The Noise Manual

Sixth Edition

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Stock Number: ENOM22-619
ISBN: 978-1-950286-07-2

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Printed in the United States of America

The Noise Manual, 6th edition, edited by
D.K. Meinke, E.H. Berger, R.L. Neitzel, D.P. Driscoll, and K. Bright
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Chapter 6: Brief High-Level Sounds

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Introduction

A wide range of people are exposed to brief high-level sounds. Exposures to impulse noise from guns are common for those in military and law enforcement occupations, which account for approximately 3.4 million workers in the U.S. (Lockard & Wolf, 2012). Rapid chemical reactions involved in automotive airbag deployment might also produce auditory effects (Passali et al., 2003). In addition, people of all ages are exposed to noise from firecrackers and other fireworks that could be intense enough to damage the auditory system. Approximately 386 million pounds of consumer fireworks were sold in the U.S. in 2020 (American Pyrotechnics Association, 2021). Recreational firearm use is also common in the U.S., with estimates of 83 to 97 civilian firearms per 100 persons (Small Arms Survey, 2007). Firearm use emerges at the population level as a significant risk factor for hearing loss. The prevalence of bilateral mid-frequency hearing loss (0.5–4 kHz, average greater than 25 dB HL) among people reporting no history of firearm use was 2.6% less than for non-shooters (5.4 versus 8.0%, respectively), and the prevalence increased to 10.8% for heavy shooters. The prevalence of bilateral high-frequency hearing loss is greater and shows greater differences across levels of shooting history (14.4, 22.1, and 31.7%, respectively [Hoffman et al., 2016]).

Our examination of responses from approximately 37,000 participants in the 2014 National Health Interview Survey (data available at https://www.cdc.gov/nchs/nhis/) suggested that 52% (95% CI: 51% to 54%) of adult men and 22% (95% CI: 21% to 23%) of adult women report having fired a gun at some point during their lives. A small proportion of these people (15% of men and 5% of women) with a history of firearm use indicated that firearm use was solely for occupational purposes. About 44% of men (14% of women) reporting a history of firearm use have fired at least 1000 rounds during their lifetimes. The rates of hearing protector use among target shooters is somewhat higher than for hunters (Stewart et al., 2011).

Impact noise exposures can be expected for construction, manufacturing, and agricultural workers, who account for almost 16 million workers in the U.S. (U.S. Bureau of Labor Statistics, 2012). In addition, many home improvement and repair tasks can involve the use of tools that produce impact noises, and automotive airbags can produce high-level sounds that might produce temporary threshold shift (Sommer & Nixon, 1973).

Exposures to brief high-level sounds that last less than one second present a hazard that is equal to or perhaps greater than continuous sounds with equal amounts of overall energy (Dunn et al., 1991; Tremolieres and Hetu, 1980; Smoorenburg, 2003). The human ear can be damaged by these sounds with comparatively few exposures. In addition to more rapid accumulation of risk, brief high-level sounds differ from longer-duration signals in many ways, including the processes by which they are generated, measurement techniques, mechanisms of auditory damage, appropriate procedures for assessing risk, and the performance of hearing protectors.

In this chapter, we use the term *brief high-level sounds* to represent any signal having an instantaneous peak level greater than 130 dB SPL and an overall duration less than one second. This includes sounds that have been conventionally labeled as impulse and impact noises. Although the physical events leading to these two types of sounds differ, their influence on the auditory system is similar and the same approaches are used to estimate risk for people exposed to these sounds. This chapter includes a description of the essential acoustic factors associated with the production and measurement of brief high-level sounds, a short description of some bioacoustic and psychoacoustic phenomena involved in the response of the auditory system to these sounds, a description of how risks for the exposed listener are assessed currently, and finally an explanation of how these risks can be mitigated via the use of hearing protectors and modifications of the source (e.g., suppressors at the muzzle, low-velocity gun ammunition, addition of damping material to processes where impacts occur).

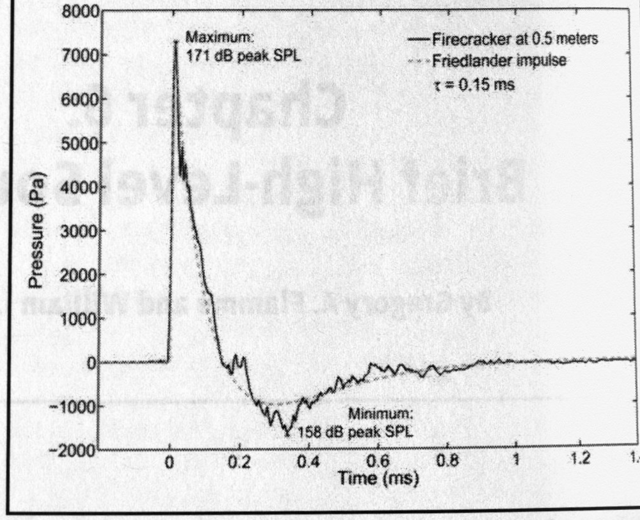

Figure 6.1 — The Friedlander wave is a kind of waveform produced by the explosive release of energy. It is characterized by a near-instantaneous departure from ambient pressure to a peak (i.e., overpressure) followed by a decline in pressure that undershoots ambient pressure (i.e., underpressure) and a comparatively slow recovery to ambient pressure. The peak amplitude and duration of the signal are determined by the energy contained in the impulsive source.

Acoustics of Brief High-Level Sounds

While the definition of an impulse is a matter of convention, this term will be used to denote an asymmetric disturbance in air pressure, typically generated by energy release (e.g., chemical explosions, compressed air bursts). This definition permits an impulse to be differentiated from an impact noise, which is defined as the sound from the collision of masses (e.g., hammer fall, punch press, etc.). Many impulsive sounds result from rapid chemical reactions producing heat and comparatively large volumes of gas. In firearm ammunition, for example, the combustion of the propellant powder generates pressures on the order of megapascals within the gun's firing chamber, and these pressures act on the bullet to accelerate it down the gun barrel. The intense pressure and heat causes pressure to build into a nearly instantaneous rise, a shock front. The blast wave includes the shock front followed by an exponential pressure decay and underpressure due to inertia and air flow (Kinsler et al., 2000). The ideal blast wave (Figure 6.1) is often called a Friedlander wave (Friedlander, 1946; Hamernik and Hsueh, 1991). Pure Friedlander waves are rarely observed in real sound sources, mostly due to the effects of the enclosure in which the energy is released (e.g., the firing chamber of a weapon or other tool) and the effects of reflective surfaces in the vicinity. As shown in Figure 6.1, a firecracker impulse has qualities similar to a Friedlander wave, but with some substantial deviations after wave onset. In firearms, only about 35% of the chemical energy in the charge is converted into kinetic energy of the projectile (ISO 17201-2, 2006), with the remaining energy released as heat, sound, and gas movement.

Impulse Sounds

Impulse waveforms can be divided into multiple components. In cases where the chemical reaction is used to accelerate a projectile (i.e., a bullet or shot) to supersonic speed, the projectile produces a ballistic N-shaped wave along its path. The initial portion of the N-shaped wave (Figure 6.2) is associated with the compression of air immediately in front of the projectile (i.e., the "bow wave" in Figure 6.3), after which the pressure decreases until the rarefaction of air immediately behind the projectile (i.e., the "stern wave") rapidly returns the pressure to ambient (Garinther and Moreland, 1965). The first component of the muzzle blast wave is the *shock front*, which is the leading edge of the Friedlander wave. The shock front is followed by the pressurized gas escaping from the enclosure. The escaping gas travels at a speed lower than the speed of sound and falls to zero once the pressure inside the enclosure equals ambient pressure.

In Figure 6.4, the shock front from the muzzle blast appears as a circle that is centered just in front of the muzzle. In the absence of objects that restrict energy flow in a given direction, the ideal blast wave would exhibit the properties of a perfect point source, radiating sound in all directions with equal efficiency. However, the environment surrounding the sound source influences how sound energy radiates from this central point. As an example, the combustion associated with gunfire takes place mostly within the cartridge itself, which is surrounded by a firing chamber built

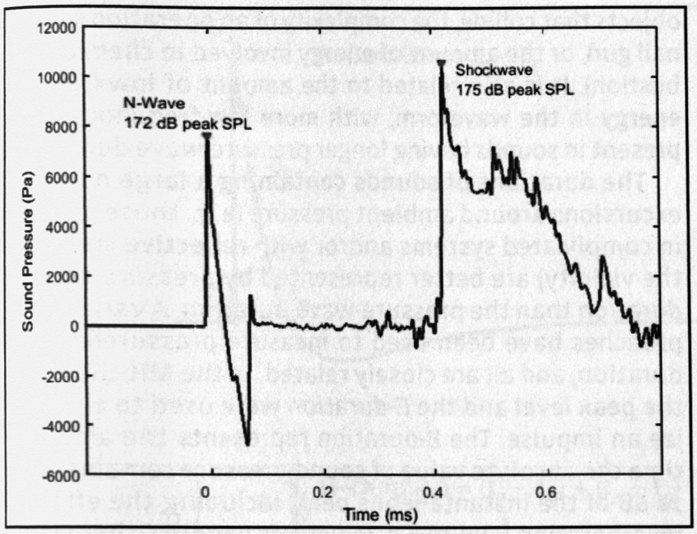

Figure 6.2 — Separation of N-wave from a passing bullet and blast wave from muzzle. The microphone was located 550 mm downrange from the muzzle of a .22 Hornet rifle. The N-wave has a pressure-wave (A) duration less than 0.03 ms and a peak of about 8000 Pa, and the muzzle blast wave has a peak of about 11,000 Pa and an A-duration of approximately 0.34 ms (see Rasmussen et al., 2009, for recording details).

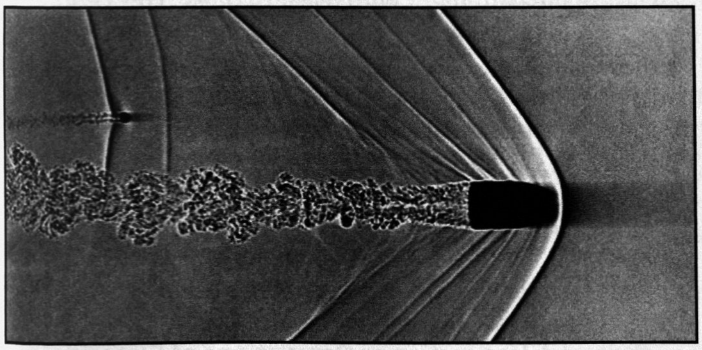

Figure 6.3 — The bow wave is at the front of the bullet, and the stern wave originates behind the bullet. Turbulence created in the wake of the bullet is also evident. A small piece of the cartridge or unspent propellant is seen above and behind the bullet (Image courtesy of Andrew Davidhazy.)

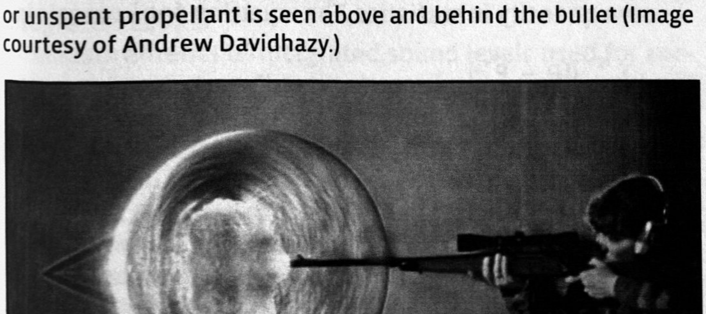

Figure 6.4 — High-speed photograph of the ballistic N-wave, muzzle blast wave, and gas ejection from a rifle (Image courtesy of Dr. Gary Settles.)

to withstand the intense pressure and heat. The energy radiates away through the gun barrel, accelerating the bullet or other projectile as it goes. Upon exiting the muzzle, the sound energy exhibits higher levels in front of and to the side of the muzzle than to the rear of the weapon and toward the shooter's ear (Walton, 1981), as shown in Figure 6.5. In addition, Figure 6.5 shows a separation from the ballistic N-wave, which merges with and disappears within the shock wave as the measurement location becomes perpendicular to the line of fire. The difference in temporal spacing between the N-wave and shock wave is due to the locations of the acoustic sources.

Impact Sounds

Impact noise is produced by collision of masses, followed by free vibration of those masses. Impact waveforms tend to have symmetric compression and rarefaction and exhibit an exponential decay after the initial onset (Atherley and Martin, 1971). The peak levels are generally lower than for impulse sounds. In addition, more low-frequency energy tends to be present in impact sounds, owing to the physical characteristics (mass, stiffness) of the materials. The duration of impact sound tends to be longer than impulse sounds. This

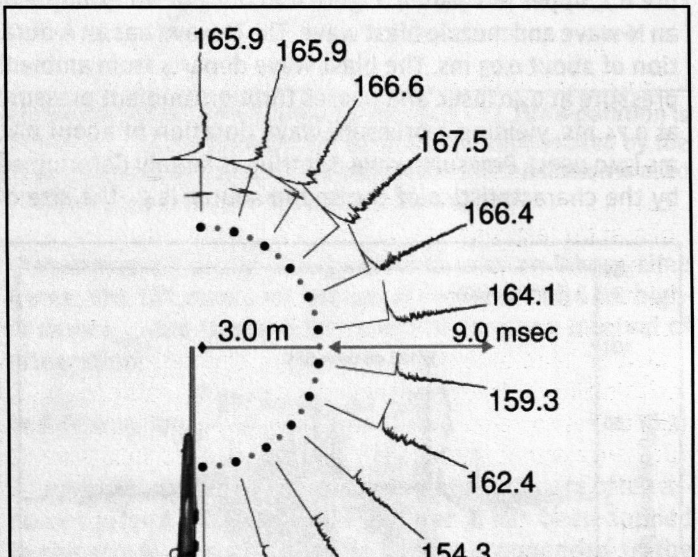

Figure 6.5 — Comparison of impulse waveforms as a function of angle, centered on the muzzle of a gun. The initial disturbance in the waveform downrange from the muzzle is the ballistic N-wave produced by the passing bullet (see Figures 6.2 through 6.4). Generally, the impulse amplitudes downrange will be greater than those to the side and behind the muzzle. The peaks behind the shooter are reduced by approximately a factor of 10 from the front. These data are from Maher and Routh, 2015.

duration depends on the amount of resistance in the materials and the degree to which the natural resonances of the materials are excited. In Figure 6.6, the waveform from the framing nailer has several distinct phases: the discharge of the gas driving the piston against the nail, the impact of the piston on the nail, the interaction of the nail with the work piece, the exhaust of the compressed gas, and finally, the reset of the piston.

Acoustical Descriptors of Brief High-Level Sounds

Fine Waveform Structure

Brief high-level sounds have been described in terms of the fine structure of the waveform and summary values after their energy has been integrated over time. Fine structure descriptors include the instantaneous peak level and various indicators of wave duration. The instantaneous peak level is defined as the greatest excursion of the waveform from ambient pressure in either a positive or negative direction.

Duration is the amount of time elapsed between sound onset and a specific event in the time waveform. For example, the amount of elapsed time for a sound to initially depart from and return to ambient pressure is called the pressure-wave duration, also known as the *A-duration* (Figure 6.7, upper left panel). Figure 6.2 contains an example of an N-wave and muzzle blast wave. The N-wave has an A-duration of about 0.03 ms. The blast wave departs from ambient pressure at 0.40 msec and passes through ambient pressure at 0.74 ms, yielding a pressure-wave duration of about 0.34 ms (340 μsec). Pressure-wave duration is largely determined by the characteristics of the sound source (e.g., the size of

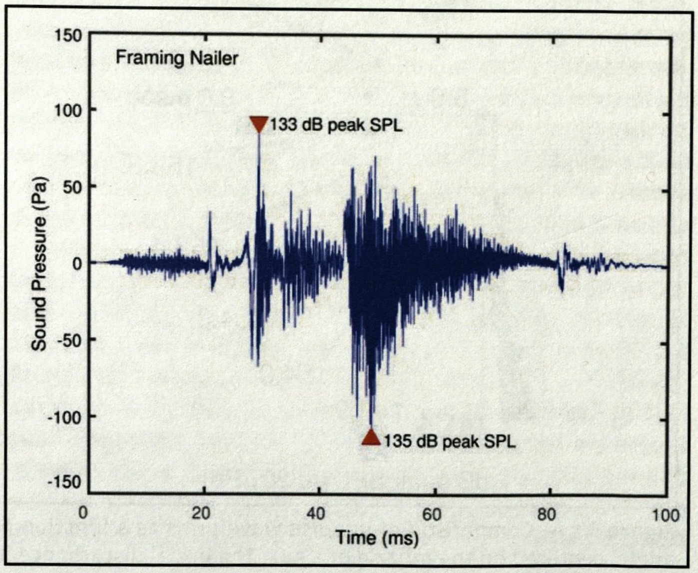

Figure 6.6 — An impulse from a framing nailer driving a nail. Different phases of the nail cycle are evident in this image: the initial release of gas to drive the nail (5–20 ms), an impact of the piston with the nail (20–28 ms), the impact of the nail with the workpiece (28–43 ms), the exhaust of the gas from the nailer (43–80 ms), and the restoration of the piston to its ready position (80 ms).

objects that collide, the complexity of an operation such as a nail gun, or the amount of energy involved in chemical combustion). It is also related to the amount of low-frequency energy in the waveform, with more low-frequency energy present in sounds having longer pressure-wave durations.

The durations of sounds containing a large number of excursions around ambient pressure (e.g., those produced in complicated systems and/or with reflective surfaces in the vicinity) are better represented by *pressure-envelope duration* than the pressure-wave duration. A variety of approaches have been used to measure pressure-envelope duration, and all are closely related. In the MIL-STD-1474D, the peak level and the *B-duration* were used to characterize an impulse. The B-duration represents the amount of time the absolute value of sound pressure remains within 20 dB of the instantaneous peak, including the effects of reverberation (Figure 6.7, lower left panel). Other metrics use C- or D-duration to characterize the impulse. The *C-duration* is closely related to the B-duration, but only the amount of time that the signal remains within 10 dB of the instantaneous peak pressure is included (Figure 6.7, upper right panel).

The B- and C- duration measurements were developed to facilitate measurement with oscilloscopes. The *D-duration* was intended to be more reliable than the oscilloscope-based estimates. Using digital signal processing, the magnitude of the Hilbert transform will yield the signal envelope of the pressure waveform (Smoorenburg, 1982). In the D-duration, the amount of time that the signal is within 10 dB of the peak is assessed after the signal envelope has been extracted (Figure 6.7, lower right panel).

Kurtosis: A growing line of research has identified waveform *kurtosis* as a potentially important component of auditory risk (see section on Descriptions of Criteria, Energy-Based DRC). Kurtosis is a measure of the height of the frequency-of-occurrence histogram, and it is a well-known quantity in statistics. The equation for kurtosis is:

$$\beta = \frac{\dfrac{\Sigma_{i=1}^{N}([P_i - \bar{P}]^4)}{N}}{s^4} \qquad (6.1)$$

where P_i are the individual samples of the pressure, $\bar{P}$ represents the mean pressure, s represents the standard deviation of the pressure samples, and N represents the number of data points in the digitized signal. A single pure-tone source will have a kurtosis value of about 1.5, while continuous flow noise typically has a kurtosis value of about 3. Impulse waveforms tend to have high kurtosis values, and there is some evidence that hazard increases with kurtosis (Davis et al., 2012; Zhao et al., 2010).

The instantaneous peaks of a brief sound correspond to the extreme edges of the histogram (Figure 6.8), while base-

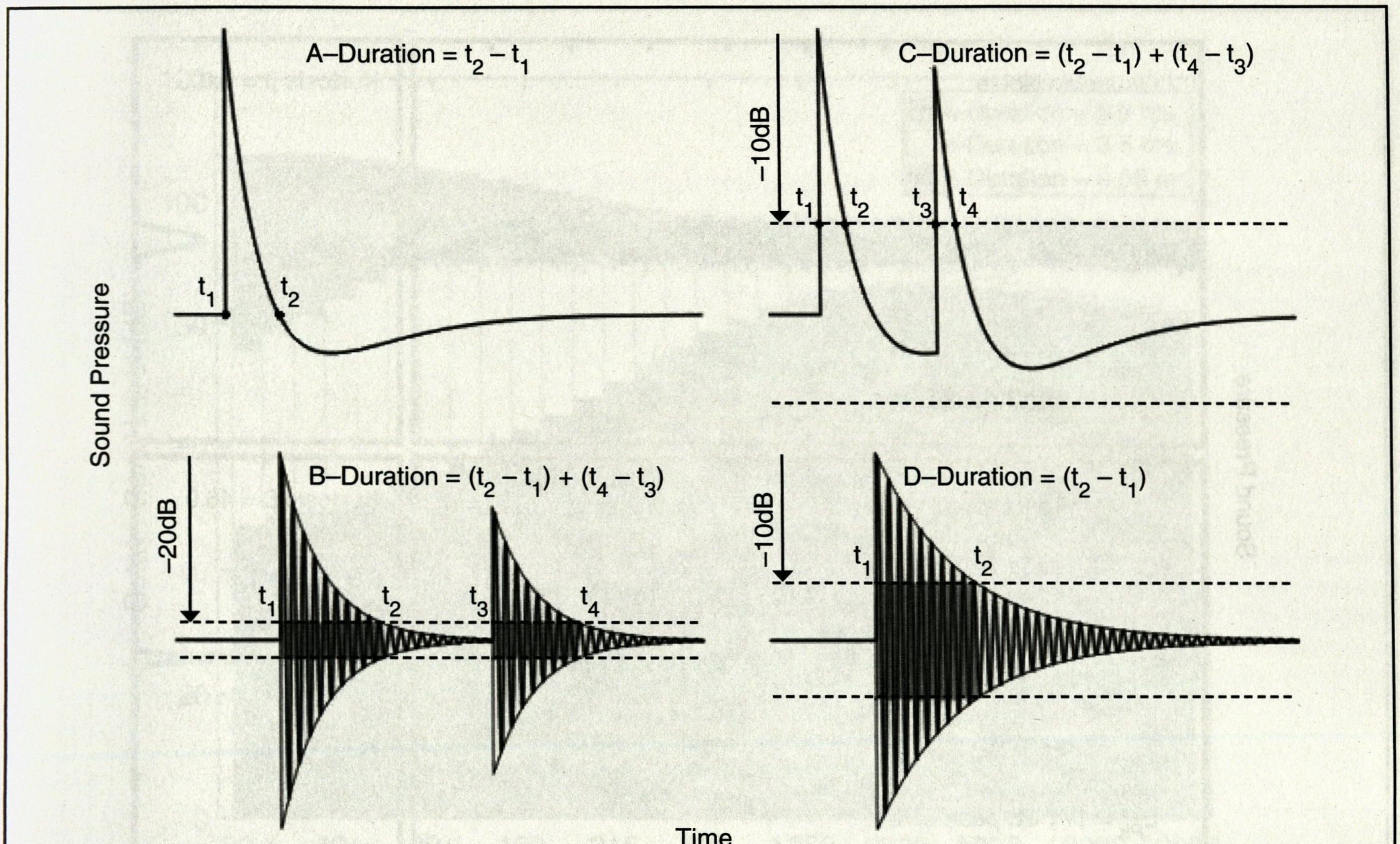

Figure 6.7 — Definition of duration parameters. The A-duration is the representation of the initial overpressure ($t_2 - t_1$). The B-duration is used by the MIL-STD-1474D and is the duration of the impulse that is within 20 dB of the peak amplitude. The C-duration is used by the Pfander et al. (1980) damage-risk criterion and is the duration of the time when it is within 10 dB of the peak level. The D-duration is used by the Smoorenburg (1982) damage-risk criterion and is the duration of the envelope that is within 10 dB of the peak level.

line amplitudes (e.g., ambient pressure) and noise will form the center of the histogram. Sounds having greater excursions (i.e., higher instantaneous peak amplitudes) relative to baseline amplitudes have greater kurtosis.

Integrated Levels

Measurements of integrated sound levels used for continuous signals (see Chapter 3) can also be applied to brief high-level sounds. The fundamental measure here is the *equivalent continuous level*, which represents the average energy in the signal over a specified period of time (see Chapter 3). For ease of comparison, integrated levels are often determined over a time interval greater than the actual duration of the sound. In such cases, the total energy in the sound is divided over a prespecified time interval.

$$L_{eq8} = 10\ \log\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{p^2(t)}{p_0^2}\,dt\right) + 10\ \log\frac{t_2 - t_1}{t_{8hr}} \qquad (6.2)$$

The *Sound Exposure Level, or SEL,* represents the amount of sound energy divided over a 1-second time frame. The *8-hour equivalent continuous level,* or $L_{eq,8hr}$ represents the amount of sound energy divided over an 8-hour time frame. The SEL levels for the same sound are 44.6 dB higher than L_{eq8} due to the adjustment of the time interval of integration:

$$44.6\ \text{dB} = 10\ \log\left(\frac{8\text{hr}\ 60\ \frac{\text{min}}{\text{hr}}\ 60\ \frac{\text{sec}}{\text{min}}}{1\ \text{sec}}\right) \qquad (6.3)$$

Integrated levels for brief high-level sounds are often assessed after A-weighting (see Chapter 3) has been applied to the signal. In such cases, an A label is appended to the level estimate (e.g., SEL_A, $L_{Aeq,8hr}$).

Spectrum

The frequency spectra of brief high-level sounds are less commonly described than summary values. Brief high-level sounds can be expected to have broad spectra, with the spectral center depending on the nature of the sound source and the environment. In general, sounds that have longer pressure-wave durations (i.e., A-durations) will tend to have more low-frequency energy (see Figure 6.9).

Spectra vary with the sound source. Firecrackers tend to have spectral peaks in the vicinity of 1000 to 4000 Hz (Flamme et al., 2009a). The spectral peaks for civilian handguns, rifles,

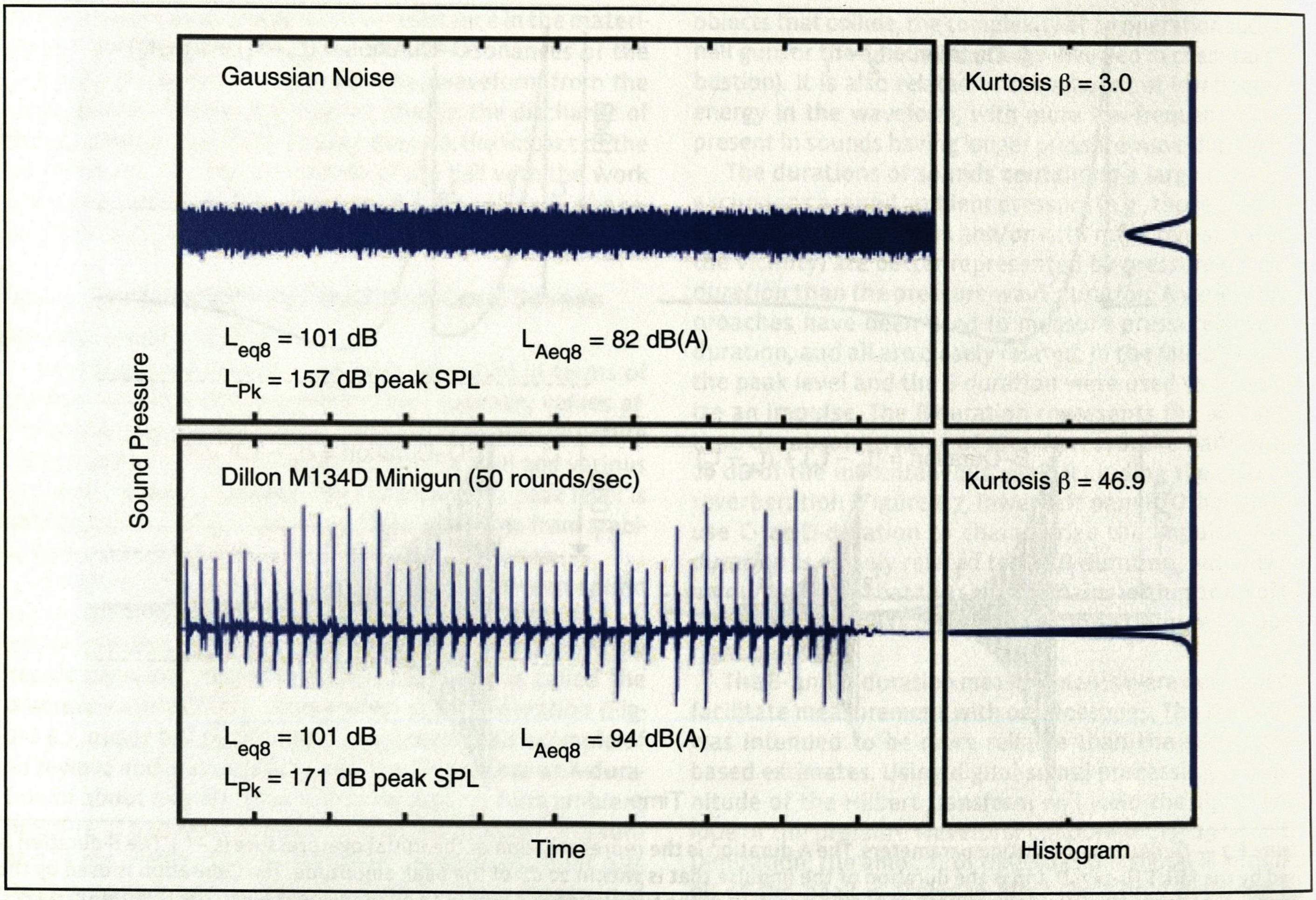

Figure 6.8 — Comparison of histogram from an impact noise and random noise. The random noise (upper panel) was generated to have the identical L_{eq} as the impulse train from the Dillon M134D minigun (lower panel). The amplitude histograms for both waveforms are shown in the panels on the right side of the figure. Minimum and maximum pressures are represented as the tails on the histogram, while the continuous noise embedded in the waveform is represented by the height of the center of the histogram. The kurtosis of the impact noise is 46.9 while the kurtosis of the random noise is 3 (see Brueck et al., 2014, for details regarding the Dillon M134D minigun).

and shotguns tend to occur between approximately 400 and 4000 Hz, depending on the type of gun and distance from the muzzle (Murphy et al., 2012b). Small-caliber firearms such as .22 or .17 pistols and rifles have spectral peaks at higher frequencies than other rifles, shotguns, and pistols. Additionally, supersonic ammunition will generate an audible crack that contains higher frequencies than comparable caliber subsonic ammunition. Large-caliber weapon systems (e.g., howitzers, rocket launchers) can be expected to produce spectral peaks at lower frequencies.

The spectra of impact noises are governed by the mass and stiffness of the colliding materials, resulting in spectra that may have very intense tonal characteristics. Materials having low mass and high stiffness will produce high-frequency spectra and vice versa.

Reflections and Continuous Noise

Impulse and impact sounds are frequently produced near reflective surfaces. In construction, nails and other fasteners must be driven near walls, and many construction and industrial tasks are conducted on elevated work surfaces. Hunters, shooters, and people in military occupations often fire guns from small enclosures that provide shelter, reduced detectability, and protective cover (e.g., hunting blinds). The proximity of reflective surfaces (walls, ceilings, floors, and other objects) increases the reverberant energy reaching the ear when compared to the hemi-anechoic condition of an impulse source and receiver in open field conditions.

Reflective surfaces near the sound source influence both the temporal and spectral features of the sound (see Chapter 10). Even for sound sources that would otherwise radiate sound in all directions with equal efficiency, energy in those portions of the sphere that would be directed away from the listener in field conditions could be reflected back toward the listener, arriving at the listener's ears moments after the signal reaches the listener directly. Reflected signals from the ground are often identifiable in pressure waveforms. In

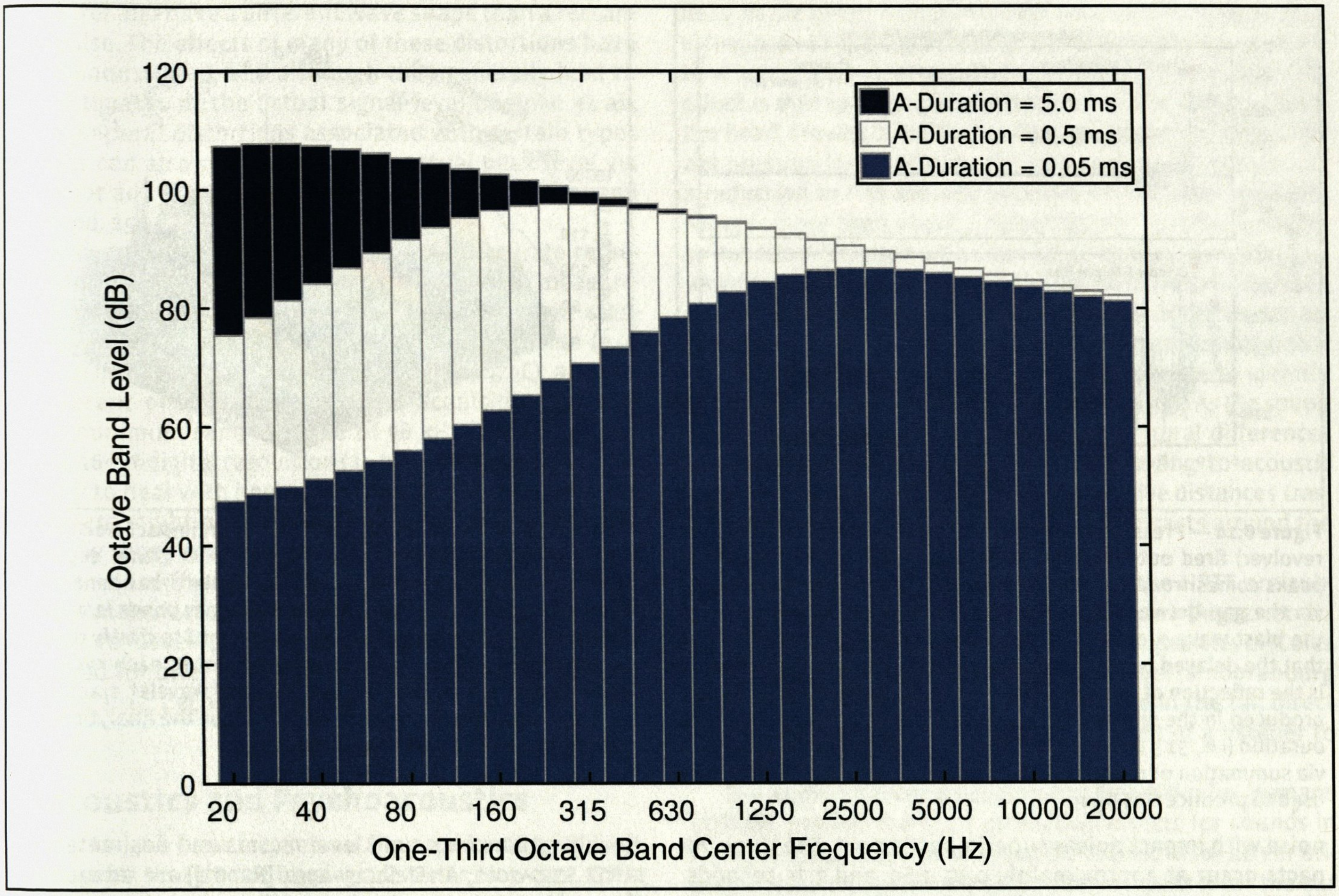

Figure 6.9 — Spectral effects of changes in pressure-wave duration for Friedlander impulses with equivalent peak amplitude. As the A-duration increases, the impulse develops more low-frequency content. The loss of energy (lower overall levels) is due to the lower integrated energy of the impulse as the A-duration decreases.

the upper panel of Figure 6.10, the weapon was fired over a flat surface and the reflected shock from the ground at about 6.5 ms is marked. As one moves away from the impulse noise source, the ground reflection will move closer in time to the incident impulse because the path length difference between the incident and reflected wave is reduced. The lower panel of Figure 6.10 illustrates the same firearm discharged from within a hunting blind (approximately 2 x 2 x 2.5 m). The greater complexity of the waveform is due to the multiple surfaces inside the blind from which the shock wave can reflect. This particular hunting blind had no absorptive material to dissipate the reflections. For both impulses, the gas of the burning propellant escapes between the cylinder and the barrel and then the gas pushes the bullet out of the muzzle, creating a second impulse.

Reflected signals have the potential to combine with later portions of the initial pressure wave, producing a greater instantaneous peak level than would be observed if the reflective surface were absent. Furthermore, if the reflected sounds travel the same distance to the receiver, the reflected signals could sum to produce a greater total reflected level at the location of the listener's ear than the direct signal. Thus, it is important to appreciate that measurements of a sound source in one environment will not necessarily generalize to other environments and/or listener positions. It is overwhelming to trace individual reflections in most enclosures, and one must often be content with examining the overall waveform consisting of both the direct and reflected components. The principal effect of enclosures is to increase the duration of the signal envelope (Figure 6.10).

Brief high-level sounds will often be present in environments that also contain continuous noise. In addition to sound sources that produce continuous noise regularly punctuated by brief high-level sounds, many activities producing brief high-level sounds will be conducted while continuous noise is being produced by other sources. An impact wrench is an example of a sound source that produces both continuous and brief high-level sounds. A plot of the sound energy produced by an industrial process as a function of both frequency and time is represented in Figure 6.11. Note that this signal contains continuous

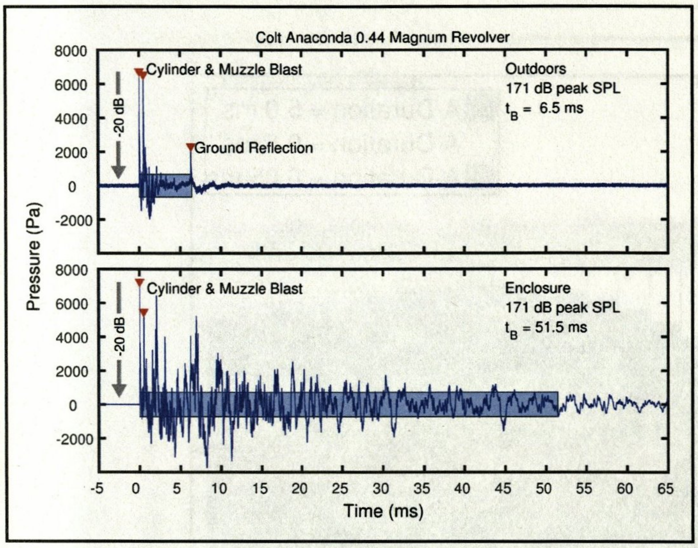

Figure 6.10 — Pressure wave produced by a handgun (.44 magnum revolver) fired outdoors and in an enclosure. The initial pair of peaks comes from the cylinder blast (i.e., sound energy escaping via the gap between the revolving cylinder and the barrel) and the blast wave produced as the bullet escapes the muzzle. Note that the delayed peak (approximately 2000 Pa) in the upper panel is the reflection of the initial blast wave off the ground. The wave produced in the enclosure has a much longer pressure-envelope duration (i.e., 51.5 ms versus 6.5 ms) and multiple peaks produced via summation of reflected waves. Data from Stewart (2013) were used to produce this figure.

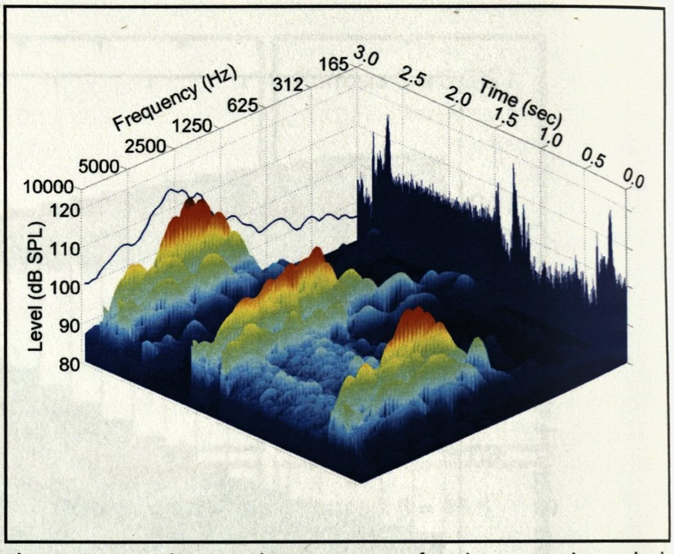

Figure 6.11 — Time-varying spectrum of an impact noise embedded with a continuous noise. The right rear panel depicts the absolute value of the time waveform. The left rear panel depicts the maximum values at the various frequency bands (1/12-octave-band intervals). The frequency axis is reversed to clarify the acoustic events preceding the final (major) event in each cycle. Three event cycles are evident in the analytic wavelet transform of the time data. (For more information about the analytic wavelet transform, see Zhu and Kim, 2006.)

noise with impact noises superimposed on it. The three impacts occur at approximately 0.35, 1.60, and 2.75 seconds. The continuous noise, analyzed in 1/12 octave bands, is often greater than 85 dB SPL in the high frequencies; thus, it is potentially hazardous on its own (see Chapter 9). The maximum 1/12-octave-band levels are greater than 100 dB SPL between about 1.25 and 10 kHz, and the levels varied considerably over the recording duration. The science of assessment of hazard for combined continuous and brief high-level noises is not yet mature, but environments containing both kinds of noise require careful measurement and evaluation to avoid underestimating hazard.

Measurements of Impulses

Conventional sound measurement devices are not often designed to measure brief high-level sounds accurately (Kardous and Willson, 2004; Kardous et al., 2005). The rapid rise time and interval at the peak of the measurement require microphones and hardware capable of capturing the rapid transition from ambient pressure to the instantaneous peak and back again. This requirement implies a maximum microphone diameter of 1/4 inch, a preamplifier and power supply system capable of rapid and extreme voltage changes, and analog-to-digital conversion hardware capable of a high sample rate (Rasmussen et al., 2009). Subsequent circuit elements must preserve the shape of the analog waveform to ensure accurate analysis and estimation of auditory risk. While standard performance specifications for sound-level meters and dosimeters (e.g., ANSI S1.4-2001; ANSI S1.25-1991 [R2007]) are adequate for longer-duration signals, their sufficiency suffers as the duration decreases and frequency content increases. For example, ANSI S1.4 allows a Type 1 device to filter out all signals above 12.5 kHz; Type 2 sound level meters are allowed to filter out all signals above 8 kHz (ANSI S1.4-1983, Table V). The rapid electrical changes required to follow high-frequency sinusoids in the conventional frequency range only begin to approach, but often fail to capture, the rapid rise times associated with many brief high-level sounds.

Unfortunately, conventional sound level meters often include time constants that would lead to inaccurate readings. As noted in Chapter 3, the *fast* time constant approaches the asymptote for a continuous sound within 125 ms. The *impulse* time constant, which would initially seem appropriate for brief high-level sounds, reaches the same amplitude within 35 ms. The *peak* setting is commonly expected to display the instantaneous peak amplitude, but the user must recognize that this peak amplitude is assessed after any effects of filtering (e.g. distortions or filter-induced ringing), inadequate system rise time, inadequate voltage supply, or analog-to-digital sample rate effects have occurred. Furthermore, ANSI S1.4 allows as much as a −2 dB error for a 100 µsec rectangular pulse relative to a 10 ms pulse having the same amplitude. Peak-detecting performance is unspecified for pulses less than 100 µsec. The peaks of many brief high-level sounds are shorter and have a different wave shape than a rectangular pulse. The effects of many of these distortions have been demonstrated, and although they generally lead to underestimates of the actual signal level (Meinke et al., 2016), temporal distortions associated with certain types of filters can also overestimate the actual peak level via overshoot and filter "ringing" phenomena (Garinther and Moreland, 1965; Walton, 1981).

In recognition of the specific needs for accurate representation of brief high-level sounds, a number of measurement conventions have emerged. There are some standards related to measuring brief high-level sounds (e.g., ANSI S12.42-2010, ANSI S12.7-1986, MIL-STD-1474E), and the more recent ones specify that data acquisition systems have a minimum sampling rate of 96 kHz (192 kHz is preferred), 16-bit digital resolution (24-bit is preferred), and the capacity to deal with impulses of 180 dB SPL. However, the 96 kHz rate might not capture the peak of many impulses, especially those near a combustive source. Most recording systems use different combinations of equipment from multiple manufacturers, but some efforts have been made recently to develop standardized systems and software optimized for brief high-level sounds (Kardous et al., 2005; Kardous, 2013; Zechmann, 2012).

Bioacoustics and Psychoacoustics

Thus far, we have focused on the aspects of brief high-level sounds that do not involve a listener. However, there are a number of important interactions between the auditory system and the signal in the undisturbed sound field, beginning with the effects of the head and torso and extending through the filtering and the time-varying impedance of the middle ear system.

The head and torso influence both the magnitude and phase characteristics of the sound, and this influence varies with frequency. The effect of the body on the sound goes by many names, including the *Transfer Function of the Open Ear (TFOE)*, the *Field-to-Eardrum Transfer Function*, and the *Head-Related Transfer Function (HRTF)*, depending on the research context and author preference. For the moment, we shall adopt the HRTF term. Briefly, the HRTF represents the difference between the signal observed at the eardrum and the signal that would be observed at the location occupied by the center of the listener's head if the listener were absent. Thus, the HRTF represents the combined influence of the head, torso, pinna, and earcanal on the signal present at the eardrum.

The HRTF varies with the azimuth, elevation, and distance of the sound source relative to the head and, to a lesser extent, the torso. Azimuth, elevation, and distance effects on the magnitude spectrum have been studied extensively (Algazi et al., 2001; Hammershoi and Moller, 1996; Shaw, 1974; Mehrgardt and Mellert, 1977; Kuhn, 1979; Blauert, 1983). As the sound source moves along the azimuthal plane, the head baffle effect exerts more influence on the signal, providing gain to the signal on the side nearer the source and, to a lesser extent, attenuation on the opposite side. This effect is due to incomplete diffraction of the signal around the head, leaving a buildup of root-mean-square (rms) average pressure (or a baffle) on the same side as the source and a reduction in rms average pressure on the other side. For sources more than about 1 meter distant, an object begins to impede diffraction when it is larger than 1/10 of stimulus wavelength (Beranek, 1996). As the sound moves along the elevation plane, constructive and destructive interference associated with the pinna structures leads to an audible notch in the frequency spectrum that listeners can use to identify the location of the sound source (Blauert, 1983). As the sound source moves closer to the listener, inter-aural differences increase and shift lower in frequency, owing to acoustic near-field effects and changes in the relative distances traveled by the sound as it propagates and diffracts around the head (Brungart and Rabinowitz, 1999).

Although intersubject differences in the HRTF are substantial, especially in the high frequencies (Algazi et al., 2001), an average difference of 4 to 5 dB in peak level (Coles et al., 1967) and equivalent continuous level (Smoorenburg et al., 2003) is expected as a sound source in the far, direct sound field is moved from directly in front of a listener to the side along the azimuthal plane.

The Auditory Hazard Assessment Algorithm for Humans (AHAAH) models the head diffraction effects for sounds in the azimuthal plane to increase the exposure for an ear oriented toward the impulse source or decrease it for the ear that is shadowed by the head (Fedele et al., 2013). More sophisticated methods can be derived to account for average azimuth effects, such as complex averaging across a reference database of HRTFs (Algazi et al., 2001), but no current methods account for the wide array of possible azimuths and elevations from which the impulsive signals might arrive, nor are between-subject differences in HRTF commonly implemented in contemporary approaches for assessing the risks of exposure to brief high-level sounds.

Middle Ear Transfer Function

The effects of the middle ear act upon the signal after it has been transformed by the HRTF. The human middle ear system behaves as a bandpass filter system that attenuates low-frequency signals (e.g., below approximately 1 kHz), optimally passes energy to the cochlea in the mid-frequency range (e.g., 1 to approximately 6 kHz), and begins to provide increased impedance for signals above that frequency. As noted in Chapter 3, the A-weighting filter function was originally developed to approximate the equal loudness contour for low-level signals, but it has found common use in noise assessment due to the association between A-weighted signals and threshold shift (Cohen et al., 1972). It is plausible that the correspondence between threshold shift and the A-weighting filter involves the

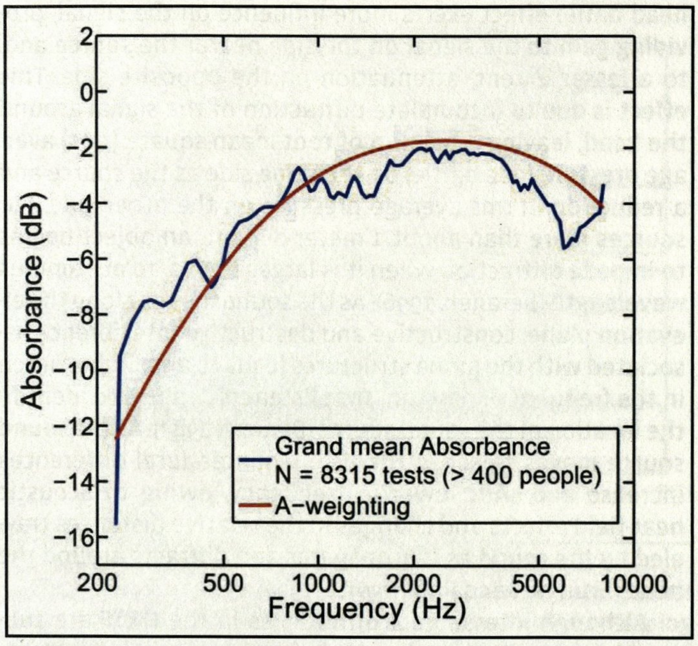

Figure 6.12 — Comparison of middle ear energy absorbance and the shape of the A-weighting filter (Flamme et al., 2013).

emulation of the average human middle ear transfer function provided by the A-weighting filter. The A-weighting filter function resembles the average sound absorbance (i.e., the complement of sound reflectance) of the adult middle ear (Figure 6.12). However, it must be recognized that considerable intersubject differences are found in middle ear transfer functions.

Annular Ligament as Peak Clipper

Many aspects of peripheral auditory function are linear, which means that an increase in the input to the system leads to a proportional increase in output, among other things. For example, a 5 dB increase in the input to the outer ear should produce a 5 dB increase (i.e., about a 1.8 multiplier) in eardrum vibration. Two aspects of middle ear function are not linear: clipping by the annular ligament and contractions of the middle ear muscles.

As described in Chapter 4, the stapes transmits vibrations into the cochlea by moving as a piston relative to the rest of the skull. The middle ear system transfers energy into the cochlea linearly through peak levels of about 160 dB SPL unless middle ear muscle contractions are active. Above this, the excursions of the stapes are limited by the annular ligament, which consequently limits the momentary peak of energy transfer into the cochlea. The point at which the annular ligament begins to limit vibrations is not well known in humans, but intracochlear measurements in guinea pig models indicate that the limiting effect begins to occur around 155 to 160 dB SPL (Dancer, 2003; Greene et al., 2015), and the stapes is expected to achieve a maximum displacement between 30 microns (Bolz and Lim, 1972; Guinan and Peake, 1967) and 150 microns (Greene et al., 2015). Thus, energy from instantaneous sound pressures corresponding to large stapes displacements should not be transmitted as efficiently into the cochlea. Intracochlear measurements at peak levels exceeding 2 kPa suggest that progressively less energy is transferred into the cochlea as a function of increased peak pressure and decreased frequency, resulting in as much as a 20 dB reduction in energy at 200 Hz and minimal influence above 1 kHz (Dancer, 2003).

Middle Ear Muscle Contractions

Energy transfer into the cochlea is also modified by changes in the tension of the middle ear muscles. Both the stapedius and the tensor tympani middle ear muscles have been shown to contract reflexively in response to high-level stimuli. Acoustic reflex thresholds among listeners with normal hearing typically range between 75 and 100 dB HL (Gelfand and Piper, 1984). During contraction, the tensor tympani draws the manubrium of the malleus medially, while the stapedius draws the stapes perpendicular to its normal vibratory axis into and out of the cochlea (Møller, 1983), thus altering the vibratory properties of the ossicular chain. The tensor tympani nerve supply follows the fifth (trigeminal) cranial nerve, while the nerve supply to the stapedius follows the seventh (facial) cranial nerve (Pickles, 2008). In humans, stapedius contractions are considered to have a greater effect on middle ear impedance than tensor tympani contractions (Mukerji et al., 2010; Pang and Peake, 1986), and contractions of the tensor tympani have been associated with the startle response (Klockhoff and Anderson, 1960).

Effect on Transfer Function

Although the evolutionary advantage conveyed by the middle ear muscle reflex is not well known (Pickles, 2008), the effect of middle ear muscle contractions on energy transfer through the middle ear is better understood. Contractions of the middle ear muscle decrease energy transfer at frequencies below about 1 kHz and either pass or increase slightly the amount of energy transferred into the cochlea at higher frequencies (Møller, 1961; Rabinowitz, 1977; Feeney and Keefe, 1999; Schairer et al., 2007). Effects of middle ear muscle contractions have been shown to extend to higher frequencies at very large contraction levels in cats whose stapedius muscles were stimulated directly and whose tensor tympani tendons were severed (Pang and Peake, 1986), but the generalizability of these results to human reflexive contractions is not clear. A demonstration of the effect of reflexive muscle contractions on the middle ear transfer function is provided in Figure 6.13, but it is important to note that there are substantial intersubject differences in changes to the middle ear transfer function (Feeney and Keefe, 1999).

Middle ear muscle contractions are expected to reduce the magnitude of temporary threshold shift (TTS) (Zakrisson et al., 1980; Fletcher, 1961), but the amount of benefit for brief high-level sounds remains unclear because the dynamic

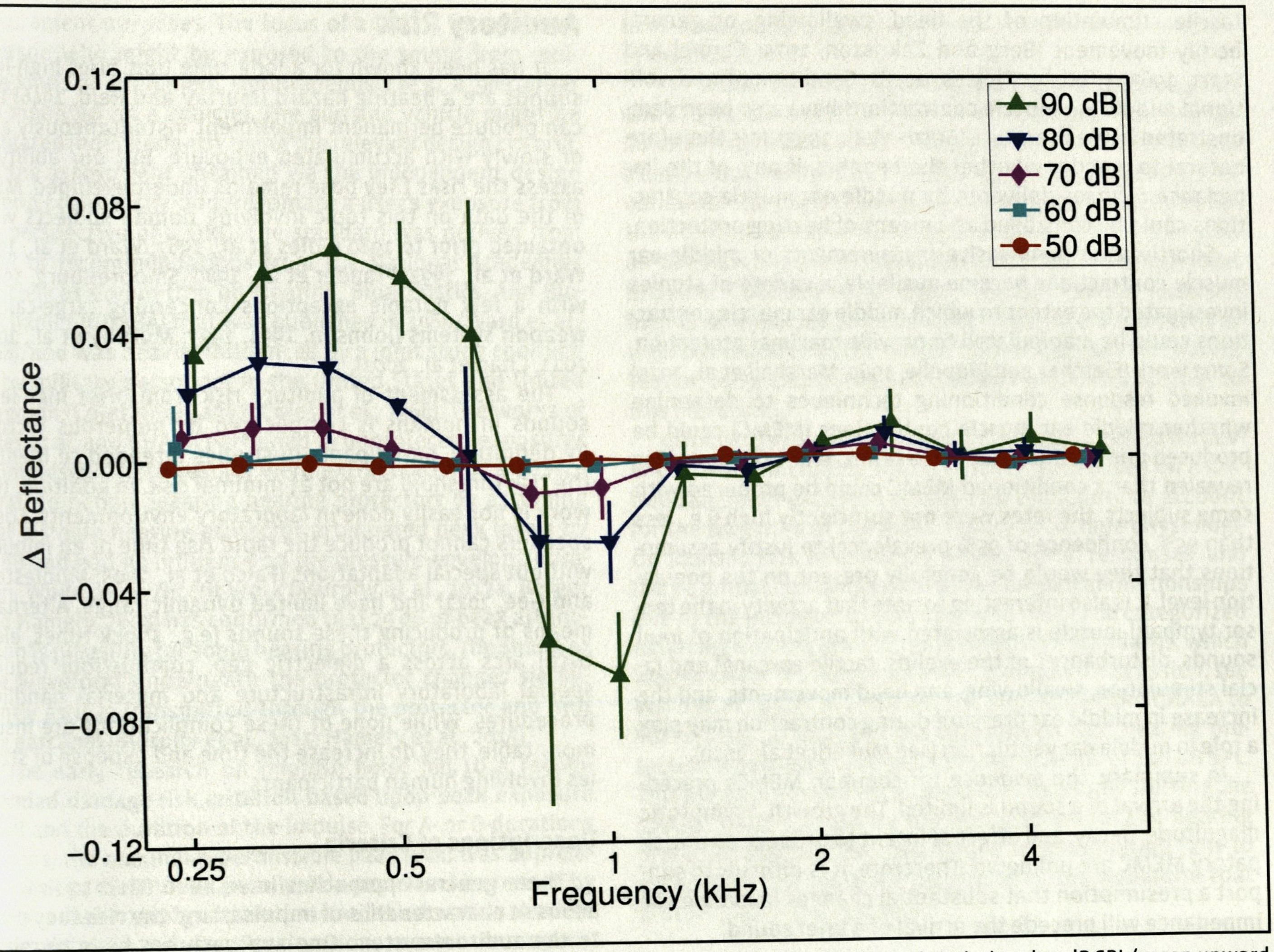

Figure 6.13 — Example of change in middle ear reflectance between stimulus levels of 50 dB SPL (red circles) and 90 dB SPL (green upward triangles). Increases in reflectance indicate reduced energy transfer into the cochlea; decreases correspond to enhanced energy transfer.

characteristics of the contraction are determined in part by the characteristics of the stimulus (Wilson et al., 1978). Although most research in this area was conducted with longer-duration stimuli, it is important to note that contractions begin earlier for low-frequency signals than for high-frequency signals. Onsets are determined in part by the stimulus level, especially for high-frequency stimuli, and the contraction duration for a 25 ms tone burst is on the order of 200 ms (Borg, 1982) or less. In addition, there is some reason to believe that there is no difference between the amount of protection afforded by reflexive middle ear muscle contractions to brief high-level sounds and longer duration noises at the same sensation level, at least up to sensation levels of 120 dB (Fletcher, 1961).

Reflexive contractions of the middle ear muscles cannot be expected for all listeners. The probability of a reflexive contraction of the middle ear muscles is lower among people with hearing impairment (Gelfand and Piper, 1984; Golding et al., 2007), and reflexive contractions are absent in some individuals with normal hearing (Gelfand and Piper, 1984; Olsen et al., 1975). A recent study examined the pervasiveness of ipsilateral acoustic reflexes in the U.S. population using data from over 15,000 participants in the National Health and Nutrition Examination Survey. Acoustic reflexes would need to be present in practically everyone (i.e., 95% confidence of 95% prevalence) to be considered pervasive. This study found that, even in young listeners with normal hearing, the prevalence of bilateral acoustic reflexes to at least one of two elicitor stimuli failed to meet the criteria for pervasiveness. In addition, the time course of the acoustic reflex was frequently too slow to be of any protective value (Flamme et al., 2016). Thus, it is doubtful that acoustic reflexes are sufficiently dependable as a general protective mechanism for impulsive noises.

Nonreflexive Contractions

The motor neurons leading to the middle ear muscles receive inputs from parts of the brain involved in a wide variety of functions (Mukerji et al., 2010). Middle ear muscle contractions can be observed during vocalization, tactile stimulation of the head, swallowing, or general bodily movement (Borg and Zakrisson, 1975; Carmel and Starr, 1963, cited by Pickles, 2008). Conditioned and volitional middle ear muscle contractions have also been demonstrated in the literature (Burns et al., 1993). It is therefore natural to wonder whether the benefits, if any, of the impedance changes delivered by middle ear muscle contractions could be controlled as a means of hearing protection.

Shortly after noninvasive measurements of middle ear muscle contractions became available, a variety of studies investigated the extent to which middle ear muscle contractions could be manipulated to provide maximal protection. Some work (Fletcher and Riopelle, 1960; Marshall et al., 1975) invoked response conditioning techniques to determine whether middle ear muscle contractions (MEMC) could be produced prior to the onset of the reflex. While these studies revealed that a conditioned MEMC could be produced with some subjects, the rates were not sufficiently high (i.e., less than 95% confidence of 95% prevalence) to justify assumptions that they would be generally present on the population level. It is also interesting to note that activity in the tensor tympani muscle is associated with anticipation of loud sounds, disturbances of the eyelids, tactile earcanal and facial stimulation, swallowing, and head movements, and the increase in middle ear pressure during contraction may play a role in middle ear ventilation (see Mukerji et al., 2010).

In summary, the evidence for common MEMCs preceding the arrival of a sound is limited. The growth, asymptotic magnitude, decay, and effect of intent to produce an anticipatory MEMC are unknown. Therefore, it is difficult to support a presumption that substantial changes in middle ear impedance will precede the arrival of a brief sound.

Loudness

Loudness is the magnitude of the auditory sensation created by an acoustic stimulus (Fletcher and Munson, 1933). Although loudness is related to stimulus amplitude, this relationship is far from perfect for brief high-level sounds with signal durations less than about 200 ms (Zwislocki, 1969). Relatively little research has been conducted with high-level impulsive sounds, but there is evidence that rank-ordering of loudness for different gunshots in an open field is correlated to the product of peak intensity and pressure-envelope (B) duration. Loudness is the result of physical (e.g., intensity, frequency), peripheral (e.g., outer, middle, and inner ear), and central (e.g., cognitive, emotional) factors, and it comes as no surprise that loudness perceptions can only occur retrospectively. While this delay is trivial for sounds with minimal amplitude changes over time, loudness perceptions for brief high-level sounds will underestimate the physical intensity of the signal, particularly if the A-duration (i.e., the pressure-wave duration) is less than about 3 ms (Coles et al., 1967). This underestimation will often lead a listener to incorrectly conclude that a brief sound is not hazardous because it is not perceived as sounding very loud.

Auditory Risk

It has been known for a long time that brief high-level sounds are a hearing hazard (Murray and Reid, 1946) that can produce permanent impairment instantaneously and/or slowly with accumulated exposure. But our ability to assess the risks they pose remains underdeveloped. Much of the data on this topic involving human subjects were obtained prior to 1980 (Coles et al., 1967; Ward et al., 1968; Ward et al., 1992; Pfander et al., 1980; Smoorenburg, 1982), with a few notable exceptions concerning large-caliber weapon systems (Johnson, 1994, 1997; Murphy et al., 2009, 2011; Chan et al., 2001).

The assessment of auditory risk from brief high-level sounds in humans is complicated by numerous factors. By definition, participants in studies intended to identify the risk threshold are not at minimal risk. In addition, this work is not easily done in laboratory environments. Loudspeakers cannot produce the rapid rise time of an impulse without special adaptations (Falco et al., 2005; Muhlestein and Gee, 2011) and have limited dynamic range. Alternate means of producing these sounds (e.g., shock tubes, electrical arcs across a dielectric gap, combustion) require special laboratory infrastructure and material handling procedures. While none of these complications are insurmountable, they do increase the time and expense of studies involving human participants.

Descriptions of Criteria

Three general approaches have been used to link the acoustic characteristics of impulses and the risk they pose to the auditory system. One approach has been to relate risk to the fine structure of the impulse waveform; another has been to relate risk to the energy contained within the impulse. The most recent work has been in the development of physiologically linked auditory system models that relate risk to an index of mechanical activity generated by the stimulus.

Waveform Parameter-Based Damage-Risk Criteria (DRC)

The bulk of the human research linking the acoustic waveform to auditory damage was done over 40 years ago, when instrumentation and computational capacity were quite limited by today's standards. However, researchers during that time had the capacity to document impulse waveforms and assess the relationship between waveform structure (e.g., instantaneous peak, pressure-wave duration, pressure-envelope duration) and auditory outcomes such as TTS and permanent threshold shift. In the United States, the predominant approach for assessing the potential for harm associated with an impulse noise was described in Military Standard 1474D (U.S. Department of Defense, 1997), which was a set of design criteria for military equipment but has been applied as a *de facto* DRC. The focus of design criteria is on the evaluation of equipment for procurement purposes. The focus of a DRC is centered on a person who might be exposed to the sound from multiple kinds of equipment simultaneously (e.g., a .50-caliber gun mounted on a vehicle). The gun and vehicle might be evaluated independently using the relevant design criteria, but the assessment obtained via the independent design criteria could easily underestimate a user's exposure from the perspective of a DRC. The standard was derived from a set of recommendations from the National Academies of Sciences Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) that was published in 1968 (Ward et al., 1968), and was heavily influenced by a joint study conducted by military personnel in the United States and United Kingdom (Coles et al., 1967; Coles et al., 1968). The works of Coles et al. and CHABA pertained to unprotected exposures to impulses. These results were extrapolated in MIL-STD-1474D to people wearing hearing protectors by assuming that a single hearing protector attenuated peak levels by 29 dB and had no influence on the pressure-envelope duration. While more recent work (Murphy et al., 2012a; Berger and Hamery, 2008) has confirmed that 29 dB of peak attenuation is plausible for some hearing protectors, the shape of the waveform underneath the protector changes significantly as it is transmitted through the protector and into the earcanal (Murphy et al., 2015; Hamery et al., 2015).

The early research on impulse noise led to a recommended damage-risk criterion based upon peak exposure level and the duration of the impulse. For A- or B-durations of 1 ms, the maximum permissible peak level was approximately 154 dB SPL. The permissible peak level increased by 2 dB for each halving of duration until the duration reached approximately 200 µsec. For durations greater than 1.7 ms, separate criteria were applied for A- and B-durations. The A-duration was considered relevant for impulses emulating a Friedlander wave function, and the B-duration was relevant for all other types of impulses. The B-duration criterion maintained a constant slope (−2 dB per doubling of duration), reaching a permissible peak level of 145 dB SPL for durations of approximately 1.7 ms. This criterion was developed to protect 75% of ears, with recognition that the most susceptible 25% of ears might not be protected. The maximum exposure limits per CHABA followed a very similar function, but all values were shifted downward by 5 dB to account for sound sources located at normal (90 degree) incidence to the head and another 5 dB to protect all but the most susceptible 5% of ears (i.e., 95th percentile) (Ward et al., 1968). Both of these correction factors were recommended by Coles et al. (1967). At the low end, the maximum permissible peak level terminated at 138 dB SPL (at a 200 ms B-duration) as a way of accounting for the expected protective effect of the middle ear muscle reflex, which was hypothesized to have a meaningful effect on the middle ear transfer function for impulses with B-durations greater than about 200 ms (Ward et al., 1968). For numbers of exposures other than 100 ms, the maximum exposure level was to be reduced by 5 dB for a tenfold increase in the number of exposures.

The CHABA recommendations are superimposed on the MIL-STD-1474D criteria in Figure 6.14. Note that the limit for double protection is intended to account for the additional attenuation provided by simultaneous use of earplugs and earmuffs. The Blast Limit curve is designed to account for the non-auditory effects of high-level impulses. Fluid- and air-filled organs are susceptible to damage from high-level impulses (Johnson et al., 1997). The association between high-level impulses and traumatic brain injury is an area of vigorous research at the time of this writing (see Kocsis and Tessler, 2009, and Leung et al., 2008, for an introduction to this literature).

Criticisms of parameter-based DRC may be levied for several reasons, including that the limits were based on a limited sample of exposure conditions, the failure to account for the spectrum of the noise, failure to include physiological limits, a lack of modeling physiological responses, and the potential contamination of the empirical relationships due to the inclusion of listeners who would be categorized as having hearing impairments by today's standards, which lead to lower TTS magnitudes (for a detailed discussion, see Ward et al., 1992). In addition, the migration from CHABA to MIL-STD-1474D included the assumption that hearing protection was used above peak pressure levels of 140 dB SPL. This assumption was accommodated by simply shifting the CHABA limits upward by the assumed amount of hearing protector attenuation. This simple transformation fails to account for the temporal distortion of the waveform that is produced in the earcanal.

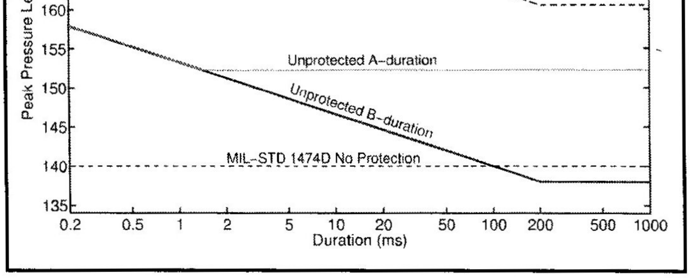

Figure 6.14 — The equal-risk contours developed by CHABA (Ward et al., 1992) and in MIL-STD-1474D. Increased risk is associated with increased duration, which leads to a decrease in the allowable peak pressure level. The pressure-wave (A) duration is shown in this figure to reach its maximum risk at approximately 1.5 ms.

Energy-Based DRC

DRC for impulse noise have also been based on the quantity of energy present in the impulse (e.g., Atherley and Martin, 1971). An energy-based DRC assumes that risk increases in proportion to the energy reaching the cochlea. This energy can be represented by either an 8-hour A-weighted equivalent continuous level ($L_{Aeq,8hr}$), or a sound exposure level (SEL_A), which differ only in the amount of time over which the energy in the impulse is summed. Thus, they differ only by the ratio of 1 second to 8 hours (44.6 dB).

Some of the earliest energy-based DRC limited exposure to a total daily exposure of 85 dB $L_{Aeq,8hr}$, regardless of the kind of sound source (Dancer et al., 1983; DTAT, 1983). Others (e.g., Smoorenburg-NATO, in Smoorenburg et al., 2003) derived different limits for impulses from small- and large-caliber sources, with lower limits for small-caliber sources due to the relative increase in energy in the high frequencies for these sources.

Energy-based DRC offer some practical advantages over parameter-based approaches. For example, energy-based DRC utilize the same units as those used with continuous noise, and this facilitates summation of risks from both types of sounds. In addition, the conceptual and computational parsimony of this approach is appealing. However, energy-based DRC have been criticized on the grounds that they fail to account for auditory system nonlinearities (e.g., middle ear muscle contractions, annular ligament displacement limits), ignorance of the role of fine pressure waveform features (e.g., kurtosis), and others (Price, 2012). When added to integrated energy measures, kurtosis has been shown to improve predictions of both threshold shift and sensory cell loss, but additional waveform features (e.g., fine structure) were not strongly associated with auditory damage (Qiu et al., 2013).

As of 2015, the U.S. Department of Defense has revised the MIL-STD-1474D with MIL-STD-1474E. MIL-STD-1474E contains significant changes in the evaluation of brief high-level sounds. Most notably, the Auditory Hazard Assessment Algorithm for Humans (AHAAH) model (described below) and the equivalent A-weighted energy for 100 ms ($L_{IAeq,100ms}$) have been incorporated. The U.S. Army has made it policy that the AHAAH model will be used for assessing the potential hazard of weapon systems. The other services, Air Force, Navy, and Marines, can use either the $L_{IAeq,100ms}$ or the AHAAH model. Both of the new metrics require that an accurate waveform recording of the exposure be collected in order to evaluate the risk of hearing loss due to a brief high-level sound. Both metrics include methods to estimate the exposure of a warfighter when hearing protection is worn.

The $L_{IAeq,100ms}$ relies on acoustic test fixture (ATF) measurements to estimate the performance of hearing protection devices (HPDs) for high levels. If the impulse noise is measured externally, then the hearing protector impulse peak insertion loss (IPIL) measured according to ANSI S12.42 is used to subtract the protection from the impulse level. Murphy (2016) and Murphy et al. (2012) presented results for four protectors measured with acoustic shock tube impulses at 150 and 160 dB peak SPL. They demonstrated that the reduction of the L_{Aeq8} as a function of angle and level was reliably predicted by the IPIL reductions. The IPIL methods will suffer similar problems seen in the AHAAH HPD module; the high-level impulses above the test levels used in the ANSI S12.42 can cause separation of the protector from the test fixture, leading to erroneous estimates of HPD protection (Buck, 2009; Berger and Hamery, 2008). However, the ATF approach can be used to determine the limits of when protection will catastrophically fail, whereas the AHAAH HPD module cannot make any determination. Hamery et al. (2015) have proposed a simple measurement of the ratio of the maximum to minimum pressures underneath the hearing protector to determine when the structural nonlinearities of the protector separating from the ATF begin to occur. This approach will identify limits of the attenuation where IPIL might be applicable.

The integrated energy approach has been recommended as an interim damage-risk criterion while uncertainties about other approaches are resolved (Zagadou et al., 2016). These investigators relied on data from a human exposure study to determine that limiting listeners to an 8-hour equivalent A-weighted sound level (i.e., $L_{Aeq,8hr}$) of 89 dB would protect 95% of the population with 95% certainty.

Ear Model-Based DRC

Price and Kalb (1991) developed an electroacoustic model of the ear called the AHAAH. This computational model of the ear uses components that represent the function of each anatomical structure of the ear. The AHAAH model was originally based on the auditory physiology of the cat. The human version (Price, 2007a, 2007b) was developed by scaling model parameters to match the physical characteristics of the human ear. The model treats the outer and inner ear as essentially linear elements. Two nonlinear elements are included in the model of the middle ear. One of these elements represents the annular ligament surrounding the stapes footplate. The other nonlinear element is the middle ear muscle contraction.

The AHAAH model provides separate risk estimates for both warned and unwarned listeners. In the warned condition, middle ear muscles are presumed to contract prior to the onset of the impulse and muscle contractions are presumed to be reflexive in the unwarned condition. The onset latency for a reflexive middle ear muscle contraction in AHAAH is 9 ms, and the time constant for the contraction is 11.7 ms (Fedele et al., 2013), which implies that the reflexive MEMC latency (to 99% of the full contraction) is 63 ms (Fedele et al., 2013). Several assumptions are integral to the development of the AHAAH software. Specifically, the developers assumed that once a sound exceeded the activation threshold of the MEMC (108 dB SPL), the middle ear muscle always reaches full contraction regardless of the characteristics of the stimulus. They assumed the MEMC always remains at its maximum for the duration of the analyzed waveform (i.e., there is no allowance for reflex release or decay) and that 100% of exposed persons have a 100% probability of middle ear muscle contractions in both warned and unwarned conditions. To account for the most susceptible ears, the input waveform is increased within the model by 10 dB and processed using the same model that depicts the average ear (Price, 2007a, 2007b). These assumptions are not necessarily true. Not all persons have middle ear reflexes. Not every stimulus will evoke a fully developed contraction. Also, the MEMC does exhibit habituation and decays due to fatigue as well as relaxing during quiet periods.

The likelihood that a randomly selected untrained human listener's middle ear muscles will contract prior to the arrival of blast noise from a gun has never been tested directly. It is unknown whether middle ear muscle contractions will have comparable effects on risk across the broad range of brief high-level sounds. Furthermore, the middle ear muscles have been shown to contract with some facial gestures and in response to tactile stimulation of the face (Djupesland, 1964). In a recent study, concurrent middle ear muscle contractions were observed in each of 60 adult listeners who performed voluntary eyelid closure (at maximum effort) on the same side of the head as the tested ear. The majority of adult participants receiving compressed air stimulation to the face also showed middle ear muscle activity (Flamme et al., 2016). These alternate pathways leading to middle ear muscle contractions are not well understood. It is possible that middle ear muscle contractions due to non-acoustic factors could have been mistaken for conditioned responses in prior studies.

Risk estimates in AHAAH are based on estimates of the sum of squared upward displacements (in microns) of individual segments of the basilar membrane (Price, 2007a). The criterion produced by AHAAH, the Auditory Risk Unit (ARU), is an arbitrary unit that is intended to be directly proportional to the maximum summed upward displacement at any point on the membrane. Displacement quantities from other membrane segments are stored in a temporary file but are not reported in the overall ARU. For susceptible listeners with occasional exposure to impulse noise, an exposure to 500 ARUs is considered unsafe (i.e., can be expected to produce more than 25 dB of threshold shift) for occasional exposures (Price, 2007a). An exposure of 200 ARU or less is considered safe (i.e., would not be expected to produce any threshold shift) for daily exposures (Price, 2007b), and temporary threshold shift between 0 and 25 dB would be expected for exposures between 200 and 500 ARUs (Price, 2007a). The ARU limits were established based on the interpolation of grouped responses from cats and have been assumed to also represent humans after model parameters were scaled to the larger size.

The AHAAH has many strengths, including its intent to extend from an empirical relationship to the underlying biophysical phenomena involved in producing hearing loss from brief high-level sounds. It can, however, be criticized on the grounds that it contains a variety of embedded assumptions, many of which have not been thoroughly tested either singly or in the context of a complete model. These assumptions can be regarded as aspirations about the auditory system that are unlikely to be achieved by actual human ears. Data supporting the position that over 95% of the population will exhibit maximal middle ear muscle contractions prior to the arrival of an impulsive sound requires confirmatory study before a "warned" condition should be used. The assumption that all exposed persons will exhibit reflexive middle ear muscle contractions is incorrect, particularly for those who are not young adults with excellent hearing sensitivity (Flamme et al., 2017).

In order to resolve some of these questions, Zagadou et al. (2015) examined the AHAAH model and found that important model parameters were scaled improperly. After correcting these model errors, Zagadou et al. evaluated the corrected version of the AHAAH model against alternative approaches. These authors found that an ear model integrating the energy entering the cochlea performed better than the revised AHAAH. The integrated cochlear energy (ICE) approach still requires independent validation, but the developer's results suggest that it is robust to changes in impulse level, duration, and spectrum and can be used to evaluate protected exposures as well.

Comparisons of Criteria

Existing DRC share many common characteristics. For sounds with instantaneous peaks below 160 dB SPL (where some DRC presume that stapes motion will be limited by the annular ligament), all DRC presume that signals containing more energy are more hazardous — even though they reach this decision via different conceptual paths. Existing DRC are strongly correlated to one another, but there are vast differences in the interpretations of hazard produced by the DRC (Flamme et al., 2009b). For small arms impulses in the open field, the correlation between the numbers of maximum permissible exposures (unprotected) for $L_{Aeq,8hr}$ and AHAAH is over 0.96, which indicates that the two DRC provide nearly redundant rank orders of permissible exposures. However, the absolute numbers of permissible exposures are vastly different (Flamme et al., 2009a; Flamme et al., 2009b; Brueck et al., 2014), especially for sounds with lower amounts of energy (Figure 6.15). The discrepancy in the numbers of allowable exposures is even greater for the Coles/CHABA criterion (i.e., the initial version of MIL-STD-1474D that did not assume any use of hearing protection), where a signal analyzed using the Coles/CHABA DRC would allow as many as 1 million unprotected exposures, while $L_{Aeq,8hr}$ would permit 1000, and the unwarned AHAAH would permit only 40 unprotected exposures. So in spite of their strong correlation, contemporary DRC can

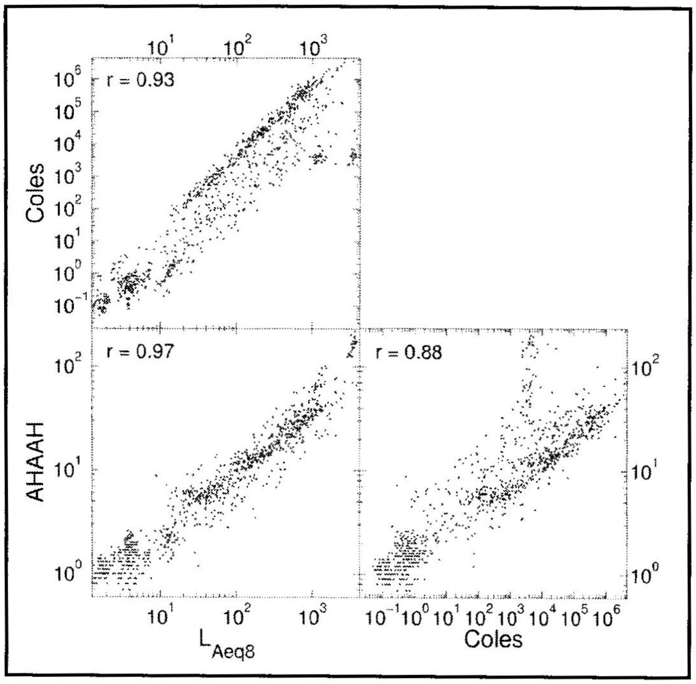

Figure 6.15 — Scatterplots of maximum permissible exposures obtained for an unprotected listener via different damage-risk criteria.

lead to mutually exclusive risk estimates. The discrepancies in permissible exposures across DRC and the modest relationship between the data returned by the criteria and threshold shifts (Murphy et al., 2009, 2011) reveal a desperate research need. However, it is possible to predict the direction of differences in permissible exposures across DRC. For low-energy impulses, AHAAH is most restrictive, $L_{Aeq,8hr}$ is in the middle, and Coles/CHABA most permissive. This order is reversed for high-energy impulses, where AHAAH is the most permissive and Coles/CHABA is the most restrictive. Many impulsive sounds (e.g., rifle noise exposures at a shooter's ear) are present in the middle levels, where only small differences between the DRC are observed.

Mitigation of Auditory Risk

Hearing Protection Devices (HPDs)

The hearing protectors that are optimal for use with brief high-level sounds might not be the same as would be selected for routine use in continuous noise. Users of hearing protectors for brief high-level sounds often require that the protectors provide minimal attenuation for low-level sounds but provide substantial protection during those moments when the high-level sound is present. In many cases, these moments will be unpredictable, requiring that the listener wear the hearing protectors at all times. A variety of other factors (e.g., number of exposures, presence of continuous noise, simultaneous eye protection, need for speech communication and situational and environmental awareness) must be considered when recommending hearing protection for people exposed to brief high-level sounds (Alali and Casali, 2011; Casali et al., 2004, 2009; Casali and Alali, 2009; Clasing and Casali, 2014; Talcott et al., 2012). (See also Chapter 11.)

The attenuation provided by a hearing protector is summarized by the *Noise Reduction Rating (NRR)* measured with continuous noise at threshold levels. For many products intended for use with impulse noise, the NRR may be negligible (< 10 dB) when tested at threshold. Thus, the *impulse peak insertion loss (IPIL)* was developed to describe attenuation of brief high-level sounds, in essence, an *impulse NRR* (ANSI S12.42, 2010). For a given hearing protection device, the open-ear and occluded-ear conditions of an acoustic test fixture (ATF) and a field-probe microphone are measured. The open ear condition is used to determine the frequency- and position-dependent transfer functions between the ATF microphones and the field-probe microphone for several impulse levels. The transfer functions are then used to estimate the open-ear response of the fixture for the same impulse levels when the fixture is occluded. The IPIL is calculated as the difference between the greatest instantaneous peak pressure levels for the estimated open-ear response and the occluded-ear conditions. Standardized measurement procedures (ANSI S12.42, 2010) must be observed when calculating IPIL. Briefly, IPIL values represent average differences in peak levels, across multiple samples of each protector model and multiple placements (or insertions) of each sample. The IPIL values are obtained at peak levels of 132, 150, and 168 dB SPL in the sound field, which corresponds to even greater peak levels at the simulated eardrum of the fixture due to the acoustic characteristics of the head and ear. Once mean IPIL values are obtained across samples and placements on the ATF, the expected 10th percentile of the distribution with the lowest mean IPIL and the expected 90th percentile of the distribution with the highest mean IPIL are identified, and those points have been used to identify the lower and upper boundaries of the impulse NRR (Murphy et al., 2012a).

For traditional hearing protection devices (plugs, muffs, and canal caps without a valve or electronic circuitry to enhance low-level signals), the NRR will provide a lower bound for the IPIL estimate. The attenuation of an impulse tends to increase with the level of the impulse (Allen and Berger 1990; Berger and Hamery, 2008; Parmentier et al., 1994; Zera and Mlynski, 2007; Murphy et al., 2012a; Khan et al., 2014; Murphy et al., 2014). Fackler et al. (2017) compared the spectral insertion loss for a hearing protector measured on an acoustic test fixture with attenuation measured by real-ear attenuation at threshold (REAT) and IPIL and insertion loss measured with continuous noise. The frequency spectra of impulses produced by an acoustic shock tube change with the impulse level. Higher level impulses tend to have more high-frequency content resulting in greater IPIL values with level because protectors are typically better at attenuating high frequencies (Murphy et al., 2014; Murphy et al., 2015; Fackler et al., 2017). Although the attenuation of the impulse does increase with the level of the impulse, it does not increase indefinitely. For very intense impulses, greater than 185 dB peak SPL, the positive pressure of the sound wave can be sufficient to remove the earmuffs off the fixture and the negative pressure can be sufficient to dislodge the plugs from the earcanal. For those outside of the military and special law enforcement units, the maximum peak pressure levels from firearms and fireworks tend to range from about 140 to 175 dB (Flamme et al., 2009a, 2009b; Murphy and Kardous 2012; Schulz et al., 2013). Thus, using traditional hearing protection in the presence of impulse noise will provide significant attenuation so long as the NRR is adequate and the protector is donned properly.

Two types of hearing protection are designed to provide better situational awareness and sufficient protection against brief high-level sounds. Electronic hearing protectors utilize circuitry to restore environmental sounds to the wearer when the levels are below about 85 dB SPL but enter compression at higher levels so that they no longer contribute to the sound penetrating the HPD. Many possible circuits can provide reasonable solutions (e.g., peak clipping, compression, active noise control). For electronic devices, manufacturers of these protectors limit the long-term average output level to about 82 dB SPL. A common question from industrial hygienists and hearing conservationists is whether the electronics react sufficiently fast to prevent amplifying the impulse. The miniature electret microphones and speakers used for sound reproduction in electronic protectors have a practical limiting level of about 120 dB SPL. The levels reproduced by the electronics must be combined with the attenuation by the transmission through the protector's structure to estimate the level that may be observed at the ear. For high-level sounds, greater than 150 dB SPL, the protector's passive attenuation (i.e., electronics turned off) will determine the attenuation. For sounds with instantaneous peaks less than 130 dB SPL, the electronics may be the dominant source of the levels observed under the protector (Murphy et al., 2014).

The second type of hearing protector designed for brief high-level sounds utilizes an orifice to provide a variable amount of attenuation with increased pressure differential across an orifice or a mechanical valve. At low levels, the acoustic pressure across an orifice is linearly related to the particle velocity through the orifice and the acoustic resistance is constant over time. However, as the sound pressure differential across the orifice increases, the flow through the orifice becomes turbulent and the acoustic resistance increases (Ingard and Ising, 1967; Allen and Berger, 1990). The nonlinear property of increasing acoustic resistance with increasing sound level enhances the attenuation of hearing protectors with orifices at high levels. However, the increased resistance does not necessarily result in adequate protection. Even when properly fit, the ear may be exposed to peak levels of more than 150 dB and upwards of 165 dB for some impulsive sources such as guns. Some products exhibit only a modicum of impulse peak attenuation (about 5 to 10 dB) at the level of a gunshot, and some valve-type systems (i.e., protectors that operate on the principle of mechanical valve closure in response to the waveform) provide less than 10 dB of noise reduction through peak SPLs of 170 dB and (unfortunately) amplified peaks below about 150 dB SPL (Berger and Hamery, 2008). Thus, there is a need to characterize the performance of these specialized hearing protectors measured with noises that encompass the range of likely exposure levels.

Murphy et al. (2012a) were the first to utilize the ANSI S12.42–2010 to evaluate IPIL for several protectors. Among the products measured in their study were the 3M™ Combat Arms™ 4th Generation nonlinear orifice earplug. The IPILs for the 130-dB impulses were 21 dB and 29 dB for the orifice open and the orifice closed, respectively. For 150-dB impulses, the IPILs were 26 dB and 31 dB for open and closed conditions, respectively. For 170-dB impulses, the IPIL were 31 dB and 33 dB, respectively. In every case, the IPIL for the closed condition is more than it was for the same level with the valve open. The difference between the open and closed IPIL decreased from about 8 dB to about 2 dB over the range of impulse levels.

Murphy et al. (2007) and Murphy and Tubbs (2007) evaluated several electronic sound restoration earmuffs with small-caliber weapons noise for different volume settings of the gain circuits. The peak reductions (external peak level minus earcanal peak level) exhibited no substantial differences (i.e., less than 2 dB) when the circuit was turned off versus the volume adjusted to unity or maximum gain. The performances of the muffs were governed by the structural characteristics of the earmuff and not the circuitry.

In a subsequent field study with an electronic sound restoration earplug tested according to ANSI S12.42–2010 (Murphy et al., 2014), an interesting phenomenon was observed. The protector yielded IPIL of about 30 dB for the 170 dB impulses, but only about 12 dB for the 130 dB impulses. When the waveforms were examined carefully, the initial impulse was attenuated substantially (~20 dB). However, the reverberant sound from the report of the weapon was amplified as soon as the electronic circuit recovered from amplifier saturation. That is, the echoes were amplified, which reduced the apparent amount of attenuation afforded by the protector. Although the peak levels of the echoes were about 120 dB, the echoes were quite brief and the protector still provided substantial attenuation. However, the amount of attenuation was less than expected based on the protector's performance at higher levels. Considering that the peak levels of the echoes were about 120 dB, this short duration protected exposure presents less risk compared to the unprotected ear.

Several studies have been published that examine the IPIL for a group of protectors that have been tested with different impulse sources and measured with the same ATF. Firearms have A-durations of 0.04 to about 0.8 ms (Flamme et al., 2009b; Murphy et al., 2012a; Murphy et al., 2012b). Sources such as acoustic shock tubes (U.S. Army Aeromedical Research Laboratories, Fort Rucker; 3M EARCAL Laboratory, Indianapolis; NIOSH Impulse Noise Laboratory, Cincinnati; U.S. Army Research Laboratory, Aberdeen Proving Ground) have longer A-durations ranging from about 1 ms to 3.5 ms (Khan et al., 2014). The peak frequency of the impulse varies between about 125 Hz (shock tubes) to 4000 Hz (gunshots). For hearing protection devices that have a significant change in attenuation over this range (earmuffs in particular), the IPIL is expected to change. Earmuffs provide less protection for low-frequency impulses than for high-frequency impulses. Furthermore, because acoustic test fixtures have the potential to isolate the ear simulator capsule more thoroughly than the human head can isolate the cochlea, the ATF's self-insertion loss (its effective "bone-conduction" pathways) differs from those of the human skull (see Chapter 11). Thus, the IPIL values for high-attenuation conditions (e.g., over 60 dB of attenuation) can overestimate the amount of attenuation that is realized in practice. This effect needs further research to properly characterize the interactions.

The AHAAH model has a hearing protector module that assumes that hearing protection can be modeled as a three-part transmission process: a main piston resonance, transmission via the material of the protector, and a bypass leakage mechanism between the skin and the protector (Kalb, 2010). The AHAAH HPD module relies upon the REAT attenuations to fit these three transmission paths and then applies the derived filter to the external waveform to estimate the exposure underneath the protector. In some cases, the HPD module does a reasonable job of estimating the waveform in the occluded volume; however, for levels above about 180 dB, the assumptions of the model begin to fail (MIL-STD-1474E).

Finally, one area, which is often overlooked, is the need to wear safety glasses and other personal protective equipment (PPE) with hearing protection. Eye protection is essential in many manufacturing environments (e.g., stamping and forging facilities). A chemical splash, spark, or shard of metal in the eye can produce permanent blindness instantly. People learn quickly to respect the need for safety glasses. Unfortunately, the ear is often ignored when safety glasses must be worn because the eye seems more vulnerable than the middle ear and cochlea. Earplugs and canal caps do not interfere with the use of safety glasses or most other PPE. Earmuffs, on the other hand, are compromised when the temple of the glasses passes underneath the cushions and breaks the acoustic seal with the head; losses average 2–4 dB in 1/3 octave bands but can be as much as 7 dB. Royster et al. (1996) reported that the mean attenuation across all test frequencies was reduced by 5 dB; less reduction was observed below 1000 Hz and more above 1000 Hz. In the Albuquerque Blast Overpressure Walk-up Study, the Racal earmuff used in the initial 5-meter exposures was tested both with and without cushions that had intentional leaks (eight holes in the cushions of 2.3 mm in diameter) to simulate a poorly fit muff (Johnson, 1994, 1997). The 8-hour equivalent A-weighted exposures under the earmuff were significantly greater (as much as 10 dB) when the earmuff cushions were perforated. NIOSH has recommended that persons exposed to more than a few impulses above 140 dB should use dual protection (Kardous, 2009). In addition, eyeglasses with small temples or that replace the rigid temples with elastic bands could maintain the seal.

Suppressors and Other Source Modifications

Firearm noise can also be reduced at the source using firearm noise suppressors, which can be called *silencers* in common and even legal references (27 CFR 478.11, U.S. Department of Justice, 2012), but this is an incorrect label because they only attenuate or muffle the impulse. The physical principles that underlie the operation of a suppressor are based on either absorptive materials or impedance changes associated with a system of chambers within the suppressor housing. These technologies are used in a variety of applications, including automobile mufflers. General descriptions of these and other engineering-based noise controls are available in Chapter 10.

Many different models of firearm noise suppressors are available, but data on the effectiveness of these suppressors are limited, particularly with respect to their effect on auditory hazard. The performance of the suppressors can be expected to depend on the gun caliber, ammunition, barrel length, and reloading action (e.g., bolt versus semiautomatic) (Lobarinas et al., 2016; Murphy et al., 2016; Stewart et al., 2015). One example of the effect of a suppressor is represented in Figure 6.16. In this example, the suppressor had a large (28 dB) effect on the peak and a smaller effect on the total amount of A-weighted energy in the signal (21 dB).

Reductions in the source acoustic energy can also help mitigate the risk to the auditory system. For firearms, the combustion of the propellant constitutes the acoustic source, and ammunition containing less propellant might produce a corresponding decrease in sound emission. Although differences of a few decibels can be found across most kinds of loads for guns (e.g., Flamme et al., 2009b), ammunition described as subsonic or low-velocity generally has a lower propellant charge and can produce differences on the order of 10 or 15 dB (Stewart et al., 2015; Murphy et al., 2016).

Summary

Exposures to brief high-level sounds such as impulses and impacts are common, and the risk of hearing impairment due to exposure to brief high-level sounds can grow rapidly. Impulse noises are generated via rapid energy release,

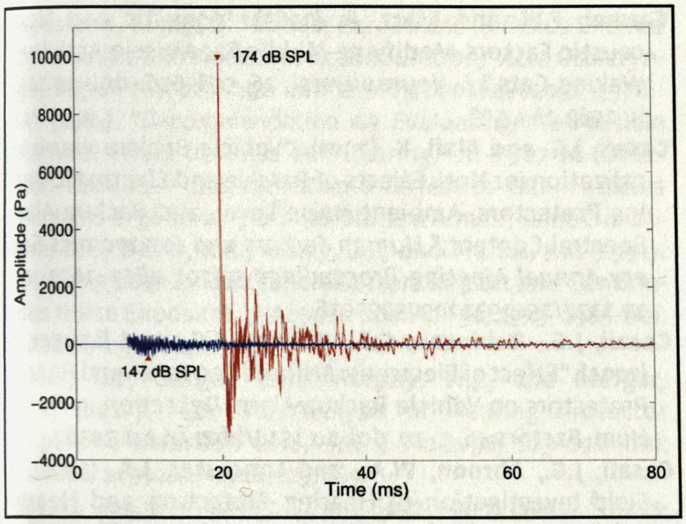

Figure 6.16 — Comparison of unsuppressed (left side) and suppressed (right side) impulses produced by the same gun. The (muffler-type) suppressor reduced the peak more than it reduced the overall energy in the signal. Data from Stewart et al. (2015) were used.

which produces asymmetric sound waveforms with a rapid rise from ambient pressure to the peak, followed by a decay that is largely determined by the environment into which the energy is released. Impact noises are generated by the collision of two masses, which produce approximately symmetric sound waveforms having longer durations than impulses. Impact noises tend to contain less sound energy than impulses, although some impulses will have instantaneous peak sound levels comparable to the most intense impact noises.

Sound energy is modified by the outer and middle ear en route to the cochlea. Up to levels of approximately 130 dB SPL, average effects of the outer and middle ear are known reasonably well, but considerable differences exist across people. The transfer function of the average middle ear is similar to the A-weighting function. At higher levels, a peak clipping effect can be expected due to the annular ligament connecting the stapes and the inner surface of the cochlear round window. Animal models suggest that annular ligament effects could begin operating at approximately 160 dB SPL, but central tendencies and dispersions among adult human ears have not been studied extensively. Middle ear muscle contractions operate at frequencies primarily below 1 kHz and are not expected to have substantial influences above 1 kHz. Nonetheless, it is possible that energy transfer into the cochlea could be increased slightly during middle ear muscle contractions. Reflexive middle ear muscle contractions in response to high-level sounds are frequently elicited by signals having comparatively long durations, but there is a limited evidence base concerning the role of reflexive middle ear muscle contractions as a potential for mitigating brief high-level sounds. The evidence base for nonreflexive (e.g., anticipatory, conditioned) middle ear muscle contractions is also limited.

Brief high-level sounds could be a more potent hazard for the auditory system than long-duration signals of equivalent energy, particularly for sounds having instantaneous peaks greater than about 140 dB SPL. The ears of the unprotected person exposed to these sounds are at risk of immediate harm. This risk grows with increased sound energy and numbers of exposures. Damage-risk criteria produce risk estimates that are strongly correlated but differ greatly with respect to the numbers of permissible exposures an unprotected listener would be allowed. Unfortunately, estimates of risk are more closely related to one another than they are to the threshold shifts produced by brief high-level sounds. Additional research in this area is urgently needed (Themann et al., 2013a, 2013b)

A person exposed to brief high-level sounds will likely need different kinds of protection than a person exposed to long-duration (i.e., continuous) noise. Many people exposed to brief high-level sounds need to communicate with others and retain situational awareness during the intervals separating the impulses or impacts. Noise reduction ratings obtained with continuous noise for conventional passive earmuffs and earplugs are often met or exceeded for impulses (Murphy et al., 2012a; Murphy and Tubbs, 2007; Murphy et al., 2014). The amount of attenuation provided by protectors increases with increased instantaneous level (Murphy et al., 2012a; Murphy et al., 2014). Electronic and orifice-based protectors cannot be evaluated using traditional threshold-based means. Recent work has been conducted with the IPIL as a representation of the effectiveness of the protector, but the interpretation of IPIL values can be complicated for peaks lower than 140 dB SPL presented to electronic hearing protectors. Other personal protective equipment (e.g., safety glasses) can compromise the effectiveness of hearing protectors, particularly earmuffs, and the measurement and prediction of these changes is another important research need. Suppressors for firearm noise and reductions in the energy in the ammunition could provide substantial reductions in instantaneous peaks, but the paucity of effectiveness research across firearms and suppressor designs prohibits general statements or recommendations at the present time.

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