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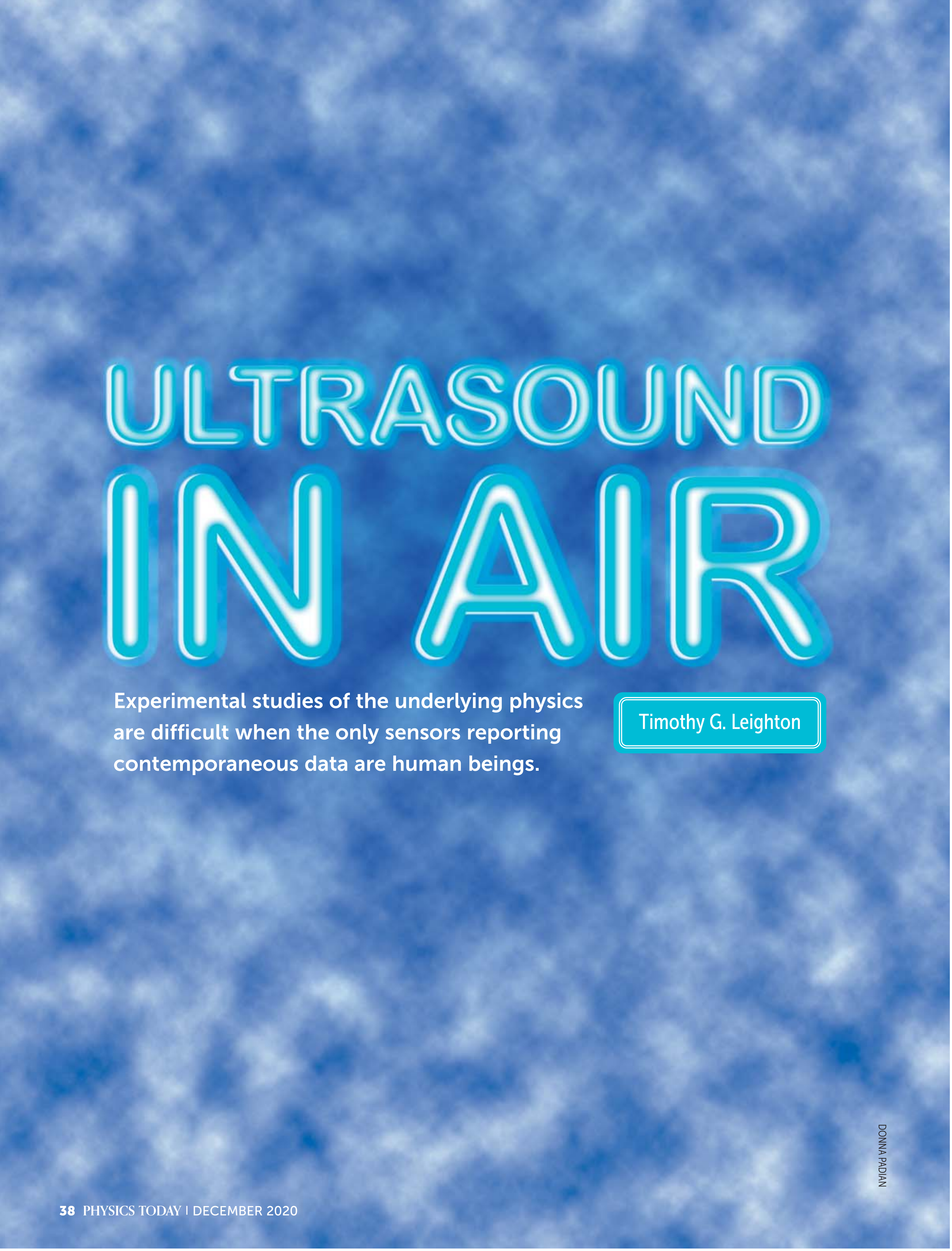

ULTRASOUND IN AIR

Experimental studies of the underlying physics are difficult when the only sensors reporting contemporaneous data are human beings.

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Airborne ultrasound is becoming more prevalent in public places. Some individuals are complaining of adverse effects, including nausea, dizziness, tinnitus, fatigue, migraines and persistent headaches, and an uncomfortable feeling of "pressure in the ears."[1] Reduced technological costs have led to ultrasound being incorporated into new technologies beyond the pest deterrents that have been used for decades[2] (see figure 1). But tracking the increased prevalence of ultrasound in public spaces is difficult because there are no requirements to report it. A complicating factor is that the symptoms individuals attribute to ultrasound can be caused by other means. Whether someone has been exposed to ultrasound and to what level and for how long is often unclear, which makes the causal relationship difficult to establish.

When researchers use humans in experiments, verifying the adverse effects caused by ultrasound is inherently problematic. Susceptibility to ultrasound varies between subjects, and ethical research standards constrain human testing to exposures at lower levels and for shorter durations than one might experience from, say, a commercial pest deterrent. The interpretation and repeatability of experiments is complicated by patterns of strong scattering and diffraction around instruments, stands, and ears. Such difficulties contribute to insufficient data for guidelines: Only one, defined and labeled as interim in 1984, relates to public exposures, and it used data from adults to establish a guideline that should also protect children.[3]

The physical effects of such radiation, which in air has a wavelength of around 1 cm and scatters readily off skin, are therefore not well understood. That uncertainty has resulted in underinformed occupational guidelines and standards regulating ultrasound exposure.

Inherent problems in human experimentation

One challenge in obtaining and interpreting repeatable experiments is illustrated in figure 2, which shows the calculated real part of a pressure wave scattered off an ear. The wave originated at a point source placed 1 m from the opening of the ear canal and in the same horizontal plane. At low frequencies (200 Hz and 2 kHz in the figure), small changes in the relative positions of the ear and the source have little effect on the real part of the pressure that reaches the ear canal's entrance. That enables the listener to localize the source based on the signals detected at both ears.

However, at higher frequencies, the wavelengths—about 2 cm at 18 kHz and 1.5 cm at 23 kHz—become comparable with the length scales of the ear canal itself and the folds in the pinna. Slight movements of the ear relative to the source cause large variations in the received signal through scattering, diffraction, and ear canal resonances. The listener consequently struggles to locate and describe the signals, and even when the same individual is used in controlled experiments, results are difficult to replicate. Although researchers might attempt to make stands and rooms anechoic, or free from echo, scattering and diffraction at the head, pinna, and ear canal remain. Different humans have individually shaped pinnae, which makes reproducing results even more difficult. That discrepancy is further compounded by huge variation in individuals' middle- and inner-ear sensitivities to ultrasound.

People tend to lose high-frequency sensitivity as they age, but the vast variation in sensitivity to ultrasonic frequencies is poorly appreciated. Recent data suggest 5% of people ages 40–49 have hearing thresholds at 20 kHz that are at least 20 dB more sensitive than the median of those in the 30–39 age bracket.[4] That means the quietest sound some listeners in the older age bracket can hear at 20 kHz has 1/100 the power of the quietest sound that is audible to the average listener in the younger group. Moreover, 5% of those ages 5–19 are reported to have a 20 kHz threshold that is 60 dB lower than the median for those in the 30–39 age group (see figure 3), meaning the quietest sound they can hear has 10^{-6} as much power as the quietest audible sound for the average person in the 30–39 age bracket.

If the propensity for adverse effects does in fact increase with hearing sensitivity—which is so far unproven, given the ethical issues with experimentation—then that factor of 1 million casts into doubt any process that bases exposure guidelines for everyone, including children, on the propensity of most adults to experience adverse effects.

Figure 4 illustrates the exposure of young people. In the sketches, a minority of the students can point to the source of a sound that they reported to be unpleasant and distracting. About half the class cannot hear the sound, nor can any of the school staff. Those students that could hear it did not all agree on its location. Fortunately, the teacher took the matter seriously and, after a web search for an adviser, contacted me. I showed the teacher how to equip smartphones with an app that could detect the sound.[1,5] A maintenance team arrived and, with equipped phones, located the source—a defective motion sensor for the classroom lights that was supposed to be functioning at 40 kHz—and removed it. (See reference 5 for the full story.)

Many of those who have complained to me of adverse effects expressed frustration that their complaints had been dismissed by those who either could not detect the sounds or questioned whether such ultrasound, if it existed, could affect humans. Skeptics have raised physics-based arguments,[6] including that the intensity of ultrasound in air would be too low to cause physical effects and that more than 99% of ultrasound is reflected by skin. But both arguments are equally true of audio-frequency sound, which is why humans have evolved a complex hearing and balance system—one that could conceivably respond to ultrasound.

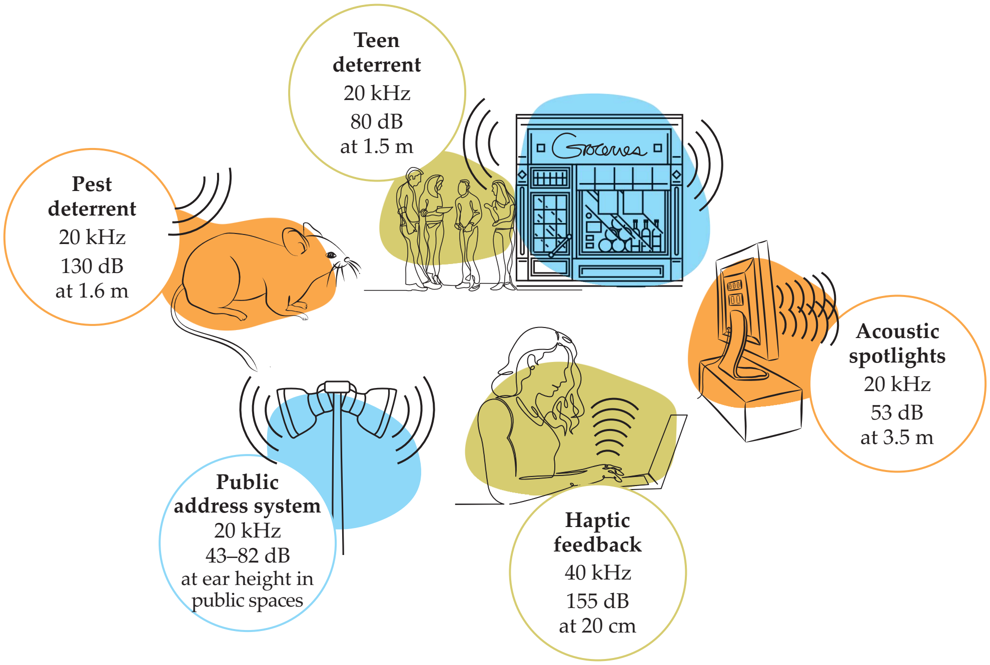

FIGURE 1. EXAMPLES OF INCIDENTAL AND DELIBERATE HIGH-FREQUENCY EXPOSURE from commercial devices. Sound pressure levels (SPLs) referenced to 20 µPa are shown. Pest deterrents use ultrasound to scare away birds, rodents, and insects. Similarly, teen deterrents are used to discourage young people from congregating by exploiting their sensitivity to high-frequency sounds. Many public address systems that use speakers to alert people to, say, a fire or a bomb threat emit a 20 kHz tone to aid in monitoring the system's function. Acoustic spotlights deliver targeted sound through two overlapping high-intensity ultrasonic beams whose interference produces a low-power audible sound. Devices with haptic feedback use modulated ultrasonic beams to produce vibrating sensations. The sources shown can also emit other frequencies.[1] Comparison with figure 3 shows that some of the measured SPLs could be perceptible to certain listeners.[12,14–16,18] Although it is unknown whether ultrasound must be audible to produce an adverse effect, it is known that audible ultrasound can.[13] (Figure by Donna Padian, based on table 1 in ref. 5.)

Setting guidelines

The regulation of ultrasound raises the question, How is ultrasound defined? Establishing it as sound above the frequency that an individual can hear is unworkable, since the highest frequency varies between individuals. Although a person's in-air hearing sensitivity decreases sharply with increasing frequency in the low ultrasonic range, pure-tone thresholds of 88 dB referenced to 20 µPa have been recorded[7] at 24 kHz. The 20–24 kHz frequency range has been a popular choice for commercial devices that emit airborne ultrasound, possibly because the frequency is low enough to avoid excessive attenuation and still be effective for applications such as pest deterrence. Use of that frequency range also provides a misguided sense of safety, since conventional wisdom says that humans cannot hear above 20 kHz.

The International Commission on Non-Ionizing Radiation Protection's charter states that the organization provides guidance on protection from exposure to "acoustic fields with frequencies above 20 kHz (ultrasound)." Thus lower frequencies are left to other bodies to provide direction. However, all national and international bodies set maximum permissible levels (MPLs) for frequency ranges in a third-octave band (TOB)—a frequency band containing one-third of an octave and referred to by its center frequency.[1] The TOB centered on 20 kHz runs from 17.8 kHz to 22.4 kHz, so any MPL set to limit exposure at 20 kHz would equally apply throughout the band. That choice effectively sets the lower bound of the ultrasonic range[6,8] at 17.8 kHz, thereby including the 18 kHz tone that disturbed the students depicted in figure 4.

Those defending the placement of commercial ultrasound-emitting devices in public places often cite occupational MPLs. They claim that regulatory bodies have reached consensus around an MPL of 110 dB re 20 µPa for the frequencies of most interest above the 20 kHz TOB, namely 22.4–56.2 kHz. But it is not a consensus based on independent data sets; rather, it is the

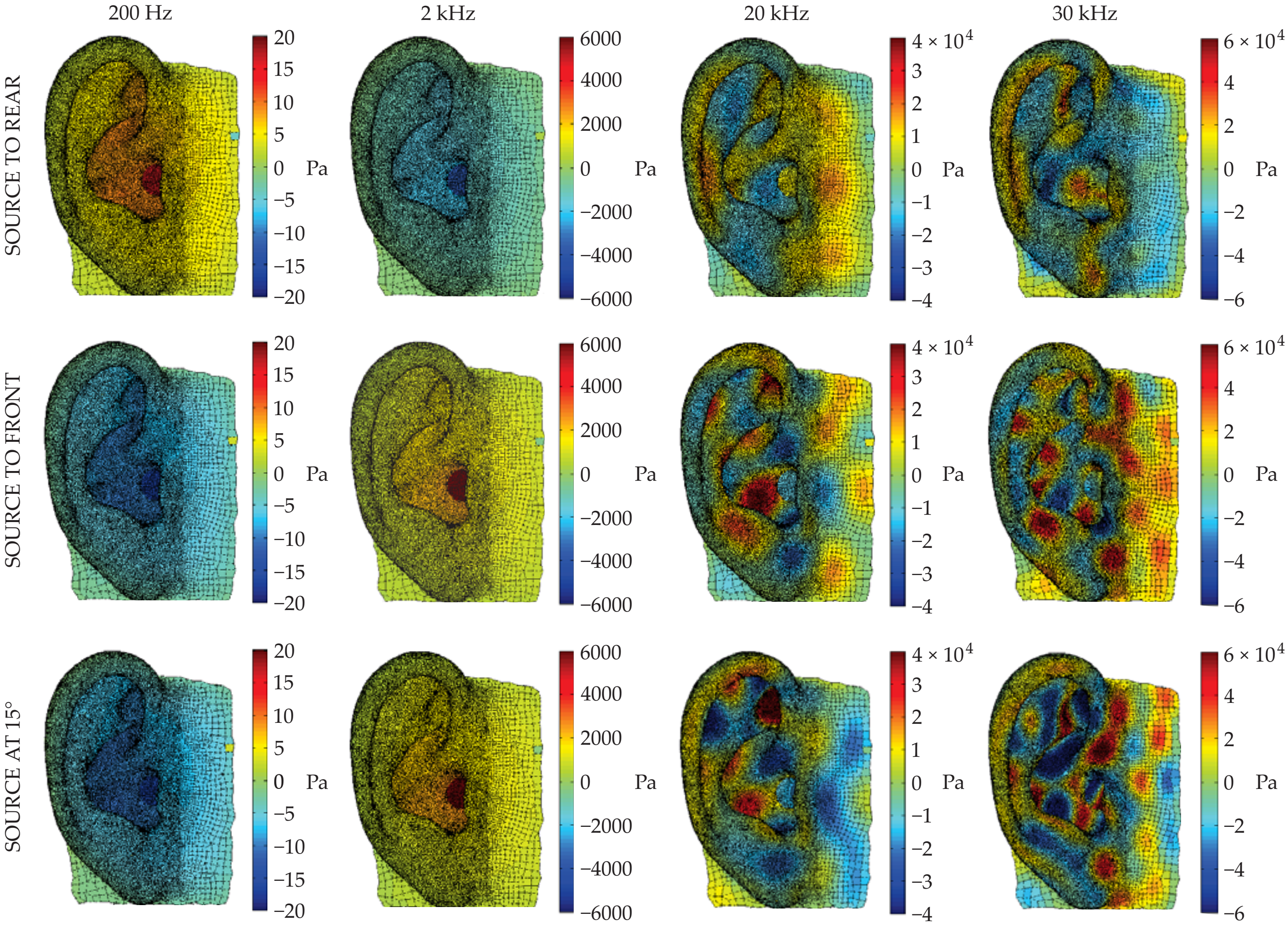

FIGURE 2. PRESSURE WAVES SCATTERING OFF AN EAR. The real part of the scattered pressure, in Pa, is calculated based on a point source placed 1 m from the ear canal's opening and in the same horizontal plane. At 200 Hz and 2 kHz, the source's location can be discerned as behind the listener (top row), in front of the listener (middle row), or angled 15° from the front position (bottom row). But at 20 kHz and 30 kHz, the wavelengths (around 1.7 cm and 1.1 cm, respectively) are of a similar size to the ear canal and pinna structures, and the signal varies greatly in response to small changes in the relative position of the head and source. Those two issues make experiments difficult to repeat and exposures tricky to reproduce. (Modeling by Erika Quaranta. Adapted from ref. 1.)

result of possibly under-resourced regulating bodies basing new guidelines on older ones.[1] The original data set underlying the guidelines appears to have been based on adult men who had worked in noisy environments. It was not large or diverse enough to typify those most in need of protection from public exposure—the minority who are adversely affected. They cannot be treated as outliers.

For the general public, such guidelines are clearly inappropriate. Millions of people might pass through or work in a railway station each day. If even a minority of those people are sensitive to ultrasound, they could number in the tens of thousands.[1] Their ages, exposure times and frequencies, medical histories, and possible health deterioration cannot be followed, and hearing protection cannot be enforced. MPLs should therefore be more conservative for public exposure than for occupational exposure.

In 2004 the US Occupational Safety and Health Administration (OSHA) reduced the appropriateness of their own guidelines[9] by voting to adopt two specific measures recommended by manufacturers through the American Conference of Governmental Industrial Hygienists. In the first, the ACGIH recommended setting MPLs by considering only one adverse effect: hearing loss caused by the subharmonics of ultrasonic frequencies. But inducing hearing loss likely requires a higher sound pressure level (SPL) compared with other adverse effects, including those experienced by the students shown in figure 4. The guideline also excludes hearing loss caused by most of the incident energy because subharmonics are usually weak relative to the fundamental frequency. OSHA nevertheless adopted the recommendation, stating, "These recommended limits (set at the middle frequencies of the one-third octave bands from 10 kHz to 50 kHz) are designed to prevent possible hearing loss caused by the subharmonics of the set frequencies, rather than the ultrasonic sound itself."

Air versus water

The second OSHA resolution adopted directly from the ACGIH's recommendation draws on a physics argument. The national and international guideline on MPLs for occupational exposure above the 20 kHz TOB cluster around 110 dB re 20 μPa. OSHA's guideline states that the allowable limits could be increased by 30 dB, from 110 dB to 140 dB re 20 μPa, "when there is no possibility that the ultrasound can couple with the body by touching water or some other medium.”

The reasoning behind that 30 dB increase was not given, but further inquiry identified the following argument: If a plane acoustic wave in air (density ρ_1 and sound speed c_1) were normally incident on water (density ρ_2 and sound speed c_2), then the proportion T of the incident intensity that is transmitted can be calculated[10] using the formula

$$T = 1 - (\rho_2 c_2 - \rho_1 c_1)^2 / (\rho_2 c_2 + \rho_1 c_1)^2.$$

Substituting the properties of air ($\rho_1 = 1.225$ kg/m^3, $c_1 = 343$ m/s) and water ($\rho_2 = 1000$ kg/m^3, $c_2 = 1500$ m/s), which is commonly used as a first-order model for soft tissue, gives $T \approx 0.001$. That is to say, only 1/1000 of the incident intensity in air is transmitted into the soft tissue, which equates to a 30 dB attenuation.

OSHA’s second resolution only makes sense, however, if one assumes that the data informing the 110 dB re 20 µPa so-called consensus limit were taken with the transducer pressed against the subject’s head or with both the head and the transducer immersed in water. They were not: Both the transducer and the head were in air. By applying the 30 dB allowance in 2004, OSHA gave the US the most lenient MPLs in the world. OSHA recently removed explicit mention of the 30 dB allowance from its webpage.[1]

A similar argument has been taken further by some manufacturers. In the early to mid 2010s, the company uBeam raised investment by advertising a system whereby ultrasound in air would wirelessly recharge mobile phones and other devices in conference venues, airports, hospitals, and other public spaces. It was coy regarding frequencies and intensities, but when pressed on safety, the company placed the following assurance on its website: “The power levels beamed are more than 50 times lower than the lowest ultrasound imaging exposure limits set by the FDA for medical imaging, making the system inherently safe and within all existing regulatory constraints.”

Rather than considering the hazard from ultrasound in air, uBeam apparently relied on the Food and Drug Administration’s guidelines for 1–30 MHz ultrasound in soft tissue, such as the womb. But that limit is inappropriate. The primary concerns in fetal imaging—namely, potential cavitation and heating—are not relevant for airborne ultrasound at the levels used in public places. In fact, the only paper the company cites for powering devices by ultrasound has no air in the propagation path.[11]

Manufacturers and academics must be transparent in their calculations, especially when using decibels to compare intensities in air and water, which often introduces two common errors.[2] First, the decibel is not an absolute measure, and the SPL uses different reference levels in air (20 µPa) and water (1 µPa). Second, the factors $\rho_1 c_1$ and $\rho_2 c_2$ that are implicit in converting SPLs to intensities differ between air and water by a factor of around 3500. Failure to account for those differences has led to erroneous conclusions, such as the suggestion “that the sound of the penis of the 2 mm-long freshwater insect *Micronecta scholtzi* rubbing against its abdomen ‘reached 78.9 decibels, comparable to a passing freight train.’ ”[10]

Devices

Given the difficulties setting MPLs and measuring SPLs, it is hard to assess the safety of available ultrasound-producing devices. Data on SPL outputs are largely unavailable because manufacturers are not obligated to publish them. Even when measurements are made, standard procedures may be inadequate. Acoustic measurement standards require, for example, the use of an anechoic chamber that reduces acoustic reflections from the wall or mapping levels in a grid of 5 cm spacings.[8] To my knowledge, however, no chambers are certified as anechoic up to 30 kHz, and many ultrasonic sources have main beams too narrow to map[12] using spacings as large as 5 cm.

Scattering, the increased directionality of sound sources and detectors, and other complications with ultrasonic frequencies are not sufficiently accounted for when using protocols designed for lower frequencies. For decades, physicists and engineers have measured the outputs of devices such as pest deterrents. But when their measurements are cited, is it noted whether they used a class 1 sound level meter, the laboratory standard? And if a class 1 device was used, were the researchers aware

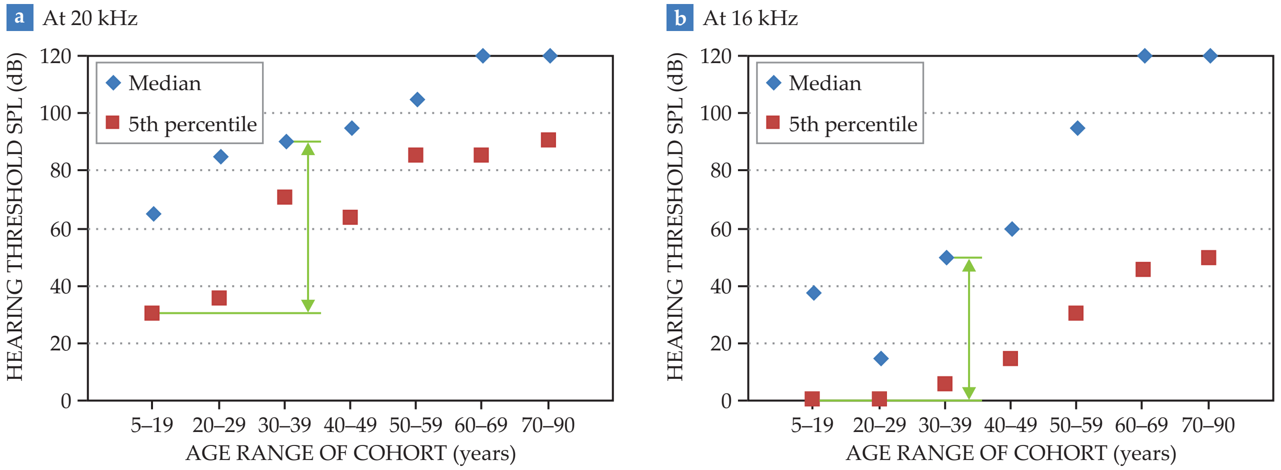

FIGURE 3. HEARING THRESHOLDS FOR PURE TONES. The median and fifth-percentile values based on 645 subjects are shown for **(a)** 20 kHz and **(b)** 16 kHz. The green arrows and lines indicate the difference between the median in the 30–39 age group and the fifth percentile in the 5–19 age group. Data at 0 dB and 120 dB are influenced by the instrumentation thresholds and saturation limits and so contribute less reliably to the statistics. All thresholds are sound pressure levels referenced to 20 µPa. (Data from ref. 4; figure adapted from ref. 1.)

FIGURE 4. LOCATING AN ULTRASOUND SOURCE IN A CLASSROOM. Some students in a classroom reported a persistent, high-pitched sound that was disrupting their work. But other students, teachers, and staff could not hear it. Sketches of photographs provided by the classroom teacher, Jill Zawatski, show the students who could detect the sound pointing to the location of the sound's source as they perceive it.

that although the device's standard performance acceptance limits are ±1 dB at 1 kHz, the limits in the 20 kHz TOB are +3 dB and $-\infty$ dB? That means that for frequencies above 17.8 kHz, the device could underestimate the SPL to any degree without notifying the operator. (The levels in figure 1 were taken, where possible, from recent papers that used traceable calibrations.)

Human experimentation

In laboratory experiments, my colleagues and I found that some individuals had adverse effects to ultrasound they could hear.[13] We observed no adverse effects when individuals were exposed to ultrasound they could not hear *at the levels and durations used*. The italicized phrase is important because otherwise, the finding—one of the few in the field—could be misinterpreted as reaffirming the yet-unproven proposition that people cannot be affected by ultrasound they cannot hear.

In our tests, the SPLs and durations were restricted by ethics guidelines: The inaudible ultrasound produced only marginal results that could not be further evaluated by increasing exposures. Indeed, they did not even reach the SPLs and durations that humans might experience in some public places.[1,6,14,15]

It is ironic that for $20, you can place a pest deterrent in your garden and expose your neighbor's children to significantly higher ultrasound levels than we could use in controlled laboratory tests on carefully monitored adults. In a Tokyo restaurant, a pest deterrent's 20 kHz ultrasonic field reached 120 dB re 20 μPa directly under the source and 90 dB re 20 μPa some 15 m away. In a survey of volunteers, 31 out of 35 said they could hear it. Some had strong responses, including "my head may split" and "I will never come here again because of the pain in the ear."[14]

Continuing research efforts have confirmed the presence of ultrasound in public places;[15] measured the outputs of commercial sources;[14–18] documented the effects on humans;[13,14,17] and improved calibrations, standards, and procedures. Public attention increased in 2017 with claims of an ultrasonic attack on US and Canadian embassy staff in Cuba, although experts (myself included) remain skeptical that ultrasonic waves were the culprit.[8] The difficulties in proving or disproving the Cuban incident and the anecdotal claims of adverse effects from airborne ultrasound in public spaces clearly illustrate the importance of further study despite the challenges posed when humans are the only contemporaneous sensors.

I am grateful to Erika Quaranta for undertaking all the modeling in figure 2 showing the interaction of sound and ultrasound with the pinna.

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