NOISE AND HEARING CONSERVATION

DAVID C. BYRNE, PH.D., CCC-A AND KEVIN L. MICHAEL, PH.D.

1 INTRODUCTION

Exposure to high-level noise and the resulting effect of occupational hearing loss is a common problem across nearly all industrial sectors. High noise levels also interfere with verbal communication and warning signals, which can have a significant impact on safety and work performance. In addition, noise can be considered a source of stress for workers, producing unwanted physiological and psychological effects that can lead to a degraded quality of life.

Typically, noise-induced hearing loss develops slowly and usually goes unnoticed until a significant impairment has occurred. Fortunately, occupational hearing loss is nearly always preventable. Preventing noise-induced hearing loss benefits the employer as well as the individual employees. An effective hearing loss prevention program promotes good labor–management relations, which can lead to increased morale and productivity. Employers enjoy the benefits of reduced medical expenses and worker compensation payments, and employees can expect to maintain their hearing health into their retirement years.

1.1 Terminology

This section defines terms that are useful in discussions related to the study of noise and hearing loss.

Absorption coefficient (α). The ratio of the acoustical energy absorbed by a surface to the acoustical energy incident upon that surface. The result will be a value between 0.0 and 1.0, which also can be considered as a percentage between 0% and 100%.

Ambient noise. The overall composite of sounds (both pleasant and unpleasant) in an environment.

Amplitude. An objective measure of the quantity or amount of sound generated by a source, generally described by the sound power or sound pressure level measured at a specific location.

Anechoic room. A room constructed with very absorptive interior surfaces that do not reflect sound energy, and therefore prevent sound build-up or "echoes" (i.e. nearly 100% of the sound is absorbed when it makes contact with the walls, floor, or ceiling). Any sound generated within an anechoic room is referred to as being in a free field (see definition).

Attenuation. Reduction in amplitude (measured in decibels) of a sound wave as it travels away from the source or as the sound wave passes through a material (e.g. hearing protector) that reduces the strength of the original sound wave.

Audiogram. A recording or graph of an individual's hearing levels referenced to a statistically normal sound pressure level as a function of frequency.

Audiometer. An instrument for measuring hearing thresholds.

Continuous noise. Noise with relatively small fluctuations in level within the measurement period.

Decibel (dB). A dimensionless unit that describes the logarithm of the ratio of two power-related quantities. It is normally defined as 10 times the logarithm of the ratio of a measured quantity to a reference quantity. When measuring sound, different reference values are used, depending on whether sound power, sound intensity, or sound pressure is being measured.

Patty's Industrial Hygiene, Seventh Edition. Edited by Barbara Cohrssen.

dB(A). See sound level, A-weighted.

dB(C). See sound level, C-weighted.

Diffuse sound field. A sound field with sound pressure levels that are essentially the same throughout and the sound waves do not appear to come from a single direction.

Effective sound pressure. The sound pressure at a given location, derived by calculating the root mean square (rms) value of the instantaneous sound pressures measured over a period of time at that location.

Exchange rate. The number of decibels that, when a sound level is increased by this amount, gives an equivalent noise exposure when the exposure duration is halved. Likewise, when a sound level is decreased by the number of decibels specified by the exchange rate, an equivalent exposure will result if the exposure time is doubled.

Free field. A sound field that exists in a homogeneous isotropic medium, such as an open outdoor area without boundaries. In a free field, sound radiated from a source can be measured accurately without influence from unwanted reflections. True free field conditions are rarely found, except in specially designed anechoic test chambers.

Frequency (f). An objective description of the rate at which complete cycles of high- and low-pressure regions are produced by a sound source, measured in Hertz (Hz). Subjectively, frequency is often referred to as "pitch," although there is not an exact correlation between the two terms.

Hertz (Hz). A unit of measurement for frequency, indicating the number of complete waves or cycles that occur in a one-second time period.

Impulse noise. Noise that is characterized by a sharp rise and rapid decay in sound level, with the total duration lasting generally less than one second. Impulse noise is created by an explosion or discharge of a firearm. The related term impact noise is used to describe the collision of two moving objects, such as hammering or stamping operations.

Infrasonic. Frequencies lower than those of audible sound (i.e. below 20 Hz for human ears).

Insertion loss (IL). The difference in sound pressure levels measured at a particular location before and after an acoustical treatment is installed. $\mathrm{IL} = L_{p0} - L_{p1}$, where L_{p0} is the sound pressure level without the attenuating device, and L_{p1} is measured at the same location with the treatment in place.

Level (L_x). The value of a quantity (x) when converted into decibels (e.g. sound pressure level (L_p), sound power level (L_W), sound intensity level (L_I), etc.). The letter L indicates that the value is being described in terms of a decibel level, and the subscript denotes the type of quantity under consideration.

Loudness. An observer's subjective impression of a sound's amplitude. Although a high-intensity sound wave is perceived as being louder than a wave of lower intensity, an exact linear relationship does not exist, and the relation between loudness and intensity is not the same for all individuals.

Noise. The terms noise and sound are often used interchangeably; however, *sound* is normally used to describe useful communication or pleasant audible signals (e.g. music), whereas *noise* is frequently considered as dissonance or unwanted sound.

Noise reduction (NR). The difference in sound levels measured on either side of a noise-reducing barrier. $\mathrm{NR} = L_{p1} - L_{p2}$, where L_{p1} is the sound pressure level on one side, and L_{p2} is the sound pressure level on the other side.

Noise reduction coefficient (NRC). The arithmetic average of the sound absorption coefficients of a material at 250, 500, 1000, and 2000 Hz.

Noise reduction rating (NRR). A single-number indication of a hearing protector's overall noise reduction capability (in dB).

Octave Band. A frequency bandwidth that has an upper band-edge frequency (approximately) equal to twice its lower band-edge frequency.

Pascal (Pa). A unit of pressure equal to one Newton per square meter (N/m^2).

Peak sound pressure level. The maximum instantaneous level of sound that occurs over any specified period of time.

Period (T). The time (in seconds) required for one complete cycle of pressure change to take place (hence the period is the reciprocal of the frequency).

Pink noise. A broadband noise whose amplitude decreases 3 dB per octave as frequency increases, maintaining an equal amount of acoustic energy per octave band. It is often produced by filtering a white noise and has a more low-frequency emphasis than white noise.

Pitch. The auditory sensation that depends primarily on frequency but also on the pressure and waveform of the sound stimulus.

Pure tone. A sound wave consisting of a single frequency.

Resonance. Enhancement in the response of a mechanical system to a periodic driving force when the driving frequency is equal to the natural undamped frequency of the system. A system is in resonance when any change in the frequency of forced oscillation causes a decrease in the response of the system.

Reverberation. The buildup of sound in a room due to reflections from the floor, walls, and ceiling. The reverberation time is the time required (after the source is turned off) for the sound level to decay 60 dB from its steady-state level.

RMS sound pressure. The square root of the mean of the squares of the instantaneous values of the measured sound pressure (see effective sound pressure).

Sound. Pressure fluctuations propagating through a physical medium such as air or water. Sound is perceived by the human ear as a pressure wave superimposed upon the ambient air pressure.

Sound intensity. The average rate at which acoustic energy is transmitted through a unit area normal to the direction of propagation. The units used for sound intensity are W/m^2. Sound intensity is also expressed in terms of a sound intensity level (L_I) in decibels, referenced to $10^{-12}\,W\,m^{-2}$.

Sound power. The total acoustic energy radiated per second by a source. Sound power is normally expressed in terms of a sound power level (L_W) in decibels. $L_W = 10\ \log(W/W_{ref})$, where W is the sound power in question, and W_{ref} is the standard reference power of 10^{-12} W.

Sound pressure. Oscillation of a sound wave above and below atmospheric pressure. Sound pressure level (L_p) is the rms sound pressure measured at a certain distance from a source with respect to the standard reference pressure of 20 µPa (20×10^{-6} Pa). $L_p = 20\ \log(p/p_{ref})$, where p is the sound pressure in question, and p_{ref} is the standard reference pressure, which closely corresponds to the softest sound a normal-hearing person can detect. The abbreviation SPL can be used interchangeably with L_p to denote sound pressure level.

Sound level, A-weighted; dB(A). The sound pressure level measured with the A-weighting network on a sound level meter.

Sound level, C-weighted; dB(C). The sound pressure level measured with the C-weighting network on a sound level meter.

Spectrum. A distribution or range of frequencies. When performing frequency analysis, a sound may be divided into octave band, third octave band, or narrowband spectra.

Speed of sound (c). The rate at which sound waves travel, depending on the density and elasticity of the medium. The speed of sound is usually considered to be constant under normal temperature and atmospheric conditions; for example, the velocity of sound is approximately $343\,m\,s^{-1}$ ($1130\,ft\,s^{-1}$) in air at 68°F, $1500\,m\,s^{-1}$ ($4921\,ft\,s^{-1}$) in water, and $6000\,m\,s^{-1}$ ($19\,685\,ft\,s^{-1}$) in steel.

Threshold of hearing. The level of sound (which is different for various frequencies) that elicits the sensation of hearing 50% of the time; the softest sound a person can hear.

Time-weighted average (TWA). A single value for noise level obtained by averaging all of the different sound levels that a worker is exposed to during the workday and normalizing that average to eight hours. The TWA represents that constant noise level in dB(A) that has the same severity over eight hours as the exposure to the actual workday noise.

Transmission loss (TL). The amount of attenuation (in decibels) provided by a wall or panel, as measured in a laboratory. TL is defined as 10 times the logarithm (to the base 10) of the ratio of the incident acoustic energy to the acoustic energy transmitted through a sound barrier.

Ultrasonic. Frequencies higher than those of audible sound (i.e. above 20 000 Hz for human ears).

Wavelength (λ). The length (in feet or meters) of one complete sound wave. Wavelength is calculated from known values of the frequency (f) and speed of sound (c) by $\lambda = c/f$.

White noise. A broadband sound spectrum with essentially equal energy at each frequency within a specified frequency range.

2 PHYSICS OF SOUND

Sound results from oscillations in pressure in any "elastic" medium such as air, water, solids, and so on, that effectively couples the sound source with the ear. When sound is transmitted through air, it is usually described in terms of variations in pressure that alternate above and below atmospheric pressure. These pressure changes are produced when vibrating objects (sound sources) cause regions of high and low pressure that propagate from the sound source. The characteristics of a particular sound depend on the rate at which the sound source vibrates, the amplitude of the vibration, and the properties of the conducting medium.

2.1 Units for Noise Measurements

2.1.1 Sound Pressure and Sound Pressure Level

The range of sound pressures encountered in many acoustical environments is usually very wide. Sound pressures as high as those produced by jet engines (about 20 Pa) are found in some work areas, whereas sound pressures down to the threshold of hearing (approximately 0.00002 Pa) are used for audiological testing. To cover this wide range of sound pressure with a reasonable number of scale divisions and to provide a scale that responds more closely to the response of the human ear, a logarithmic scale is used. This logarithmic notation was termed the Bel, in honor of Alexander Graham Bell. The Bel was found to be too large of a unit for practical use, so one Bel was subdivided into 10 smaller units, and the prefix "deci" was added to form *decibel*. (*Note*: decibel and the plural decibels are both abbreviated as dB.)

TABLE 1 Relation between sound pressure and sound pressure level.

Sound pressure (Pa)	Sound pressure level in dB re: 20 μPa	Sound environment (Examples)	Subjective description
200	140	Near jet engine	Painful
	130	Pneumatic chipper	
20	120	Plant air compressor room	Uncomfortably loud
	110	Automatic punch press; jackhammer	
2	100	Chainsaw; snowmobile; outboard motor	Very noisy
	90	Construction site; noisy urban area	
2×10^{-1}	80	Curbside of busy street; school cafeteria	Loud
	70	Loud radio; vacuum cleaner	
2×10^{-2}	60	Restaurant; department store	Moderate
	50	Conversational speech; typical office	
2×10^{-3}	40	Residential area at night	Quiet
	30	Living room	
2×10^{-4}	20	Background in TV studio	Faint
	10	Rustle of leaves	Very faint
2×10^{-5}	0	Normal threshold of hearing	

Any time the word *level* is used in acoustics, decibel notation is implied. By definition, the decibel is a dimensionless unit and is related to the logarithm of the ratio of a measured quantity to a reference quantity. Decibel notation sometimes causes confusion because it is often associated with different reference quantities. Acoustic intensity, acoustic power, hearing thresholds, electric voltage, electric current, electric power, and sound pressure level may all be expressed in decibels, each having a different reference. The decibel has no meaning unless a reference quantity is specified, or the reference quantity is understood from the context in which it is being used.

Most sound-measuring instruments are calibrated to provide a reading of rms sound pressure in decibels. The decibel reading taken from such an instrument is called the sound pressure level. Sound pressure level is denoted by the symbol L_p, where the capital letter L represents a decibel *level*, and the subscript p indicates sound pressure. The term "level" is used because the measured pressure is at a particular level above a given pressure reference. For sound measurements in air, 0.00002 Pa (or equivalently, 20 μPa) typically serves as the reference sound pressure (p_{ref}). This reference is an arbitrary pressure chosen many years ago as an approximation of the normal threshold of human hearing at 1000 Hz. Because the eardrum responds to the intensity of the sound wave, and since intensity is proportional to the pressure squared, sound pressure levels are calculated from the square of the sound pressures. Mathematically, L_p is written as follows:

$$L_p = 10 \log \left(\frac{p}{p_{ref}} \right)^2 \text{ dB} \qquad (1)$$

where p is the measured rms sound pressure, p_{ref} is the reference sound pressure, and the logarithm is base 10. Utilizing the properties of logarithms, this equation is commonly rewritten as

$$L_p = 20 \ \log \left(\frac{p}{p_{ref}} \right) \text{ dB} \qquad (2)$$

Using this form of the equation for L_p sometimes causes confusion regarding the multiplication factor of 20 in front of the logarithm. This confusion can be eliminated by an understanding that the basic definition of the decibel is based on power-related quantities (e.g. intensity), and power is proportional to the square of the pressure (i.e. power $\propto$ pressure^2). Table 1 shows the relationship between sound pressure (in Pa) and sound pressure level (in dB re: 20 μPa). This table illustrates the advantage of using the decibel scale rather than the wide range of direct pressure measurements – the range of decibel values is more compact and manageable. Using decibel notation, a doubling of sound pressure is equivalent to a 6 dB increase in level, and a 10-fold increase in pressure raises the level by 20 dB.

2.1.2 Sound Power and Sound Power Level

Sound power was briefly mentioned in the previous section; it is defined as the amount of acoustic energy that is produced per second by a noise source. Sound power is measured in watts and is represented by the symbol W. Power units are also frequently described in terms of decibel levels because of the wide range of powers covered in practical applications.

Sound power level (L_W) is defined by

$$L_w = 10 \log\left(\frac{W}{W_{ref}}\right) \text{dB} \quad (3)$$

where W is the power of the source in watts and W_{ref} is the standard reference power of 10^{-12} W. In air, this reference corresponds to the reference pressure of 20 μPa used for sound pressure levels.

For most hearing conservation purposes, familiarization with the concepts of sound pressure and sound pressure level is sufficient. However, it is important to understand that the measured sound pressure is actually a result of the amount of sound power generated by a source. In other words, there is a cause-and-effect relationship between sound power and sound pressure: Sound power is the "cause" of a noise, and sound pressure is the resulting "effect." Conversion from power to pressure (or vice versa) is routinely performed when developing engineering noise control treatments. Sound pressure levels can be predicted (calculated) from known sound power levels, depending on the environment in which the sound source is located, the exact distance from the source, as well as other variables.

2.1.3 Sound Intensity and Sound Intensity Level

Sound intensity at any specified location may be defined as the average acoustic power passing through a unit area, in the direction of wave propagation. For a spherical or free-progressive sound wave, the intensity may be expressed by

$$I = \frac{p^2}{\rho c} \text{W/m}^2 \quad (4)$$

where p is the rms sound pressure, ρ is the density of the medium, and c is the speed of sound in the medium. The unit of sound intensity is W/m^2. Sound intensity, like sound power and sound pressure, covers a wide range, and it is often desirable to use decibel levels to compress the measuring scale. Sound intensity is converted into decibels through the use of the following equation:

$$L_I = 10 \log\left(\frac{I}{I_{ref}}\right) \text{dB} \quad (5)$$

where I is the measured intensity at some given distance from the source and I_{ref} is the standard reference intensity of $10^{-12}\,\text{W m}^{-2}$.

As mentioned previously, once the sound power level of a source is known, then the resulting sound pressure level can be predicted for any particular environment where that source may be placed. Unfortunately, there is no way to measure sound power directly, although certain instruments can measure sound intensity, which is simply the amount of acoustic power radiated over a given surface area. Sound intensity instruments make it possible to determine the sound power of a source *in situ*, sometimes eliminating the need for special-purpose acoustical test facilities such as anechoic rooms and reverberation chambers to determine sound power.

2.1.4 Combining Sound Levels

It is often necessary to combine sound levels – for example, individual frequency band levels may be combined to obtain the overall or total sound pressure level of a particular noise. Another example is the estimation of total sound pressure level resulting from adding a machine of known noise spectrum to a noise environment of known characteristics. However, because decibels are logarithmic quantities, they cannot be combined by simply summing the individual sound pressure levels. Instead, the actual acoustic intensities represented by the logarithmic expressions must first be determined by taking the antilogs of the level readings. Then the intensities can be added together, and the resulting level is determined from the logarithm of that sum. An equation commonly used for summing any number of individual sound levels is

$$L_p(\text{total}) = 10 \log(10^{L_{p1}/10} + 10^{L_{p2}/10} + 10^{L_{p3}/10}) + 10^{L_{p4}/10} + \ldots \text{ dB}) \quad (6)$$

where each level to be added is arbitrarily assigned as L_{p1}, L_{p2}, and so on. An example of decibel addition using this equation follows.

Example. Add 90 dB + 95 dB + 88 dB

$$L_p(\text{total}) = 10 \log(10^{L_{p1}/10} + 10^{L_{p2}/10} + 10^{L_{p3}/10})$$
$$L_p(\text{total}) = 10 \log(10^{90/10} + 10^{95/10} + 10^{88/10})$$
$$L_p(\text{total}) = 10 \log((1 + 3.16 + 0.63) \times 10^9)$$
$$L_p(\text{total}) = 10 \log(4.79 \times 10^9)$$
$$L_p(\text{total}) = 96.8 \text{ dB}$$

Alternatively, a decibel addition table may be used to determine the resultant level when two or more individual levels are combined (Table 2). To use a decibel addition table, first determine the difference between the first two levels to be added, and then find where this number falls in the left-hand column of the table. Next, move across to the right-hand column and locate the number that corresponds to this difference. Finally, determine the total sound pressure level by adding the value in the right-hand column to the higher of

TABLE 2 **Table for combining decibel levels of sounds with random frequency characteristics.**

Numerical difference between the two levels to be added (dB)	Amount (in dB) to be added to the higher of the two levels
0.0–0.1	3.0
0.2–0.3	2.9
0.4–0.5	2.8
0.6–0.7	2.7
0.8–0.9	2.6
1.0–1.2	2.5
1.3–1.4	2.4
1.5–1.6	2.3
1.7–1.9	2.2
2.0–2.1	2.1
2.2–2.4	2.0
2.5–2.7	1.9
2.8–3.0	1.8
3.1–3.3	1.7
3.4–3.6	1.6
3.7–4.0	1.5
4.1–4.3	1.4
4.4–4.7	1.3
4.8–5.1	1.2
5.2–5.6	1.1
5.7–6.1	1.0
6.2–6.6	0.9
6.7–7.2	0.8
7.3–7.9	0.7
8.0–8.6	0.6
8.7–9.6	0.5
9.7–10.7	0.4
10.8–12.2	0.3
12.3–14.5	0.2
14.6–19.3	0.1
19.4–∞	0.0

the two levels being added together. If more than two levels are to be added, any two may be combined first, then that result should be added to the third level, and the resultant of the three sources added to the next level, and so on, until all levels have been summed. Although the order in which the levels are added usually does not matter, one typically starts with the highest levels first. This is done because once the difference between two levels is 10 dB or greater, the addition process can be discontinued since the addition of smaller values does not add significantly to the overall total. The use of a decibel addition table may be illustrated by the following example.

Example. Add 85 dB + 87 dB + 90 dB + 71 dB

Starting with the highest levels, the difference between 90 and 87 dB is 3 dB. Locating this value in the left-hand column of Table 2 and looking across to the right side of the table, it can be seen that 1.8 dB should be added to the higher level, which gives 91.8 dB. Next, the difference between 91.8 and 85 dB is 6.8 dB, so according to Table 2, 0.8 dB should be added for a total of 92.6 dB. Finally, due to the large (i.e. greater than 10 dB) difference between 92.6 and 71 dB, nothing more needs to be added, and the total sound pressure level from summing all four levels is 92.6 dB.

Most industrial noises have random frequency characteristics and can be combined as described in the preceding paragraphs. However, in the few cases when noises have a certain "pitch" or major pure tone component(s), these calculations are not accurate, and phase relationships must be considered. For example, with no phase difference between two identical pure tone sources, adding these two pure tones produces a level 6 dB greater than the value of either single level. At other phase differences, the resultant level is somewhat less than 6 dB greater than either level. With a phase difference of 180°, complete cancellation of sound occurs. The fact that one sound can actually cancel out another is a very important principle in acoustics, as it forms the basis for active noise control (also referred to as active noise reduction (ANR) or noise cancellation technology).

2.2 Frequency Analysis

The most common frequency bandwidth used for industrial noise measurements is the octave band. An octave is the interval between two frequencies where the higher frequency is twice the value of the lower frequency. The width of each octave band is twice as wide as the next lower octave band. Octave bands are commonly used for measurements directly related to the effects of noise on the human ear, and for general noise control purposes, because they provide a useful amount of information with a limited number of measurements.

Frequency bandwidths narrower than octave bands are used when more specific characteristics of a noise source are required (e.g. for identifying a particular noise source among a background of other sources). One-third octave and narrower bands are used for these purposes. A one-third octave bandwidth is obtained by dividing an octave band into three smaller parts. Other bandwidths such as 1/6, 1/12, and 1/24-octave are available on some measuring instruments.

It should be noted that the upper and lower band-edge frequencies describing a frequency band do not imply abrupt cut-offs at these frequencies. When depicted on a graph, instead of being comprised of simple straight line segments, the frequency passband is somewhat "rounded" at the lower and upper edges, and taper off gradually rather than instantaneously. Therefore, band-edge frequencies are conventionally defined as the "half-power" or "3 dB down" points. Performance requirements for filters are contained in the American National Standard Specification for Octave Band and Fractional-Octave Band Analog and Digital Filters (ANSI S1.11) (1). See Section 5.1 for an explanation of how noise-measuring instruments use these filters when analyzing sounds.

3 THE EAR

Normal human ears respond to a remarkably wide frequency range that covers approximately 20–20 000 Hz. As might be expected, the characteristics of any individual ear are extremely complex, and large differences exist among the population. An ear's response characteristics may change as a result of physical or mental conditions, ambient sound level, medications, environmental stresses, diseases, and other factors.

A normal healthy human ear is also capable of detecting a remarkable range of sound levels. It is sensitive to very low sound pressures that produce a displacement of the eardrum no greater than the diameter of a hydrogen molecule. At the other extreme, it can receive sounds whose sound pressures are more than one million times greater than the lower threshold value; however, exposure to high-level sounds may cause temporary or permanent damage to the hearing mechanism.

3.1 Anatomy and Physiology of the Ear

As shown in Figure 1, the ear can be divided into three sections: the *outer* or *external ear*, the *middle ear*, and the *inner ear* (2). Sound waves impinging on the eardrum cause it to vibrate, and these vibrations are transmitted to the fluid-filled inner ear that contains the nerve endings by which aural information is detected. The acoustic (auditory) nerve carries these impulses to the hearing center in the brain.

3.1.1 Outer Ear

Although the auricle is what most people think of when the term "ear" is used (Figure 2), it plays only a limited role in the hearing process. To a certain extent, the auricle helps direct high-frequency sounds into the ear canal, assisting the hearing system in determining the direction from which a sound originates. Sound waves enter the ear canal and travel toward the eardrum, which is the dividing point between the outer and middle ear regions.

Typical ear canals are about 1 in. long and approximately 1/4 in. in diameter. They are seldom as straight as depicted in Figures 1 and 2, and the shape and size of ear canals differ significantly among individuals (and even between ears of the same individual). The ear canal is closed at one end by the eardrum; therefore, from an acoustical viewpoint, it can

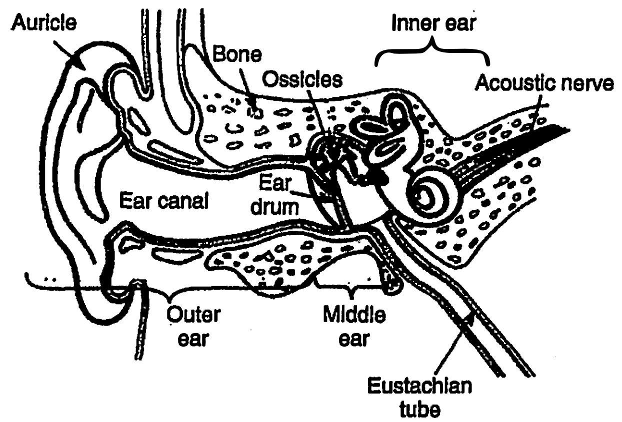

FIGURE 1 Cross-section of the ear showing the outer (external), middle, and inner ear configurations.

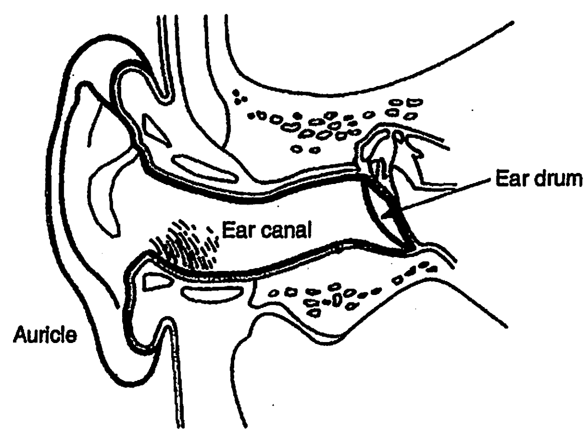

FIGURE 2 The outer or external ear.

be modeled as a cylinder with a quarter-wavelength resonance of about 3000 Hz. This resonance effectively increases the sensitivity of the ear in the higher frequencies around 3000 Hz.

Glands producing cerumen (earwax) are located in the ear canal. Normally, cerumen gradually flows outward, toward the entrance of the ear canal, carrying with it any foreign particles that may accumulate in the canal. The normal progression of wax may be interrupted by changes in body chemistry that can cause excessive wax to be produced, or the wax may become hard or "impacted." At times, the cerumen may build up to the point of totally occluding the canal, and a temporary loss of hearing will result. Any buildup of wax deep within the ear canal should be removed very carefully (preferably by an experienced healthcare provider), to prevent damage to the eardrum and middle ear structures.

The surface of the external ear canal is extremely delicate and easily irritated. Cleaning or scratching with fingernails or other sharp objects can break the skin and cause a

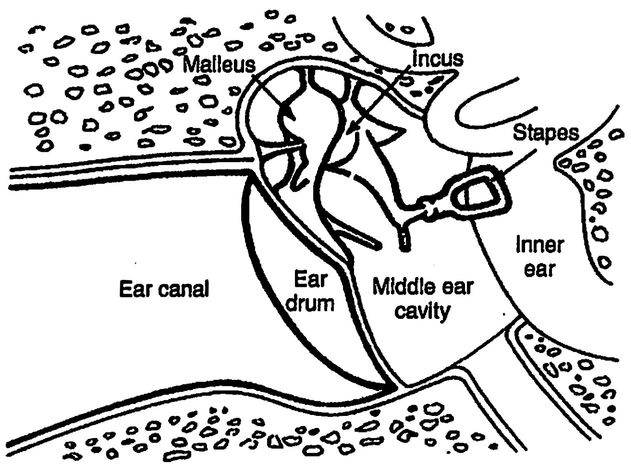

FIGURE 3 The middle ear.

very painful and persistent infection. Infections can cause swelling of the canal walls and, occasionally, a loss of hearing if the canal swells shut. An infected ear canal should be given prompt attention by a physician.

3.1.2 *Middle Ear*

The air-filled space between the eardrum and the inner ear is called the middle ear (Figure 3). The middle ear contains three small bones or ossicles that mechanically connect the eardrum to the oval window of the inner ear. Sound energy is converted into mechanical energy by the middle ear system.

The eardrum is a very thin and delicate membrane that responds to very low sound pressures at the lower threshold of hearing, yet it seldom suffers physical damage from routine exposure to continuous high-level noises. Although an eardrum may be damaged or perforated by an explosion or a rapid change in ambient air pressure, most common steady-state noise exposures do not produce a noticeable effect on the eardrum itself.

The ossicles (three smallest bones in the human body) in the middle ear are commonly known as the hammer, anvil, and stirrup, although their correct anatomical names are the malleus, incus, and stapes, respectively. These three tiny bones are connected together to form a "chain," with the handle of the malleus physically attached to the eardrum. Therefore, any movement of the eardrum is transmitted directly to the bones of the middle ear. The construction of the eardrum/ossicle system forms a mechanical advantage or lever action, which is necessary to match the impedance of air in the ear canal with the fluid in the adjacent inner ear structure.

If the eardrum is ruptured, it may or may not heal by itself. Furthermore, when an eardrum is ruptured the attached middle-ear ossicles may be dislocated. Anytime an eardrum injury is known or suspected, the individual should be referred to a physician. Surgical procedures are usually successful in repairing eardrum tears or perforations. Dislocated ossicles may be realigned, or a prosthesis may be inserted, resulting in little or no permanent hearing loss from this type of injury.

The middle ear cavity is completely enclosed except for the small Eustachian tube that connects the middle ear to the back of the throat (Figure 1). The purpose of the Eustachian tube is to equalize the air pressure inside the middle ear space with that of the surrounding atmosphere. When flying in an airplane or when driving in mountainous territory, changes in the ambient barometric pressure are normally compensated for when the Eustachian tube briefly opens, thereby allowing air to enter or escape from the middle ear space. In this manner, the same amount of air pressure is always maintained on both sides of the eardrum.

Occasionally, the Eustachian tube will remain closed as a result of an infection or an allergy, resulting in a pressure imbalance between the middle ear and the outside air. This situation may produce a temporary loss of hearing sensitivity and extreme discomfort for the individual. Medications are often successful in remediation of this condition. Even a healthy ear may suffer a loss of hearing if the Eustachian tube becomes blocked, but this loss of hearing can often be quickly restored simply by yawning, swallowing, or chewing gum, which allows the Eustachian tube to open momentarily and restore the pressure balance.

3.1.3 *Inner Ear*

As illustrated in Figure 1, the inner ear is completely surrounded by bone; a closeup of the inner ear is shown in Figure 4. One end of the inner ear is shaped like a snail shell and is called the cochlea. The other end of the inner ear contains three semicircular loops or canals. The fluid-filled cochlea serves to detect incoming sound signals and to translate them into nerve impulses, which are then transmitted to the brain. Although they are part of the inner ear anatomy, the semicircular canals are balance organs and are not actually part of the hearing mechanism.

Mechanical energy from the middle ear is transferred to the inner ear by the stapes, whose footplate rests on the oval window of the cochlea (Figure 4). Movement of the stapes forces the oval window in and out with the dynamic characteristics of the incident sound, setting the fluid of the cochlea into motion, thereby transforming these mechanical vibrations into hydraulic energy. Thousands of hair cells located along the two-and-half turns of the cochlea detect these motions and translate them into nerve impulses. A sound is "heard" when this neural energy is sent along the acoustic or eighth cranial nerve up to the auditory centers of the brain.

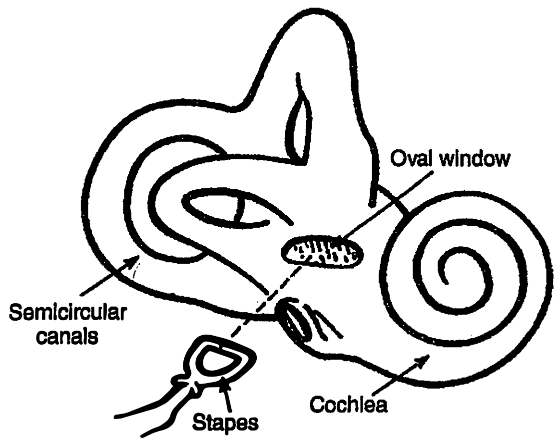

FIGURE 4 The inner ear.

3.2 How Noise Damages Hearing

A noise-induced hearing impairment results from damage to the hair cells located in the cochlea. This type of hearing loss is called a sensorineural hearing loss, which is not reversible and cannot be corrected by conventional medical or surgical procedures. Initially thought to be the result of a mechanical overload of the delicate inner ear structures, current research suggests that noise exposure triggers the formation of destructive molecules called free radicals, which cause hair cell death. In the future, medical treatments such as antioxidants may be used to either prevent or reverse hair cell damage.

Development of a noise-induced hearing loss depends on the level and frequency characteristics of the noise, the duration of exposure, and the susceptibility of the individual (3). Initially, the loss may be temporary, after which the original hearing sensitivity is usually restored within a matter of hours. However, in some cases, temporary losses may last for days or weeks. Permanent losses result when these temporary losses do not recover completely. The terms temporary threshold shift (TTS) and permanent threshold shift (PTS) are used to describe these conditions. Individual susceptibility to noise-induced hearing loss can be quite variable within the population, and the reasons for these variations remain largely unknown.

For commonly encountered noise exposures, hearing loss generally occurs first in the frequency range from 3000 to 6000 Hz, with most affected persons showing a loss in sensitivity at 4000 Hz. This is often referred to as a 4000 Hz "notch" due to the shape of the configuration when plotted on an audiogram. If high-level exposures are continued, the loss of hearing generally increases around 4000 Hz and spreads to adjacent frequencies. For noise exposures having significant components concentrated in narrow frequency bands below 4000 Hz, impairments usually are found about one-half to one octave above the predominant exposure frequencies.

Noise-induced hearing loss is usually an insidious problem, because a person does not necessarily have to experience pain or even be immediately aware that significant hearing damage has taken place. Alternatively, the damage may occur instantaneously, depending upon the noise characteristics and exposure circumstances. Generally, impulsive or impact noises are most likely to produce significant losses with short exposure periods, and steady-state continuous noises are responsible for impairments that develop over a long period of time. In addition, workers suffering from noise-induced hearing loss may hear continuous "ringing," "chirping," or "buzzing" noises in their ears, which is called tinnitus.

Even after a significant amount of damage, a person with noise-induced hearing loss is still able to hear low-frequency vowel sounds very well, but the high frequencies in speech (i.e. consonants) are not clearly heard. Perceived loudness levels may be nearly normal, but intelligibility may be poor because the consonant sounds carry most of the distinguishing characteristics of speech, and degraded high-frequency hearing will cause misunderstanding or confusion between similar-sounding words. A noise-induced hearing loss becomes particularly noticeable when verbal communication is attempted in noisy or reverberant areas. Speech is "masked" or obscured most effectively by background noises containing the speech frequencies, such as the sounds encountered in a crowd of people where many are talking simultaneously.

In addition, a loss of functional capacity may be attributed to a phenomenon termed cochlear synaptopathy or "hidden hearing loss." Individuals may have normal results on their annual audiogram; however, physical damage to connections between auditory nerve fibers and sensory cells may be present. This may explain decreases in speech recognition ability – especially in noisy or difficult listening situations – without any other evidence of a hearing impairment. Future research may reveal that noise exposures that did not produce a PTS (and therefore were traditionally considered to be safe) may not be safe after all (4).

3.3 Ototoxic Agents

The unfortunate ototoxic side effects of certain medicinal drugs have been recognized for a long time. Likewise, the ototoxicity of chemicals found in the environment from contaminants in air, food, or water, and in the workplace has become a concern for health professionals. Hearing loss from administering ototoxic drugs often has its onset in the high-frequency range and appears as irreversible and bilaterally symmetrical. These same symptoms are common to noise-induced hearing losses; consequently, some hearing losses may be erroneously attributed exclusively to noise.

Certain toxins such as solvents, metals, asphyxiants (e.g. carbon monoxide), PCBs, and pesticides can reach the inner ear through the bloodstream and may cause damage to some of the inner ear structures and functions. The damage is not always restricted to the cochlea; it can also reach portions of the central auditory system (5, 6). The onset latency, site of lesion, injury mechanism, and extent of ototoxic damage from these toxins vary according to various risk factors such as the type of chemical, interactions with other agents, and exposure level/duration.

Noise exposure may potentiate or interact synergistically with several toxins. For this reason, the detection and diagnosis of an ototoxic effect can be difficult. Research has prompted the proposal of new guidelines and standards on hearing loss prevention programs where chemical agents might present an additional hearing loss risk. The European Agency for Safety and Health at Work and the Nordic Expert Group have published comprehensive evaluations of ototoxic substances and have documented (i) disorders associated with workplace exposure to noise and ototoxic chemical substances, including qualitative information on noise–chemical interactions and (ii) key policies from specific countries and multinational agencies (7, 8). In the United States, the American Conference of Governmental Industrial Hygienists (ACGIH) recommends periodic hearing tests for workers exposed to noise and these substances: carbon monoxide, hydrogen cyanide, lead, and solvent mixtures. In addition, periodic audiograms are advised for exposures to ethylbenzene, styrene, toluene, or xylene (9). The Occupational Safety and Health Administration (OSHA) in conjunction with the National Institute for Occupational Safety and Health (NIOSH) developed a Safety and Health Information Bulletin to advise employers on how to control exposures and limit the effects of ototoxic substances (10). This document provides information and guidance for preventing hearing loss that is caused by workplace chemicals and noise exposure. Recommendations include identifying potential ototoxicants in the workplace, replacing a hazardous chemical with a less toxic chemical, using engineering controls (e.g. enclosures, ventilation), and using the correct personal protective equipment to guard against respiratory and dermal exposures.

4 HEARING MEASUREMENT

The only way to monitor the overall effectiveness of a hearing conservation program is to periodically check the hearing of all persons exposed to potentially hazardous noise. Hearing thresholds must be obtained for each ear, in order to determine whether employees are losing any of their hearing ability. Hearing loss due to medical conditions unrelated to occupational noise exposure may also be identified from periodic hearing tests.

To ensure the accuracy of hearing tests, audiometric equipment must be periodically calibrated, a quiet test environment must be maintained, and a well-trained audiometric technician or hearing conservationist must perform the hearing tests. Requirements for audiometer performance and for the background noise limits in test rooms have been specified in standards published by the American National Standards Institute (ANSI S3.6 and ANSI S3.1) (11, 12). Guidelines for training Occupational Hearing Conservationists have been established by the Council for Accreditation in Occupational Hearing Conservation (CAOHC) (13).

4.1 Audiometers

An audiometer is the instrument used for measuring pure tone, air-conduction hearing thresholds. It may be designed for manual or automatic operation; most of the newer audiometers are microprocessor-based and can be used in conjunction with a computer for data storage.

The American National Standard Specification for Audiometers provides the specifications that audiometers must meet to provide accurate hearing threshold information (ANSI S3.6) (11). Strict attention should be given to equipment calibration because instrumentation inaccuracies are seldom obvious, and there is a strong tendency to automatically accept dial readings as being accurate. Modern audiometers are much more stable than their older counterparts; however, they may lose their specified accuracy if not cared for properly. Earphones are particularly susceptible to damage from rough handling. Dust or dirt on electrical contacts, jack panels, or switches may produce electrical noise or intermittent operation. The normal aging of components and exposure to temperature extremes may also cause changes in audiometer accuracy.

OSHA requires that functional or biological calibration checks (audiograms taken on persons with known stable hearing thresholds) be performed before each day's use of an audiometer (14). Accuracy checks should also be made any time there is a reason to suspect a problem. The person used for daily biological calibration checks does not need to have perfectly normal hearing; the main consideration is that this individual's hearing thresholds do not fluctuate. A baseline hearing test is established immediately following a comprehensive or exhaustive electroacoustic calibration of the audiometer. Subsequent daily audiograms should not deviate by more than 10 dB at each frequency if the audiometer remains correctly calibrated.

Hearing sensitivity may temporarily decrease as much as 20 dB because of allergies, colds, or other causes; therefore, it is strongly recommended that at least two individuals be made available for daily functional checks. Alternatively, an "electroacoustic ear" may be used in place of a live human subject. An electroacoustic ear (sometimes called a bioacoustic simulator) is an instrument that is calibrated to take a hearing test and respond as a person would. The audiometer's headphones are placed on the instrument, and a regular hearing test is run. Test results are compared to the electroacoustic ear's baseline audiogram to determine whether a change in calibration has occurred, just as would be done for a human listener. The advantage of using an electroacoustic ear is that this instrument will always be available for daily biological calibration checks and will not respond differently on successive hearing tests.

Technicians should also check the audiometer daily using the following additional procedures:

a. Check all controls on the audiometer, and make sure all cable connections between the audiometer and jack panel are correct and secure. Visually inspect the earphones for correct headband tension, missing parts, and serviceability of the cushions. Cushions should be replaced if they are not resilient or if cracks have developed. A new acoustic calibration is not required when replacing earphone cushions.
b. Straighten the earphone cords so that there are no sharp bends or knots. Cords with worn or cracked insulation should be replaced. With the audiometer set to 1000 Hz and 60 dB, test the earphone cords for electrical continuity by listening while gently manipulating/bending the cords along their length. Typical trouble spots are where the cord connects to the earphones, or at the other end where the cord attaches to the jack. Any static, intermittency, or change in test tone indicates a need for new earphone cords. A complete acoustical calibration is not required when replacing only the earphone cords.
c. With the frequency set to 1000 Hz, check the linearity of the hearing level attenuator by listening to the earphone while slowly increasing the hearing level, starting at 0 dB. Each 5-dB step should produce a steady increase in loudness without changes in tone quality or any other audible extraneous noise.
d. With the audiometer set to 1000 Hz and 60 dB, test the operation of the tone interrupter by listening to the earphones and operating the interrupter several times. No audible noises (such as clicks or scratches) or changes in tone quality should be heard when the interrupter is operated.
e. With a steady 60 dB tone coming from the right earphone, cover that earphone with the palm of your hand and listen for extraneous noises from the left earphone. No tones or noises should be heard in the nontest earphone. Repeat this procedure with the tone coming from the left earphone.
f. With the hearing level set to 60 dB, check for the presence of a tone at each test frequency. There should be a noticeable difference between each frequency, without any wavering or abrupt changes in tone quality.

According to Appendix E in the OSHA Hearing Conservation Amendment, audiometer calibration should be checked "acoustically" once per year, or sooner if the functional check indicates a deviation of 10 dB or more between the dial setting and actual output of the audiometer. The two main checks performed during an acoustic calibration are a sound pressure output check and a linearity check. When any of the measured sound levels deviate by ±3 dB at any test frequency between 500 and 3000 Hz, 4 dB at 4000 Hz, or 5 dB at 6000 Hz, an exhaustive calibration is *advised*. An exhaustive calibration is *required* if the deviations are 15 dB or greater at any test frequency.

An exhaustive calibration is typically done by an authorized repair service or the audiometer's manufacturer. This is the only stage at which changes to the audiometer are made, in order to exactly meet the requirements in the ANSI S3.6 standard. This type of comprehensive electroacoustic calibration must be performed at least every two years, regardless of whether any discrepancies have been noted in the functional or acoustical calibration checks.

4.2 Test Rooms

The sound pressure level of the background noise in rooms used for measuring hearing thresholds must be limited to prevent masking effects that cause incorrect threshold values. In particular, an individual's hearing thresholds at 500 Hz may be artificially elevated (i.e. appear worse than they really are) due to interference from the background noise. Maximum allowable octave band sound pressure levels for audiometric test rooms, as specified in Appendix D, Table D-1, of the OSHA Standard, are shown below (14):

500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
40 dB	40 dB	47 dB	57 dB	62 dB

It should be noted that the maximum background levels specified by OSHA are not low enough to permit accurate testing down to 0 dB hearing threshold level. More accurate tests can be obtained if the test room meets the background noise level criteria established in the American National Standard Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms (ANSI S3.1) (12). The ANSI S3.1 background noise levels are more stringent than those specified by OSHA and are preferred by proactive hearing conservation program managers. The lower ambient noise levels may be difficult to obtain in some noisy industrial facilities; therefore, an alternate location for the audiometric booth should be selected if the first choice is found to be above the ANSI S3.1 ambient noise limits.

After ensuring that OSHA's background noise level requirements are met, examiners should conduct subjective tests on-site to ensure that no transient noises (e.g. talking, footsteps, etc.) are audible inside the test booth. In particular, short impact-type noises may be heard even though the measured sound pressure levels are below the specified limits. Any extraneous noises may distract the person being tested and interfere with obtaining accurate hearing threshold measurements. If possible, these nuisance sounds should be eliminated, or the tests must be delayed until the nuisance sounds no longer present a problem.

The noise reduction provided by a good prefabricated audiometric test booth should be adequate when the booth is placed in a reasonably quiet area of the plant or facility. However, it is recommended that the burden of on-location performance be placed on the booth supplier, to ensure that an acceptable booth is obtained. The vendor should be willing to guarantee in writing the performance of the booth when installed at the specified test site, particularly if some on-site assembly is required. If the booth is equipped with a ventilation system, the interior noise level should remain below the limits specified for the room while the fan is operating. Attention must also be paid to proper vibration isolation for permanently installed booths. If the booth is portable (or if a mobile test van is brought on-site), background noise levels inside the booth must be checked each time the unit is moved.

In addition to the attenuation characteristics, several other factors should be considered when selecting a test room or booth. Smaller facilities with relatively few employees will only require a one-person booth, while larger programs will need a multi-station booth. The observation window and seating arrangement should provide an easy view of the subject but block the subject's view of the audiometer controls or computer screen. Access for disabled employees and emergency exit procedures should also be considered.

4.3 Hearing Threshold Measurements

Annual testing of pure tone, air-conduction hearing thresholds is performed in an industrial setting to monitor the effectiveness of the facility's hearing conservation program. Unless the test results are to be used for another

Name ______ Date ______ Recorded by ___ Employee Inital ___

History	YES	NO	Comments
Have you had a previous hearing test?			
Do you now have any trouble hearing?			
Have you ever worked in a noisy industry?			
Do you think you can hear better in your Right ear?			
or Left ear?			
Have you ever had noises in your ears?			
Have you ever had dizziness?			
Have you ever had a head injury?			
Has anyone in your family lost his hearing before age 50?			
Have you ever had measles, mumps, or scarlet fever?			
Do you have any allergies?			
Are you now taking or have you regularly taken drugs, antibiotics, or medication?			
Have you ever had an earache?			
Have your ears ever run? Right ear?			
Left ear?			
Have you been in the Military service? Describe			
Have you been exposed to any sort of gunfire? Describe			
Do you have a second job? Explain			
What hobbies do you have?			

FIGURE 5 Sample medical history form.

purpose, there is no need for detailed diagnostic information that would require the use of sophisticated audiometric techniques and/or specialized equipment. According to OSHA, testing must be done at 500, 1000, 2000, 3000, 4000, and 6000 Hz separately, for each ear. Many audiometers support the option of also testing 8000 Hz, which provides more information to characterize an individual's hearing ability and is routinely performed in clinical diagnostic testing.

The conventional technique for obtaining hearing threshold levels is referred to as the modified Hughson–Westlake method (15). In this procedure, the initial tone is presented to the subject at a level well above the anticipated threshold, and then decreased in 10 dB steps until it is no longer audible. Next, the level is increased in 5 dB steps until the patient responds. After a positive response, the tone is lowered by 10 dB and testing resumes, with the level again raised in 5 dB steps until another positive response occurs. This "up 5 dB, down 10 dB" approach is referred to as an ascending bracketing technique. The hearing threshold typically is defined as the level at which the patient responds 50% of the time. A minimum of three ascending series is required, and a fourth is necessary if the patient responds twice at a particular level and once at a lower level. Initially, audiometers were operated manually using this technique; however, microprocessor-based audiometers programmed to conduct the hearing test in a similar manner are now more commonly used.

4.4 Audiometric Records

Audiometric test records must be complete and accurate if they are to have medicolegal significance. Records should be kept in ink, without erasures. If a mistake is made in recording, a line should be drawn through the erroneous entry, and the initials of the person making the correction should be placed above the line along with the date. The original entry must not be obliterated.

Whether hand-written or maintained in a computer database, the model, serial number, and calibration dates of the audiometer should be recorded on each audiogram. Records should also be kept of periodic noise level measurements in the test booth. In addition to the individual's threshold levels, an audiogram should have space provided for the recording of pertinent medical and noise exposure information. Some typical questions asked of test subjects are given on the form depicted in Figure 5.

5 NOISE MEASUREMENT

A wide variety of measurement instrumentation is available. Some sound level meters provide only the basic measurements required by OSHA, while others provide a very wide range of functions including integration for dose and impulse noise measurements. Sophisticated measuring equipment can be used to obtain an enormous amount of data in a relatively short period of time. Even with this advanced technology, however, careful consideration of the objectives of the measurement must be made prior to equipment selection. In all cases, accurate sound level measurements require a well-trained operator and calibrated instruments.

5.1 The Sound Level Meter

A basic sound level meter consists of a microphone that converts air pressure variations into an electrical signal, an amplifier/filter, an exponential time-averaging circuit, a device to determine the logarithm of the signal, and an indicating meter or digital display. All instruments used for hearing conservation purposes should conform to the American National Standard Specification for Sound Level Meters (ANSI S1.4) (16).

The two primary classifications of sound level meters used in industrial noise monitoring are the precision (Type 1) and the general purpose (Type 2). Generally, the main difference between these instruments is simply a matter of how accurate the sound level readings are. According to ANSI S1.4, the allowable tolerances across the measurement range are approximately one decibel for Type 1 and two decibels for Type 2 instruments. Most regulations require the use of a Type 2 meter; Type 1 instruments are used when a greater degree of accuracy is required.

Two meter-response settings are usually available on a sound level meter. The "fast" response is used to follow rapid changes in level, while the "slow" response essentially slows the meter's display down and is intended to provide an averaging effect that makes widely fluctuating sound levels easier to read. The fast response uses a one-eighth second time constant, and the slow response has a time constant of one full second. Neither of these settings actually affects the signal itself; "fast" and "slow" refer only to the speed with which the display indicator on the meter moves. The OSHA noise exposure regulation states that the slow response setting is to be used for industrial noise monitoring purposes (14). When impulse or impact noise (i.e. a transient sound less than one second in duration) is present, a measurement of the true peak sound pressure level is required. Some sound level meters have an "impulse" setting; however, this is not suitable for industrial noise measurements because it is not designed to actually measure the true unweighted peak sound level.

General-purpose sound level meters are normally equipped with two filters or frequency-weighting networks, designated by the letters A and C (Table 3). Other frequency-weighting networks (e.g. B and D) have been developed but

TABLE 3 Relative response as a function of frequency for A- and C-Weighting.

Frequency (Hz)	A-Weighting (dB)	C-Weighting (dB)
10	−70.4	−14.3
12.5	−63.4	−11.2
16	−56.7	−8.5
20	−50.5	−6.2
25	−44.7	−4.4
31.5	−39.4	−3.0
40	−34.6	−2.0
50	−30.2	−1.3
63	−26.2	−0.8
80	−22.5	−0.5
100	−19.1	−0.3
125	−16.1	−0.2
160	−13.4	−0.1
200	−10.9	0
250	−8.6	0
315	−6.6	0
400	−4.8	0
500	−3.2	0
630	−1.9	0
800	−0.8	0
1 000	0	0
1 250	+0.6	0
1 600	+1.0	−0.1
2 000	+1.2	−0.2
2 500	+1.3	−0.3
3 150	+1.2	−0.5
4 000	+1.0	−0.8
5 000	+0.5	−1.3
6 300	−0.1	−2.0
8 000	−1.1	−3.0
10 000	−2.5	−4.4
12 500	−4.3	−6.2
16 000	−6.6	−8.5
20 000	−9.3	−11.2

are not used for industrial noise measurements. Readings obtained using any of these weighing scales are termed sound levels rather than sound pressure levels, and the particular weighting network used must always be indicated. The A-, B-, and C-weighting curves approximate the response characteristics of the human ear at various sound levels, and in the earliest sound level meters, they could be easily produced with a few common electronic components. Empirically, the A-weighting has been found to give a good estimation of the hearing-damage risk potential from exposure to continuous noise. Therefore, OSHA specifies that the A-weighting scale be used for industrial noise measurements (14).

Figure 6 illustrates the frequency response characteristics of the A- and C-weighting networks. A linear or flat response, also included on some sound level meters, does not apply any correction values (i.e. it weights all frequencies equally) and would correspond to the 0 dB line in Figure 6.

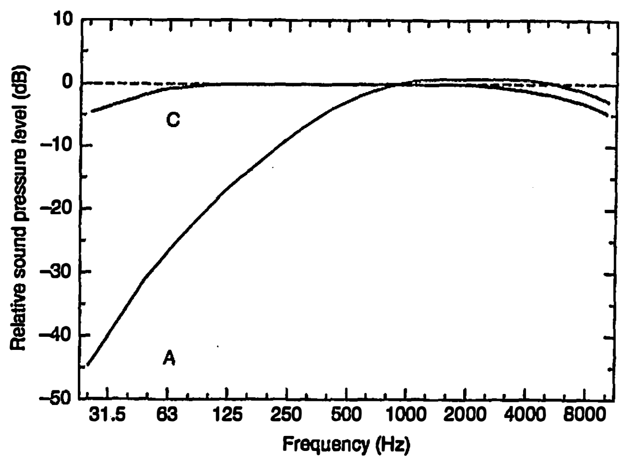

FIGURE 6 Sound level meter weighting curves.

The frequency distribution of noise energy can be estimated by comparing the levels measured with each of the frequency weightings. For example, if the noise levels measured using the A and C networks are approximately equal, it can be reasoned that most of the noise energy is above 1000 Hz, because this is the only portion of the spectrum in which the weightings are similar. On the other hand, a large difference between these readings indicates that most of the energy will be found below 1000 Hz.

The rough estimate of frequency content provided by the weighting networks of a sound level meter is not always adequate, particularly for engineering noise control work. In such cases, frequency analyzers are used. The most common types are the octave band (commonly abbreviated as 1/1), one-third (1/3) octave band, and narrower band analyzers using filters or fast Fourier transform (FFT) digital calculations. Table 4 shows the frequency range encompassed by each octave and one-third octave band, where the center frequency is used as the "name" of the particular band. It should be noted that the frequencies are rounded values rather than the exact values obtained from mathematical equations. These "preferred" frequencies are used for convenience and are defined by the American National Standard Preferred Frequencies, Frequency Levels, and Band Numbers for Acoustical Measurements (ANSI S1.6) (17). Full octave bands provide adequate spectral information to solve many hearing conservation and noise control problems, and one-third octave bands are used when more detail is required. However, depending on the way an instrument captures the frequency information, significantly more measurements are necessary to cover the overall frequency range when smaller bandwidths are used; thus a compromise must be reached between the resolution

TABLE 4 Center and cut-off frequencies for full octave and one-third octave bands (Hz).

1/1 Octave bands			1/3 Octave bands		
Lower	Center	Upper	Lower	Center	Upper
			22.4	25	28
22.4	31.5	45	28	31.5	35.5
			35.5	40	45
			45	50	56
45	63	90	56	63	71
			71	80	90
			90	100	112
90	125	180	112	125	140
			140	160	180
			180	200	224
180	250	355	224	250	280
			280	315	355
			355	400	450
355	500	710	450	500	560
			560	630	710
			710	800	900
710	1 000	1 400	900	1 000	1 120
			1 120	1 250	1 400
			1 400	1 600	1 800
1 400	2 000	2 800	1 800	2 000	2 240
			2 240	2 500	2 800
			2 800	3 150	3 550
2 800	4 000	5 600	3 550	4 000	4 500
			4 500	5 000	5 600
			5 600	6 300	7 100
5 600	8 000	11 200	7 100	8 000	9 000
			9 000	10 000	11 200
			11 200	12 500	14 000
11 200	16 000	22 400	14 000	16 000	18 000
			18 000	20 000	22 400

required and the number of measurements that must be taken.

5.2 The Noise Dosimeter

A noise dosimeter consists of a miniature microphone connected to a small microprocessor-based sound level meter that stores noise data. The microphone is positioned at the top of the employee's shoulder, and the sound level meter control unit is clipped to the wearer's belt or placed in a pocket. Noise dosimeters continuously measure sound levels obtained near a worker's ear, then provide an average value for the exposure that occurred throughout the individual's workday. Specifications for these devices are contained in ANSI S1.25, American National Standard Specification for Personal Noise Dosimeters (18).

A dosimeter is essentially identical to any other sound level meter, with the addition of an integrating function that keeps track of the noise level as well as the accumulated exposure time. Dosimeters make it convenient to measure and assess employees' noise exposures, by eliminating the need for the surveyor to follow a worker throughout the workday with a sound level meter and a stopwatch to keep track of the worker's exact amount of exposure to different noise levels. Many instruments can continuously log or store noise exposure levels at 1 minute, 10 seconds, or even 1 second intervals. This noise exposure history information can be printed out and analyzed in any number of ways to help pinpoint periods of high noise levels or other significant occurrences during a work shift. Most regulatory inspectors use dosimeters to determine compliance with the applicable noise standards.

5.3 Instrument Calibration

It is very important to carefully read and understand the operator's manual prior to using any sound level meter or dosimeter. One of the critical points of interest is the proper calibration procedures for the particular instrument. If valid data are to be obtained, it is essential that all measurement and analysis equipment be in calibration. When equipment is purchased from the manufacturer, it should have been calibrated to the pertinent ANSI specifications. However, it is the responsibility of the user to keep the instrument calibrated by conducting periodic checks.

Acoustic calibrators are available for checking the overall acoustical and electrical performance at one or more frequencies. Specifications for acoustical calibrators can be found in ANSI S1.40 (19). Calibration checks should be made according to the manufacturer's instructions at the beginning and end of each day's measurements, using a calibrator specifically designed for the sound level meter or dosimeter microphone. A battery check should also be done at these times. These calibration procedures cannot be considered to be of high absolute accuracy, nor will they allow the operator to detect changes in performance at frequencies other than those used for calibration. Nevertheless, they do serve as a warning for most common instrument failures, thus helping operators to avoid making invalid measurements.

Periodically, sound-measuring instruments should be sent back to the manufacturer or to a competent laboratory for a comprehensive recalibration. This includes sound level meters, dosimeters, and their calibrators. How frequently these complete calibrations should be performed depends on the purpose of the measurements, how carefully the instruments are handled/maintained, and how often they are used. In most cases, it is good practice to have a complete calibration performed at least once a year, and at any time an unusual reading is suspected or found.

5.4 Smartphone Apps for Sound Measurement

Substantial interest and progress have been made in the development of smartphone apps to measure sound pressure level; some of these have been tested and shown to be quite accurate (20, 21). Apps for taking noise measurements in the work setting have been developed, and more will be available in the future (22). This technology has the potential not only to raise the awareness of noise exposure but also to inform decisions concerning hearing protection.

6 ASSESSMENT OF NOISE EXPOSURE

6.1 Harmful Noise Exposures and Damage-Risk Criteria

Four major factors contribute to the development of noise-induced hearing impairment (23): (i) the overall noise level, (ii) the frequency content, (iii) the duration of exposure, and (iv) the susceptibility of the individual. Studies leading to the development of comprehensive damage-risk criteria require complex statistical evaluations of large groups over long periods of time. Many factors can compromise the accuracy of these studies because the combination of noise levels, frequency component distributions, and exposure durations can be quite variable. In addition, there are wide differences in the susceptibility of individuals to noise-induced hearing impairment. Also, hearing losses found in a study may be due in part to noise exposures away from work that are not considered. Therefore, it is impossible to set a specific exposure level as the dividing line between safe and unsafe conditions that applies to all individuals or any particular individual. Damage-risk criteria are also influenced by practical considerations. Typically, exposure level limits are established as a compromise between (i) the amount of hearing impairment that may result from a specified exposure dose and (ii) the economic or other impact that may result from noise control expenditures.

6.2 Noise Regulations

The Safety and Health Standards for Federal Supply Contracts (Walsh-Healy Public Contracts Act), U.S. Department of Labor, was revised on 20 May 1969, to include the first national noise exposure regulation in the United States (24). This regulation stemmed from the Social Security Act of 1935, which expressed the philosophy that a worker has the right to earn a living in an environment that does not endanger his or her health. The Occupational Safety and Health Act of 1970 created the OSHA and NIOSH (25). OSHA is responsible for the establishment and enforcement of regulations for most industries (one exception is mining, where the Mine Safety and Health Administration (MSHA) has responsibility). NIOSH conducts research and develops criteria documents covering all areas of occupational safety and health for both general industry and mining.

The OSHA Occupational Noise Exposure Standard (29 *CFR* 1910.95) was released in 1971 and was designed to protect workers exposed to hazardous noise environments from incurring permanent hearing loss (14). This regulation sets the maximum level of industrial noise to which an employee may be exposed over an eight hours workday to 90 dB(A), measured with the slow meter response. Higher levels are permitted as long as the exposure time is less; a 5 dB(A) increase is allowed for each halving of exposure time (i.e. 95 dB(A) for 4 hours, 100 dB(A) for 2 hours, 105 dB(A) for 1 hour, 110 dB(A) for 30 minutes, and 115 dB(A) for 15 minutes or less). In addition, the OSHA regulation states that exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level. The MSHA noise regulation – which was published in 1999 and became effective in 2000 – closely follows the OSHA regulation (26).

It is important to note that most health and safety regulations are designed to keep damage risk within "acceptable limits," which means that some people are likely to incur a hearing loss even when exposed to less than the maximum daily amount of noise specified in the regulation. Adherence to NIOSH's current occupational noise exposure criteria would reduce the "excess risk" of incurring noise-induced hearing loss from 25% down to 8% (27). Excess risk is defined as the difference between the percentage of individuals in an occupational noise-exposed population whose hearing impairment exceeds the maximum acceptable limit and the percentage of nonoccupationally exposed individuals who would normally incur such impairment from other causes.

Based on the above information, many companies find it prudent to adopt the more stringent NIOSH criteria and use exposure limits lower than OSHA's wherever possible. Obviously, the lowest feasible noise exposure levels are desirable for the health, safety, and well-being of workers. Moreover, these lower limits are of significant value to employers because they help maximize morale and work productivity and minimize the number of compensation claims for noise-induced hearing impairment.

6.3 Determination of Employee Exposures

When an employee's daily noise exposure is composed of two or more periods of exposure at different levels, the combined effect is determined by adding the individual contributions as follows:

$$D = \frac{C_1}{T_1} + \frac{C_2}{T_2} + \frac{C_3}{T_3} + \cdots + \frac{C_n}{T_n} \times 100\% \qquad (7)$$

where D represents the noise dose (in %), the values C_1 to C_n indicate the total time of exposure at a specific noise level, and the corresponding values of T_1 to T_n indicate the total number of hours of exposure permitted at each of these levels. Values of T can be obtained from Table G-16 in the OSHA noise regulation, which is based on the equation

$$T_n = \frac{8}{2^{(L_n-90)/5}}\,\mathrm{h} \qquad (8)$$

where L_n is equal to the A-weighted sound level that corresponds to each of the exposure time intervals. If the sum of the individual contributions in Eq. (7) exceeds 1.0 (i.e. the value for D exceeds 100%) then the mixed exposures are considered to exceed the overall limit value. For example, if a person were exposed to 90 dB(A) for five hours, 95 dB(A) for two hours, and 100 dB(A) for one hour during an eight-hour workday, the times of exposure are $C_1 = 5$ h, $C_2 = 2$ h, and $C_3 = 1$ h. In this example, the corresponding time limits (reference durations) for these exposures are $T_1 = 8$ h, $T_2 = 4$ h, and $T_3 = 2$ h. Therefore, the total dose for this combined exposure is $5/8 + 2/4 + 1/2 = 1.625$ (about 163%), which exceeds the specified limit of 1.0 (100%).

A significant Hearing Conservation Amendment was added to the OSHA Occupational Noise Exposure Standard in 1983 (28). No changes were made to the original regulation – that is, the same exposure limit still applies – and administrative or engineering controls are still required before the use of hearing protection is to be considered. The Amendment gives directions for administering a hearing conservation program that must be implemented when employee noise exposures equal or exceed an eight-hour TWA sound level of 85 dB(A). This 85 dB(A) TWA is referred to as the "Action Level" and is equivalent to a dose of 50%; it is computed without regard to any attenuation provided by the use of personal hearing protection. An employee's TWA may be determined from the following equation:

$$\mathrm{TWA} = 16.61 \log\left(\frac{D}{100}\right) + 90\,\mathrm{dBA} \qquad (9)$$

where D is the percentage dose obtained from Eq. (7). Alternatively, the corresponding TWA for a particular dose can be obtained from Table A-1 in Appendix A of the OSHA noise regulation.

The information contained in the American National Standard Measurement of Occupational Noise Exposure (ANSI S12.19) is a valuable resource for plant hearing conservation program managers (29). This standard presents methods that can be used to measure a person's noise exposure received in an occupational setting. The methods have been developed to provide uniform procedures and repeatable results for the accurate measurement of occupational noise exposure.

6.4 Noise Exposures Outside the Workplace

High-level noise exposures outside of the workplace can be just as harmful as those obtained in the workplace, so all noisy activities must be considered in order to get an accurate assessment of an individual's total noise exposure. Potentially hazardous nonoccupational noise sources include power tools, snowmobiles, powered lawn maintenance equipment, motorboats, motorcycles, automobile or motorcycle races, farm equipment, and shooting hobbies (skeet, targets, hunting, etc.). Listening to loud music, particularly personal stereos with earphones/headphones, has been identified as a potential source of excessive sound levels. Even riding in a car at legal speeds with the windows down may be harmful to some noise-sensitive individuals. An important consideration for nonoccupational noise is the exposure duration. A few hours of unprotected exposure on a weekend is generally not as hazardous as continuous exposures for 40 hours each week while at work. Nevertheless, a high noise level has the potential to cause a hearing loss, regardless of where the exposure occurred.

6.5 Ultrasound Limits

Exposure to high-intensity sound in the upper audible frequency range (10 000–20 000 Hz) or ultrasonic range (above 20 000 Hz) is not common, although it does occur in certain industries. Ultrasonic equipment (e.g. cleaners, welders) will often emit subharmonics of the fundamental ultrasonic frequency that fall into the audible range of human hearing. These subharmonics (rather than the ultrasonic sound itself) are of concern for potential noise-induced hearing loss or other health effects such as nausea and headaches. The OSHA noise exposure regulation does not specifically address ultrasonic frequencies, although technically they should be considered along with any other noise in the work environment. However, frequencies above 10 000 Hz cannot be reliably measured with a standard Type 2 sound level meter, due to its inherent design tolerances. Instead, a Type 1 or better instrument should be used for ultrasonic measurements. The ACGIH has published threshold limit values (TLVs) for one-third octave bands of sound from 10 000 to 100 000 Hz (9). These TLVs represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effects on their ability to hear and understand normal speech.

7 NOISE CONTROL TECHNIQUES

7.1 General Considerations

An ideal engineering noise control solution focuses directly on the actual source of the noise. Eliminating the noise-generating mechanism altogether obviates the need for further hearing conservation considerations. However, in cases where this is not practical or possible, engineering controls must be oriented toward blocking the path that the sound waves travel before reaching employees, or a method must be provided for shielding the employees' workstations from exposure to the harmful noise. More than one noise control treatment may be necessary if source treatment alone does not provide sufficient sound attenuation.

No single approach to noise control is applicable in all situations. Practical noise control solutions combine the exact science of acoustics with the production, maintenance, and economic constraints imposed upon a particular situation. Successful noise control projects are usually the result of a joint effort involving individuals from engineering, operations, and management. A compromise or balance must be struck between what is technically possible and what is truly feasible in each circumstance.

7.2 Noise Source Identification and Prioritization

The first step in a noise control project is to accurately define the problem and determine its extent. In most cases, the problem will be the potential for employees to sustain a noise-induced hearing loss, although issues of verbal communication or simply complaints of annoyance often necessitate a reduction in noise levels. Area sound levels and employee noise exposures should be thoroughly measured at the outset of the project, and the data obtained will form the basis for future decisions. Questions such as "how many and/or which employees are affected?" and "exactly how much noise reduction is required?" must be answered before any other work is done.

After determining that a noise problem exists, the actual noise source(s) or "root cause" of the problem must be identified. Although this seems somewhat elementary, in reality, this is often the biggest challenge encountered throughout the entire project. Noise may be produced by mechanical impacts, vibrating surfaces, exhaust gases, rotating machinery, and so on. There may be hundreds of potential noise-generating mechanisms within a relatively small space in a plant or factory, and the difficulty arises when attempting to pinpoint the *exact* source of the excessive acoustical energy. Generally, it is not sufficient to simply state that the noise is coming from the "assembly line" or a particular machine – precisely what part of the equipment that is responsible for the high noise level must be known in order to implement an effective control. The services of an acoustical consultant or noise control engineer may be invaluable for this purpose; however, many noise problems can be successfully solved in-house by individuals without extensive acoustical training. The key is to systematically track down the noise source by turning different equipment (or individual components) on and off, or by using temporary controls and observing their effects.

The noise produced by one source can be distinguished from another by analyzing the differences in the octave or one-third octave band spectrums. More sophisticated approaches to source identification involve using vibration measurements or performing calculations based on rotational speed, physical dimensions, or other known characteristics of the equipment in question.

Another problem encountered early in the noise control process is the prioritization of engineering control treatments. Installing a noise control device on a particular piece of equipment simply because it is "easy" or relatively inexpensive may be ineffective because the device might not affect the overall noise level, depending on what else in the immediate area is also generating noise. As a rule of thumb, when multiple noise sources are present, the loudest source(s) must be reduced first. For example, three noise sources of 91, 96, and 102 dB(A) combine to create a noise level of 103 dB(A). If only the 91 dB(A) source is removed, no overall reduction would occur, since the sum of the 96 and 102 dB(A) sources is still 103 dB(A). Likewise, if the 91 and 96 dB(A) sources are eliminated, only a one-decibel reduction would occur because the overall level would be 102 dB(A) due to the lone remaining source. However, if the 102 dB(A) source is removed, the 91 and 96 dB(A) sources added together produce 97 dB(A), resulting in a 6 dB(A) decrease from the original level of 103 dB(A). When multiple noise sources are present, this type of analysis should be applied to determine how much noise reduction is necessary to meet the intended goal.

7.3 Basic Noise Control Solutions

Successful noise control efforts do not always involve the purchase of "soundproofing" materials or products. Excessive noise levels are often produced by machinery when it is in need of adjustment, alignment, or repair (30). Therefore, restoring equipment to its optimum performance condition should be completed before investing in any noise control treatment(s). Rotating members should be dynamically balanced, with bearing and other rotating contact surfaces properly maintained. No machine should be operated at an unnecessarily high speed. In many instances, a significant reduction in noise can be achieved by using a larger machine that can do the same job while operating at a lower speed. Also, it may be necessary to periodically inspect and/or replace existing noise control devices because items such as pneumatic silencers will eventually become plugged and be rendered ineffective. Wherever possible, other maintenance-related controls should be investigated. Attempts should be made to prevent or reduce mechanical impacts between machine parts; replace metal components with quieter plastic parts; and reduce the amount of force, pressure, air velocity, and so on, to the absolute minimum amount required to perform the task. Relocating noisy equipment (e.g. motors, pumps, fans) to unoccupied areas of the plant (e.g. rooftops or warehouse areas) can greatly reduce the amount of ambient noise. Even simple measures such as tightly closing access doors/panels will keep noise from "leaking out."

7.4 Quiet-By-Design Initiatives

A successful noise control program also gives consideration to the initial procurement of noise-generating machinery and equipment. Purchase orders for new equipment should include noise limits, with the intent that noise control features will be designed and built into noisy equipment from the start. The desired sound levels may not always be met, but these specifications will provide an incentive for the development of quieter products in the future. Although the process of building quieter equipment generally increases its cost, the cost of retrofitting that piece of equipment is usually several times greater than if the same noise controls were installed in the first place.

The American National Standard Guidelines for the Specification of Noise of New Machinery (ANSI S12.16) provides guidelines for obtaining noise level data from manufacturers of stationary equipment (31). This standard references existing American National Standards Institute, trade, and professional association measurement standards and techniques, to aid in formulating and submitting requests for manufacturer's noise level data. Appendices in ANSI S12.16 provide guidance for interpretation of the data received from the manufacturer. In the future, American-based standards committees are not expected to update and maintain this Standard, considering that other International Organization for Standardization (ISO) documents cover this topic.

7.5 Noise Control Materials and Products

When it is not economically feasible to replace an older, noisy machine with a new quieter unit, and it is impossible to move the noise-generating equipment away from employee workstations, many noise control problems can be effectively solved through the proper selection and installation of appropriate commercially available noise control devices, systems, or materials. Once the dominant sources are treated, the new noise environment should be evaluated to determine whether any additional noise control measures are warranted. If sufficient noise reduction is not achieved, the process should be repeated, focusing on the noise sources that have been "uncovered" by the first application of noise control treatments. Standard noise control techniques include the use of sound-absorbing materials, sound-attenuating materials/barriers, mufflers/silencers, vibration isolation devices, and damping treatments. Monthly publications such as *Sound and Vibration* periodically publish a listing of manufacturers of currently available noise control materials (32).

7.5.1 Absorptive Materials

Absorptive materials convert sound energy into small amounts of heat. The amount of heat generated is quite small (and not readily detectable) because the acoustic power is normally very small. Porous materials such as glass fiber (e.g. standard building insulation), open-cell foam, and acoustical ceiling tile are all examples of sound-absorbing materials. Acoustical performance of these materials is determined by their absorption coefficient (α), which is the fractional amount of sound energy absorbed by a surface. Absorption coefficients are determined by specific laboratory procedures and are designated as a value between 0.0 and 1.0, which also can be considered as a percentage between 0% and 100%. Materials that are good sound absorbers have absorption coefficients approaching unity. In general, most materials perform better at higher frequencies and are less able to absorb low-frequency sound. The arithmetic average of the sound absorption coefficients of a particular material at 250, 500, 1000, and 2000 Hz provides a single-number rating of the acoustical performance of that material, called the NRC.

Noisy machinery is often located in large, acoustically reflective areas that reverberate and build up the sound level in the room. Sound-absorbing materials on walls and ceilings are often used to reduce this effect. However, the amount of reduction up close to the actual noise source(s) may be slight, because most of the sound energy comes directly from the machines and not from the reflecting surfaces. The type, amount, configuration, and placement of absorption materials depends on the specific application. Correct selection of sound-absorbing materials can be guided by reviewing the absorption coefficients listed in manufacturer's brochures. The NIOSH published a very useful *Compendium of Materials for Noise Control* in 1980 containing data tables as well as further explanation of acoustical absorption applications (33).

7.5.2 *Noise Barriers, Enclosures, and Pipe Lagging*

Sound is attenuated or "blocked" by materials that have high TL values. TL is calculated in decibels, and measurements to determine the TL characteristics of a material must be done in a laboratory, according to specific test procedures. Heavy, dense materials such as concrete, steel, and thick plywood are effective as noise barriers or enclosure walls because they restrict the amount of acoustical energy that can pass through the material to the other side. Also, commercially available heavy acoustic blankets or loaded vinyl curtains are commonly used for partitions and enclosures. The main precaution that must be taken with any enclosure or barrier system is to be sure that there are no unnecessary openings. The effectiveness of an acoustical wall or barrier can be severely degraded even with only a small percentage of open area in an otherwise solid barrier.

The amount of NR that can be attained with a simple noise barrier wall depends on the characteristics of the noise source, the construction and materials used for the barrier, and the acoustic environment on each side of the barrier. Free-standing noise barrier partitions are usually not very effective in indoor situations, due to the ability of the sound to reflect off nearby surfaces (e.g. the building's walls and ceiling). Essentially, the sound bounces over or around the barrier with little or no attenuation. Therefore, partial or complete enclosures are used instead to contain the noise produced by noise sources inside buildings.

Noise radiated from pipelines, valves, and ducts is controlled by wrapping a barrier material around the noise source, which is essentially the same as installing a close-fitting enclosure. This technique is called acoustical lagging and actually consists of a combination of sound absorption and sound attenuation materials. Typically, a resilient absorptive material is covered with a high TL outer shell, where the absorptive layer essentially decouples the barrier material from the pipe surface. Often, the entire length of a noisy pipeline or duct must be covered for the treatment to be effective.

7.5.3 *Acoustical Silencers*

Silencers, also referred to as mufflers, baffles, or sound traps, are installed in air ducts or pipelines to attenuate the noise generated in a flowing medium. There are three distinct types of acoustical silencers, although two of the types may be combined into a single device to achieve a particular result. The first type, called absorptive or dissipative silencers, contains a fibrous or porous filler material that absorbs noise energy, without significantly restricting the flow through the silencer. These silencers are used to reduce broadband noise, with greater noise reduction in the higher frequencies because the internal packing materials are typically better at absorbing high-frequency sound waves.

The second type of acoustical silencer is called a reactive silencer and does not contain any kind of absorptive filler. Instead, it causes the sound waves to cancel out by reflecting them back toward the source. Reactive silencers are used in applications such as automotive exhausts because most absorptive filler materials would eventually disintegrate or become clogged by a high-temperature, particulate-laden exhaust stream. Reactive silencers are useful for reducing low-frequency noise and are often designed or "tuned" to attenuate a certain frequency range.

The third type of commercially available silencers employs active noise cancellation technology, where loudspeakers installed in the pipe or duct produce an inverted sound wave (i.e. 180° out of phase) that reduces the noise through destructive interference with the original wave pattern. These systems are best suited for very low-frequency applications and are particularly effective at reducing pure tones that may be present.

7.5.4 *Vibration Isolation*

Most industrial equipment and machinery vibrate during operation, and these vibrations can be felt and heard throughout a plant or factory. Vibrations can travel very long distances through solid support columns and beams, and eventually be reradiated as sound through adjoining walls, ceilings, and floors. Therefore, it is important that the vibrating equipment be adequately isolated from the building structure. Vibration isolators are used to reduce the transmission of shaking forces to an acceptable level. A wide variety of these devices are available as off-the-shelf items, or they can be specially designed for a particular application.

Three factors need to be considered when selecting the correct vibration isolator for a specific application: the size and weight of the machine, its movements and speed, and the magnitude of the vibrations it produces. Small machines might only require a cork, felt, or rubber pad for proper isolation, while a large machine may be mounted on specially designed steel springs. In most situations, the product supplier or a knowledgeable engineer should be assigned to select the correct vibration mount, because the incorrect use of an isolator can actually make the vibration problem *much worse* if a resonance condition develops.

7.5.5 *Vibration Damping*

Metal panels or an entire machine casing may generate noise (i.e. the surface may "ring" or resonate) when excited by internal or external vibrations. A damping material may be attached to a vibrating panel or surface in order to reduce the panel motion, and thus reduce the amount of sound that can be radiated. Damping treatments may be thought of as "absorbing" solid-borne sound, by converting the vibrational energy into small amounts of heat. Both steady-state and impact-type noises can be reduced by applying the correct damping treatment.

There are two types of damping treatments: extensional (also known as free-layer or homogeneous) damping and constrained-layer damping. The first type is generally used for panels less than 1/4 in. thick and is typically a sheet of viscoelastic material or a compound that is troweled or sprayed directly onto the vibrating surface. In this case, vibratory energy is dissipated through extension and compression of the damping material as the panel or machine casing bends and flexes. Constrained-layer damping consists of a damping material being "sandwiched" between the vibrating panel and a stiff outer retaining layer, such as aluminum or steel. In this configuration, the damping material dissipates vibratory energy through shear deformation, rather than extension and compression. Constrained-layer systems are usually used for treating very stiff structures, or when the vibrating panel is thicker than 1/4 in.

8 HEARING PROTECTORS

8.1 General

If personal hearing protection devices (commonly abbreviated as HPDs) are properly selected, fitted, and worn, they can provide adequate protection against noise-induced hearing impairment in a high percentage of industrial work areas. In many cases, however, the protective devices are not worn effectively, if at all. Because noise does not have to be painful to be potentially harmful, many employees do not understand the need for wearing hearing protectors. Also, employees should be informed that cotton balls, cigarette butts, and other small objects are not hearing protectors, and should not be used in place of an approved device. A significant effort must be made to instruct and motivate employees in order to develop and maintain an effective hearing protector management program.

8.2 Types of Hearing Protectors

Hearing protectors usually take the form of either insert-type earplugs that are inserted into the ear and seal against the ear canal walls, or muff-type devices that seal against the head around the ear. There are also concha-seated protectors that provide an acoustic seal right at the entrance to the external ear canal. There is no single "best" type for all individuals or situations, although some types are better than others for use in specific noise environments, for some work activities, or for some environmental conditions. Historically, NIOSH has published a Compendium of HPDs that contains descriptions and laboratory attenuation data for all the HPDs marketed in the United States (34).

8.2.1 Insert-Type Earplugs

Several different styles of insert-type earplugs may be required to fit the wide differences in ear canal configurations. This is because ear canals differ in size, shape, and position among individuals and even within the same individual. Typically, ear canals are elliptical-shaped, although some are round, and many have only a small slit-like opening at the canal entrance. Some canals are directed in a straight line toward the center of the head, but most are directed toward the front of the head, and they may bend in various ways. Ear canals can be opened and straightened by pulling the auricle upward and backward, or directly away from the head, making it possible to seat the earplug securely. All earplugs must fit snugly and have an airtight seal to be effective.

8.2.1.1 Molded Earplugs Molded (sometimes called premolded) earplugs are constructed of soft and flexible materials that make for a snug, airtight fit in the ear canal. Molded plugs are usually made of a silicone-type material and are available in a variety of styles. Often, these earplugs utilize one or more circular flanges to provide a seal against the canal walls (Figure 7). Different sizes of molded plugs are available from many manufacturers because a single size may not adequately fit all ear canal sizes and shapes. Molded earplugs are usually reusable and should retain their size and flexibility over long periods of time.

FIGURE 7 Example of molded earplugs. Source: Photo courtesy of Honeywell Industrial Safety.

8.2.1.2 Malleable Earplugs Malleable (or formable) earplugs are made of materials such as silicone putty, beeswax, wax-impregnated cotton, glass wool, or mixtures of these materials. Typically, a small cone or sphere of the material is hand-formed and inserted into the ear with sufficient pressure so that the material conforms to the shape of the canal and holds itself in position. The manufacturer's instructions should be followed regarding the depth of insertion of the plug into the canal. In all cases, care should always be taken to avoid deep insertions that may cause the material to touch the eardrum. Malleable plugs have the obvious advantage of fitting almost any ear canal, eliminating the need to keep a supply of various sizes, as is necessary for most other types of earplugs.

8.2.1.3 Foam-Type Earplugs Earplugs made of cylindrical or tapered foam are very popular (Figure 8). Generally, these plugs must be rolled down and quickly inserted so that most of the plug is in the ear canal, and then momentarily held in place while they begin to expand and fill the canal. If these plugs are not inserted properly (e.g. not adequately rolled down), their performance may drop significantly. It may not be possible to insert foam plugs properly into some small, sharply bending, or slit-shaped ear canals.

Foam earplugs are typically composed of either vinyl or urethane-based material. Vinyl plugs are usually stamped out of sheets of foam material into cylinders or into hexagon-shaped plugs. Urethane earplugs are manufactured through a molding process and are usually tapered instead of being cylindrical. Urethane plugs are typically somewhat softer than the vinyl plugs but may be more expensive due to the more complicated manufacturing process. Foam earplugs are generally comfortable to wear and are reusable on a limited basis. Both of these materials provide excellent noise attenuation when the plugs are fitted and worn properly.

FIGURE 8 Example of foam-type earplugs. Source: Photo courtesy of Honeywell Industrial Safety.

8.2.1.4 Custom-Molded Earplugs A custom-molded earplug is manufactured from an exact impression of the wearer's ear. The initial cost of individually molded protectors is relatively high, but most should last a long period of time. When made and worn properly, these protectors can be expected to provide consistent daily protection levels. A unique feature of custom-molded hearing protectors is the capability of "venting" the protector to adjust the level of attenuation provided. The venting process involves manufacturing the plugs with a small hole completely through the plug and inserting various types of dampers with different attenuation characteristics.

8.2.2 Concha-Seated Protectors

Protectors that provide an acoustic seal in the concha (i.e. the "bowl" part of the external ear) and/or at the entrance to the ear canal can be referred to as "canal caps," banded, semi-aural, or semi-insert devices (Figure 9). This class of hearing protectors makes use of various plug shapes attached to a lightweight headband that holds the plugs at the entrance of the external ear canal. The performance and comfort of this kind of protector vary significantly among different models. These devices are often used where only a minimal amount of protection is required and/or the wearer frequently moves in and out of a noisy area (or the ambient noise frequently drops below a hazardous level). In these situations, the device

FIGURE 9 Example of concha-seated hearing protectors. Source: Photo courtesy of Honeywell Industrial Safety.

FIGURE 10 Example of earmuffs. Source: Photo courtesy of Honeywell Industrial Safety.

can be worn around the neck and it is readily available when hearing protection is again required.

8.2.3 Passive Earmuffs

Many manufacturers of muff-type hearing protectors (Figure 10) offer a choice of two or more models having different physical characteristics. Generally, larger and heavier earmuffs provide greater protection, while lighter weight protectors may provide somewhat less attenuation. Earmuff cushions are generally made of a smooth, plastic envelope filled with a foam, gel, or fluid material. Instead of being attached to a metal or plastic headband, some earmuff models are designed to be mounted onto a hardhat.

8.2.4 Electronic Earmuffs

In addition to the common passive-attenuation earmuffs, several types of electronic earmuffs are available. Earmuffs that use electronic circuitry to amplify ambient sounds, but also limit the wearer's exposure level are called "sound restoration," "amplitude sensitive," "sound transmission," or "level-dependent" earmuffs. Electronic earmuffs typically have a microphone on the outside shell of one or both earcups that senses the sound outside the protector and provides input to an internal amplifier. The amplifier is connected to a speaker inside the earcup to let the wearer hear the ambient sounds at a safe level (usually limited to less than 85 dB(A)). In some of these devices, equalization is performed on the signal to enhance the speech frequencies. Sound restoration earmuffs are frequently used by hunters to listen for approaching game, and their hearing is protected by the passive qualities of the earmuff when the gun is fired.

Noise-canceling or active noise reduction earmuffs use a microphone to sample the noise, then reverse the phase of the sampled signal and playback the out-of-phase signal into the earcup through a small speaker. The magnitude of the attenuation provided by noise-canceling circuits is greatest at low frequencies, and there are usually no noise-canceling effects at frequencies above about 1000 Hz. Active noise cancellation is an evolving technology, and the future will likely bring better performance with a lower cost for these devices.

8.2.5 Advantages and Disadvantages of Protector Types

Earplugs, earmuffs, and canal caps all have distinct advantages and disadvantages. Insert-type protectors are convenient to carry and store, and can be worn effectively without interference from eyeglasses, headgear, earrings, or long hair. They are practical to wear in hot environments and do not restrict head movement in close quarters. The initial cost of earplugs is usually significantly less than muffs or canal caps, although in the long term the overall cost depends on how often employees replace their earplugs. Plugs may not be appropriate for use in very dirty areas because dirt or foreign substances from one's hands may be introduced into the ear canal during insertion. For this reason, malleable and foam plugs (and to a somewhat lesser extent, all earplugs) may be a poor choice if the work area is excessively dirty, and intermittent noise levels make it desirable to frequently remove HPDs.

Earmuffs are sometimes chosen because their use can be monitored from greater distances than insert-type protectors. They are also easier to fit than insert types because one size fits most wearers. Comfort is also better for muff-type protectors in some work environments; however, earmuffs may be very uncomfortable to wear in hot work areas, particularly when the work involves a vigorous activity. Muff-type protectors may also feel cumbersome or restrict head movement when work is performed in areas having limited headroom. Earmuffs normally provide less protection when worn over long hair, and they may not be compatible to wear with eyeglasses, welding helmets, or other safety equipment. Because skin oil and perspiration can have adverse effects on cushion materials, earmuff cushions tend to become stiff or brittle over time and require periodic replacement.

Almost all insert protectors require more time and effort for proper fitting than do earmuffs, and a small percentage of employees cannot effectively wear any off-the-shelf plugs due to the shape/size of their ear canals. Differences in the amount of training and fitting experience cause the amount of protection provided by earplugs to be quite variable between wearers. Conversely, muffs are easier to fit properly, and they provide relatively consistent attenuation across users. Workers might deliberately bend the headband to reduce pressure on the skull and increase comfort, which can lead to a significant reduction in the amount of protection. Some concha-seated ear canal caps can exert a substantial amount of pressure on the ears, and therefore are usually better suited for brief, intermittent noise exposures.

8.3 Hearing Protector Ratings

In most cases, hearing protector attenuation is determined by conducting tests on human subjects, where hearing tests are taken by a panel of listeners with and without the protector in place. This test method is referred to as real-ear attenuation at threshold (REAT). First, thresholds (typically from 125 to 8000 Hz) are determined with a listener's ears open, and then another hearing test is administered with the subject's ears occluded by the HPD being evaluated. The decibel difference between the open-ear threshold and the occluded-ear threshold indicates the amount of sound attenuation provided at each test frequency. A detailed description of the test facility and procedures required to accurately use this technique can be found in the American National Standard Methods for Measuring the Real-Ear Attenuation of Hearing Protectors (ANSI S12.6) (35).

8.3.1 Standard Rating Methods

In 1975, NIOSH published a "List of Personal Hearing Protectors and Attenuation Data" that contains attenuation rating methods known as NIOSH methods #1, #2, and #3 (36). Method #1 has been referred to as the "long method," and is generally regarded as the most accurate, although it is the most complex method because it uses the largest amount of spectral information from the actual noise environment. The steps for calculating the amount of protection provided by a hearing protector using NIOSH method #1 are as follows:

1. Measure and record the octave band sound pressure levels at the employee's workstation.
2. Adjust the octave band values with the corresponding A-frequency weightings.
3. Logarithmically sum the octave band noise levels to determine the overall A-weighted sound exposure level for the unprotected ear condition.
4. Select the particular hearing protector to be evaluated and record the mean attenuation value and standard deviation (supplied by the protector manufacturer) for each frequency.
5. At each frequency, subtract the mean attenuation value from the corresponding A-weighted workplace sound level, and then add two standard deviations to each result. This will provide the A-weighted exposure level under the protector at each frequency.
6. Logarithmically sum the protected A-weighted exposure levels obtained in step 5. This will provide an estimate of the highest sound pressure level to which a population of wearers of this protector would be exposed 97.5% of the time if the protectors are fitted and worn properly.
7. Subtract the overall unprotected sound level (step 3) from the overall protected exposure level (step 6). This provides the overall amount of protection (in dB(A)) that may be expected for the hearing protector chosen in step 4 as used in the particular noise environment identified in step 1.

A simplification of the second NIOSH method (NIOSH method #2) was adapted by the Environmental Protection Agency (EPA) in 1979 and is called the noise reduction rating. The NRR is a single-number rating that is required by law to be shown on the label of each hearing protector sold in the United States (37). It is intended to describe how much noise reduction a particular protector can provide. The values of sound attenuation used for calculation of the NRR are determined in accordance with ANSI S3.19-1974, "Method for the Measurement of Real-Ear Hearing Protector Attenuation and Physical Attenuation of Earmuffs" (38). It should be noted that ANSI S3.19 was revised and published in 1984 as ANSI S12.6, American National Standard Method for the Measurement of the Real-Ear Attenuation of Hearing Protectors (39). Further, ANSI S12.6 was updated three more times and renamed "Methods for Measuring the Real-Ear Attenuation of Hearing Protectors" and contains the most current methodology (35). However, even the earliest version of ANSI S12.6 was adopted after the EPA hearing protector labeling laws were written, and because the EPA regulations did not make any provision for adopting newer standards, hearing protector manufacturers must still use the older S3.19 method for labeling purposes. In an effort to correct this situation, the EPA has an open docket and is planning to publish a revised hearing protector labeling regulation in the future.

8.3.2 NRR Calculations

To determine the NRR according to the 1979 EPA rule, the experimenter (not the test subject) is responsible for fitting the hearing protector for each occluded test run. The formula for calculating the NRR is

$$\text{NRR} = L_{\text{C(pink noise)}} - L_{\text{A(protected)}} - 3\,\text{dB} \qquad (10)$$

The first term of the equation ($L_{\text{C(pink noise)}}$) is always 107.9 dB(C) and is obtained by assuming a level of 100 dB SPL in each of the nine octave bands from 125 to 8000 Hz, subtracting the C-weighting corrections, and logarithmically summing to calculate the overall C-weighted level at the unprotected ear. Next, A-weighting corrections are subtracted from the pink noise octave band levels to calculate the A-weighted octave band levels at the unprotected ear. In an intermediate step, two standard deviations are subtracted from the average attenuation at each frequency. (An adjustment of two standard deviations provides an NRR that 97.5% of the subjects will theoretically meet or exceed, provided that the wearers use the HPD in the manner that the laboratory subjects did.) The adjusted attenuation value for each frequency is subtracted from the unprotected A-weighted octave band levels, which yields the protected A-weighted level at the ear for each octave band. The overall protected A-weighted level at the ear is determined by adding the individual octave band levels. Finally, the NRR is computed by subtracting 3 dB from the difference between the unprotected C-weighted and the protected A-weighted levels at the ear. Subtracting this additional 3 dB accounts for spectral uncertainty because the pink noise used in the calculations may not actually match the noise environment where the hearing protector is being worn.

A worker's noise exposure when wearing the hearing protector is estimated by subtracting the NRR from the ambient C-weighted sound level (not the A-weighted sound level). For example, if a protector has an NRR of 20 dB and is used in a work area where the noise level is 95 dB(C), the amount of noise entering the ear could be expected to be 75 dB(A) or lower in 97.5% of the cases.

Accuracy is lost when calculating hearing protection if only A-weighted sound pressure levels are known because the NRR is based on a flat noise spectrum. When only A-weighted ambient noise levels have been measured, a 7-dB correction factor must be subtracted from the NRR to better estimate the exposure under the hearing protector. This adjustment technique originated as NIOSH Method #3. In this case, a person working in 93 dB(A) noise while wearing an HPD with an NRR of 20 dB can be expected to be receiving 80 dB(A) at the ear.

8.3.3 Limitations of the NRR

Hearing protectors are often selected with consideration being given only to the magnitude of the NRR. Although a single-number rating is useful in initiating a hearing protection program when more precise octave band noise measurement data are not available, it should be used cautiously because of the inherent lack of precision. A fundamental weakness of the NRR is that it can end up being based on just one or two of the nine one-third octave band test signals used in the laboratory measurements. Generally, the controlling test signals are at or below 1000 Hz, and performance levels for other test signals may have little or no effect on the NRR. For example, two protectors may have the same NRR because of their limiting attenuation values at 250 or 500 Hz, but one of these protectors may provide 15 dB greater protection than the other at higher frequencies. The NRR values in this example would be a reasonably accurate assessment of protector performance if the primary noise source were centered at 250 or 500 Hz; however, if the noise exposures contain prominent high-frequency components, the NRR values may be very misleading.

Another limitation of the NRR is that attenuation values obtained from laboratory testing tend to overestimate the amount of protection received by individuals during everyday use. This is not surprising, considering that well-trained and highly motivated individuals are normally used in the laboratory as subjects, and the experimenter directly fits the HPDs prior to testing. This discrepancy has led to the development of derating procedures that are applied to laboratory data. An early OSHA directive called for dividing the labeled NRR by two (i.e. a 50% derating) before calculating exposure under the protector (40). The *Criteria for a Recommended Standard: Occupational Noise Exposure*, published by NIOSH in 1998, suggested derating the NRR on earmuffs by 25%, formable/foam earplugs by 50%, and molded earplugs by 70% (27).

8.3.4 Alternative Rating Methods

The NRR Subject Fit is determined from the Method B procedure (which is outlined in the 1997 version of ANSI S12.6), and typically yields lower protection values that are expected to be closer to the "real-world" values than those obtained with ANSI S3.19 (41). A significant difference between the older S3.19 and the S12.6 Method B procedures is that the test subjects don the protectors themselves according to the manufacturer's instructions, and testing is conducted with minimal experimenter involvement. Because the NRR (SF) is based on A-weighted sound levels, the 7 dB A-weighting-to-C-weighting correction is not necessary, and HPD selections can be based directly on A-weighted exposure measurements.

European hearing protector tests are performed according to the International Standard ISO 4869-1 (42). In Europe, the most common single-value indicator of hearing protector performance is the single-number rating (SNR). The SNR has the same pitfalls as the NRR, although it is somewhat less sensitive to outlier data during the laboratory testing. The European market also utilizes a three-number rating system, called the high–middle–low (HML) system. The three numbers in the HML rating estimate the attenuation provided in the high test frequencies, middle test frequencies, and low test frequencies, respectively. The HML values are used in conjunction with measurements of A- and C-weighted sound pressure levels to obtain the HPD attenuation that can be expected in specific noise environments.

8.4 Hearing Protector Fit-Testing

Hearing protector fit-testing is a procedure to measure the noise reduction an HPD provides for an individual worker. Fit-testing can be used to determine how well an individual fits a specific hearing protector at a particular point in time. This personalized approach eliminates the need for single-number ratings (e.g. NRR) and the rough approximations associated with them. Fit-testing is recommended as a "best practice" for hearing loss prevention programs (43, 44).

As mentioned above, the NRR is derived from laboratory test methods designed to estimate attenuation afforded to a population, not to an individual. Therefore, field monitoring systems have been developed to measure hearing protector attenuation outside of a laboratory setting. Different manufacturers use various rating algorithms, although results are typically reported as the worker's personal attenuation rating (PAR). On-site testing systems are needed because laboratory performance ratings do not always correlate with the actual attenuation achieved in the workplace. Fit-test systems are portable and affordable and may be used by plant nurses, safety managers, or other in-house personnel.

For insert-type protectors, field monitoring systems are available that essentially replicate the laboratory REAT tests, except that the stimuli are presented via headphones instead of through loudspeakers in a diffuse sound field. Hearing thresholds of the HPD wearer are measured at selected test frequencies with and without the HPD in place, and the difference in hearing threshold at each test frequency is equal to the amount of noise attenuation provided by the hearing protector. Other test paradigms include a loudness balance technique, where the attenuation is determined by asking the wearer to judge the loudness of pure tones that alternate between right and left ears.

For muff-type protectors, field measurement systems typically include two microphones, one located under the muff at the entrance to the ear canal and the second located outside the cup of the muff. The difference in sound pressure level between the two microphones represents the attenuation provided by the earmuff. These units are designed to be used at the employee's workplace; therefore, the attenuation measured will be accurate while the wearer is in that particular noise environment. Use of the protector in noises with differing spectral characteristics will likely affect the amount of noise attenuation provided.

Objective measurements with earplugs are also possible, using a microphone-in-real-ear (MIRE) technique. Similar to field measurements of earmuffs, the sound level in the ear canal ("under" the hearing protector) is simultaneously measured with the level outside the earplug. MIRE measurements are usually conducted with probe measurement systems that consist of a thin flexible tube connected to a microphone. The probe tube may be situated between the earplug and the canal wall, or may be inserted through a hole drilled through a test earplug specifically for this purpose. Instructing the user to insert the earplug as it is normally worn will enable the examiner to obtain attenuation for the individual user.

Individual/field measurement systems are, in general, well-received by HPD wearers. Employees are typically interested in how well the protectors function, and they appreciate the attention to their individual needs. Individual HPD attenuation measurements are particularly valuable as a training tool during the initial selection of insert-type HPDs. Assistance can be provided to the wearer during initial fitting, and an on-the-spot attenuation measurement can be obtained. If the measured attenuation is insufficient, the employee should refit the HPD and repeat the measurement procedure until a satisfactory result is achieved. These measurements document that adequate and proper protection was provided to the worker and empower employees to take on the responsibility of effective HPD usage.

Field measurement systems perform several functions for the industrial hearing conservation program administrator, including (i) training of wearers in correct fitting procedures, (ii) random as well as routine (e.g. annual) field sampling of protector effectiveness, (iii) documentation that training was provided and that proper protection was provided to the employee, and (iv) identification of failing or deteriorating protectors and changes in ear size/shape. Careful hearing protector selection and periodic checks with a field monitoring system should result in a successful hearing protector management program.

8.5 Performance Limitations

A primary limitation to protection afforded by a hearing protector is the way it is fitted and worn. Other important limitations of a hearing protector depend upon its construction and on the physiological and anatomical characteristics of the wearer. Sound energy may reach the inner ears of persons wearing protectors by four different pathways: (i) by passing through bone and tissue around the protector; (ii) by causing vibration of the protector, which in turn generates sound into the external ear canal; (iii) by passing through leaks in the protector; and (iv) by passing through leaks around the protector. These pathways are illustrated in Figure 11.

Even if there are no acoustic leaks through or around a hearing protector, some noise reaches the inner ear by bone

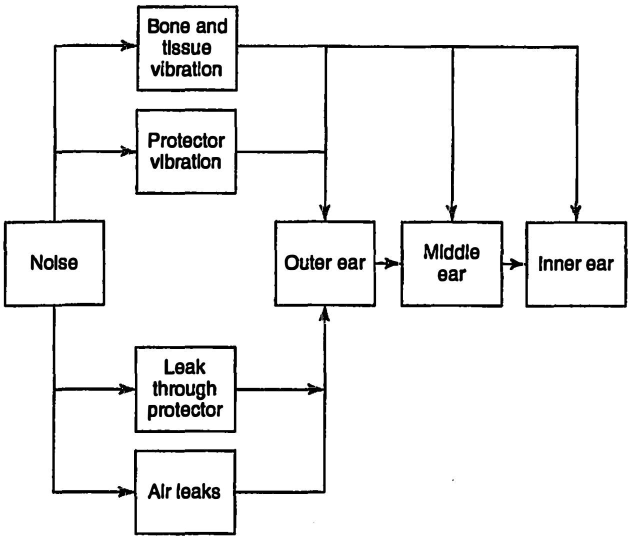

FIGURE 11 Noise pathways to the inner ear.

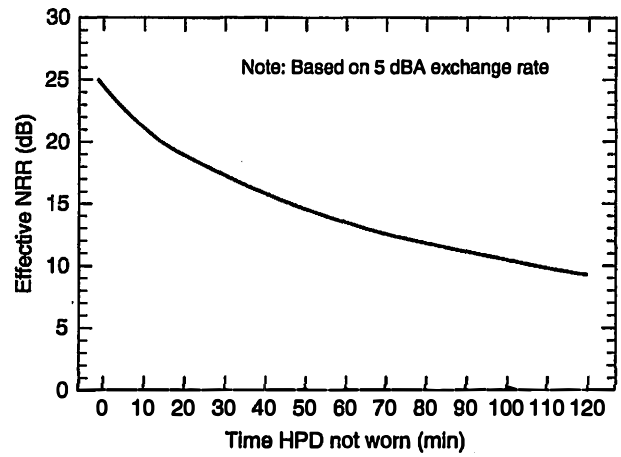

FIGURE 12 Effective NRR when an HPD with a labeled NRR of 25 dB is not worn full-time.

and tissue conduction or protector vibration if noise levels are sufficiently high. The practical limits set by the bone- and tissue-conduction threshold vary significantly among individuals and among protector types, generally from about 40 to 55 dB. Limits set by protector vibration also vary widely, generally from about 25 to 40 dB, depending upon the protector type and design and on the materials used. Contact surface area and compliance of materials are major contributing factors. If hearing protectors are to provide noise reduction values approaching practical limits, acoustic leaks through and around the protectors must be minimized by proper fitting and wearing.

Perhaps the major reason why hearing protective devices fail to protect employees from noise exposure is because the protector is not always worn when it should be. Workers fail to wear hearing protection for reasons of comfort or communication, or because the HPDs were misplaced or forgotten. Whatever the reason, failure to wear hearing protection for even a small fraction of a work shift will greatly reduce the effective protection. For instance, an HPD with an NRR of 25 dB not worn for 30 minutes out of an eight-hour workday will lose nearly 8 dB of effective attenuation (Figure 12).

8.6 Moderate Attenuation and Flat Attenuation Hearing Protectors

Many purchasers of hearing protection have fallen into the trap of thinking that a higher NRR is always better. However, a moderate amount of attenuation (rather than automatically selecting a device with the highest available NRR) may afford adequate protection in many industrial noise environments. Flat (or "uniform") attenuation hearing protectors with a moderate amount of attenuation have been introduced, in both muff and insert styles. A flat attenuation device "distorts" the incoming sound less than a conventional HPD because approximately equal attenuation is provided across all frequencies. This is in contrast to most other hearing protectors, where more attenuation is provided in the high frequencies, and, consequently, the balance between the low and high frequencies is altered. Flat attenuation earplugs are sometimes sold as hearing protection for musicians, as they are intended to maintain the music's spectral balance while providing a moderate amount of sound attenuation. Thus, the resulting effect is that all frequency components of the music are heard, but at a uniformly reduced level. Industrial workers can also benefit from these types of HPDs, because machine/equipment sounds can essentially be heard undistorted. It is important to note that if these protectors are not fitted properly, it is likely that the low-frequency attenuation will decrease, and the overall attenuation will not be as uniform as intended.

8.7 Double Hearing Protection

The combined attenuation from wearing both a muff-type and an insert-type protector cannot be accurately predicted because of complex coupling factors. It is not correct to simply add the two NRRs to determine the overall expected noise reduction. If the attenuation values of the muff and insert protectors are about the same in a frequency band, the combined attenuation should be approximately 3–6 dB greater than the higher of the two individual values. If one of the two protectors provides significantly greater attenuation in a specific frequency range, the increased attenuation provided by double protection in that range will be minimal. In practice, 5 dB is typically added to the higher labeled NRR value to determine the protection afforded by wearing double hearing protection.

8.8 Hearing Protectors and Communication

Performance and safety aspects of a job often depend on a worker's ability to hear warning signals, machine sounds, and speech in the presence of high noise levels. Therefore, interference with communication is one of the most common and legitimate complaints related to hearing protector use. The effect of noise on communication depends to a large extent on the spectrum of the noise, the hearing ability of the worker, and the attenuation characteristics of the particular hearing protectors in use.

Hearing protectors attenuate both speech and background noise by equal amounts, and therefore should not adversely affect the speech reception ability of normal-hearing listeners. In fact, wearing hearing protection in high noise areas above 85 dB(A) actually improves speech recognition by lowering the overall sound level reaching a listener's ear and reducing the potential for auditory distortion. There are situations, however, where a particular hearing protector may attenuate high frequencies substantially more than the low frequencies. In these cases, the residual low-frequency sounds will mask or obscure the high-frequency components and cause the important consonant sounds to be unintelligible. Similarly, when hearing-impaired employees wear hearing protection, the higher frequency sounds may be attenuated to a point below the level of audibility. Therefore, too much attenuation (i.e. inadequate hearing protector selection, or the use of hearing protection in areas with sound levels below 80 dB(A)) may be the cause of communication problems for normal hearing as well as hearing-impaired employees. Optimal communication is usually achieved when hearing protectors are selected to match the noise spectra of the environment where they will be worn.

To address the above issues, hearing protectors should be selected that provide sufficient protection against noise-induced hearing loss without unnecessarily inhibiting the natural perception of warning signals, machine operating sounds, speech, and so on. Unfortunately, few hearing protectors are selected and purchased with any thought being given to user communication requirements. Overprotection may be considered as acceptable, even desirable, against many health and safety hazards, but overprotection against noise exposure may cause significant communication problems and can also lead to the deliberate misuse or rejection of hearing protectors.

The European guidance document, EN 458, entitled "Hearing Protectors-Recommendations for Selection, Use, Care, and Maintenance," addresses the issue of selecting hearing protectors that maximize the ability to communicate in a noisy environment (45). This document includes several methods of HPD selection, including the octave band method, the HML method, the HML Check, and the SNR method. Recommendations for hearing protector attenuation are based on the relationship between exposure under the protector and allowable exposure criteria in dB(A). Five HPD selection categories ranging from insufficient protection to overprotection are described, depending on how closely the exposure under the protector and allowable exposure criteria are matched. The underlying principle for these guidelines is that properly fitted individuals are more likely to wear their protectors consistently because they will not be unnecessarily "isolated" from other workers, and they will be less likely to intentionally disable protectors to decrease attenuation.

9 HEARING CONSERVATION PROGRAMS

9.1 Specific Requirements

In cases where employees are subjected to sound exceeding permissible exposure levels, feasible administrative or engineering controls must be used (14). Administrative controls usually involve an attempt to lower daily noise exposures by rotating employees through a "less noisy" workstation; however, this practice is seldom feasible due to production constraints and/or employee training requirements. Engineering controls would work better in most circumstances, although they may be considerably more expensive to implement. If noise controls fail to sufficiently reduce exposure levels, personal protective equipment (i.e. hearing protection) must be provided.

The objective of a Hearing Conservation Program (also referred to as a Hearing Loss Prevention Program) is to prevent noise-induced hearing loss. This obvious fact is often forgotten or ignored when pressures are applied for compliance with local, state, or federal noise regulations. Simply handing out earplugs or providing yearly hearing tests is not sufficient to prevent noise-induced hearing loss. As described in the OSHA Hearing Conservation Amendment, an effective hearing conservation program should provide for (14)

1. The identification of noise hazardous areas and the determination of employee noise exposures.
2. The measurement of exposed persons' hearing thresholds through monitoring audiometry.
3. The establishment of a personal hearing protection plan, including provisions for evaluating the effectiveness of hearing protectors.
4. The training of employees about the need for hearing conservation, and the instruction of employees in the use and care of personal hearing protectors.

5. The maintenance of accurate and reliable records of hearing tests and noise exposure measurements.

9.1.1 Identification of Noise Hazardous Areas and Employee Monitoring

Noise exposure monitoring is necessary to identify employees that should be included in the hearing conservation program. Whenever employee noise exposures equal or exceed the action level (i.e. an eight-hour TWA of 85 dB(A), or, equivalently, a dose of 50%), they must be included in the program. Although a specific sampling strategy is not described in the regulation, the monitoring procedures must be able to identify noise-exposed employees and also enable the proper selection of hearing protectors. If employees are stationary throughout their work shift and the noise environment does not fluctuate, area monitoring is sufficient to characterize the daily noise exposure. However, a more likely scenario is that employees will be mobile and sound levels will vary somewhat, which makes personal dosimetry sampling a more practical method. All continuous, intermittent, and impulsive sound levels from 80 to 130 dB(A) must be integrated into the noise measurements. Monitoring must be repeated whenever a change occurs in the production process, equipment, or noise control devices that could change the number of exposed workers or require the use of a different type of hearing protector.

9.1.2 Audiometric Testing Program

A baseline audiogram must be established within six months of an employee's first exposure at or above the action level. All subsequent audiograms are compared to the baseline audiogram to determine if changes have occurred in the worker's hearing ability. When mobile test vans are used to conduct hearing tests, the employer has one full year to establish the baseline audiogram. If the baseline is not obtained within the first six months of that year, employees must wear hearing protection for the remaining time period until the baseline audiogram is obtained. Employees must avoid occupational as well as nonoccupational noise for at least 14 hours prior to baseline testing. If this is not possible, hearing protection should be worn to reduce any noise exposures before the baseline audiogram is conducted.

Annual audiograms must be administered to all employees who are exposed to an eight-hour TWA of 85 dB(A) or greater. Annual hearing tests provide the most information when conducted sometime during the middle or toward the end of the work shift. The reason for this is that incorrectly fitted hearing protection may cause the employee to sustain a TTS that day, which can be identified when a comparison to the baseline audiogram is made. Identifying this temporary condition at the time of the annual hearing test and reinstructing the individual on the proper use of hearing protection can help prevent a PTS in the future.

As defined by OSHA, a Standard Threshold Shift (STS) is a persistent change in hearing threshold relative to the baseline audiogram of an average of 10 dB or more at 2000, 3000, and 4000 Hz in either ear. Allowances for age corrections are permitted when determining an STS, according to the procedure described in Appendix F of the OSHA regulation. If an STS occurs, the employer may obtain a retest within 30 days, and consider those results as the annual audiogram. In practice, a retest is justified in most cases when an STS is found, because there are many common reasons why a temporary loss of hearing sensitivity may occur. However, if the retest confirms the STS, it must be reported in writing to the affected employee within 21 days. Also, unless a physician determines that the STS is not work related, the employer must ensure the following steps are taken when an STS occurs:

1. Employees not currently using hearing protection must be fitted with hearing protectors, trained in their use and care, and be required to use them.
2. Employees already using hearing protection must be refitted and retrained in the use of hearing protectors, and be provided with protectors offering greater attenuation, if necessary.
3. Employees must be referred for a clinical audiological evaluation or an otological examination (as appropriate) if additional testing is necessary or if the employer suspects that a medical pathology of the ear is caused or aggravated by the wearing of hearing protectors.
4. Employees must be informed of the need for an otological examination if a medical pathology of the ear that is unrelated to the use of hearing protectors is suspected.

New audiometric baselines may be established if the audiologist or physician in charge of the hearing conservation program determines that an STS is persistent, or if the annual audiogram indicates significant improvement over the baseline audiogram.

In addition, if an employee's hearing test (audiogram) reveals that a work-related STS in one or both ears has occurred, and the employee's total hearing level is 25 dB or more above audiometric zero (averaged at 2000, 3000, and 4000 Hz) in the same ear(s) as the STS, the case must be reported to OSHA. This is accomplished by placing a checkmark in the Hearing Loss column of OSHA's Form 300 – Log of Work-Related Injuries and Illnesses (46).

9.1.3 Hearing Protectors

According to the OSHA standard, hearing protection must be made available to employees when their daily noise exposures equal or exceed the 85 dB(A) action level. The regulation specifies mandatory hearing protection for those employees with a daily noise dose equal to or greater than 100%, which is equivalent to an eight-hour TWA of 90 dB(A). Hearing protection is not absolutely required for employees with TWAs less than 90 dB(A); however, it is mandatory for employees with a daily exposure between 85 and 90 dB(A) who have experienced an STS, and for those who have been employed for greater than six months but have not yet received a baseline audiogram.

Job performance, worker health and safety, morale, and the overall effectiveness of a hearing conservation program may be adversely affected if attention is not given to correct hearing protector selection. Employees must be given a choice of different types of protectors, although the regulation does not explicitly state exactly how much of a variety should be provided. Typically, an employer will offer two or more types of earplugs, and at least one style of earmuff. Whichever type is selected, the employer must ensure proper fitting and usage, and provide training and supervision to employees. If individuals are permitted to fit themselves without being checked, they might select an inappropriate type/size of hearing protector and not receive adequate protection.

The employer must evaluate hearing protector attenuation for the specific noise environments in which the protector will be used. Hearing protectors must attenuate employee exposures down to a TWA of 90 dB(A), or 85 dB(A) for workers who have previously suffered an STS. Appendix B in the OSHA regulation describes the acceptable evaluation methods that can be used. The quickest method is to use the protector's NRR and perform a few simple calculations either using A- or C-weighted noise measurements. The adequacy of hearing protector attenuation must be reevaluated whenever employee exposures increase to the extent that the current devices may no longer provide sufficient attenuation.

The "American National Standard Methods of Estimating Effective A-Weighted Sound Pressure Levels When Hearing Protectors are Worn" (ANSI S12.68) provides a more useful indication of what an individual might expect when using hearing protection (47). This standard specifies three methods for the estimation of the sound pressure levels when a hearing protector is worn. The simplest method is the Noise Level Reduction Statistic for use with A-weighting (NRS_A) that can be directly subtracted from an A-weighted sound level or sound exposure estimate. A more accurate procedure is the Noise Level Reduction Statistic, Graphical (NRS_G) that requires measurements of both the A- and C-weighted sound levels or exposures. Potentially the most accurate approach is the octave band method using octave band real-ear attenuation and noise measurement data. The NRS_A and NRS_G are computed at both the 80th and 20th percentiles to reflect the range of performance to be expected based on the variation in the attenuation data. An informative computer spreadsheet is provided with this Standard to easily perform the computations.

9.1.4 *Training Program*

A hearing conservation program cannot be entirely effective unless each individual limits his or her noise exposure both at work and away from work. All hearing conservation programs must emphasize the need for constant awareness of noise hazards through a continuing education effort. The OSHA standard requires employers to institute a training program for all employees who are exposed to noise at or above the 85 dB(A) action level. This training must be repeated annually and should be updated to be consistent with changes in available hearing protection and on-site work processes. Instruction must be provided on

1. the effects of noise on hearing;
2. the purpose of hearing protectors, the advantages, disadvantages, and attenuation of various types, and instructions on selection, fitting, use, and care; and
3. the purpose of audiometric testing, and an explanation of the test procedures.

Hearing conservation measures away from work can be encouraged or assisted by lending or giving hearing protectors to employees for use during noisy activities at home. The cost of supplying hearing protectors for nonoccupational uses may be far less than potential worker's compensation costs and often directs more positive attention to the hearing conservation program at work.

9.1.5 *Recordkeeping*

OSHA requires that audiograms be retained for the length of employment for the affected employee. Audiometric records must include the employee and examiner's names, employee's job classification, date of the audiogram, date of the last equipment calibration, and the employee's most recent noise exposure assessment. The employer must also keep a record of the background sound pressure levels in the audiometric test room.

According to the regulation, noise exposure measurements must be retained for two years. In many cases, companies will save records indefinitely, even after an employee is terminated. These records could be invaluable if there is ever a question of legal responsibility for an employee's hearing impairment, or if the employee returns to the same job in the future. Both the employer and employee benefit from having complete medical records retained after the employee is terminated, for reasons including compensation claims and general health references.

9.2 Setting Up a Hearing Conservation Program

Setting up a hearing conservation program entails the development and maintenance of all of the factors mentioned in the preceding sections. Ideally, a team made up of management, industrial hygiene, preventive medicine, safety, and production personnel will work together toward building an effective hearing conservation program. In practice, these teams may function only as advisors on general items such as company policy. Many successful hearing conservation programs have been highly dependent upon the competence and dedication of one single person who is given the time and support required to develop and maintain the program. This individual must be motivated and knowledgeable and be respected by both management and workers. Extensive formal training in any specific field is not usually necessary, but he or she must have a good practical knowledge of noise-induced hearing impairment, hearing testing requirements, and personal hearing protectors. If a single dedicated person is not available for this job, it may be necessary to use a hearing conservation committee to establish general policies and to appoint different individuals to be responsible for carrying out particular assignments. Generally, it is highly desirable to have well-defined tasks given to each individual.

The development of effective and practical hearing conservation programs has proven to be difficult. Many ineffective programs remain even after years of effort. Two major reasons for poor programs are as follows:

1. The responsibility for the program is given to a person within the company who is already overburdened with other tasks, and essentially no support is allotted for a hearing conservation program.
2. The responsibility for the hearing conservation program is contracted to an outside firm, and nobody within the plant acknowledges ownership of the program.

One of the apparent reasons for hiring an outside firm is to transfer responsibility for the hearing conservation program to the contractor. However, problems may arise when the employer does not take the time to fully understand the requirements of a comprehensive hearing conservation program. This often leads the employer to believe that the contractor is handling the entire program, but in reality, the contractor satisfies only one or two requirements (e.g. hearing tests; noise measurements), and the remainder of the program is left incomplete. Money is spent inefficiently, and without the benefit of a complete program, employees may continue to suffer hearing impairment.

Outside firms can be useful for specific jobs, such as conducting annual hearing tests, noise exposure measurements, or noise control projects, although the responsibility for developing an effective hearing conservation program must be accepted by the employer. At least one person within the company who has overall knowledge of the essential components of the company's operations must work with any outside contractors that are used. The company representative must have knowledge of internal production processes, work schedules, company politics, and so on. An outside firm or individual cannot be expected to know these things, nor is an outside party likely to have a deep interest in the employees' or the company's well-being that an employee should have. Also, an employee is usually the only logical person to maintain the program continuously after it is first established.

Personnel and work conditions may vary widely between plants, or from one work area to another within the same facility. Significant differences are found in management/employee relationships, and in motivation, education, and communication skills of hearing conservationists from one location to another. As a result, a program that works well in one place may fail in another. Therefore, it is generally necessary to develop a unique program for each situation, if it is to be effective.

Obviously, upper management must support the program, and others in middle management should be enthusiastic and knowledgeable. Perhaps even more important are the shift supervisors, safety officers, and the plant nurses. These key individuals often have the respect of all workers, and they may be the only persons at the plant with whom some employees will communicate freely. The first-line supervisor must be genuinely concerned about the health and safety of the employees and be able to answer questions about the effects of noise exposure, the use of safety equipment, and the overall importance of the program.

9.3 Hearing Conservation Program Evaluation

The OSHA noise regulation does not prescribe a method to determine absolutely whether a hearing conservation program is effective or not. At a minimum, an audit of all essential elements should be conducted, and a checklist should be used to ascertain compliance with the OSHA regulation. However, the real test of effectiveness is to look closely at the amount of hearing loss that is occurring. Ideally, the number of STSs will be zero, which indicates a successful program.

Evaluating the hearing conservation program from a group perspective rather than looking at each individual may help to identify an ineffective program before large threshold shifts occur for many individuals. Audiometric database analysis (ADBA) techniques have been developed for this purpose and are presented in the ANSI/ASA Technical Report – Evaluating the Effectiveness of Hearing Conservation Programs through Audiometric Data Base Analysis (ANSI S12.13) (48). The scope of this document, as well as other epidemiological methods, is to specify procedures for systematically assessing the effectiveness of hearing conservation programs in preventing noise-induced hearing loss based on the results of regular monitoring audiometry for noise-exposed employees. When ADBA results show undesirable trends, the follow-up action involves changes in overall program policies or procedures, rather than changes in the treatment of individual employees.

ACKNOWLEDGMENT

The findings and conclusions in this chapter are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Bibliography

1. ANSI S1.11-2004 (R 2009) (2009). *American National Standard Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters*. New York, NY: American National Standards Institute.
2. Geisler, C.D. (1998). *From Sound to Synapse: Physiology of the Mammalian Ear*. New York, NY: Oxford University Press, Inc.
3. Morata, T.C. and Dunn, D.E. (ed.) (1995). *Occupational Medicine: State of the Art Reviews (Occupational Hearing Loss)*, vol. 10. Philadelphia, PA: Hanley & Belfus, Inc.
4. Liberman, M.C., Epstein, M.J., Cleveland, S.S. et al. (2016). Toward a differential diagnosis of hidden hearing loss in humans. *PLoS One* **11**: e0162726.
5. Morata, T.C. (2003). Chemical exposure as a risk factor for hearing loss. *J Occup Environ Med* **45** (7): 676–682.
6. Fuente, A. and McPherson, B. (2006). Organic solvents and hearing loss: the challenge for audiology. *Int J Audiol* **45** (7): 367–381.
7. Campo, P., Venet, T., Thomas, A. et al. (2014). Neuropharmacological and cochleotoxic effects of styrene: consequences on noise exposures. *Neurotoxicol. Teratol.* **44**: 113–120.
8. EU-OSHA–European Agency for Safety and Health at Work (2019). Combined exposure to noise and ototoxic substances. Luxembourg Office for Official Publications of the European Communities, 2009. https://osha.europa.eu/en/tools-and-publications/publications/literature_reviews/combined-exposure-to-noise-and-ototoxic-substances/view (accessed 19 August 2019).
9. American Conference of Governmental Industrial Hygienists (ACGIH) (2018). 2018 TLVs and BEIs. Cincinnati, OH: ACGIH.
10. Occupational Safety and Health Administration (OSHA) (2019). Preventing hearing loss caused by chemical (Ototoxicity) and noise exposure. Safety and Health Information Bulletin 03-08-2018, DHHS (NIOSH) Publication No. 2018-124. https://www.osha.gov/dts/shib/shib030818.html (accessed 19 August 2019).
11. ANSI S3.6-2018 (2018). American National Standard Specification for Audiometers, American National Standards Institute, New York.
12. ANSI S3.1-1999 (R2018) (2018). *American National Standard Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms*. New York, NY: American National Standards Institute.
13. Hutchison, T.L. and Schulz, T.Y. (2014). *Hearing Conservation Manual*, 5the. Milwaukee: Council for Accreditation in Occupational Hearing Conservation.
14. Occupational Safety and Health Administration (1983). Occupational noise exposure standard and hearing conservation amendment, Code of Federal Regulations, Title 29, Chapter XVII, Part 1910, Subpart G.
15. ANSI S3.21-2004 (R2019) (2019). *American National Standard Methods for Manual Pure-Tone Threshold Audiometry*. New York, NY: American National Standards Institute.
16. ANSI/ASA S1.4-2014/Part 1 (2014). *American National Standard Electroacoustics – Sound Level Meters – Part 1: Specifications*. New York, NY: American National Standards Institute.
17. ANSI/ASA S1.6-2016 (2016). *American National Standard Preferred Frequencies and Filter Band Center Frequencies for Acoustical Measurements*. New York, NY: American National Standards Institute.
18. ANSI S1.25-1991 (R2017) (2017). *American National Standard Specification for Personal Noise Dosimeters*. New York, NY: American National Standards Institute.
19. ANSI/ASA S1.40-2006 (R2016) (2016). *American National Standard Specifications and Verification Procedures for Sound Calibrators*. New York, NY: American National Standards Institute.
20. Kardous, C. and Shaw, P.B. (2014). Evaluation of smartphone sound measurement applications. *J Acoust Soc Am* **135**: EL186–EL192.
21. Kardous, C. and Shaw, P.B. (2016). Evaluation of smartphone sound measurement applications (apps) using external microphones: a follow-up study. *J Acoust Soc Am* **140**: EL327–EL333.
22. Williams, W. and Sukara, Z. (2013). Simplified noise labelling for plant or equipment used in workplaces. *J Health Saf Res Pract* **5**: 18–22.
23. ANSI S3.44-2016 (2016). *American National Standard Acoustics – Estimation of Noise-Induced Hearing Loss – Part 1: Method for Calculating Expected Noise-Induced Permanent Threshold Shift*. New York, NY: American National Standards Institute.
24. U.S. Department of Labor (1969). Safety and health standards for federal supply contracts (Walsh-Healy Public Contracts Act). *Fed Register* **34**: 7948.
25. U.S., Department of Labor (1971). Occupational safety and health standards (Williams-Steiger Occupational Safety and Health Act of 1970). *Fed Register* **36**: 10518.

26. Mine Safety and Health Administration (1999). Health standards for occupational noise exposure, 30 CFR Parts 56, 57, 62, 70, and 71. *Fed Register* **64**: 49548–49634.
27. Criteria for a Recommended Standard: Occupational Noise Exposure (1998). Revised Criteria 1998, DHHS (NIOSH) Publication No. 98-126, National Institute for Occupational Safety and Health (NIOSH).
28. Occupational Safety and Health Administration (OSHA) (1983). Occupational noise exposure; Hearing conservation amendment, final rule, 29 CFR Part 1910. *Fed Register* **48** (42).
29. ANSI S12.19-1996 (R2016) (2016). *American National Standard Measurement of Occupational Noise Exposure*. New York, NY: American National Standards Institute.
30. U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) (1980). *Noise Control: A Guide for Workers and Employers*, Publication No. 3048. Washington, DC: OSHA.
31. ANSI S12.16-1992 (R2013) (2013). *American National Standard Guidelines for the Specification of Noise of New Machinery*. New York, NY: American National Standards Institute.
32. (2017). Buyer's guide to products for noise and vibration control. *Sound Vibration* **51** (7): 15–17.
33. Compendium of Materials for Noise Control (1980). Publication No. 80-116 (NTIS Stock No. PB298307), National Institute for Occupational Safety and Health (NIOSH), Cincinnati.
34. The NIOSH Compendium of Hearing Protection Devices (1994). Publication No. 95-105, National Institute for Occupational Safety and Health (NIOSH), Cincinnati.
35. ANSI S12.6-2016 (2016). *American National Standard Methods for Measuring the Real-Ear Attenuation of Hearing Protectors*. New York, NY: American National Standards Institute.
36. National Institute for Occupational Safety and Health (NIOSH) (1975). *List of Personal Hearing Protectors and Attenuation Data*. Cincinnati, OH: U.S. Department of HEW, Publication No. 76-120.
37. Environmental Protection Agency (EPA) (1979). Noise labeling requirements for hearing protectors, 40 CFR PART 211. *Fed Register* **44** (190): 56130–56147.
38. ANSI S3.19-1974 (1974). *American National Standard Method for the Measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs*. New York, NY: American National Standards Institute.
39. ANSI S12.6-1984 (1984). *American National Standard Method for the Measurement of the Real-Ear Attenuation of Hearing Protectors*. New York, NY: American National Standards Institute.
40. Industrial Hygiene Technical Manual (1987). *OSHA Instruction CPL 2-2.20A, Change 2, March 1*, VI-13–VI-20. Washington, DC: Occupational Safety and Health Administration (OSHA).
41. Royster, L.H. (1995). In search of a meaningful measure of hearing protector effectiveness. *Spectrum* **12** (2): 1, 6–13.
42. International Organization for Standardization (ISO) (2018). *Acoustics-Hearing Protectors-Part 1: Subjective Method for the Measurement of Sound Attenuation*, ISO 4869-1. Geneva: International Organization for Standardization (ISO).
43. Hager, L.D. (2011). Fit-testing hearing protectors: an idea whose time has come. *Noise Health* **13**: 147–151.
44. Schulz, T.Y. (2011). Individual fit-testing of hearing protectors: a review of uses. *Noise Health* **13**: 152–162.
45. Hearing Protectors-Recommendations for Selection (2016). Use, care, and maintenance, guidance document, EN 458, European Committee for Standardization (CEN), Brussels, Belgium.
46. Occupational Safety and Health Administration (2002). Recording and reporting occupational injuries and illness. Code of Federal Regulations, Title 29, Section 1904.10, Federal Register (67 FR 77165-77170).
47. ANSI/ASA S12.68-2007 (R2017) (2017). *American National Standard Methods of Estimating Effective A-Weighted Sound Pressure Levels When Hearing Protectors are Worn*. New York, NY: American National Standards Institute.
48. ANSI S12.13 TR-2002 (R2016) (2016). *ASA Technical Report: Evaluating the Effectiveness of Hearing Conservation Programs through Audiometric Data*. New York, NY: American National Standards Institute.