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Special Topic Overviews

The Fundamentals of Sound and its Measurement

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The purpose of this article is to provide directors of animal care facilities with a basic understanding of some of the principles of acoustics and the measurement of sound. This knowledge likely will enable directors to work effectively with sound and hearing specialists at their institutions to monitor and control the acoustic environments of laboratory animal facilities.

Abbreviations: ΔL, difference (in dB) between 2 sound levels; f_C, center frequency of a filter band; f_L, lower frequency of a filter band; f_U, upper frequency of a filter band; P, pressure; rms, root mean square; SPL, sound pressure level; T, period

Sounds produced by equipment, animals, and animal-care activities are inherent in the operation of animal facilities. Sound can have both auditory and nonauditory effects,[1,5,8,11] including eosinopenia, increased adrenal weights, and reduced fertility in rodents;[6,7,14] audiogenic seizures in some species of mice, rats, rabbits, gerbils, and domestic fowl; and increased blood pressure in nonhuman primates.[9] Many animal species hear sounds that are inaudible to humans.[2,4,12] Therefore, sound-monitoring devices must have sufficient sensitivity through a broad frequency range so that the potential effects of equipment, materials, and procedures that produce sound in the hearing range of nearby animals can be assessed accurately. Assessment of the potential effects of sound on animals requires consideration of the intensity, frequency, and duration of the sound as well as the hearing range, noise-exposure history, and sound-effect susceptibility of the species or strain. This brief review will concentrate on some of the basic properties of sound and its measurement.

Sound

Sound is the propagation of a temporary change in the density of particles of an elastic medium. Sound is produced when a body within an elastic medium is caused to vibrate. For the purposes of this review, air will be the only elastic medium considered. Air particles can be considered as tiny masses that are uniformly distributed within a given volume when no vibration is present and thus no sound is produced. Air particles can be displaced by vibrating bodies (such as the tine of a tuning fork), and each particle exerts a force on adjacent particles. The momentary displacement of some particles will cause a momentary change in the density of the air particles. Sound pressure (force per unit area) is a function of density.

Figure 1 illustrates what happens in the surrounding air when a tuning fork vibrates. Tuning forks (when properly struck) vibrate in a sinusoidal fashion to produce sinusoidal variations in the sound pressure of the surrounding medium. Sinusoidal variations in sound pressure are the least complex sounds and are known also as 'pure tones.' When the tine of a tuning fork is struck, it moves from its rest position in the direction and to the extent of the force applied to it. During part of each oscillation, a region exists where the air particles will be pushed together. Such a region is called a condensation and results in an increase in sound pressure. Because some air particles are pushed together to produce a condensation, a region is formed in which the air particles are further apart. This region is a rarefaction and results in a decrease in sound pressure. As shown in Figure 1, the condensations and rarefactions that originate near the tine are propagated away from it. Propagation occurs because air particles in contact with the tine impart their motion to adjacent particles, which in turn impart theirs to their neighbors. However, the motion of a single air particle (illustrated by the rectangles) is that of simple sinusoidal oscillation. Therefore, condensations and rarefactions are propagated outward, whereas individual air particles experience no permanent displacement.

As the propagation continues through the air, the magnitude of particle movement decreases, with a consequent decrease in the sound pressure. In general, the reduction in sound pressure is proportional to the square of the distance from the sound source. This relationship is one reason why it is important to specify the location of a sound pressure measurement in addition to its value and is why sound level measurements should be taken where the animals will be located. However, other factors can complicate the measuring process.

When a sound (a propagated pressure disturbance) encounters an object in the surrounding medium, several things happen that primarily depend on (1) the density of the object relative to the density of the medium and (2) the size and shape of the object relative to the wavelength of the sound. Some of the sound will be reflected, and some will cause the object to vibrate and transmit the sound. Generally, the more similar the densities of the object and medium, the greater the proportion of the sound that will be transmitted rather than reflected. The amount of sound energy transmitted or reflected also depends on the absorptive characteristics of the object (absorption causes sound energy to be dissipated in the form of heat). Materials that are hard and smooth typically are poor absorbers of sound energy, whereas those that are soft, porous, or have rough surfaces usually are better absorbers.

An object that is very large relative to the wavelength (Figure 1) of the sound impinging on it can cast a 'sound shadow.' Therefore, interposed objects affect shorter wavelength (higher frequency) sounds more than longer wavelength, lower frequency sounds.

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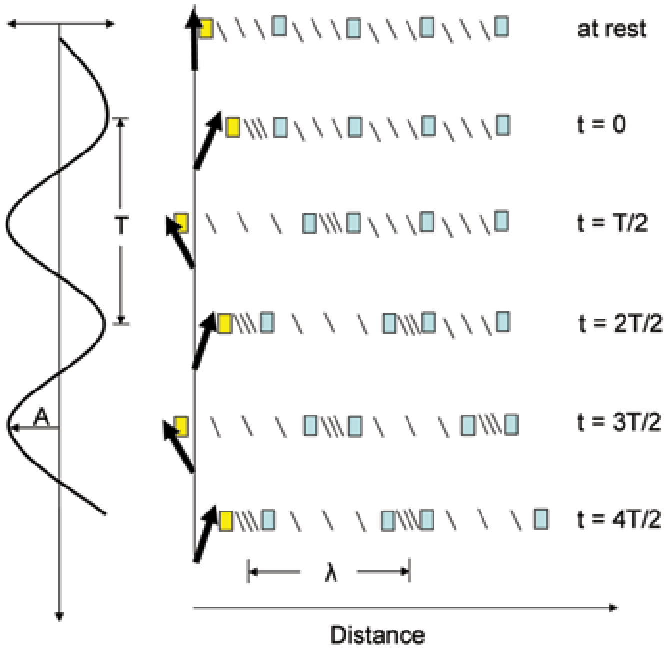

Figure 1. A schematic drawing showing rightward propagation of condensations (\\\\\\) and rarefactions (\\ \\ \\) produced by sinusoidal vibration of a tuning fork tine (↑) at half-period (T/2) intervals. The rectangles represent air particles, which are more dense (closer together) during condensations and less dense (further apart) during rarefactions. The rectangles illustrate the local sinusoidal displacement of a single air particle; the air particle is not propagated toward the right but instead oscillates about its rest position. Sinusoidal displacement (tuning fork tine / individual air particles) is plotted to the left showing the period (T) and amplitude (A) of the oscillation. Time (t) progresses from the top to bottom of the figure. λ, wavelength.

The presence of 'sound shadows' is an additional reason to take sound level measurements where animals are located, including inside cages. Some cages may change the sound environment dramatically, and the amplitude and phase characteristics of this change will differ for different frequencies.

All of these factors come into play when sound is produced in an enclosed space (room). The distribution of direct and reflected sound energy will not be distributed uniformly throughout the room, and the incident and reflected sound waves will interfere with each other, thus producing areas within the room where the sound pressures from the direct and reflected waves will sum (constructive interference), sometimes exceeding the sound pressure of the source itself, and other locations where they will cancel (destructive interference). Delays between the arrival times of direct and reflected waves generally are small enough that only a single sound is perceived yet the duration of the sound is extended as it is gradually absorbed. The time necessary for the sound pressure to decay to 0.1% of its initial value is called the reverberation time. The larger the room and the harder and smoother the surfaces, the greater the reverberation time will be. Small rooms covered with highly absorptive materials will have a very short reverberation time. Reverberation is one important aspect of the acoustic environment that may be relatively simple to change. The presence of reverberation also emphasizes the importance of obtaining time-averaged sound level measurements.

Parameters of sinusoidal pressure variations

Amplitude. Force exerted on a particle will cause the particle to move. Because the magnitude of displacement is so small, direct measurement of the displacement of air particles is impractical. By the same token, measuring the rate of change in particle displacement (particle velocity) or the rate of change in particle velocity (particle acceleration) is not practical. However, if particle displacement is sinusoidal, particle velocity and acceleration vary sinusoidally. Changes in particle velocity require that the particle undergo acceleration, which means that a force has been applied. Although measuring the forces acting on individual particles is impractical, measuring the force acting upon a large surface, such as the diaphragm of a microphone, is relatively easy. Force per unit area is pressure (P), and sound pressure amplitudes are measured in N/m^2.

Pressure. The unit of measure for sound pressure amplitude is the Pascal, and 1 N/m^2 is equal to 1 Pa. Sound pressure amplitude is a measure of the amount of variation in pressure caused by sound. In silence, the atmosphere exerts a constant pressure of about 100,000 Pa. Sounds create deviations in air pressure that oscillate above and below the normally constant air pressure. The average size of the pressure variations about the atmospheric level is the amplitude of the sound pressure. However, because deviations are both above (positive) and below (negative) the atmospheric level, the typical way of calculating average values would always yield a sound pressure amplitude of zero. Therefore sound pressure amplitudes are calculated by using a special type of average (the root mean square, rms), which is discussed in more detail in the section titled Measurement.

The pressures that move the tiny air particles to produce sound waves are very small. The smallest pressure variation that produces a sound audible to humans at 1000 Hz is near 20 μPa (2×10^{-5} Pa), whereas sound pressures of about 20 Pa produce sound waves that virtually always damage the ear if they last long enough and are of an appropriate frequency. Calculating the ratio of the least audible pressure amplitude to atmospheric pressure yields a sound pressure amplitude of only 0.00000002%, whereas a loud sound that is 1,000,000 times more intense than the least audible sound represents only a 0.02% change from atmospheric pressure. Because the ear is sensitive to such a large range in pressure variations, the convention is to express sound pressure amplitude in terms of decibels. The decibel scale for pressure amplitude is the sound pressure level (SPL). The SPL value for a sound with a pressure amplitude of P is

$$SPL = 20 \log (P/P_r),$$

where P_r is the reference pressure amplitude. The most common reference value (chosen to correspond approximately with the threshold of human hearing) is 2×10^{-5} Pa (20 μPa). For example, to obtain the decibel reading corresponding to a pressure amplitude of 0.02 Pa, assuming the use of the above reference value,

$$SPL = 20 \log (P/P_r)$$
$$P/P_r = 2 \times 10^{-2} \text{ Pa} / 2 \times 10^{-5} \text{ Pa}$$
$$= 1 \times 10^3$$
$$= 1000$$

The log of 1000 is 3. Therefore,

$$SPL = 20 \times 3$$
$$= 60 \text{ dB}$$

Notice that in the first step, one pressure amplitude value is divided by another, thus eliminating all units of measure. The decibel scale has no units of measure.

Condenser microphones convert pressure to an electrical signal. Upon application of known pressures to the microphone, sound level meters calibrate the electrical signal, process it, and convert directly into SPL readings. Proper calibration of these meters before measurements are taken is important, and the reference value for the readings must be specified. Note that any 2 sounds with the same pressure ratio will have the same decibel value regardless of their absolute pressures.

Intensity. Intensity is a measure of the energy of a sound that flows through a given area each second. Intensity is related to displacement of air particles in the following manner: the work done to displace an air particle is expressed in terms of the force exerted on the mass of the air particle multiplied by the distance that the mass is moved. The amount of work done when 1 Newton of force displaces a mass by 1 meter is 1 joule. The rate of doing this work (the amount of work done per unit of time) is power and is measured in joules/s , which is called one watt (W). The power transmitted along a sound wave through an area of 1 square meter at right angles to the direction of propagation is the intensity of the sound wave and is measured in terms of W/m^2. An important thing to remember is that intensity is a measure of energy flow and that not all sounds with the same displacement amplitude have the same energy. This variation results because energy is proportional to frequency as well as amplitude. Sounds of a higher frequency (more cycles per second) contain more energy than lower frequency sounds with the same displacement amplitude.

The exact relationship between sound pressure and intensity (I) requires knowledge of the characteristic impedance (Z) of the medium through which the sound is being transmitted ($I = P^2/Z$). Characteristic impedance is related to the mass and stiffness of the medium; for air at 20 °C near sea level, Z = 415 rayls. With air as the medium, the intensity that corresponds to the SPL reference pressure amplitude of 2×10^{-5} N/m^2 is:

$$I = (2 \times 10^{-5})^2 / 415$$
$$= (4 \times 10^{-10}) / (4.15 \times 10^2)$$
$$= {\sim}1 \times 10^{-12} \ W/m^2$$

If the medium is changed, the value of the intensity reference that corresponds to the SPL reference will change, but the intensity will remain proportional to the square of the pressure.

In typical practice, sound pressure is measured, and intensity is inferred from the pressure variation of air particles, because the sound intensity is proportional to the square of the variations in pressure of the sound wave. For sound pressure to increase by a factor of 10, intensity must increase by a factor of 100. More specifically, the dB equivalent for a particular intensity ratio is $10 \log(I / I_R)$, whereas the dB equivalent for a particular pressure ratio is $10 \log(P/P_R)^2$, which is equal to $20 \log(P/P_R)$. The square law relationship between pressure and intensity explains how different pressure and intensity ratios can generate the same change in dB.

Frequency. The time that elapses between the occurrence of 2 successive condensations or rarefactions, at any arbitrary point in the medium, is the period of the sinusoidal oscillation. In other words, a period is the amount of time needed for completion of 1 cycle of sound pressure variation. The unit of measure for frequency is hertz.

Propagation velocity. Wavelength is defined as the distance between 2 successive condensations (or between any 2 successive rarefactions). Because a condensation or a rarefaction advances a distance of 1 wavelength in the time interval of 1 period, the velocity of propagation (speed of sound) can be determined by dividing the wavelength by the period. Wavelength is a function of both the medium (its relative mass [density] and stiffness) and the frequency of the vibratory source. Denser mediums tend to propagate sound more slowly than less-dense mediums with the same stiffness, and stiffer mediums tend to propagate sound faster than less-stiff mediums with the same density. Therefore, wavelengths will be shorter in mediums with a slower rate of propagation than in mediums with a faster rate of propagation. However, the amplitude, frequency, and complexity of the vibratory motion depend on the sound source and are independent of propagation velocity.

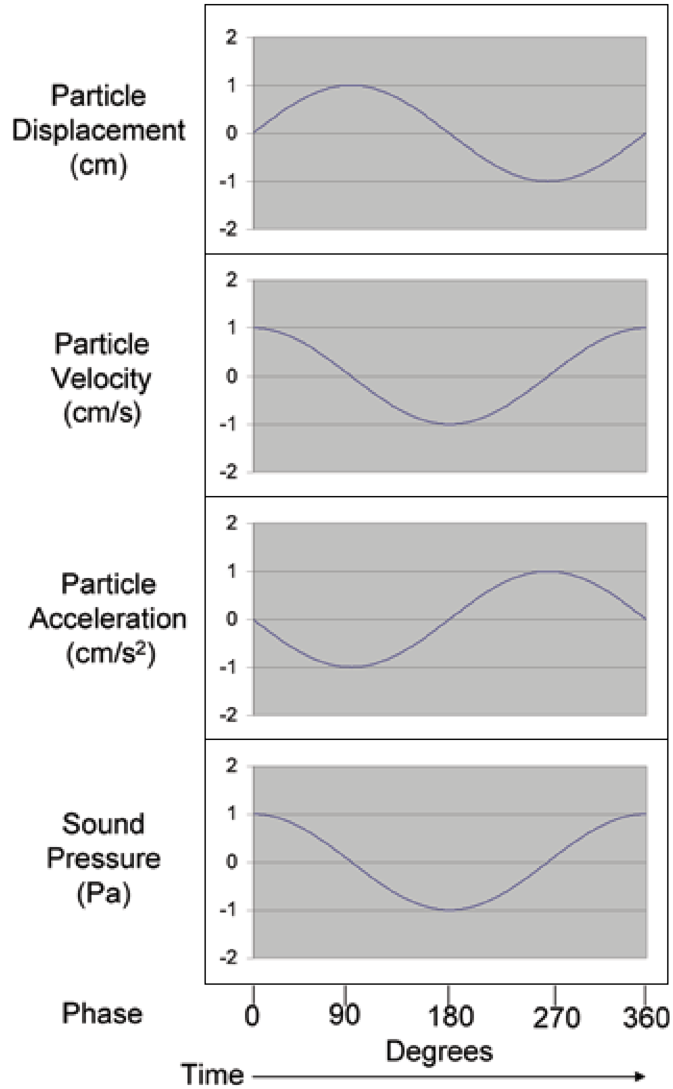

Figure 2. Plots depicting the phase relationship between the various characteristics of sinusoidal particle motion during one cycle of vibration of the sound source. The top panel shows the sinusoidal displacement of particles. Particles immediately adjacent to the sound-generating source will be in phase with the source (phase difference, 0°). The second panel shows particle velocity (the rate of change in particle displacement), which leads particle displacement by 90° (1/4 cycle). The third panel shows particle acceleration (the rate of change in particle velocity), which leads particle velocity by 90°. The bottom panel shows instantaneous sound pressure changes that occur during a single cycle. Instantaneous sound pressure changes are in phase with particle velocity.

Phase. The term phase refers to the location of a point within a sinusoidal cycle relative to its beginning. The beginning is defined as 0° and the end as 360°. Figure 2 shows the phase relationships between particle displacement, velocity, acceleration, and instantaneous sound pressure.

Complex sounds. In accordance with Fourier's theorem[13], a complex sound can be represented by the specific sum of its component sinusoidal sounds. Spectral analysis is the process whereby the amplitudes, frequencies, and phases of the sinusoidal components of complex waves are determined. The sum of several simple sinusoidal waves yields a nonsinusoidal complex waveform (Figure 3). Summation of the waveforms in panels A, B, and C (by adding the relative displacement of each of the waveforms for each instant of time) results in the waveform in panel D. Note also that the basic nonsinusoidal wave repeats itself with the periodicity of the lowest frequency component (the fundamental). If the phase of wave A is changed with respect to waves B and C, the waveform in panel E is obtained. Although a waveform changes markedly whenever a single component changes in phase relative to the others, the ear cannot always detect these phase changes. Complex sounds, such as speech, often sound the same regardless of the differences in phase relationship of their components. For this reason, and because over the long term power is unaffected by phase, it is common to consider only the amplitude and frequency of the sinusoidal components when specifying the spectrum of the complex wave. Because complex sounds can be regarded as the sum of a number of simple sinusoidal waves, the shape of the wave is seldom considered at all; instead, the corresponding spectrum is addressed. Instruments that measure the spectra (amplitude and frequency content) of the sound waves are frequently used in monitoring sound.

Measurement

Because of the wide range of auditory sensitivity among animals used in biomedical research and the need to minimize dust, dander, and so forth, laboratory animal facilities present a special challenge for acoustic measurement and noise abatement. Various kinds of equipment can be used to measure sound pressure. Most sound-level meters consist of a nondirectional condenser microphone, an attenuator, an amplifier, a meter, and weighting and filter networks. Most recent equipment is digital and uses software to accomplish the filtering and weighting functions. Unfortunately, less-expensive commercially available sound-measuring systems are designed for the human range of auditory sensitivity (20 to 20,000 Hz) and are incapable of sensitive measures of acoustic energy in the auditory range of most common laboratory species. However, most university physics, engineering, architectural, and hearing-science departments likely have the necessary equipment and expertise to assist directors of animal facilities to take the proper measurements (for example, as high as 150 kHz if bats are housed). Although using local expertise for monitoring and controlling the acoustic environment of the animal facilities is always prudent, the actual hands-on gathering of the data will most likely involve someone in the animal facility, thus requiring the facility director to have a general understanding of the measurement process.

Sound-measuring systems usually are calibrated to give sound pressure in terms of the rms of the pressure variation, to eliminate the problem of averages of 0, as mentioned earlier. The rms pressure accurately reflects the pressure deviations in complex sounds. In complex sounds, the peak pressure varies as a function of the phase relationship of the components (Figure 3), but the rms measure is relatively unaffected by such variations in the phases of the component sinusoids.

Complex sounds have pressure variations over time that are composed of oscillations of varying amplitude and duration; these variations are often irreproducible across measurement intervals. Instead of measurements that try to describe precisely the time-associated pattern of pressure variations, various averages (such as rms) are taken to measure the amplitude and frequency content of sound over time.

The accuracy of the measurements obtained with sound-monitoring equipment is dependent on its proper calibration. Basic steps in this process are to first check the batteries of the acoustic calibration device, which produces a fixed and precise sound pressure level when properly affixed to the microphone,

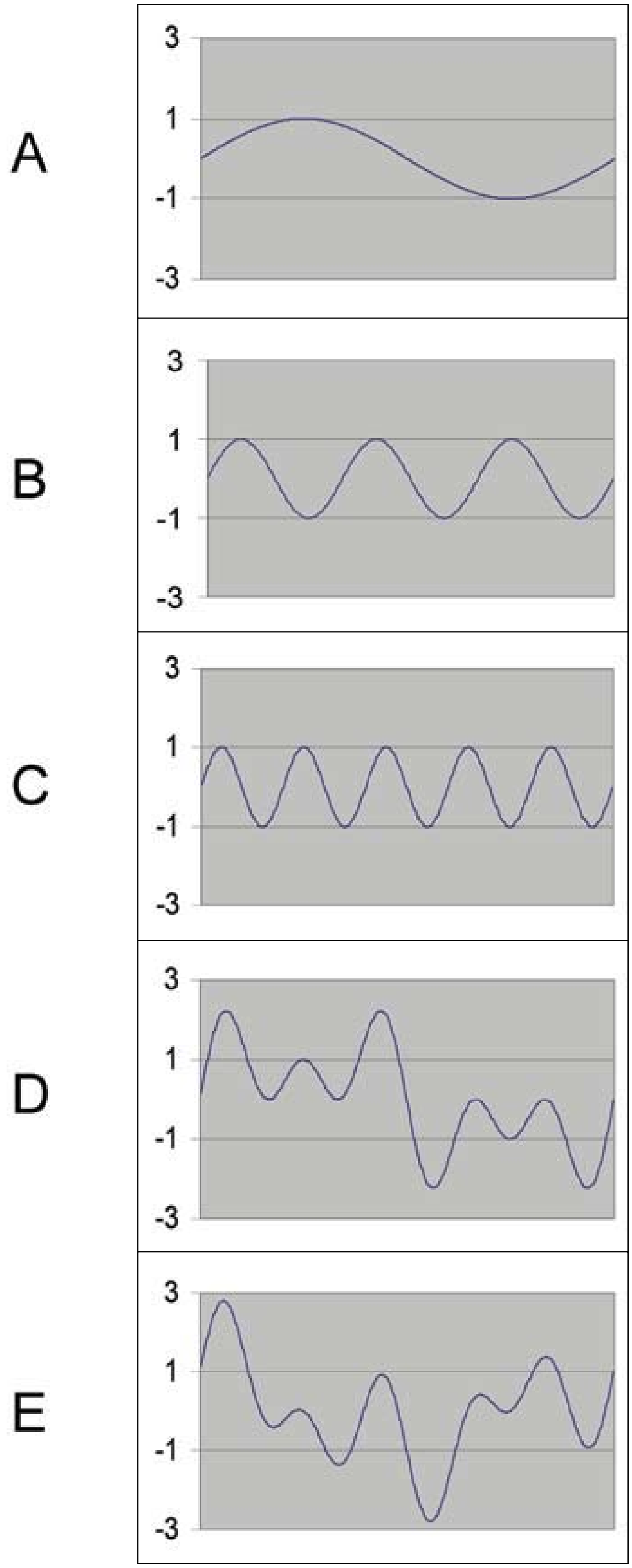

Figure 3. Depiction of complex waveforms and their sinusoidal components: waveforms A, B, and C are the sinusoidal components of waveforms D and E. Waveform A has a frequency of 100 Hz, B of 300 Hz, and C of 500 Hz. The nonsinusoidal sums (complex waveforms) of components A, B, and C are represented in panels D and E, which differ from each other as a result of phase-shifting of component A by 90°.

Table 1. Value to add to highest sound level when determining a combined sound level

If ΔL equals	Add
0 or 1	3
2 or 3	2
4, 5, 6, 7, 8, or 9	1
10 or more	0

then turn on the calibration device, and verify that the sound-level meter gives the expected reading. If not, the meter should be adjusted to achieve the proper value.

Several types of microphones are available for use with sound-level measuring equipment; each microphone has a range of frequencies for which it is maximally sensitive. For example, microphones with good sensitivity to ultrasonic sounds generally will have poor sensitivity to low-frequency sounds. Selecting the microphone with the appropriate frequency range for the desired measurements is important, and each microphone will have its own calibration specifications.

The microphone of sound-level measuring equipment detects all pressure variations that are within its frequency range. In linear mode, the equipment develops an overall reading that is the unweighted sum of all the sound pressure variations detected by the microphone. Other modes include A-weighting (which considerably de-emphasizes both low and high frequencies but not mid-frequencies), B-weighting (which also de-emphasizes low and high frequencies but less so than A-weighting), and C-weighting (most similar to linear mode). For animal facility environments, the linear setting generally will be the most appropriate. Sound-level measuring equipment typically has built-in or attached octave or 1/3-octave band filters.[10]

Frequency band analysis. The Fourier theorem[13] states that if the amplitudes and relative phases of the pressure variations in contiguous frequency bands of unit width are known, the sound pressure variations of a complex sound can be specified. With their digital filters and fast Fourier transform capability, recently developed digital equipment comes very close to achieving this goal. With analog systems, this characterization of complex sounds can be obtained by use of filters that partition the frequency range into contiguous octave or 1/3-octave bands. An octave band is a frequency band for which the upper-limit frequency (f_U) is equal to twice the lower-limit frequency (f_L; $f_U = 2\ f_L$). The center frequency of the band (f_C) is defined as the geometric mean of the upper and lower frequencies of the band ($[f_U \times f_L]^{1/2}$). The frequency scale has been apportioned into proportional bands when the ratio of f_U to f_L is the same for all bands. For octave bands, $f_U/f_L = 2$ for all bands; for 1/N-octave bands $f_U/f_L = 2^{1/N}$.

The ratio of the center frequencies of successive proportional bands is the same as the ratio of the upper and lower frequencies for any one band. Consequently, a proportional frequency band is defined by its center frequency and N. For example, an octave band (N = 1) with a center frequency (f_C) of 1000 Hz has a low-frequency cutoff (f_L) of 707 Hz and an upper-frequency cutoff of 1414 Hz (because $f_U = 2\ f_L$). For the adjacent, higher octave band, $f_C = 2000$ Hz (twice that of the previous octave band), $f_L = 1400$ Hz, and $f_U = 2800$ Hz; for the next higher band, $f_C = 4000$ Hz, $f_L = 2800$ Hz, and $f_U = 5600$ Hz. Obviously compromises have been made to maintain reasonable values for the center and cutoff frequencies. Tables for standard octave and 1/3-octave band values can be found in acoustics and audiology texts.[10]

Adding sound levels. Sometimes it is convenient to combine sound levels from 2 or more sources or frequency bands. Because the decibel scale is a logarithmic scale, the decibel levels of various sounds cannot simply be added together. For example, 2 musicians playing a lullaby at 70 dB each will not produce ear-damaging 140-dB noise but instead 73-dB music. Even when the sounds are not at the same level, they can be combined rather easily. Consider, for example, the need to combine sound levels of 78 and 84 dB. First, calculate the difference in dB between the 2 levels (ΔL), which in this case is 6 dB. Second, refer to Table 1 to determine the amount that corresponds to ΔL = 6. Third, add this increment (in this case, 1 dB) to the larger of the original 2 values. In this example, adding 1 dB to 84 dB yields a combined sound level of 85 dB.

Table 2. Example sound level values recorded inside a chinchilla cage by use of octave bands ranging from 31.5 to 16,000 Hz

Center frequency (Hz)	dB
31.5	42
63	47
125	52
250	56
500	58
1000	66
2000	74
4000	85
8000	72
16,000	50

For any other situation, a pairwise sum can be generated in which one level is always be smaller by some amount ΔL. The larger ΔL, the less the smaller sound level contributes to the combined value. When ΔL = 0 the additional amount is 3 dB; ΔL = 1, add 2.54 dB; ΔL = 2, add 2.12 dB; and so on until when ΔL = 10, add 0.41 dB. A convenient approximation for applications requiring only integer accuracy has been suggested.[3] Although the order in which the pairs are combined makes no difference ($L_1 + L_2 + L_3 = [L_1 + L_2] + L_3 = [L_1 + L_3] + L_2 = [L_3 + L_2] + L_1$), the accumulation of computational errors typically is minimized if the values are ordered and combined from smallest to largest.

For example, suppose the sound levels given in Table 2 were recorded in a chinchilla cage by use of octave bands ranging from 31.5 to 16,000 Hz. To determine the overall combined sound level, begin by ordering these values from smallest to largest results in the sequence 42, 47, 50, 52, 56, 58, 66, 72, 74, and 85 dB. For the first 2 sound levels, ΔL = 5; referring to Table 1 reveals that 1 dB must be added to the larger of the 2 sound levels (that is, 47 dB) for a combined sound level of 48 dB. This combined sound level of 48 dB is paired with the next measured sound level in the sequence (that is, 50 dB) to generate the next combined sound level (ΔL = 2; 2 + 50 = 52 dB). The process in which a preliminary combined sound level is paired with the next measured sound level in the ordered sequence is repeated until the overall combined sound level (86 dB in the example given) is obtained.

Combining data regarding the sound pressure levels at multiple frequency bands with information regarding the range of frequencies audible to the strain or species of animal of interest can help in decisions about the appropriateness of the sound environment. For example, sound level measurements and an octave-band analysis may reveal that the new whisper-quiet, ultrasonic wigit washer indeed produces very little sound audible to humans but generates considerable high-frequency sound. Because sound intensity decreases with the square of the distance from the source, one might place animals able to hear high frequencies as far from the wigit washer as possible and orient their cages to take advantage of large objects in the environment that might cast sound shadows. However, low-frequency-hearing animals could safely be placed near the wigit washer, but these animals should be housed as far as possible from air handlers, cage-washing machines, and other equipment that produce predominately low-frequency noise.

Caretaking operations sometimes generate 'impulse noise' when hard objects bang against one another, such as might happen when caretakers attempt to remove wet bedding from cages. This type of noise, although brief, generates large amounts of energy that is spread across a large range of frequencies and therefore affects all animals regardless of their range of hearing. The environment in laboratory animal facilities has many sound sources: noise from ventilation and cleaning equipment, hum from lighting ballast and so forth, animal vocalizations, and sounds due to caretaking procedures. All of these sounds have auditory and nonauditory consequences for the animals that are housed there and for the caretakers who work there.

General Considerations for a Measurement Protocol

1) Take advantage of the expertise of audiologists, biologists, psychologists, physicists, engineers, architects, and other hearing-related specialists.
2) Use sound-level meters, condenser microphones, attenuators, amplifiers, weighting, and filter networks that are designed to sensitively measure sound pressures throughout the appropriate range of frequencies.
3) Always ensure that sound-measuring equipment is properly calibrated before use.
4) Monitor chronic background noise levels as well as the intensity and frequency information associated with common activities, keeping in mind that the majority of noise in an animal facility is due to caretaking activities and the animals' response to the presence and actions of caretakers.
5) The reverberant nature of animal facilities leads to constructive and destructive interference. This characteristic requires spatially distributed measurements that use prolonged measurement intervals.
6) Animals within a room not only produce sounds; their presence also alters the acoustic environment. They are objects with size, shape, and texture and, as such, alter the absorption and reflection of sound and, depending upon the frequency components of the sound, can cast sound shadows as well. Sound measurements taken without animals present will be different than those taken when they are present.
7) When taking the measurements for a particular area, keep in mind the hearing range and any unique hearing attributes of the strain or species that may be housed in that area. For example, a colony of older mice that develop deafness early in life might be considered for a space that would be unsuitable for younger mice of the same strain.
8) One size does not fit all. Specific research protocols may require special monitoring or precautions regarding the acoustic environment. For example, rats that are susceptible to audiogenic seizures may require customized caretaking procedures.
9) The noise spectrum may provide clues regarding the source of some sounds. Particular items of equipment may be associated with a characteristic 'spectral signature,' although the source(s) of much background noise likely will be unidentifiable.
10) Careful recordkeeping is a must. Accurate and detailed records may give valuable insights into sources of otherwise unexplainable variability in research data. In addition, careful recordkeeping may suggest actions that could be taken to minimize unwanted sound.

Suggested Publications

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