering and administrative controls are essential to reducing exposures to hazardous levels of noise and increasing the effectiveness of a hearing loss prevention program. Within the NIOSH hierarchy of controls, the hazard should be removed or the worker should be removed from the hazard (NIOSH, 1996). Engineering noise controls can take several forms: reducing the noise at the source, interrupting the noise path, reducing the reverberation, and reducing the structure-borne vibration.

#### *30.6.3.1 Reducing Noise at the Source*

Engineering noise control identifies the noise sources and seeks a solution to reduce the contribution of the source to the exposure. In many cases, multiple sources exist that must be treated with a variety of techniques. For instance in coal mining, the continuous mining machine has a rotating cutter head at the face of the coal seam, fans that operate and ventilate the operator(s), and a conveyor bed and chain with flight bars to move the coal away from the seam. Each element requires unique noise controls to reduce their respective contributions to the exposure. The cutter head may be enclosed to reduce exposure; fans may be modified to move air with less turbulence; the conveyor bed may be treated with constrained layer damping to reduce impact noise; and the flight bars and chain may be coated to reduce the impact of coal with the metal bars (Camargo et al., 2008).

High-velocity fluid/air flows represent a common source of excessive noise, which can be treated by implementing different techniques from the elimination of leakage paths to the manipulation with the flow velocity. The latter is often effective given that, under common aerodynamic conditions, noise increases with the fifth power of flow speed. For the same flow rate, choosing a bigger duct cross-sectional area may thus considerably reduce the emitted sound energy. If a duct diffuser is utilized as a noise control technique, abrupt expansions should be avoided because rapid pressure changes may produce additional acoustic waves.

#### *30.6.3.2 Interrupting the Source*

Interruption of the path can be a highly effective means of controlling exposures. Noisy machinery may be housed in an enclosure designed to contain or absorb the acoustic energy from reaching the worker. For example, NIOSH's work with indoor firing ranges identified that adjacent rooms at one range had peak impulse SPL of about 130 dB. If walls are inadequately constructed, acoustic energy can be transmitted through direct and/or flanking pathways such as ventilation ducts, electrical chases, or inadequate isolation of the range (Kardous et al., 2003). High levels in adjacent spaces prevent full utilization of the spaces when weapons training occurs. At another firing range, the control rooms were isolated behind poured concrete walls with doors and windows that had sound transmission class (STC) ratings of 45 dB. During weapons training, conversations could be held in the control room. In the other spaces in the building, the activity on the range was audible but quieted due to the physical separation across a corridor and the control and preparation rooms (Kardous and Murphy, 2010).

#### *30.6.3.3 Reducing the Reverberant Exposure*

Reduction of reverberant exposure involves control of reflected sound, as opposed to control of direct sound (discussed earlier). Indirect sound is controlled by application of surface treatments. Absorptive treatments can significantly improve the usability of a noisy space. For instance, recent studies of the noise exposure of workers at animal shelters found maximum exposure levels of about 100 dBA (NIOSH, 2006a,b, 2007). Through the application of absorptive batting applied to the ceiling of the kennel area, the levels were reduced to about 3–4 dB. Before acoustical treatment, the workers experienced considerable difficulty communicating with one another while in the kennel area. After treatment, the reverberation times were reduced dramatically and speech intelligibility levels were improved.

#### *30.6.3.4 Structure-Borne Vibration*

Anytime a structure is vibrating, there is a potential of noise generation. In a work environment, tools may be poorly designed and have sympathetic vibrations produced by the equipment operation. For instance, table saws can be built with little more than a sheet metal enclosure to shield the worker from the rotating pulleys, belt, and blade. More expensive, cabinet-grade saws have enclosures that typically extend to the floor and are constructed from heavier stock to minimize vibrations of the saw blade. The unintended side effect is that cabinet-grade saws are often more quiet than portable contractor-grade table saws. The additional mass changes the resonance frequencies, the additional shrouding isolates the noise-producing elements, and the reduced vibrations result in a higher quality by reducing the tool marks on the workpiece.

#### *30.6.3.5 Quantification of Noise Reduction*

The sound reduction by a noise control treatment is characterized by absorption-reflection properties of its surfaces and transmission properties of the material. The absorption coefficient ($\alpha$) is used to describe the ability of a surface area to absorb sound energy. It is defined as the ratio of acoustic energy absorbed by a surface to the acoustic energy incident on the surface. The $\alpha$ values varies from 0 to 1 with $\alpha = 0$ corresponding to the case when all the incoming sound is reflected (no absorption) and $\alpha = 1$ representing the opposite case when the sound is fully absorbed (no reflection). Absorptivity of 0.5 means that the surface absorbs 50% of the sound energy. The transmission coefficient ($\tau$) of the barrier is defined as the ratio of the sound energy transmitted through its unit area to the sound energy incident on the barrier. The $\tau$ values varies from 0 to 1. Materials that can effectively absorb sound energy have $\tau$ close to 0 ($\tau = 0$ is designated for a perfect barrier), while $\tau = 1$ represents open space. Both absorption and transmission coefficients are dependent on frequency.

To express the ability of a given barrier to attenuate sound, a transmission loss (TL) occurring when the acoustic wave penetrates through the barrier is

$$\mathrm{TL} = \mathrm{SPL}_1 - \mathrm{SPL}_2 = 10\log_{10}\frac{1}{\tau} \tag{30.25}$$

where $\mathrm{SPL}_1$ and $\mathrm{SPL}_2$ are the SPLs inside and outside the barrier, respectively. For example, if SPL on one side of a wall is 100 dB and on the other side it is 80 dB, the resulting TL is 20 dB. The material's transmission coefficient calculated for these conditions from Equation 30.25 is $\tau = 0.01$.

Adding barriers (such as walls and ceiling) around the noise source traps sound, thereby creating a reverberant sound field in the space containing the source. The size of the space and the reflectivity of its surfaces affect the reverberant sound field. If all the surfaces have the same absorption coefficient $\alpha$ and the total surface area is $S_t$, the total sound absorption area in the room is calculated as $A = \alpha \cdot S_t$. Wallace Clement Sabine, a Harvard physics professor, introduced the so-called room constant

$$R = \frac{\alpha \cdot S_t}{1-\alpha} \tag{30.26}$$

as an indicator of the amount of sound absorption in the room. $R$ is expressed in Sabine square meters or Sabine square feet, depending on the unit chosen for the total surface area.

If the room is composed of wall surfaces of $n$ different acoustic properties, the average absorption coefficient ($\bar{\alpha}$) is calculated as follows:

$$\bar{\alpha} = \frac{S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n}{S_1 + S_2 + \cdots + S_n} \tag{30.27}$$

and the room constant is

$$R = \frac{\bar{\alpha} \cdot S_t}{1 - \bar{\alpha}} \tag{30.28}$$

If a worker is exposed to a source located at a distance $r$ with directivity $Q$ in a room with a room constant $R$, the sound pressure relates to the sound power as follows (modified Equation 30.15):

$$L_p = L_W + 10 \cdot \log\left[\frac{Q}{4\pi r^2} + \frac{4}{R}\right] + 10.5 + CF(T, P) \tag{30.29}$$

The maximum noise reduction (in decibels) from adding absorption can be calculated as follows:

$$NR_{\max} = 10 \cdot \log_{10}\left(\frac{A_{\text{after treatment}}}{A_{\text{before treatment}}}\right) \tag{30.30}$$

where $A$ is the absorption area.

Sample calculation 9:

Question: A noise reduction treatment was applied to the room with an initial absorption of 270 Sabine square feet by introducing 1000 $ft^2$ of material with $\alpha = 0.6$. Determine the maximum noise reduction.

Answer: According to Equation 30.5, the maximum achievable noise reduction is

$$NR_{\max} = 10 \cdot \log_{10}\left(\frac{0.6 \times 1000}{270}\right) = 10 \cdot \log_{10} 2.22 = 3.47\,\text{dB}$$

The maximum noise reduction from a partial enclosure can be calculated through the percentage of the open area (area free to radiate):

$$NR_{\max} = -10 \cdot \log_{10}\left(\frac{\%\,\text{area free to radiate}}{100}\right) \tag{30.31}$$

Sample calculation 10:

Question: A partial enclosure is placed around the sound source so that 75% of the surface area is covered with absorptive material. Determine the maximum noise reduction.

Answer: The remaining area (free to radiate) accounts for 25%. Consequently, the maximum possible noise reduction can be calculated as

$$NR_{max} = -10 \cdot \log_{10} 0.25 \approx 6\,\text{dB}$$

#### *30.6.3.6 Administrative Controls*

Administrative controls can be defined as changes in the work schedule or operations that reduce noise exposure. Some equipment should be operated during different shifts to expose fewer workers. Shifting workers from noisier to quieter equipment is another way of reducing an individual's exposure. In the military, some weapons systems create highly intense exposures that cannot be avoided if the personnel are expected to become competent users. In such cases, the military has implemented administrative restrictions on the number of shots fired, kind and location of weapon, and the number of personnel around the weapons. One other practical administrative control is to provide a quiet area where workers may get relief from workplace noise. Break rooms or quiet rooms should have background noise levels limited to less than 70 dBA to allow for recovery from any noise insult. If the room is near the production line, then appropriate acoustic isolation is necessary to achieve lower background noise levels.

### 30.6.4 Audiometric Evaluation

Audiometric evaluation is critical for the execution of any successful hearing conservation program (NIOSH, 1996; Berger, 2000). Without an accurate assessment at the beginning (an end) of a worker's employment, the employer is effectively liable for any hearing loss the worker might have incurred prior to and after they have terminated employment. Thus, audiometric screening is recommended on the following five occasions:

1. Preemployment
2. Prior to an initial assignment to a hearing-hazardous area
3. Annually for as long as the employee is assigned to a noisy job (TWA > 85 dBA)
4. Whenever the employee is reassigned out of a noisy job
5. At the termination of employment

OSHA and NIOSH have different requirements and recommendations. OSHA currently requires that employees' hearing be tested at 0.5, 1, 2, 3, 4, and 6 kHz for occupational hearing screening. OSHA further requires that a standard threshold shift (STS) must be reported when the employee's average hearing at 2, 3, and 4 kHz shifts by more than 10 dB. NIOSH recommends that hearing also be tested at 8 kHz and that a significant threshold shift be considered to have occurred when hearing at any frequency has shifted by more than 15 dB and the shift is present at the same frequency in the same ear following an immediate retest. OSHA's occupational screening criteria use a higher maximum permissible ambient background noise limit (MPANL) than NIOSH. NIOSH recommends that the MPANL should not exceed the ANSI S3.1-1999 (2008) levels for audiometric test condition requiring ears be covered and test frequencies ranging from 500 to 8000 Hz. The background noise levels are critical to uncovering early threshold shifts that might signal the onset of occupational hearing loss. Whenever the test room is moved, the levels should be measured to assure compliance. If the testing is performed in a mobile unit, then every time the unit is set up in a new location, the levels should be measured and documented. NIOSH recommends daily checks of the MPANL. Conducted with a microphone installed in the test booth and linked to the audiometer, the testing can be suspended if the ambient room noise exceeds the prescribed limits.

Audiometric monitoring requires that a baseline audiogram be collected. The worker should not be exposed to noise levels at or above 85 dBA for a minimum of 12 h prior to the audiometric test. This test is critically important as all subsequent tests will be compared to this baseline. Annual testing is required for workers enrolled in the hearing loss prevention program. The audiograms should be conducted during the worker's normal work shift. Ideally the audiogram should be immediately examined to compare it to the baseline audiogram. Hearing testing software and computer-controlled audiometers are capable of flagging differences during the test to immediately retest suspicious thresholds. When monitoring identifies a shift, a retest should be conducted. Repositioning the headphones and reinstruction of the worker on how to take the audiometric test may affect the threshold that is measured. The important task is to identify a persistent threshold shift and recommend follow-up with an audiologist and/or occupational physician.

If a worker has a persistent threshold shift, a confirmation audiogram is required. NIOSH recommends that the confirmation testing take place within 30 days. Waiting another year or several months may result in further hearing loss. If a worker has an STS, then the employer is required to take appropriate action to protect the worker from additional hearing loss. Some of the actions include counseling on how hearing loss occurs, reinstructing the worker on the proper use of HPDs, or even reassignment of the worker to a quieter work area.

Finally, whenever a worker leaves employment, the employer should obtain an exit audiogram. The employee should be counseled regarding changes in the worker's hearing over the duration of employment.

## 30.7 PERSONAL HEARING PROTECTION DEVICES

HPDs have always been an essential element of a hearing loss prevention program. When engineering and administrative controls have not been practical solutions, HPDs have become the de facto fallback solution. Several aspects of hearing protector use must be considered when being incorporated into a hearing loss prevention program: determination of the necessary level of protection, selection of appropriate products for workers, training and education of workers to use HPDs, and verification of the use of HPDs by workers.

### 30.7.1 Hearing Protection for Hearing Loss Prevention

The OSHA mandates that "a variety of suitable hearing protectors" be made available to workers at no cost to the employees if they are exposed to an 8 h TWA level of 85 dBA (the action level). Once TWA reaches PEL = 90 dBA, the exposed workers are required to wear hearing protection. Responsible employers will do more than just provide protectors; they will include suitable training to educate the employees on protectors that are best fit to the head or ear canals. Recent research has demonstrated that the most effective tools for training are one-on-one sessions where the employee learns to competently fit the protector and understands the need to wear the protector whenever they are exposed to high levels of noise (Joseph et al., 2007; Witt, 2007; Murphy et al., 2010; Schulz, 2010).

### 30.7.2 Determination of Level of Protection

Currently, all HPDs sold in the United States are required to be labeled according to the U.S. EPA's regulation 40 CFR 211 subpart B (EPA, 1978). This regulation stipulates that the protectors shall be tested with a panel of 10 subjects where the experimenter fits the protectors on the subject's head or in the ear canals. This is referred to as the experimenter-fit protocol and was derived from the American National Standard ANSI S3.19-1974 for measuring the real ear attenuation of HPDs (ANSI S3.19-1974). While that standard has been in place since 1978, the U.S. EPA recently proposed a revision of the regulation to update the standard and provide specifications for additional tests for unique classes of HPDs. Both the current rating and the proposed rating are described in the following text.

In August 2009, EPA proposed significant revisions to the labeling regulation (EPA, 2009), including the utilization of a dual number rating system that informs the user of the range of attenuation that the product can provide (ANSI/ASA S12.68-2007, 2007). Products will be tested using an experiment-trained protocol whereby the experimenter will be allowed to teach the test subject how to properly fit the protector, but will not actually put the protector on the subject's head when the testing is carried out (ANSI/ASA S12.6-2008, 2008). Ratings will be required for two new classes of hearing protectors: active noise reduction (ANR) and level dependent (ANSI S12.42-2010). The proposed changes are expected to significantly affect hearing loss prevention programs.

#### *30.7.2.1 Noise Reduction Rating (1978)*

The noise reduction rating (NRR) provides the consumer with information regarding the potential performance capability of a hearing protector if it is worn in the manner in which it was tested. Shortly after the regulation was promulgated, the occupational safety and health community came to recognize that the NRR was the performance estimate rarely achieved by most users. As mentioned earlier, the use of an experimenter-fit protocol is the principal reason for the inflation of this estimate. When the product was tested in the laboratory, the evaluator ensured the best possible fit for every subject.

The NRR is a measure of attenuation that is designed to be used with C-weighted noise measurements. Industrial hygienists often collect noise measurements using the A-weighted scale, and therefore, the NRR must be converted from C- to A-weighting. In the EPA regulation, this conversion is accomplished by a spectral correction factor of 7 dB.

For example, suppose a noise exposure is 95 dBC and 91 dBA and that the worker is wearing a protector that has a 25 dB NRR. The estimated C-weighted exposure is 95 − 25 dB = 70 dBC while the estimated A-weighted exposure is 91 − (25 − 7 dB) = 73 dBA. As one can see, even a seemingly simple correction between C- and A-weighting yields two different answers.

The U.S. EPA requires that the mean and standard deviation of the octave band attenuations be provided for each product. These detailed attenuation values can be used to estimate exposure levels for specific noise exposures. Any hearing protector, when worn correctly, can provide 10–15 dB of protection and reduce the exposure to below 85 dBA. However, for high levels of noise exposure or for exposures that contain specific frequencies that must be reduced to protect the worker, the expanded methods must be applied. NIOSH has published several example calculations to describe the octave band method of estimating the protected exposure level (Kroes et al., 1975; Lempert, 1984; Franks et al., 2003). The last of these references is an online Compendium of Hearing Protection Devices that has been continually updated as manufacturers have developed more products.

*30.7.2.2 Noise Reduction Rating (2009)*

The proposed dual number on the primary label gives the user a sense of the range of protection that can be achieved if the protector is worn properly (see Figure 30.6). The lower value (19) is representative of what 80% of the test panel was able to achieve, and the greater value (27) is representative of what 20% of the test panel was able to achieve. Most trained users should be able to achieve between 19 and 27 dB of noise reduction. One difference between the NRR (1978) and the proposed rating is that the new rating is determined

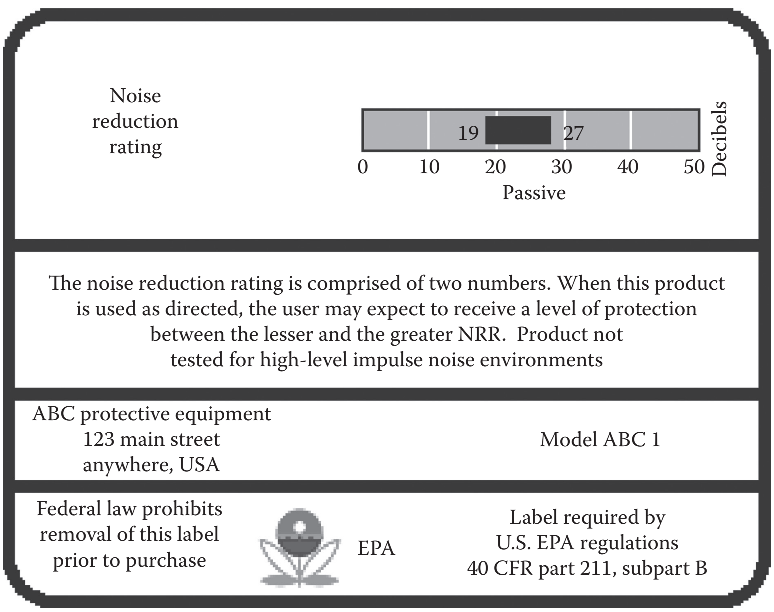


FIGURE 30.6 Proposed label for a typical passive HPD. Passive devices rely upon structural features to attenuate sound energy.

for A-weighted noise; in other words, it may be subtracted directly from an A-weighted noise level and not require adjustment for the C- to A-weighting scales. Again, assuming a 91 dBA noise exposure, the estimated exposure levels with the product worn will be between 72 dBA (=91–19) and 64 dBA (=91–27).

When more accurate assessments are required, the proposed regulation provides two methods for estimating the exposure. The first one employs a graph that illustrates how the attenuation of the protector changes as a function of the spectral balance (the difference between the C- and A-weighted measurements) of the noise. The second uses the octave band analysis. To provide the graphical information, the industrial hygienist should first measure the exposure with both the C- and the A-weighted scales and calculate the difference. Using the noise level from the previous example, the spectral balance is calculated as 95 − 91 = 4 dB. From the graph in Figure 30.7, the estimated noise reductions at the 80th and 20th percentiles are about 16 and 22 dB (as denoted with the red circles in the graph), respectively.

The estimated exposure level would be the A-weighted noise level minus the adjusted NRR for the 80th percentile: 91 − 16 = 75 dBA. The 20th percentile protection level would be 91 − 22 = 69 dBA.

This method provides the industrial hygienist a new means of understanding the effect of hearing protection interacting with the environmental noise exposure. First, the exposure is shown to be explicitly dependent upon the noise spectrum. As low-frequency content becomes more prevalent, the protector's effective protection is degraded from about 19–16 dB. In the worst-case noise, one dominated by energy around 125 Hz, the protection could be as low as 6 dB. Second, the range of protection can be used to determine whether

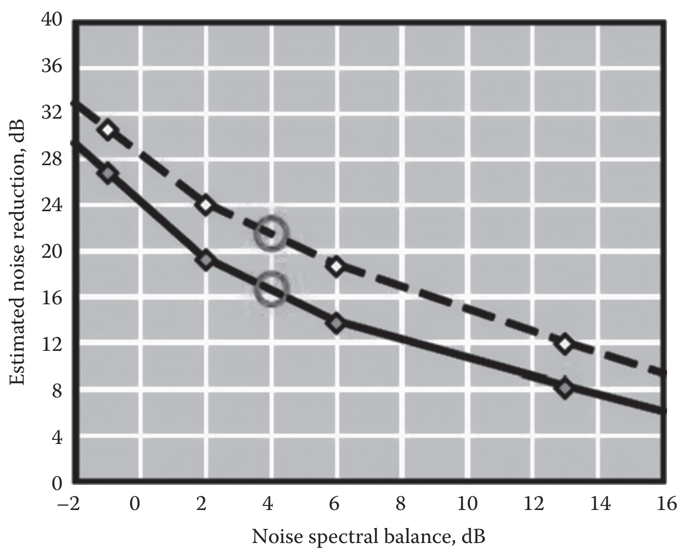


FIGURE 30.7 Estimated noise reduction as a function of spectral balance of a noise: the difference of C-weighted and A-weighted SPLs. Overall hearing protector performance is dependent upon both the attenuation of the protector and the noise in which it is worn. This particular protector has reduced performance when used in predominantly low-frequency noise.

the predicted protection is excessive. If a protector provides more attenuation than is needed, employees may tend not to fit the protector well or may remove the protector when communication becomes a problem. The upper value for the NRR or the graphical NRR provides an estimate of the maximum attenuation and therefore the potential for isolation and the appropriateness of protector selection.

### 30.7.3 Protector Types

#### *30.7.3.1 General*

Several styles of protection are available to meet just about every specific need in hearing protection. According to the NIOSH Compendium of Hearing Protection Devices, over 400 protectors are currently sold in the United States (Franks et al., 2003). Protectors come in three basic styles: earplugs, banded protectors, and earmuffs. In the EPA's proposed regulation, several different types of ratings cover specific features of the protectors. All protectors will be rated according to their basic performance due to the attenuation of the structural elements of the protector and without any electronics being activated. For those devices that incorporate noise cancellation, an NRR will be provided to demonstrate the additional protection that the protector provides when noise cancelling is operating. Another type of rating will be provided to describe the performance of devices in an impulsive noise environment. Some devices utilize electronic circuits to limit the exposure to high SPLs. Others are designed with physical acoustic features to vary the amount of attenuation with sound pressure. These protectors will be tested for a range of impulse levels (130–170 dB peak SPL) to estimate their performance.

#### *30.7.3.2 Earmuffs*

Earmuffs tend to have the most consistent performance when worn correctly. Workers must be careful that jewelry, safety glasses, hats, and hair do not interfere with the seal of the earmuff cushion against the side of the head. In studies conducted at NIOSH and other laboratories, muffs typically had the smallest variation in the overall attenuations measured for groups of naïve and trained subjects (Murphy et al., 2004, 2009). Earmuffs can be uncomfortable if one is working in high heat and humidity due to sweat and condensation under the muff. Muffs can also be perceived as bulky and be uncomfortable if the headband is not adjusted properly.

#### *30.7.3.3 Banded Protectors*

Banded protectors are something of a hybrid between earplugs and earmuffs. The earplugs or canal caps are attached to a flexible, springy band that provides force to seal the entrance of the ear canal with the cap or plug. Canal caps do not extend very far into the ear canal. They are slightly larger than the canal and are pressed against the entrance of the canal. Other banded protectors have earplugs that are meant to insert into the ear canal; these are also referred to as semi-insert devices. Banded protectors are popular with workers when the noise environment is changing or intermittent. Because they are banded, the user only needs to handle the band and not the actual plug; thus, transference of dirt on the hands and fingers to the ear canal is minimized. Banded protectors tend to be more comfortable than earmuffs when working in high heat and humidity. The attenuation of canal caps is often lower than that achievable by earplugs due to the smaller surface area. For some persons with irregularly shaped ear canal openings, the canal cap may not completely seal the entrance and may provide little if any protection.

*30.7.3.4 Earplugs*

Earplugs accounted for about 62% of sales of HPDs in the United States (Frost & Sullivan, 2009). Earplugs can be formable, premolded, or custom molded to ears. Formable earplugs are typically made from polyvinyl or polyurethane foams that need to be rolled into a tight cylinder and inserted into the ear canal. Premolded or no-roll-down earplugs have traditionally been made of a flexible polymer (rubber or vinyl) that has flanges to make contact with the ear canal walls. Recently, manufacturers have developed foam plugs that can be pushed into the ear canal by means of a solid stem surround by a flexible material. Custom earplugs are manufactured similar to hearing aids (with an impression of the user's ears and ear canals being taken). Another custom earplug manufacturer uses an inflatable bladder that is filled with a silicon gel that sets in the ear canal in a matter of minutes.

While earplugs are considered to be the most comfortable and least obtrusive forms of protection, they can also be the most ill-used product. Many users fail to properly roll or insert the plugs and achieve only a fraction of the intended attenuation. The workers require additional training to implement correct fitting and continuous use of the protectors.

*30.7.3.5 Specialty Products*

Specialty products such as sound restoration protectors, ANR protectors, and level-dependent hearing protectors are available. Sound restoration devices function similarly to a hearing aid. When the ambient noise levels are low, the electronic circuitry samples and amplifies the environmental sounds and reproduces them underneath the protector. In this manner a worker is able to hear low-level sounds without having to remove the protector.

Sound restoration devices work best in intermittent noise environments when the exposure is unpredictable and intense. Examples include use of pneumatic or powder-actuated tools on a construction site or the use of firearms at a firing range. The sound restoration circuitry quickly turns off the amplification when the ambient levels exceed 85 dB. Some devices use peak clipping circuits; others have compression circuits and still others may use voltage-controlled amplifiers to control the sound levels reproduced by the protector.

ANR protectors applied a sophisticated algorithm of sampling the ambient sound and reproducing it 180° out of phase underneath the protector. When the transmitted sound and the out-of-phase sound are combined underneath the protector, they cancel out one another and actively reduce the noise levels that reach the ear. Currently ANR devices are popular among airplane pilots as they can reduce strong tonal components produced by the engines. ANR algorithms can be tuned to remove specific components with high efficiency. The U.S. Air Force has developed ANR earplugs that are capable of providing a combined active and passive attenuation of 50 dB from 63 Hz to 8 kHz. ANR protectors tend to be more expensive than sound restoration and traditional protectors, but they yield attractive solutions for very specific noise environments.

Level-dependent protectors as a broad classification could encompass sound restoration devices. However, the acoustics of sound transmission through small orifices provides a completely passive means of providing attenuation at high levels without having to provide a power source. As sound passes through a small orifice, it encounters a viscous boundary layer near the walls of the orifice. As the sound pressure increases, the boundary layer extends further into the channel where the air is flowing back and forth through the orifice. The flow resistance increases with increasing sound pressure and the attenuation also increases (Allen and Berger, 1990; Franke et al., 1994; Parmentier et al., 2000; Berger and Hamery, 2008). The advantage of this style of protector is that it can provide almost as much attenuation as a solid protector of the same design but allows one to hear low-level sounds. The disadvantage is that the significant changes in attenuation do not occur until the noise reaches truly harmful levels such as about 140 dB or more. If one uses these protectors, the plug or muff must be fit tightly on the head or in the ear canal. Otherwise, leaks that bypass the orifice may permit excessive exposure. Such leaks could be formed due to the use of safety glasses that interrupt the seal of the earmuff cushion with the side of the head or a poorly fit earplug that has not sealed the ear canal. Most of these level-dependent products were designed for high-level impulsive noise. The protection they provide may just as easily be achieved by using a more traditional earmuff, banded protector, or earplug.

### 30.7.4 Training in Hearing Protector Use

Recent studies have evaluated the effect of training provided to hearing protection users and demonstrated that one-on-one training is the most effective means of teaching (Joseph et al., 2007; Murphy et al., 2010). Key to this training is the empowerment of the worker to understand what protector should be selected and be able to teach a coworker. Training does not require long sessions and examination. Rather, a simple video combined with individualized demonstration and evaluation by the instructor suffices to increase average attenuations by 7–15 dB (Joseph et al., 2007; Murphy et al., 2010). Even among experienced workers, training in proper rolling and insertion of formable earplugs can provide a 3–4 dB improvement (Murphy and Stephenson, unpublished).

Hearing conservationists have now developed applications that can provide a fit test of a user's hearing protectors. One system employs a dual microphone to sample the sound levels just outside the protector and the levels underneath the protector. The measured TL must be coupled with correction factors to account for the acoustics of the occluded environment (Voix and Laville, 2009). Another solution employs a psychophysical method called loudness balance to estimate the attenuation of each earplug separately (Schulz, 2010). Real ear attenuation at threshold using a headphone presentation measures the hearing threshold with and without earplugs to provide an estimate of the earplug attenuation (Edwards et al., 1978, 1983). While each system has advantages and disadvantages, the acceptance of fit testing has been increasing. Similar to fit-testing respirators for hazardous breathing environments, fit testing for hazardous noise environments is an important tool in hearing conservation. Visual examination of an earplug or earmuff alone is not sufficient to know whether protection is being provided to the worker. Everyone has a uniquely shaped head, pinna, and ear canal. Fit testing allows the employer to document that the employees have received counseling and training and demonstrated the ability to properly wear hearing protection. Finally, the hearing conservationist must recognize that the management should reinforce good practices at a workplace.

*Disclaimer: The findings and conclusions in this report are those of the authors and do not represent any official policy of the Centers for Disease Control and Prevention, The National Institute for Occupational Safety and Health, or the Environmental Protection Agency. Mention of company names and products does not constitute endorsement by CDC, NIOSH, or the EPA.*

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