The Case of the NOISY WORKPLACE

By Mitch Ricketts

Math Toolbox is designed to help readers apply STEM principles to everyday safety issues. Many readers may feel apprehensive about math and science. This series employs various communication strategies to make the learning process easier and more accessible.

It has long been known that overexposure to loud sounds may cause hearing loss, tinnitus (i.e., ringing in the ears) and other serious health effects (Basner, Babisch, Davis, et al., 2014). Hazardous noise levels are common in many workplaces and the effects on health may surface even among relatively young workers, as illustrated in Figure 1.

OSH professionals are often asked to identify and control noise hazards. Although noise control may seem straightforward, certain concepts are frequently misunderstood. This article explores terminology and calculations to help explain how sound pressure, sound-pressure level and the decibel scale relate to the pressure variations that we call sound.

Sound & Noise Exposure Concepts

Noise is sometimes defined as unwanted sound. In air, sound consists of pressure waves emitted from objects that vibrate or move suddenly. Sound-producing objects include guitar strings, tuning forks, clapping hands, vocal cords, rustling leaves, machinery and explosives. Each passing sound wave compresses the air, crowding the molecules together. After the wave's high-pressure band passes, the air rebounds and expands as molecules move apart again. Thus, sound waves can be imagined as repeating cycles of high and low pressure that spread outward from a source (Figure 2, p. 46). Sound waves may also travel as disturbances of matter in liquids and solids, such as water and steel.

We perceive sound because pressure waves transmit energy, causing vibrations in our eardrums, middle ear bones (ossicles), cochlear fluid and inner ear nerve cells. At moderate sound levels, our auditory systems extract useful information from sound waves. Unfortunately, nerve damage and hearing loss can occur when sound levels are extreme.

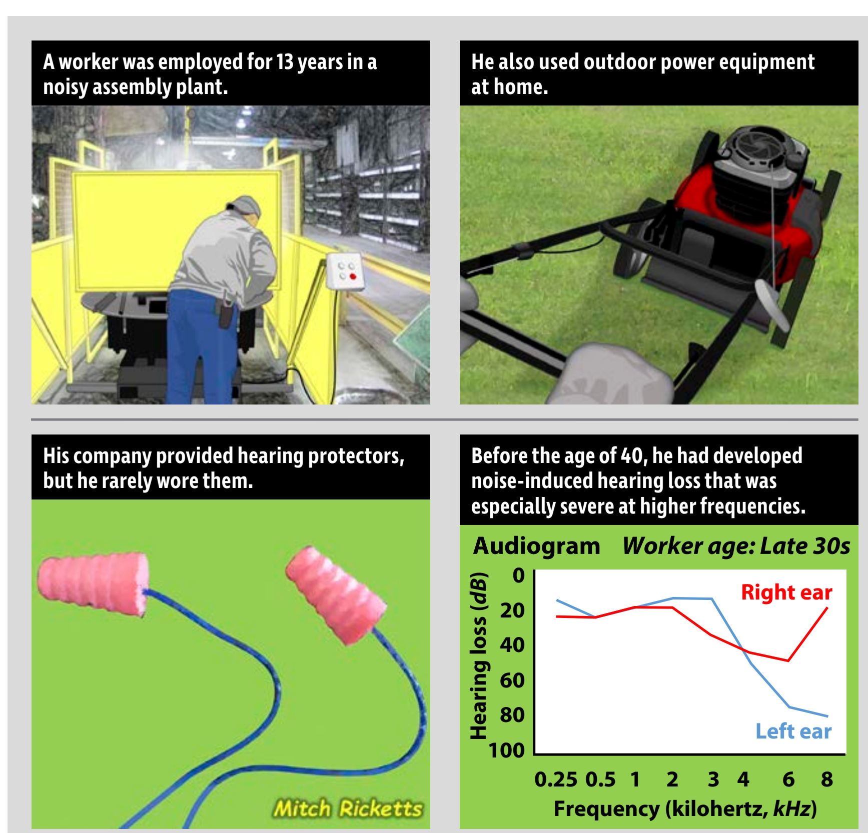
Sound pressure (p) is the measurable fluctuation in pressure caused by a sound wave. As shown in Figure 2 (p. 46), sound pressure is reflected in the amplitude of a wave. Sound pressure is stated in the international unit known as the pascal (or more commonly, the fractional unit called the micropascal):

- One pascal (Pa) is about one hundred-thousandth of standard atmospheric pressure. Standard atmospheric pressure is equal to about 14.7 pounds per square inch (14.7 psi). This means one pascal represents a very small pressure of about 0.000147 psi (1.47 x 10^{-4} psi).
- One micropascal (µPa) is one millionth of one pascal, or about 1.47 x 10^{-10} psi.

In contrast to the direct measurement of sound pressure in pascals, sound pressure level (L_p) is an indirect logarithmic measure based on a ratio of two different sound pressures: p and p_0. The sound pressure, p, is the actual sound pressure measured in the environment. The other sound pressure, p_0, is a hypothetical reference sound pressure. In OSH, the reference sound pressure is usually taken to be 20 µPa, or alternatively, 0.00002 Pa. This is because 20 µPa represents the softest sound the average person can distinguish at a range of sound frequencies important to the human auditory system. In other words, 20 µPa is the threshold of hearing, equal to a sound pressure level of 0 decibels.

In workplaces, sound pressure levels (L_p) are normally expressed in units of decibels (dB) that reflect loudness increments that

FIGURE 1
WORKPLACE HEARING LOSS, MICHIGAN



Note. Adapted from "2008 Annual Report on Work-Related Noise-Induced Hearing Loss in Michigan," by K.D. Rosenman, A. Krizek, M.J. Reilly, et al., 2009), East Lansing, MI: Michigan State University & Michigan OSHA.

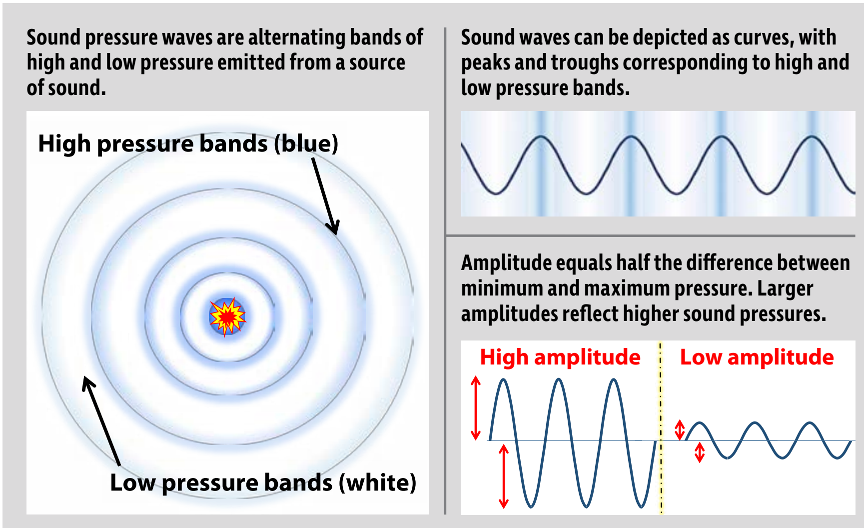
can be detected by average people. For quiet sounds, people can detect small changes in loudness; however, for loud sounds, only large changes are detected. Near the threshold of hearing (0 dB), the average person can detect an increase in sound pressure of about 2.24 µPa, which represents an increase of about 1 dB in a very quiet environment. On the other hand, if the same person is exposed to a sound pressure of 2,000,000 µPa (100 dB), s/he will not detect a change in loudness unless the sound pressure increases by about 244,037 µPa (representing an increase of about 1 dB in this noisier environment). We will see in the following exercises that an increase of just a few decibels in a loud environment represents a serious hazard because the corresponding rise in micropascals is large. In contrast, a small decibel increase is less hazardous in a quiet environment, where the change in micropascals is small.

An important note: OSHA and NIOSH normally express exposure limits as dBA, which stands for decibels on the A-weighted scale. Sound pressure levels can be expressed on different frequency-weighting scales. The A-weighted scale emphasizes sound frequencies to which humans are most sensitive, while other scales (such as the C- and Z-weighted scales) do not. When monitoring sound pressure levels in the workplace, we normally set our noise meters to the A-weighted scale if we plan to compare our results with exposure limits established by OSHA and NIOSH.

In this article, we will calculate decibels based on sound pressures (p) in workplaces. In the next Math Toolbox article, we will practice other decibel calculations based on sound power, in watts per square meter (W/m^2). Although these two methods are based on different characteristics of sound, we will obtain the same result in decibels regardless of the method we use.

FIGURE 2

SOUND PRESSURE WAVES



Sound Pressure Level Equation

To calculate decibels from sound pressure, we may use either micropascals or pascals as our unit of pressure as long as we maintain consistency throughout the following equation:

$$L_p = 20 \cdot log_{10} \frac{p}{p_0}$$

where:

L_p = sound pressure level, in decibels (dB)

log_{10} = base-10 logarithm (i.e., common log)

p = actual sound pressure measured in the environment (the sound pressure to which a worker is exposed), in micropascals (µPa), or alternatively, pascals (Pa)

p_0 = reference sound pressure (threshold of hearing; 0 dB); p_0 = 20 µPa, or alternatively, 0.00002 Pa

Note: Be sure to use the same pressure metric (either µPa or Pa) to express variables p and p_0 throughout the equation.

Calculating Decibels Based on Sound Pressure

Today's noise monitoring devices automatically calculate and display sound pressure levels in decibels (Figure 3). However, it is easier to interpret these numbers if we understand the calculations. Furthermore, we may be asked to perform the calculations on certification exams.

To begin, imagine a worker's 8-hour time-weighted average (TWA) A-weighted sound pressure exposure is found to be 283,000 µPa. Since our measured sound pressure is stated in units of µPa, we will use 20 µPa for the reference sound pressure because this is equivalent to zero decibels.

Here is a summary of the information we will use to calculate the sound pressure level in decibels:

•The measured A-weighted sound pressure is 283,000 µPa as an 8-hour TWA exposure for the worker in this environment. This is the value of p in the formula.

•We are using units of micropascals, so the reference sound pressure is 20 µPa. This is the value of p_0 in the formula.

With this information, we can solve the problem as follows:

Step 1. Start with the equation for sound pressure level in decibels:

$$L_p = 20 \cdot log_{10} \frac{p}{p_0}$$

Step 2. Insert the known values for the sound pressure measured in the environment (p = 283,000 µPa) and the reference sound pressure (p_0 = 20 µPa). Then solve for sound pressure level in decibels (L_p):

$$L_p = 20 \cdot log_{10} \frac{283{,}000}{20} = 83.02\ dB$$

(on the A-weighted scale)

Note: Most calculators have a *LOG* button that will provide the correct answer, with keystrokes similar to the following in this case: *20 X LOG (283000 ÷ 20)* =. Alternatively, in a spreadsheet, the proper formula for this example is *= 20*LOG10(283000/20)*.

Step 3. Our calculation indicates the sound pressure level is 83.02 dB on the A-weighted scale (83.02 dBA) as an 8-hour TWA exposure.

To interpret the measured result, refer to the NIOSH recommended exposure limit (REL) of 85 dBA as an 8-hour TWA.

Our calculated daily average noise exposure of 83.02 dBA does not exceed the NIOSH REL of 85 dBA as an 8-hour TWA. Thus, we conclude that an average exposure to 83.02 dBA does not trigger any special NIOSH recommendations.

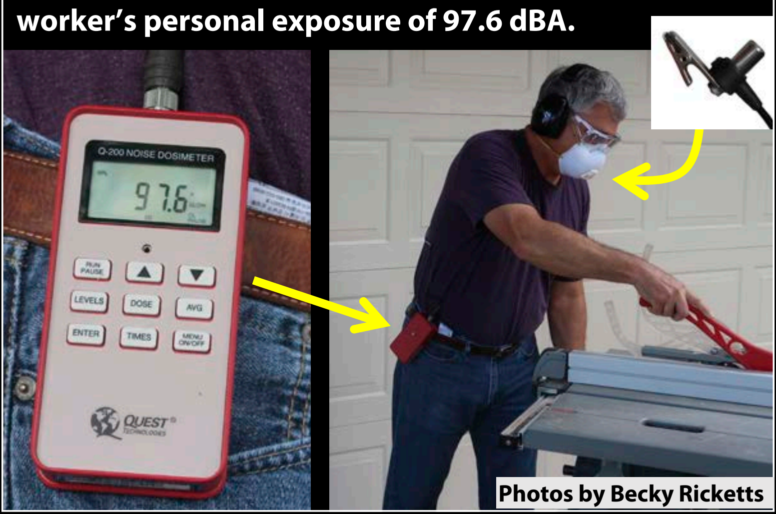
Alternate example: Calculate the sound pressure level in decibels for a different environmental sound level. In this case, imagine a worker's 8-hour TWA A-weighted sound pressure exposure is 1,124,683 µPa, which is equivalent to 1.124683 pascals (Pa). To illustrate how to solve the equation in different units of measurement, first perform the calculations using µPa, then repeat with Pa.

Based on micropascals, insert the measured sound pressure (p = 1,124,683 µPa)

FIGURE 3
ENVIRONMENTAL NOISE MONITORING

Work area noise measurements with a sound level meter (i.e., area monitoring) may misrepresent some workers' exposures. Compare this table saw area exposure of 93.1 dBA with the operator's personal exposure at bottom.

Dosimeter with a lapel microphone records the worker's personal exposure of 97.6 dBA.



Photos by Becky Ricketts

and reference sound pressure (p_0 = 20 µPa) to obtain the following result:

$$L_p = 20 \cdot log_{10}\frac{1{,}124{,}683}{20} = 95\ dB$$

(on the A-weighted scale)

To solve the same problem based on pascals, we insert 1.124683 Pa for the measured sound pressure (p) and .00002 Pa for the reference sound pressure (p_0):

$$L_p = 20 \cdot log_{10}\frac{1.124683}{0.00002} = 95\ dB$$

(on the A-weighted scale)

Both calculations result in an average sound pressure level of 95 dBA for the worker in this environment. Since the example states that the exposure was measured as an 8-hour TWA, the result does exceed the NIOSH REL of 85 dBA. This means the worker faces an increased risk of noise-induced hearing loss, and we must implement the corresponding NIOSH recommendations.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 55.

1) Measured in accordance with the A-weighted scale, a worker's 8-hour TWA sound pressure exposure is 632,456 micropascals (µPa). What is the sound pressure level (L_p) in dBA? Since the measured sound pressure (p) is stated in units of µPa, use 20 µPa as the reference sound pressure (p_0). Does the result exceed the NIOSH-recommended exposure limit (85 dBA)?

2) Measured in accordance with the A-weighted scale, a worker's 8-hour TWA sound pressure exposure is 2.5179 pascals (Pa). What is the sound pressure level (L_p) in dBA? Since the measured sound pressure (p) is stated in units of Pa, use 0.00002 Pa as the reference sound pressure (p_0). Does the result exceed the NIOSH-recommended exposure limit (85 dBA)?

Calculating Actual Sound Pressure (µPa or Pa) Based on Decibels

One of the most practical on-the-job applications of our equation is to convert the decibels displayed on a sound level meter back to actual sound pressures. This exercise is useful because it helps us understand the true magnitude of small differences in decibels at noisy work sites.

We convert from decibels to actual sound pressures by rearranging the formula, as follows:

Begin with the original formula:

$$L_p = 20 \cdot log_{10}\frac{p}{p_0}$$

Rearrange the equation to solve for p. Keep in mind that we can perform any operation on one side of the equation as long as we perform that same operation on the other side. Let's begin by dividing both sides of the equation by 20:

$$L_p \div 20 = 20 \cdot log_{10}\frac{p}{p_0} \div 20$$

Next, cancel the 20 where you can:

$$L_p \div 20 = \cancel{20} \cdot log_{10}\frac{p}{p_0} \cancel{\div 20}$$

Simplify by eliminating the canceled terms:

$$L_p \div 20 = log_{10}\frac{p}{p_0}$$

Continue rearranging by taking the inverse logarithm (antilogarithm) of each side of the equation:

$$10^{(L_p \div 20)} = 10^{\left(log_{10}\frac{p}{p_0}\right)}$$

Cancel where you can:

$$10^{(L_p \div 20)} = \cancel{10}^{\left(\cancel{log_{10}}\frac{p}{p_0}\right)}$$

Simplify:

$$10^{(L_p \div 20)} = \frac{p}{p_0}$$

Multiply both sides by p_0:

$$10^{(L_p \div 20)} \times p_0 = \frac{p}{p_0} \times p_0$$

Cancel where you can:

$$10^{(L_p \div 20)} \times p_0 = \frac{p}{\cancel{p_0}} \cancel{\times p_0}$$

Simplify:

$$10^{(L_p \div 20)} \times p_0 = p$$

Rearrange, and use the resulting equation to solve for p:

$$p = 10^{(L_p \div 20)} \times p_0$$

Imagine that monitoring indicates a worker's 8-hour TWA noise exposure is 92 dB on the A-weighted scale (92 dBA). What is the sound pressure in micropascals?

Step 1. Start with the sound pressure level equation, modified to solve for p:

$$p = 10^{(L_p \div 20)} \times p_0$$

where:

p = actual sound pressure measured in the environment (the sound pressure to which a worker is exposed), micropascals (µPa), or alternatively, pascals (Pa)

L_p = sound pressure level, decibels (dB)

p_0 = reference sound pressure (threshold of hearing; 0 dB); p_0 = 20 µPa, or alternatively, 0.00002 Pa

Step 2. Insert the known values for sound pressure level in decibels (L_p = 92 dBA) and reference sound pressure (use p_0 = 20 µPa because the question asks for micropascals). Solve for sound pressure measured in the environment (p):

$$p = 10^{(92 \div 20)} \times 20 = 796{,}214.34\ \mu Pa$$

Note: Check your calculator's user manual for instructions on raising 10 to a power, as required for the equation. Most calculators have a button such as *INV*, *10X*, ^ or similar for this purpose. In Excel, the formula for this example is *= (10^(92/20))*20*.

Step 3. The result indicates a sound pressure level of 92 dBA equals an actual sound pressure of 796,214.34 µPa (approximately 800,000 µPa, which equals about 0.8 Pa).

Alternate example: Imagine that monitoring indicates a worker's 8-hour TWA noise exposure is 98 dBA, an increase of 6 dB from the previous example. What is the new sound pressure in micropascals? Again, the question asks for the result in micropascals, so use 20 µPa as the reference sound pressure (p_0).

Insert the known values for the new sound pressure level in decibels (L_p = 98 dBA) and reference sound pressure (p_0 = 20 µPa). Solve for sound pressure measured in the environment (p):

$$p = 10^{(98 \div 20)} \times 20 = 1{,}588{,}656.47\ \mu Pa$$

The result indicates that the sound pressure level of 98 dBA equals an actual sound pressure of 1,588,656.47 µPa (approximately 1,600,000 µPa, which equals nearly 1.6 Pa). Compare this sound pressure with the previous example's result of approximately 800,000 µPa (0.8 Pa) for 92 dBA. Taken together, these results illustrate an important aspect of the decibel scale, namely, at high sound pressure levels, even a small increase in decibels can represent a dramatic increase in sound pressure.

You Do the Math

Answers are on p. 55.

3) Imagine that monitoring indicates a worker's 8-hour TWA noise exposure is 104 dBA, an increase of 6 dB from the previous example. What is the new sound pressure in micropascals? Use 20 µPa as the reference sound pressure, p_0, since the question asks for micropascals.

4) Imagine that monitoring indicates a worker's 8-hour TWA noise exposure is 84 dBA, a decrease of 20 dB from the example in Question 3. Again, use 20 µPa as the reference sound pressure, p_0, to calculate micropascals. What is the new sound pressure?

How Much Have I Learned?

Try these problems on your own. Answers are on p. 55.

5) Measured in accordance with the A-weighted scale, a worker's 8-hour TWA sound pressure exposure is 399,052 micropascals (µPa). What is the sound pressure level (L_p) in dBA? Since the measured sound pressure (p) is stated in units of µPa, use 20 µPa as the reference sound pressure (p_0).

6) Imagine a worker's 8-hour TWA noise exposure is 112 dBA. What is the sound pressure in pascals (Pa)? The question asks for the result in pascals, so use 0.00002 Pa as the reference sound pressure (p_0).

The Language of Sound Pressure Levels

Readers will encounter the following concepts in codes, certification exams and conversations with other professionals. Match the numbered concepts with their paraphrased definitions (lettered). All concepts have been defined in the text, formulas and illustrations. Answers are on p. 55.

Concepts

7) decibel (dB)
8) micropascal µPa)
9) pascal (Pa)
10) reference sound pressure (p_0)
11) sound pressure (p, p_0)
12) sound pressure level (L_p)
13) sound waves

Definitions (in random order)

a) A direct measure of the pressure fluctuation caused by a sound wave in µPa or Pa.

b) Threshold of hearing (0 dB; the softest sound the average person can hear). This value equals 20 µPa, or 0.00002 Pa.

c) International unit of pressure that equals about 0.000147 psi (1.47×10^{-4} psi).

d) International unit of pressure that equals about 1.47×10^{-10} psi.

e) Unit of measure for sound pressure levels, reflecting differences in loudness that can be detected by average people.

f) Alternating bands of high and low pressure spreading outward from an object that vibrates or moves suddenly.

g) Indirect measure of sound expressed in decibels.

For Further Study

Learn more from the following sources:

• *ASSP's ASP Examination Prep: Program Review and Exam Preparation*, edited by Joel M. Haight, 2016.

• *OSHA Technical Manual* (TED 01-00-015), Section III, Chapter 5: Noise, by OSHA, 2013; **www.osha.gov/dts/osta/otm/new_noise/index.html**.

• *Criteria for a Recommended Standard: Occupational Noise Exposure (Revised Criteria)*, by NIOSH, 1998; **www.cdc.gov/niosh/docs/98-126/pdfs/98-126.pdf**. PSJ

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If the day feels like an off day, the feeling that things are not quite right should equate to a large yellow caution sign in your mind.

have personal issues, the feeling that things are not quite right should equate to a large yellow caution sign in your mind.

Consider the safety impact of your actions, not only on yourself, but also on coworkers and other people in the area.

Two OSHA records describe incidents in which workers were electrocuted while they were attempting to fix equipment and another worker saw a circuit breaker turned to the off position and reset it (which is why we have lockout/tagout procedures) (OSHA, 2012; 2017). Power line incidents on construction sites often kill or severely injure workers who are not responsible for the contact.

In my incident at the store, the worker who dangerously propped up the map stand was not thinking of the safety of others. The worker was likely inexperienced and trained to keep everything in the store in its proper place. The map stand was broken and should have been removed. Not only did I err in judgment, but the store worker (i.e., administrative control) also erred and, in doing so, created an unsafe environment.

My knee injury is a daily reminder that mistakes are part of the human experience. The best way to prevent a workplace injury or fatality is to remove potential human error from the equation.

In the U.S. and in many countries around the world, workplaces have made great strides in training workers, developing safer work practices and creating safer workplaces. In 1992, 2003 and 2017, U.S. fatal occupational injury rates were 5, 4 and 3.5 per 100,000 workers, respectively (BLS, 2019a;b); these rates are much lower than the 1971 U.S. worker fatality rate of 17.1 (Manuele, 2013). As shown in Figure 1, the number of fatal worker injuries has not consistently declined since 2009. Mendeloff and Staetsky (2014) found that the U.K. (as well as several other European countries) has fatal overall and electrical injury rates of about one-third and one-quarter of those in the U.S.; they attribute the lower rates to high-level-management focus on safety issues and in-house risk assessments.

Even well-trained workers can make mistakes. Identifying and removing the potential for human error would certainly reduce the number of workplace injuries in the U.S. **PSJ**

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Math Toolbox, continued from pp. 45-48

Answers: The Case of the Noisy Workplace

You Do the Math

Your answers may vary slightly due to rounding.

1) $L_p = 20 \cdot log_{10} \frac{632,456}{20} = 90\ dB$

If the worker is exposed 8 hours per day, 40 hours per week, this A-weighted result exceeds the NIOSH recommended exposure limit of 85 dBA.

2) $L_p = 20 \cdot log_{10} \frac{2.5179}{0.00002} = 102\ dBA$

If the worker is exposed 8 hours per day, 40 hours per week, this A-weighted result exceeds the NIOSH recommended exposure limit.

3) $p = 10^{(104 \div 20)} \times 20 = 3,169,786.39\ \mu Pa$

4) $p = 10^{(84 \div 20)} \times 20 = 316,978.64\ \mu Pa$

How Much Have I Learned?

5) $L_p = 20 \cdot log_{10} \frac{399,052}{20} = 86\ dBA$

6) $p = 10^{(112 \div 20)} \times 0.00002 = 7.96\ Pa$

If you calculated the answer as 7,962,143.41, remember the question asked for pascals, rather than micropascals.

The Language of Sound Pressure Levels

7) e; 8) d; 9) c; 10) b; 11) a; 12) g; 13) f.