The Case of the DEAFENING SIREN

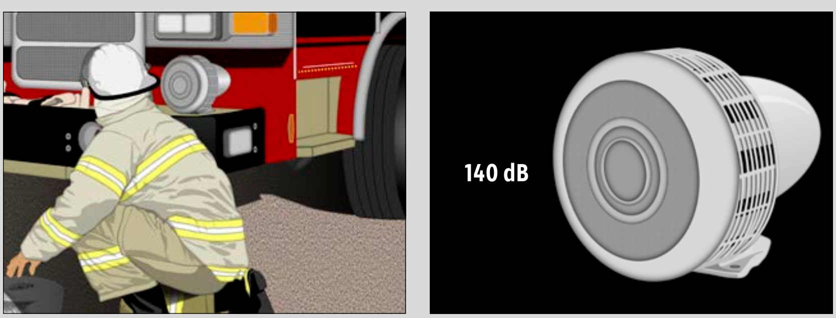
By Mitch Ricketts

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.

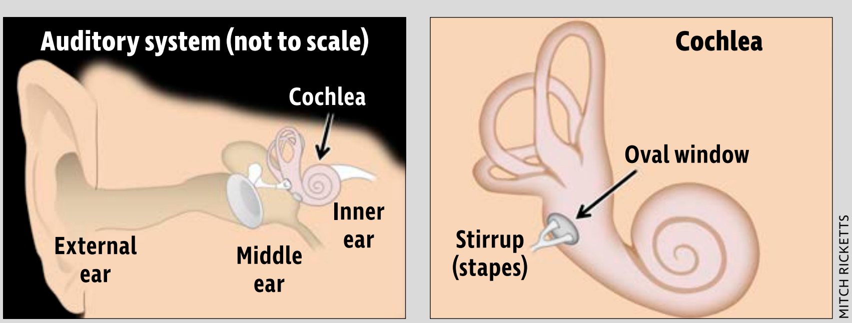
We often associate the hazardous health effects of noise with long-term exposures in chronically noisy environments. For sufficiently loud sounds, however, severe hearing damage may result from as little as a single exposure. "Acoustic trauma" is a general term that describes injuries to the auditory system caused by a brief exposure to intense sound (usually at a level of 130 decibels, dB, or more; Wada et al., 2017). Damage may be permanent when trauma affects the cochlea, where the auditory hair cells are located, or the cochlear nerve, which transmits nerve impulses from the auditory system to the brain (Dinh et al., 2015). Figure 1 illustrates the details of one such case, in which a firefighter suffered permanent damage to the auditory system as the result of an acute exposure to a 140-dB blast from a nearby siren.

FIGURE 1
FIREFIGHTER INJURED FROM NEARBY SIREN BLAST

A 27-year-old firefighter was working next to the siren of a fire engine. The siren was silent, but it was just 18 in. from the firefighter's right ear. Suddenly, the siren sounded with an intensity of 140 dB. The blast caused immediate pain, loud tinnitus (ringing of the ears) and dizziness. Although the tinnitus subsided after about 6 hr, the dizziness persisted, as did a loss of hearing on the right side.



Continuing symptoms prompted the firefighter to visit a specialist 3 weeks later. He was diagnosed with a pronounced sensorineural hearing loss in the right ear as well as involuntary eye movements known as nystagmus. Dizziness worsened over the next few weeks. He underwent surgery, and doctors observed fluid leaking from his cochlea due to a tear in the oval window. The cochlea was surgically repaired four times over the next few months, but his hearing never fully recovered. He also continued to suffer episodes of dizziness due to disruption of the vestibular system—all caused by the acoustic trauma of the siren blast.



Note. Adapted from "Noise-Induced Perilymph Fistula," by B. Kung and R.T. Sataloff, 2006, *Ear, Nose and Throat Journal, 85*(4), 240-246 (https://doi.org/10.1177%2F014556130608500413).

The energy of intense sound waves may cause ringing in the ears (tinnitus) as well as a loss of hearing (Hertzano et al., 2020). Suspected but unconfirmed effects of brief acoustic trauma may also include permanent disruptions in the sense of balance (vestibular dysfunction) and uncontrolled movements of the eyes that affect vision and coordination (nystagmus; Le et al., 2017). Chronic exposures to lower sound pressure levels (on the order of 80 dB and above) may also be harmful, causing many of the same effects over longer intervals (Mirza et al., 2018).

Previous Math Toolbox articles examined the impact of sound levels when measured with a microphone placed near the worker's ear (Ricketts 2020a, 2020b). In this article, we estimate sound pressure levels at various distances from a source using a form of the inverse square law modified for measurements in decibels. These exercises illustrate how sound emanating from one location may affect workers positioned some distance away.

Estimating Noise Levels at Increasing Distances From a Source

Two important characteristics of a sound wave include sound power and sound pressure. Sound power is a measure of the rate at which sound waves transmit energy capable of performing work in the environment, for example, by causing vibrations in the tissues, bones and fluids of the auditory system. Sound pressure, on the other hand, is a fluctuation in measurable pressure caused by a sound wave as it moves through air or another medium (e.g., water, steel).

The standard form of the inverse square law can be applied to some direct measures of energy to estimate the degree to which the energy falls off with distance in an ideal environment (see Ricketts, 2021, for examples involving ionizing radiation). In practice, however, sound pressure levels (L_p) and sound power levels (L_w) are normally expressed in units of decibels, which are indirect logarithmic measures. We cannot apply the standard inverse square law to sound levels expressed as decibels. Instead, we use a modified form of the inverse square law that accounts for the logarithmic nature of the decibel scale. This equation is valid regardless of whether we base our calculations on sound pressure levels or on sound power levels. The equation is:

$$dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$$

where:

dB_0 = sound pressure level or sound power level at the nearer distance, in decibels (dB)

dB_1 = sound pressure level or sound power level at the farther distance (dB)

log_{10} = base-10 logarithm

d_0 = the nearer distance, in any conventional unit of measure, such as inches, feet, centimeters or meters

d_1 = the farther distance, in the same unit of measure as d_0

Calculated example. Let's consider the case illustrated in Figure 1. According to the report, the firefighter's ear was located 18 in. from the siren, and the sound level at this distance was 140 dB. We might ask what the sound level would be if the firefighter's ear had been located 60 in. from the siren instead of 18 in. Using the inverse square law modified for decibels, we can estimate the sound level at 60 in. from the siren based on the following data.

•The nearer of the distances we are comparing is 18 in., so this is the value of d_0 in the formula.

•The farther of the two distances is 60 in., so this is the value of d_1.

•The sound level at the nearer distance is 140 dB, so this is the value of dB_0.

•The equation will solve for dB_1, which is the sound level at the farther distance.

Step 1: Start with the equation:

$$dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$$

Step 2: Insert the known values for the nearer sound level (dB_0 = 140 dB), the value of the nearer distance (d_0 = 18 in.) and the value of the farther distance (d_1 = 60 in.). Then solve for dB_1:

$$dB_1 = 140 + 20 \cdot log_{10}\left(\frac{18}{60}\right) = 129.54\ dB$$

(rounded two places past the decimal)

Note: Most calculators have a *LOG* button that will provide the correct answer

We often associate the hazardous health effects of noise with long-term exposures in chronically noisy environments. For sufficiently loud sounds, however, severe hearing damage may result from as little as a single exposure. "Acoustic trauma" is a general term that describes injuries to the auditory system caused by a brief exposure to intense sound.

with keystrokes similar to the following in this case: *140+20XLOG(18÷60)=*. Alternatively, in an Excel spreadsheet, the proper formula for this example is: *=140+20*LOG10(18/60)*.

Step 3: The calculation indicates the sound level at 60 in. from the siren is about 129.54 dB, assuming the sound radiates uniformly in all directions and assuming there are no sound-reflective or sound-absorptive surfaces in the immediate environment. The sound level at 60 in. is still substantial and may be capable of causing acoustic trauma even at this distance. (See "Concluding Comments" for important limitations regarding our estimate.)

Alternate example. Now imagine a different scenario in which a gunshot produces a sound level of 153 dB at a distance of 2 ft. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 70 ft? The variables can be summarized as follows:

•The nearer of the two distances is 2 ft. This is the value of d_0 in the formula.

•The farther distance is 70 ft. This is the value of d_1.

•The sound level at the nearer distance is 153 dB. This is the value of dB_0.

•The equation will solve for dB_1, which is the sound level at the farther distance.

Step 1: Start with the equation:

$$dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$$

Step 2: Insert the known values for the nearer sound level (dB_0 = 153 dB), the value of the nearer distance (d_0 = 2 ft) and the value of the farther distance (d_1 = 70 ft). Then solve for dB_1:

$$dB_1 = 153 + 20 \cdot log_{10}\left(\frac{2}{70}\right) = 122.12\ dB$$

(rounded)

Step 3: The calculation indicates the sound level at 70 ft from the gunshot is about 122.12 dB.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 45.

1. Imagine a church bell produces a sound level of 145 dB at a distance of 1,500 m. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 4,000 m?

2. Imagine a car alarm produces a sound level of 118 dB at a distance of 400 cm. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 12,000 cm?

Estimating Noise Levels Closer to a Source

In previous examples, we estimated noise levels at a distance that was farther from the noise source, compared with the original measurement. By rearranging the equation, we can estimate noise levels at a nearer distance. Steps for rearranging are as follows:

Start with the equation we used earlier:

$$dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$$

Rearrange the equation to solve for dB_0. 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 subtracting dB_0 from both sides of the equation:

$$dB_1 - dB_0 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) - dB_0$$

After making this change, we note that we are both adding and subtracting dB_0 on the right side of the equal sign. Since $dB_0 - dB_0 = 0$, we can cancel both of these terms on the right side of the equation:

$$dB_1 - dB_0 = \cancel{dB_0 +} 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) \cancel{- dB_0}$$

Next, we simplify by eliminating the canceled terms:

$$dB_1 - dB_0 = 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$$

We continue rearranging by subtracting dB_1 from each side of the equation:

$$dB_1 - dB_0 - dB_1 = 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) - dB_1$$

Now we are both adding and subtracting dB_1 on the left side of the equal sign, so we can cancel these terms on the left:

$$\cancel{dB_1} - dB_0 \cancel{- dB_1} = 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) - dB_1$$

Again, we simplify by eliminating the canceled terms:

$$-dB_0 = 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) - dB_1$$

We wish to solve for dB_0; however, the equation at this point will actually solve for $-dB_0$. To get rid of the negative sign on the left, we first multiply both sides by (-1):

$$-dB_0 \cdot (-1) = \left(20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) - dB_1\right) \cdot (-1)$$

We then simplify by changing the sign of the first term on both sides of the equation. The resulting formula will solve for dB_0:

$$dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$$

Calculated example. Let's return to the case illustrated in Figure 1. Remember that the sound level was 140 dB at a distance of 18 in. from the siren. This time, let's determine what the sound level would be if the firefighter's ear had been located just 9 in. from the siren:

•The nearer of the two distances is now 9 in. This will be the value of d_0.

•The farther of the two distances is now 18 in. This is the value of d_1.

•The sound level at the farther distance is now 140 dB, so this is the value of dB_1.

•The equation will solve for dB_0, which is the sound level at the nearer distance.

Step 1: Start with the rearranged equation:

$$dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$$

Step 2: Insert the known value of the nearer distance (d_0 = 9 in.), the value of the farther distance (d_1 = 18 in.) and the farther sound level (dB_1 = 140 dB). Then solve for dB_0:

$$dB_0 = -20 \cdot log_{10}\left(\frac{9}{18}\right) + 140 = 146.02\ dB$$

(rounded)

The inverse square law has long been used as a tool for estimating sound levels at varying distances from a source. The formula works well under controlled circumstances when sound radiates uniformly in all directions, with no sound-reflective or absorptive surfaces to amplify or dampen the sound. In practice, sound is often projected more strongly in one direction than another

Note: Most calculators have a "change sign" key that will convert a positive number to a negative, and vice-versa. This key is often designated by the symbol of a negative sign within parentheses: *(-)*. For a calculator with a change sign key, the correct keystrokes will be similar to the following in this case: *(-)20XLOG(9÷18)+140=*. In an Excel spreadsheet, the ordinary minus sign can be used to change the sign of the number. The proper spreadsheet formula for this example is: *=-20*LOG10(9/18)+140*.

Step 3: The calculation indicates that the sound level at 9 in. from the siren is about 146.02 dB, which is much greater compared to the sound level at 18 in. Again, we have assumed the sound radiates uniformly in all directions, with no reflective or absorptive surfaces.

Alternate example. Imagine a different scenario in which each impact of a drop forge produces a sound level of 111 dB at a distance of 2.4 m. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 0.3 m? The variables can be summarized as follows:

•The nearer of the two distances is 0.3 m. This is the value of d_0 in the formula.

•The farther distance is 2.4 m. This is the value of d_1.

•The sound level associated the farther distance is 111 dB. This is the value of dB_1.

•The equation will solve for dB_0, which is the sound level at the nearer distance.

Step 1: Begin with the rearranged equation:

$$dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$$

Step 2: Insert the known value of the nearer distance (d_0 = 0.3 m), the value of the farther distance (d_1 = 2.4 m) and the farther sound level (dB_1 = 111 dB). Then solve for dB_1:

$$dB_0 = -20 \cdot log_{10}\left(\frac{0.3}{2.4}\right) + 111 = 129.06\ dB$$

(rounded)

Step 3: The calculation indicates the sound level at 0.3 m from the drop forge is about 129.06 dB. Again, this is much greater compared to the farther distance.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 45.

3. Imagine a holiday firework produces a sound level of 125 dB at a distance of 20 ft. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 5 ft?

4. Imagine a steam whistle produces a sound level of 116 dB at a distance of 36 m. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 7 m?

Concluding Comments

The inverse square law has long been used as a tool for estimating sound levels at varying distances from a source. The formula works well under controlled circumstances when sound radiates uniformly in all directions, with no sound-reflective or absorptive surfaces to amplify or dampen the sound. In practice, sound is often projected more strongly in one direction than another (as in the case of a siren having directional apertures). Furthermore, floors, walls and other reflective surfaces may cause sound waves to bounce back and forth in a work environment. Conversely, intervening absorptive materials, such as insulation in wall cavities (indoors) or vegetation (outdoors), may reduce the intensity of passing sound waves. With these limitations in mind, the inverse square law may not provide valid estimates in all situations, and calculations should always be verified with appropriate monitoring equipment.

As a final note for readers who enjoy more advanced mathematical puzzles, consider that we used a modified form of the inverse square law to account for the logarithmic nature of the decibel scale. It is possible to confirm our calculations with the standard form of the inverse square law if we express sound level as energy transmitted in watts per square meter (W/m^2) instead of dB. The procedure is as follows: For each problem, first convert sound level in dB to W/m^2 using the formula:

$$W = 10^{(L_W \div 10)} \cdot W_0$$

(See Ricketts, 2020b, for explanations and examples of the formula.) Next, calculate distance-based changes in W/m^2 with the standard forms of the inverse square law:

$$I_2 = I_1 \cdot \frac{(d_1)^2}{(d_2)^2}$$

and

$$I_1 = I_2 \div \frac{(d_1)^2}{(d_2)^2}$$

(See Ricketts, 2021, and use W/m^2 as the units of nearer and farther intensity, I_1 and I_2, respectively, along with the corresponding distances, d_1 and d_2.) Finally, convert the outcome from the standard inverse square calculations back to dB from W/m^2 with:

$$L_w = 10 \cdot log_{10} \frac{W}{W_0}$$

(See Ricketts, 2020b.) These procedures will confirm the results for the problems in this article, within the range of rounding differences. Important: The standard form of the inverse square law cannot be used to calculate distance-based changes in sound pressure levels of pascals (Pa) because the pascal is not a unit of energy transmission.

How Much Have I Learned?

Try these problems on your own. Answers are on p. 45.

5. Imagine a major pressure safety valve at a chemical manufacturing facility produces a sound level of 163 dB at a distance of 8 ft. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 100 ft? Use the formula for estimating noise levels at increasing distances from a source:

$$dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$$

6. Imagine the detonation of a blasting cap produces a sound level of 128 dB at a distance of 4 m. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 75 m? Use the formula for estimating noise levels at increasing distances from a source:

$$dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$$

7. Imagine the coupling of a railroad car produces a sound level of 92 dB at a distance of 30 m. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 1 m? Use the formula for estimating noise levels closer to a source:

$$dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$$

8. Imagine a backup alarm produces a sound level of 104 dB at a distance of 15 cm. Assuming the sound radiates uniformly in all directions, with no reflective or absorptive surfaces, what sound level would we expect at a distance of 6 cm? Use the formula for estimating noise levels closer to a source:

$$dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$$

The Language of Acoustic Trauma

Readers may encounter the following concepts in certification exams and conversations with engineers and healthcare 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. 45.

Concepts

9. Acoustic trauma
10. Cochlea
11. Cochlear nerve
12. Nystagmus
13. Sound power
14. Sound pressure
15. Tinnitus
16. Vestibular dysfunction

Definitions (in random order)

a. A fluctuation in measurable pressure caused by a sound wave as it moves through air, water or another medium.
b. A measure of the rate at which sound waves transmit energy capable of performing work in the environment.
c. Structure that transmits nerve impulses from the auditory system to the brain.
d. Inner ear structure where the auditory hair cells are located.
e. The most general term describing injuries to the auditory system caused by a brief exposure to intense sound.
f. Specific term for disruptions in the sense of balance.
g. Specific term for ringing (or hissing, humming) in the ears.
h. Specific term for uncontrolled movements of the eyes that affect vision and coordination.

References

Dinh, C.T., Goncalves, S., Bas, E., Van De Water, T.R. & Zine, A. (2015). Molecular regulation of auditory hair cell death and approaches to protect sensory receptor cells and/or stimulate repair following acoustic trauma. *Frontiers in Cellular Neuroscience, 9*, 96. https://doi.org/10.3389/fncel.2015.00096

Hertzano, R., Lipford, E.L. & Depireux, D. (2020). Noise: Acoustic trauma to the inner ear. *Otolaryngologic Clinics of North America, 53*(4), 531-542. https://doi.org/10.1016/j.otc.2020.03.008

Kung, B. & Sataloff, R.T. (2006). Noise-induced perilymph fistula. *Ear, Nose and Throat Journal, 85*(4), 240-246. https://doi.org/10.1177%2F014556130608500413

Le, T.N., Straatman, L.V., Lea, J. & Westerberg, B. (2017). Current insights in noise-induced hearing loss: A literature review of the underlying mechanism, pathophysiology, asymmetry, and management options. *Journal of Otolaryngology-Head and Neck Surgery, 46*, Article 41. https://doi.org/10.1186/s40463-017-0219-x

Mirza, R., Kirchner, D.B., Dobie, R.A. & Crawford, J. (2018). Occupational noise-induced hearing loss. *Journal of Occupational and Environmental Medicine, 60*(9), e498-e501. https://doi.org/10.1097/jom.0000000000001423

Ricketts, M. (2020a, April). The case of the noisy workplace. *Professional Safety, 65*(4), 45-48, 55.

Ricketts, M. (2020b, May). The case of the quieter workplace. *Professional Safety, 65*(5), 46-49, 55.

Ricketts, M. (2021, Feb.). The case of the misplaced radioactive element. *Professional Safety, 66*(2), 44-47, 49.

Wada, T., Sano, H., Nishio, S., Kitoh, R., Ikezono, T., Iwasaki, S., Kaga, K., Matsubara, A., Matsunaga, T., Murata, T., Naito, Y., Suzuki, M., Takahashi, H., Tono, T., Yamashita, H., Hara, A. & Usami, S. (2017). Differences between acoustic trauma and other types of acute noise-induced hearing loss in terms of treatment and hearing prognosis. *Acta Oto-Laryngologica, 137*(Suppl. 565), S48-S52. https://doi.org/10.1080/00016489.2017.1297899

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Agricultural Safety and Health Council of America; http://ashca.org


RAPHAEL RYCHETSKY/UNSPLASH

Math Toolbox, continued from pp. 36-39

Answers: The Case of the Deafening Siren

You Do the Math

Your answers may vary slightly due to rounding.

1. $dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$
$= 145 + 20 \cdot log_{10}\left(\frac{1{,}500}{4{,}000}\right) = 136.48\ dB$ (rounded)

2. $dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$
$= 118 + 20 \cdot log_{10}\left(\frac{400}{12{,}000}\right) = 88.46\ dB$ (rounded)

3. $dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$
$= -20 \cdot log_{10}\left(\frac{5}{20}\right) + 125 = 137.04\ dB$ (rounded)

4. $dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$
$= -20 \cdot log_{10}\left(\frac{7}{36}\right) + 116 = 130.22\ dB$ (rounded)

How Much Have I Learned?

5. $dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$
$= 163 + 20 \cdot log_{10}\left(\frac{8}{100}\right) = 141.06\ dB$ (rounded)

6. $dB_1 = dB_0 + 20 \cdot log_{10}\left(\frac{d_0}{d_1}\right)$
$= 128 + 20 \cdot log_{10}\left(\frac{4}{75}\right) = 102.54\ dB$ (rounded)

7. $dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$
$= -20 \cdot log_{10}\left(\frac{1}{30}\right) + 92 = 121.54\ dB$ (rounded)

8. $dB_0 = -20 \cdot log_{10}\left(\frac{d_0}{d_1}\right) + dB_1$
$= -20 \cdot log_{10}\left(\frac{6}{15}\right) + 104 = 111.96\ dB$ (rounded)

The Language of Acoustic Trauma

9. e; 10. d; 11. c; 12. h; 13. b; 14. a; 15. g; 16. f.