# Measurements of ultrasonic deterrents and an acoustically branded hairdryer: Ambiguities in guideline compliance

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Acoustic radiation from three commercial pest deterrents and two hair dryers were measured in an anechoic chamber. The deterrents were chosen because the frequency range at which they emit the most energy is either in the very high-frequency sound band (11.2–17.8 kHz) or the ultrasound band (greater than 17.8 kHz). These are sources that may be heard by a subset of the general population, with the young typically having better high frequency sensitivity. A hairdryer reported to increase the frequency of the motor noise above the audible hearing range was compared with a standard hairdryer. The outputs of the deterrents are compared against six international regulations and guidelines for audible and ultrasound exposure. Multiple ambiguities in the application of these guidelines are discussed. These ambiguities could lead to a device being considered as in compliance despite unconventionally high levels. Even if a device measured here meets a guideline, actual exposures can exceed those taken here and may therefore breach guidelines if the listener is closer to the device or reflections increase the exposure level. 
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## I. INTRODUCTION

The everyday use of ultrasound in air is on the increase.[1] Ultrasound is being proposed for purposes that range from turning your phone screen off when you answer a call (using an ultrasonic range sensor to determine proximity to the face),[2] to creating feedback for virtual keyboards,[3,4] to deterring pests.[5] In light of this expansion, there have been concerns over existing guidelines for public exposure to ultrasound.[6] Reports have claimed that very high frequency sound (VHFS) and low frequency ultrasound (US) may produce annoyance, dizziness, nausea, or hearing loss.[7–10]

Not only does the sensitivity of human hearing vary enormously between individuals,[11–13] but typical audiology practice[14] does not test frequencies higher than 8 kHz where this exposure is occurring. Many guidelines treat the highest region of audible sound and US as though they are distinct regions when they are in reality part of a continuum. Some sources operate simultaneously in both and the variation in hearing threshold across the population is so large that a single dividing frequency between the two is a product of the need for standards bodies to define remits.[6] Some people cannot hear anything above 8 kHz while others[15–17] still have significant sensitivity at 22 kHz. This study uses the definitions of VHFS and US proposed by Leighton.[1] The VHFS regime spans from 11.2 to 17.8 kHz and since [following Leighton (2016)][1] the maximum permissible levels (MPLs) for ultrasound cover tones that fall in the third-octave band centered (TOB) at 20 kHz, we here take "ultrasonic" to refer to any acoustic wave with a frequency of 17.8 kHz or greater. There is insufficient evidence for VHFS/US on how adverse symptoms are related to levels or durations of exposure.[1,18,19]

Knowing the safe levels and durations of exposure and knowing current practice go hand in hand. There is currently very little published information regarding the levels, frequencies of operation, and time domain characteristics of commercial pest deterrents. Ideally, researchers would have access to a large database of device levels including characteristics such as variability and directivity. Such measurements are difficult at high frequencies owing to the need to use instruments and facilities certified at those frequencies and the additional time and/or instrumentation required to map sound fields with small wavelengths. While future rigorous measurements conforming to international standards are necessary, it is hoped that the measurements presented here will, along with studies of similar type that look at controlled and *in situ* exposures,[20–22] allow an appreciation of

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the variety of output from VHFS/US sources. If these devices exceed exposure guidelines at any point then detailed studies need to be commissioned, otherwise ongoing deployment of those sources in public places could cause adverse effects. The measurements will be used to investigate device compliance with guidelines. They will also be used to highlight ambiguities that make the safety of devices difficult to assess.

It is important to ask, to what extent current measurement guidelines established as best-practice for measurements at voice frequencies become difficult or even unhelpful at ultrasonic frequencies in air. The first issue encountered when looking at standard measurement techniques is the qualification of an anechoic chambers between the desired frequency range. This is challenging[23] with respect to finding an omnidirectional source for the qualification measurements and the number of measurements required to ensure the complexity of the field is captured. Assuming the measurements desired are between the highest and lowest frequencies for which the chamber is qualified, then sound pressure levels (SPLs) can be used to estimate the sound power levels of the source. The current international standard for determining sound power levels of noise sources using SPLs in an anechoic chamber,[24] states that the procedure can be extended to frequencies between which the test room is qualified and gives no upper frequency limit for the technique. The microphone spacing specified, however, could completely miss the primary lobe of a high-frequency source. Using the 40 microphone option specified in Annex D of ISO 3745:2012, each microphone covers an average solid angle of $\pi/10 \approx 0.31$ sr. For example, a pest deterrent with a radiating element of 5 cm diameter operating at 25 kHz treated as a baffled piston would have a theoretical primary lobe with a half-power solid angle[25] of 0.25 sr. Therefore, the primary lobe could exist between measurement microphones. Denser arrays would be required to ensure VHFS/US sources are rigorously measured. Other regulations for the controlled measurement of sound power can not be extended to higher frequencies at all, such as the method for measuring sound power using intensity probes,[26,27] which does not cover frequencies higher than the 6.4 kHz TOB.

After considering the measurement methods available it is important to also draw distinctions between the different types of sources possible. Not all public exposure to VHFS and US is intentional. This distinction will be expressed by dividing sources into three main categories of: noise exposure, unintentional exposure, and deliberate exposure.[28] The three categories presented by Leighton[28] for ultrasound are here being generalized for both VHFS and US. Noise exposure occurs when a process or device generates sound as a by-product of its operation. Unintentional exposure occurs when a process requires the generation of a specific signal as critical to completing its task. Deliberate exposure occurs when a device is designed to specifically expose an animal or person to sound in air. This study presents a survey of six sources to which the public may be exposed, of which two fall in the noise exposure category and four fall in the deliberate exposure category. While sources classified as unintentional exposure are common in an industrial setting, the authors did not identify any sources from this category for testing.

The sources chosen in the study were a series of commercially available pest deterrents and two hairdryers. The pest deterrents are classified as deliberate exposure sources. The two other devices tested were an acoustically branded hairdryer and a standard hairdryer. Since advertisements state "By designing a motor impeller with 13 blades instead of the usual 11, Dyson engineers have pushed one tone within the motor to a sound frequency beyond the audible range for humans"[29] the amount of energy still present in the signal was of interest. The hairdryers are classified as noise exposure sources. Spot-checks of the SPL on-axis were conducted to determine if the device levels approached guideline limitations.

The relevant regulations and guidelines that might apply to these noise sources are discussed in Sec. II. The experimental methodology is presented in Sec. III. The results are outlined in Sec. IV and discussed individually in Sec. V. Concluding remarks are given in Sec. VI.

## II. CURRENT REGULATIONS AND GUIDELINES

Multiple reviews exist concerning the current regulations and guidelines for VHFS and US.[1,30] Here three guidelines targeted at audible noise and three targeted at ultrasonic exposure are considered for simplicity. These are the Occupational Safety and Health Administration (OSHA) regulations for noise,[31] the National Institute for Occupational Safety and Health (NIOSH) noise exposure guidelines,[32] the European Parliament (EP) directive on occupational noise exposure,[33] the OSHA recommendations for US,[31] and the interim guidelines for US exposure published by the International Non-Ionizing Radiation Committee of the International Radiation Protection Association (ICNIRP)[34] for continuous sources. The ICNIRP recommendations are separated into both occupational exposure and exposure of the general public whereas the rest are specifically for occupational exposure. Inherent ambiguities start to appear when looking at the filtering used to assess guideline compliance. The multiple methods for applying weightings, including the A, U, and Z weightings are discussed, along with the different application methods for determining TOBs.

The noise regulations given by OSHA state that hearing protection must be made available if workers are exposed to an 8-h A-weighted time weighted average (TWA) SPL of 85 dB (re: 20 $\mu$Pa, convention maintained throughout paper). The TWA is defined by OSHA and is a system of averaging exposure over a period of time (in this case 8 h). Exposure below a threshold level of 80 dB is ignored for this calculation. There is an exchange rate of 5 dB, which means if the level increases by 5 dB then the allowed time of exposure is halved. A worker exposed to an A-weighted SPL of 90 dB for four hours and then silence (or a level below the threshold of 80 dB) for four hours would still experience an 8-h TWA of 85 dB. For simplicity we will consider that the sources presented here are continuous exposures, even if some are unlikely to be so. The allowed exposure under the OSHA noise exposure regulations is an 8-h A-weighted TWA of 90 dB, which is equivalent to being exposed to an A-weighted 90 dB source for eight hours. Any higher exposure is in violation of the regulation.

Independent noise exposure guidelines are also issued by NIOSH. NIOSH recommends that the A-weighted 8-h TWA does not exceed 85 dB and has an exchange rate of 3 dB, meaning that the maximum exposure time for 88 dB is four hours. After four hours of exposure to an 88 dB level, the worker would have to be exposed to noise below 80 dB for the remainder of their shift or end their shift to comply with the guidelines.

The legislation passed by the European Parliament establishes three daily exposure levels: lower exposure action values, upper exposure action values, and exposure limit values. Each level specifies an A-weighted daily noise exposure level ($L_{EX,8h}$) as defined[35] by ISO 1999:2013. The levels at which an employer is not meeting their requirements for exposure is the upper exposure action value, which is $L_{EX,8h} = 85$ dB. This daily noise exposure level is effectively equivalent to the NIOSH recommendation.

For ultrasound OSHA uses the exposure guidelines presented in Table I, which are taken from an American Conference of Governmental Industrial Hygenists (ACGIH)[36] report. A Ceiling Value (CV) is defined as the "exposure limit that should not be exceeded even instantaneously"[36] and is elsewhere also known as a maximum permissible level (MPL). The level that should not be exceeded is the TOB level from a sound level meter set to slow detection, which means that levels are averaged over one second periods. For Table I the use of an A-weighting is not mentioned, so it is assumed that no weighting should be applied. This is supported by the fact that the A-weighting is not defined above the 20 kHz TOB.

As previously stated, these OSHA recommendations follow directly from a report published by the ACGIH.[36] The report states "These values assume that human coupling with water or other substrate exists. These thresholds may be raised by 30 dB when there is no possibility that the ultrasound can couple with the body by touching water or some other medium."[36] This has been interpreted as meaning, if someone was exposed to ultrasound and their head or body was directly coupled to the source through water or some other medium, the maximum permissible level should be 105 dB for the 20 kHz TOB and 110 dB for the 25 kHz TOB. The interpretation taken by many[30,37] goes on to assume that if no direct coupling other than air exists, the threshold level value may be increased by 30 dB. This approach has been criticized.[1,6,37] As of the latest version of the OSHA Technical Manual appendix on ultrasound published in 2015, the exception for a 30 dB increase is no longer mentioned.[31] For most of the world the acceptable workplace levels are limited to, or are lower than, an 8 h TWA of 110 dB for the 20–50 kHz TOBs. The evidence base for this consensus is slim.[1] A comprehensive list can be found in the 2016 review by Leighton.[1]

TABLE I. A selection of OSHA recommended ceiling values (CV) and 8-hour A-weighted time weighted averages (TWA) and ICNIRP recommended maximum 8-hour exposure values for occupational (occ.) and public (pub.) exposure.

| | OSHA (occ. only) | | ICNIRP | |
|---|---|---|---|---|
| TOB [kHz] | CV [dB] | TWA [dB] | Occ. [dB] | Pub. [dB] |
| 10 | 105 | 88 | — | — |
| 12.5 | 105 | 89 | — | — |
| 16 | 105 | 92 | — | — |
| 20 | 105 | 94 | 75 | 70 |
| 25 | 110 | — | 110 | 100 |
| 31.5 | 115 | — | 110 | 100 |
| 40 | 115 | — | 110 | 100 |

The guidelines published by ICNIRP are presented in Table I. The modification for exposures less than 8 h long is different from the TWA used by OSHA. For the ICNIRP recommendations the level my be increased by 9 dB if the exposure is less than 1 h, 6 dB if it is less than 2 h, and 3 dB if it is less than 4 h, which is equivalent to a 3 dB exchange rate, but applied over discrete time intervals.

All of these guidelines are affected by weighting functions, even if it is a flat-frequency weighting with rectangular cut-offs in the frequency domain. The Z-weighting is often used as a representation of the unweighted energy in an acoustic signal. According to Annex E of IEC 61672–1:2013, the Z-weighting is defined as "$Z(f) = 0$ dB" where $f$ is any frequency in the range of a sound level meter (SLM). This means that any citation of a Z-weighting could have a high-frequency cut-off at any frequency higher than 17.8 kHz (as class 1 SLMs are not required to be sensitive above that frequency). For this paper we will consider the Z-weighting with a rectangular cut-off in the frequency domain at the top of the 20 kHz TOB (Z-20) to be comparable with the A-weighting and another going up to the top of the 40 kHz TOB (Z-40) to represent the total energy. It was determined that higher harmonics of pest deterrents did not contribute to the total energy above the 40 kHz TOB. For the normal A-weighting, a rectangular filter in the frequency domain was also implemented at the top of the 20 kHz TOB as the A-weighting is not defined above that frequency.

Typical implementations of SLMs calculate filters and weightings in real time. As such, rectangular band-pass filters in the frequency domain are not possible. This means that above 17.8 kHz a variety of filters could be used to block higher-frequency energy. A version of such a filter for the measurement of audible sound in the presence of ultrasound is defined[38] by IEC 61012:1990. This standard defines a U-weighting that can be used as a separate accessory or built into conventional sound level meters. The SPL is cited as having an AU-weighting when the U-weighting is used in conjunction with an A-weighting. Part 1 of IEC 61672-1-2013 notes[39] that the AU frequency weighting can be applied for measurements of A-weighted sound levels of audible sound in the presence of a source that contains components at frequencies greater than 20 kHz. Therefore, if a source contains any components above 20 kHz then the AU-weighting can be substituted for the A-weighting. Since most tonal sources have harmonics, this definition could be applied to many cases. This could lead to a significant under-reporting of the SPL measured from a device. At

12.5 kHz the AU-weighting is −6.9 dB, at 16 kHz it is −20.2 dB, and at 20 kHz it is −34.8 dB. This means that a tonal source at 19.5 kHz could have a Z-20-weighted SPL of 123 dB and still comply with the OSHA regulations for workplace exposure. Of course, this then violates the OSHA guidelines for ultrasound exposure. The reduction in level above 12.5 kHz is so significant that it would be difficult to find a source above that frequency that would then violate the regulations designed for audible noise.

## III. EXPERIMENT

Acoustic measurements in the VHFS and US bands are complicated by several issues that are discussed in depth elsewhere.[1] As mentioned in Sec. I, a significant issue is that the very short wavelengths mean that the sound field is often complex and large amplitude variations occur over small distances.[40] Because this data set is meant to provide an illustration of the type and range of exposures the public can expect, neither the sound intensity nor a map the entire sound field were measured. Instead, spot checks were performed with the knowledge that if guideline levels are exceeded at any point then future detailed studies are required. The recordings were performed in an anechoic chamber at the Institution of Sound and Vibration Research. The chamber was commissioned to have free field radiation up to 20 kHz, where it is certified to a 1 dB tolerance. Anechoic behavior above that frequency can not be guaranteed. The mounting of devices introduces significant variation in exposure levels due to early reflection and interference patterns. An anechoic environment allows device levels to be measured in such a way that the environment is no longer a variable and measurements will be comparable with those performed in independent studies. It is important to note that *in situ* levels could exceed the levels measured here.

This data set was taken with a calibrated B&K type 4191 microphone with a type 2669 preamplifier, a type 2690 Nexus signal conditioner, and an National Instruments USB-6212 16-bit digital recording system with a sampling rate of 250 kHz. While the manufacturer calibration for the microphone only extends to 40 kHz, the microphone and preamplifier were calibrated from 20 to 50 kHz by the National Physical Laboratory (NPL). The calibration is traceable back to primary standards for VHFS/US at the NPL, and the Danish Fundamental Metrology A/S. For each measurement a calibration tone from a B&K type 4231 calibrator was recorded *in situ* to ensure the correct levels are reported. The relative humidity during the tests was $63 \pm 5\%$, the temperature $20.2 \pm 0.2\,°\mathrm{C}$, and the barometric pressure $99.45 \pm 0.01$ kPA. The attenuation in air for the signals in this study are estimated[41,42] to be less than 0.2 dB/m.

The deterrents were mounted on absorptive foam and the hairdryers on a microphone stand from behind. The devices were placed on foam to ensure reflections from the stand were not measured and anechoic conditions were maintained. For practical reasons the hairdryers were clamped to a microphone stand with foam around the clamp to reduce reflections and vibration radiating into the stand. Whilst in practice mounting pest deterrents on a wall will tend to increase levels over those measured in anechoic conditions, the complexities of the reflected field at such high frequencies mean that an anechoic mounting is an approach that assists other groups in replicating these studies. The pest deterrents in this study were measured at a distance of 1.7 m on axis with the speaker in front of the device, with the exception of the highest setting of the Balcony-Guard device, which was also measured at 1.1 and 2.5 m. A range of 1.7 m was chosen as a distance that was outside the near-field, could fit in the anechoic chamber, and at which a person might pass in front of a pest deterrent device and held constant. These locations are unlikely to be the most common exposure positions. Any *in situ* exposure would be affected by reflections from walls, floors, ceilings and other surfaces rendering the environment far from anechoic, therefore *in situ* measurements are an important compliment to those conducted here. The hairdryers were measured at a distance of 1.7 m from the handle grip for consistency. The expression $r > 2D^2/\lambda$, where $r$ is the distance from the source, $D$ the diameter of the source, and $\lambda$ the wavelength of the source, can be used to estimate where a $1/r$

TABLE II. Frequencies and levels of sources considered in this study for spot checks at 1.7 m. All devices without citations were measured by the authors in this study.

| Source | Peak [kHz] | TOB [kHz] | TOB SPL [dB] | Z-20 SPL [dB] | A SPL [dB] | U SPL [dB] | AU SPL [dB] | Z-40 SPL [dB] |
|---|---|---|---|---|---|---|---|---|
| BD Low | 16.1 | 16 | 84 | 84 | 77 | 70 | 63 | 84 |
| BD Mid | 19.8 | 20 | 92 | 92 | 83 | 68 | 59 | 93 |
| BD High | 26.8 | 25 | 97 | 42 | 39 | 56 | 44 | 97 |
| MD Set 1 | 17.0 | 16 | 84 | 84 | 77 | 69 | 62 | 84 |
| MD Set 2 | 19.7 | 20 | 80 | 84 | 76 | 67 | 60 | 84 |
| MD Set 3 | 20.0 | 20 | 83 | 83 | 73 | 57 | 48 | 83 |
| SD | 21.6 | 20 | 67 | 66 | 56 | 43 | 39 | 69 |
| TD (Ref. 44) | 17.0 | 16 | 108 | 108 | 101 | 91 | 84 | 108 |
| H 1 Set 1 | 1.5 | 2 | 39 | 47 | 47 | 47 | 47 | 48 |
| H 1 Set 2 | 1.8 | 2 | 57 | 61 | 62 | 61 | 62 | 61 |
| H 1 Set 3 | 1.8 | 2 | 55 | 60 | 61 | 60 | 61 | 60 |
| H 2 Set 1 | 17.0 | 16 | 55 | 67 | 53 | 66 | 51 | 67 |
| H 2 Set 2 | 19.2 | 20 | 52 | 70 | 53 | 70 | 53 | 70 |
| H 2 Set 3 | 23.9 | 25 | 47 | 77 | 56 | 77 | 56 | 77 |

TABLE III. Z-weighted TOB SPLs for spot checks at 1.7 m.

| Source | 12.5 kHz | 16 kHz | 20 kHz | 25 kHz | 31.5 kHz | 40 kHz |
|---|---|---|---|---|---|---|
| BD Low | 43 | 84 | 68 | 60 | 70 | 47 |
| BD Mid | 40 | 43 | 92 | 69 | 52 | 74 |
| BD High | 31 | 32 | 35 | 97 | 53 | 41 |
| MD Set 1 | 34 | 84 | 72 | 34 | 56 | 43 |
| MD Set 2 | 33 | 82 | 80 | 34 | 54 | 59 |
| MD Set 3 | 31 | 33 | 83 | 70 | 34 | 60 |
| SD | 30 | 31 | 67 | 66 | 57 | 47 |
| TD (Ref. 44) | ? | 108 | ? | ? | ? | ? |

geometrical pressure spreading law can be applied. For the deterrents, the conservative values of 10 cm for the horn diameter and $\lambda = 1.28$ cm for the wavelength of a 27 kHz frequency tone, radial spreading can be used at distances greater than 1.56 m. A geometrical spreading correction back to 1 m would increase the levels taken at 1.7 m by 4.6 dB. While a 1 m distance might not be in the far-field region, it is common to scale levels to 1 m for comparison. Here, we present the measured levels, but others may want to add 4.6 dB for comparable source levels.

The microphone was placed on axis with the presumed radiating element. The distance between the source and receiver was measured with a laser tape measure. It should also be noted that there are anecdotal suggestions that some pest deterrents suffer changes in level and frequency over a few hundred hours of use, however, there were insufficient resources to test for such instabilities in this study. A calibration tone was recorded at the beginning and end of each recording session. The calibration levels taken before and after sessions were in agreement within 0.02 dB.

The sources consisted of a bird deterrent (BD), a multifunction deterrent (MD), spider deterrent (SD), and two hairdryers (H1 & H2). The BD tested was a Balcony Guard produced by the company Bird-X, which has three settings: low, medium, and high. The advertised purpose is to be placed on balconies in yards to prevent birds from soiling or damaging property. The published specifications[43] are that the device produces a 90 dB acoustic signal in the frequency range 15–25 kHz. The MD also has three settings. While the documentation does not specify any acoustic levels, it does specify the frequency ranges of the three settings, which are 13.5–17.5 kHz, 15.5–19.5 kHz, and 19.5–23.5 kHz. The SD specification sheet indicates the product operates in the bandwidth 20–30 kHz, but did not specify an amplitude. There is published data for a teen deterrent (TD), which is a Mosquito device[44] manufactured by Compound Security Systems. While the manufacturer advertizes that the TD operates at volumes up to 108 dB at 8 or 17 kHz, there is no reference to the distance at which this level is measured. In addition, the advertisement claims that the device operates at a range of 35 to 40 m, but does state the levels within this distance range. Neither hairdryer had published noise exposure levels. The standard hairdyer is referred to as H 1 and the acoustically branded hairdryer as H 2.

## IV. RESULTS

A summary of the analysis is provided in Table II. The auto-spectral density was calculated for each time series. The period of analysis was chosen to be a segment of at least 5 s and was chosen differently depending if the source was constant or intermittent. A description of the analysis period for each source is discussed in Sec. V. The sampling frequency for all sources was 250 kHz. The single sided auto-spectral density (ASD), $S_{xx}(f)$, was calculated using block sizes of 16 384 and a hanning window. This means at least 75 blocks of data were averaged for each ASD. For each source the highest energy tone in the ASD is noted, along with the Z-weighted SPL of the TOB it occurs in, the Z-weighted overall SPL, the A-weighted SPL, and an extended SPL that is inclusive of ultrasonic frequencies up to 44 670 Hz (the upper boundary of the 40 kHz TOB). The A-weighting curve, $A(f)$, is defined[39] by IEC 61672-1 and applies to energy in the 10–20 kHz TOBs, effectively from 8.9 Hz to 22 390 Hz. The A-weighted SPL (A SPL) is calculated by applying the A-weighting to the ASD and integrating from 8.9 Hz to 22 390 Hz as shown in Eq. (1),

$$\mathrm{SPL} = 10\log_{10}\left(\frac{\left(\int_{8.9}^{f_{\mathrm{high}}} S_{xx}(f)10^{(W(f)/20)}\mathrm{d}f\right)}{p_{\mathrm{ref}}^2}\right), \qquad (1)$$

TABLE IV. Compliance (✓) or failure (×) of the spot checks of sources to various regulations and guidelines for continual exposure. (*) This setting passes all guidelines since the primary tone is in the 25 kHz TOB. Had the tone fallen into the 20 kHz TOB it would not have passed any of the guidelines. (N/A) The bandwidth of this source lies outside the remit of the specific regulation/recommendation. Shaded columns are for occupational exposure, the unshaded column is for public exposure.

| | A-weighting | | AU-weighting | | | | |
|---|---|---|---|---|---|---|---|
| Source | OSHA Noise | NIOSH & EP | OSHA Noise | NIOSH & EP | OSHA US | ICNIRP Occ. | ICNIRP Pub. |
| BD Low | ✓ | ✓ | ✓ | ✓ | ✓ | N/A | N/A |
| BD Med | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| BD High | N/A | N/A | N/A | N/A | * | * | * |
| MD Set 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × |
| MD Set 2 | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| MD Set 3 | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| SD | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| TD (Ref. 44) | × | × | ✓ | ✓ | × | N/A | N/A |

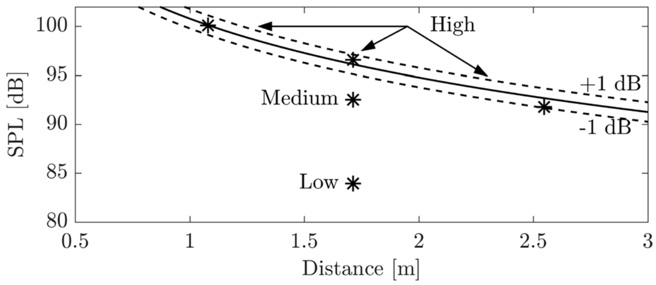


FIG. 1. Z-40-Weighted SPL of the Balcony Guard for three settings at one distance and three distances at the high setting. The solid line is a best-fit assuming spherical spreading. The ±1 dB dashed lines show that the three distances fall within that bound.

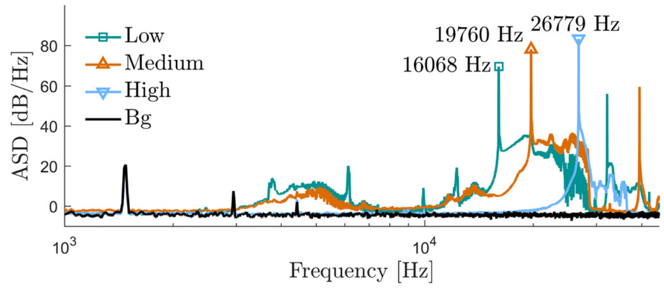


FIG. 3. (Color online) Autospectral Density of the Balcony Guard on the low, medium, and high settings along with the background noise floor (Bg) of the measurements. The highest amplitude tones are marked and labeled with the frequency at which they occurs.

where $W(f)$ is the A-weighting function in dB, $f_{high} = 22\,390$, and $p_{ref}$ is the 20 $\mu$Pa reference pressure mentioned in Sec. II. An A-weighting could alternatively be applied to the integrated TOBs or implemented in the time domain. An implementation of the A-weighting to the TOBs, however, could differ greatly because of the narrow band nature of the noise and the larger size of the high-frequency TOBs.

The Z-weighting means that no gain is applied. Two implementations of the Z-weighting were calculated. For Z-20 the signal and the ASD is integrated from 8.9 to 22 390 Hz, which is equivalent to Eq. (1) with $W(f) = 0$ and $f_{high} = 22\,390$. For Z-40 is an integration of the ASD from 8.9 Hz through 44 670 Hz, given by Eq. (1) with $f_{high} = 44\,670$ and $W(f)$ set to zero. The Z-weighted TOB SPLs are presented in Table III.

The U and AU-Weighting were applied in the same way as the other weightings. The U-weighting curve, $U(f)$, is defined[38] by IEC 61012 and applies to energy in the 10 Hz–40 kHz TOBs. For the U/AU-weighted SPLs the upper integration constant of Eq. (1) was $f_{high} = 44\,670$ and $W(f)$ was $U(f)$ and $U(f) + A(f)$, respectively. The relations for $A(f)$ were extrapolated to higher frequencies using the equations that define it up to the 20 kHz TOB.

All entries are from data taken by the authors except for the Mosquito device, whose levels were taken from the manufacturer's specifications.[44] This device was beyond our research budget limits and therefore could not be obtained for direct measurement.

The compliance of the sources to the regulations and guidelines discussed in Sec. II assuming the respective measurement distances are shown in Table IV. Again, the assumption is made that the exposure would be continuous as actual behavior near these sources is unknown. The placement and directivity of the device will also greatly affect the *in situ* exposure levels.

## V. DISCUSSION

The BD emits a primary tone and harmonics that do not vary during each activation of the device. The operating frequencies for the low, medium, and high modes were 16.1, 19.8, and 26.8 kHz, respectively. The Z-40-weighted SPL for the low, medium, and high modes were 84, 93, and 97 dB, respectively, which puts the levels for the two highest settings above the published value. The product documentation made no indication of what weighting or frequency range was used. The device levels were measured at two additional distances for the highest setting, as shown in Fig. 1. The three data points fall within ± 1 dB of the $1/r$ pressure spreading rule mentioned in Sec. III. A transient signal accompanies the start and end of the continuous signal, which is visible in the signal envelope presented in Fig. 2. This transient is broadband and similar in amplitude to the tonal signal on the highest setting. The transient does not contribute significantly to the US energy. The device is triggered by an integrated motion sensor and there is no direct way to control the length of the tone emitted. The autospectral densities of the signal produced when the device is on the low, medium and high settings at 1.7 m are shown in Fig. 3. Figure 3 also shows a background spectrum taken during the tests. Three background tones were found to be

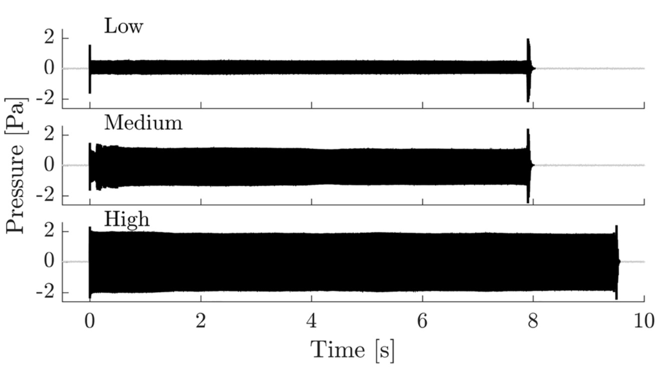


FIG. 2. Time series showing the signal envelope of the Balcony Guard on the low, medium, and high settings. Analysis period in black.

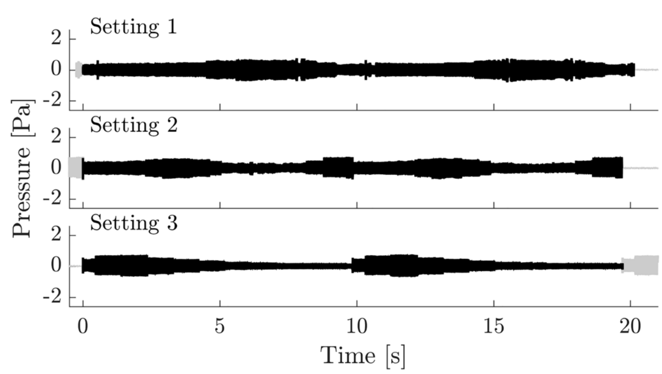


FIG. 4. Time series showing the signal envelope of the multipurpose pest deterrent on the settings 1, 2, and 3. Analysis period in black.

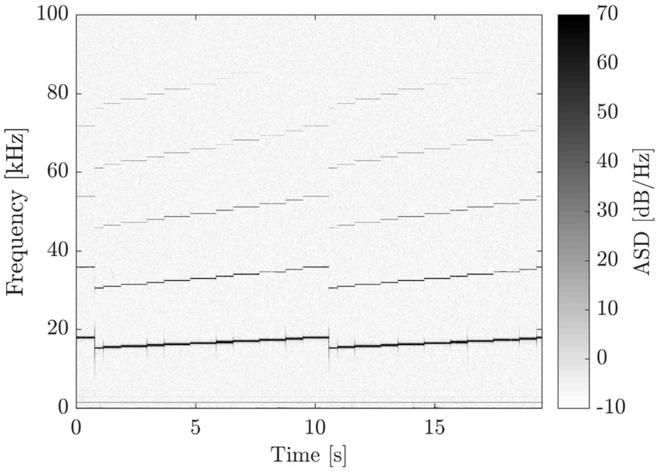


FIG. 5. Spectrogram of the multipurpose pest deterrent on the first setting.

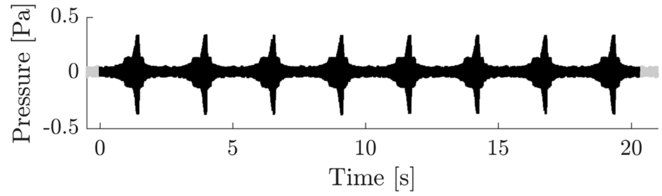


FIG. 7. Time series showing the signal envelope of the SD. Analysis period in black.

present in the anechoic chamber at 1.4, 2.9, and 4.4 kHz, but their amplitudes were lower than the sources of interest. The OSHA guidelines for audible sound recommend hearing intervention if sources have sustained A-weighted levels above 90 dB. On the highest setting the spot checks of the BD were well below those guidelines because the primary tone is in the 25 kHz TOB. On the medium setting the device does not exceed the A-weighted 90 dB threshold, despite the unweighted SPL being above 90 dB in the 20 kHz TOB. The medium setting fails both ICNIRP guidelines and the lowest setting complies with all applicable recommendations.

The multipurpose deterrent (MD) cycles through a series of tones and had three nondescript settings. Like the BD it is activated by a motion sensor. The envelope of the time series for the three settings at 1.7 m are shown in Fig. 4. Each cycle was approximately ten seconds long. The analysis period covered two cycles of the device on each setting. The signal is harmonic and steps through frequencies in a narrow range. The frequency stepping, variable amplitude of tones, and rate of modulation is visible in Fig. 5, which shows the spectrogram of the signal produced when the device is on setting 1. The ASDs for the three settings are shown in Fig. 6. The actual bandwidths of the three settings are 15.2–18 kHz, 15.2–20.2 kHz, and 19.2–23.8 kHz. The ASDs reveal that setting 1 and 2 have the same lower start frequency, but setting 2 has a larger overall bandwidth. At 1.7 m the device complies with all the OSHA recommendations, but the only ICNIRP guideline passed was for occupational exposure on setting number one.

The SD was the quietest of the sources tested. The product specification sheet indicates the product operates in the bandwidth 20–30 kHz, but did not specify an amplitude. The results show a sweeping tone between 21.6 and 36.3 kHz with a repetition period of approximately 2.5 s. The envelope of the time series of the device is shown in Fig. 7. Unlike the multipurpose deterrent which cycled through discrete tones the SD cycled smoothly through the frequency band of operation. The ASD of the device is shown in Fig. 8. As the quietest device, the three background tones at 1.4, 2.9, and 4.4 kHz are prominent in the ASD and are not part of the pest deterrent signal. A background recording is shown in Fig. 3 that shows these peaks when all other sources are off. The SD was the only device to fall under and pass all guidelines at 1.7 m under the mounting conditions used in this test.

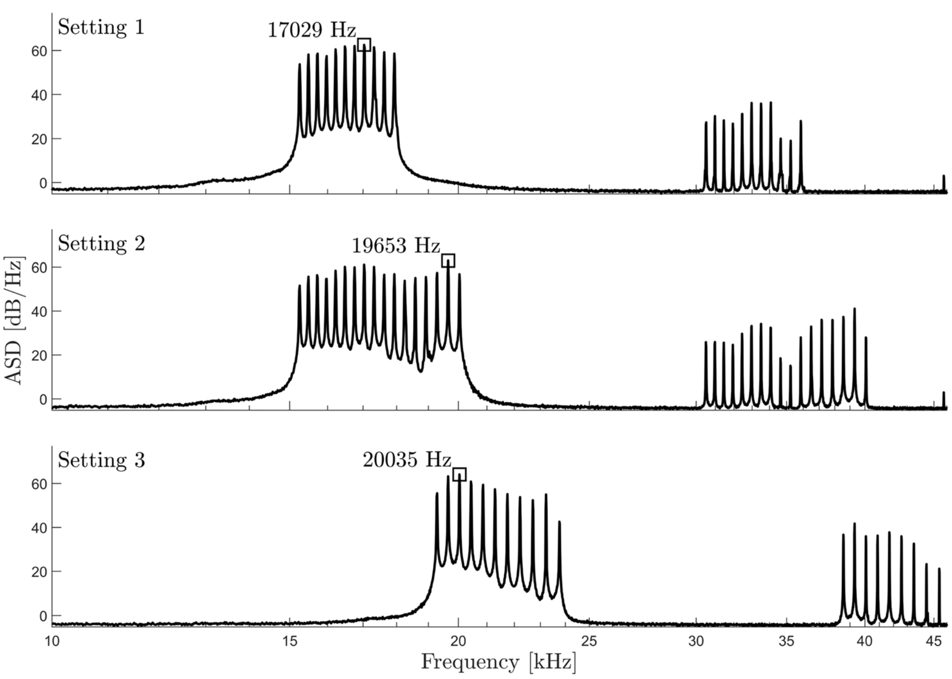


FIG. 6. ASD for each setting of the multipurpose pest deterrent. The highest amplitude tone is marked with an asterisk and labeled with the frequency at which it occurs.

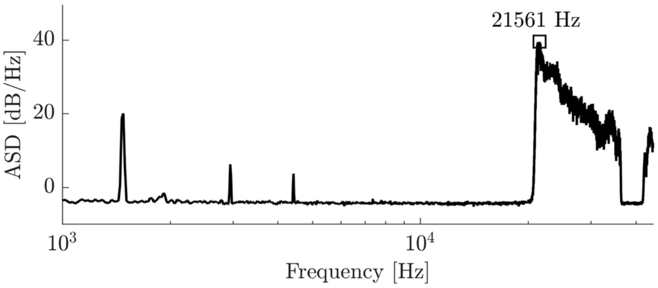


FIG. 8. ASD for the SD. The highest amplitude is marked with as square and labeled with the frequency at which it occurs.

The last remaining deliberate exposure sources is the TD Mosquito device. As a consequence of the frequency of the output, the Mosquito device does not fall under the ICNIRP guidelines. It fails both the OSHA regulations for noise exposure and the OSHA recommendations for ultrasound exposure. Despite that, if the device had a harmonic above 20 kHz it could be evaluated under an AU-weighting which would allow it to pass all the audible noise regulations and guidelines.

The two hairdryers were chosen because of the claim[29] that a tone within the motor was at a frequency above the audible range in a recent device. The first hairdryer, subsequently referred to as "hairdryer 1," was made by Remington. The second hair dryer, subsequently referred to as "hairdryer 2," was a Dyson HD01 Supersonic hairdryer. While typical use of a hairdryer would place it within 1 meter of the head, the measurements presented here were taken 1.7 m from the handle to place the measurement in the far field and allow comparison with the pest deterrents. Measurements were taken with and without a wind-screen on the microphone. For the data presented here the wind-screen was in place as the reduction of flow noise was deemed more important than any possible high frequency attenuation that could have resulted from the windscreen use. Manufacturer supplied charts indicate that the wind screen may cause measurements to be underestimated by 1.4 dB at 20 kHz, but do not provide corrections for higher frequencies. The measurements were taken on axis with the nozzle. The ASDs of both hairdryers on their third settings are shown in Fig. 9. The tonal energy is at a much higher frequency for hairdryer 2. A comparison between the three settings on the hairdryers is presented in Fig. 10. The broadband noise of the devices are prominent above 300 Hz.

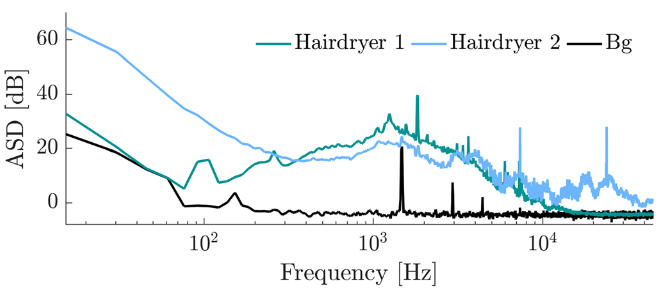


FIG. 9. (Color online) Autospectral density of the hairdryers on the highest setting.

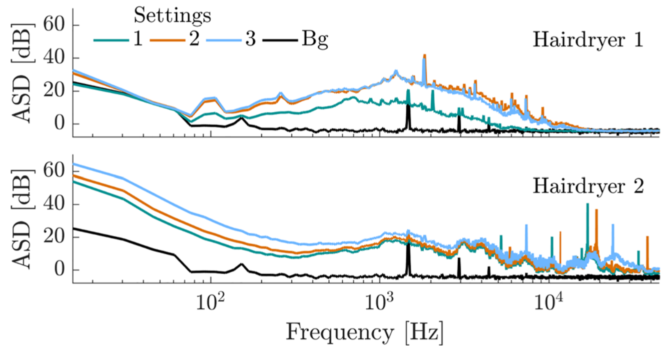


FIG. 10. (Color online) Autospectral density of the two hairdryers on three setting.

Ignoring tones, between 300 Hz and 3.5 kHz hairdryer 1 has higher broadband noise. Above 3.5 kHz hairdryer 2 has higher broadband noise levels. At setting three the largest tonal noise for hairdryer 2 is at 23.9 kHz. At a 25 kHZ TOB SPL of 46.9 dB this tone is still well below the reported minimum threshold value for detecting a 20 kHz signal.[16] All tones measured from the device on-axis had TOB SPLs below 56 dB. Figure 11 provides a directivity of hairdryer 2 on setting 3 showing the extended SPL along with the two TOBs with prominent tones taken at 5° increments. For the vertical directivity, the microphone was pointed to the center of rotation on the handle rather than along the axis of the nozzle. Of the off-axis positions measured, the 25 kHz tone goes as high as 76 dB. While the amplitude of the tones increase off-axis, they do not increase enough to violate any of the exposure guidelines for a listener placed 1.7 m from the hairdryer.

## VI. CONCLUSION

The acoustic output for several sources that output energy in VHFS and US bands were measured. The anechoic measurements revealed that, at certain settings, the pest deterrent devices output levels that are too high for continual use in a work or public environment according to international guidelines even in the nominally anechoic test settings at a range of 1.7 m.[34]

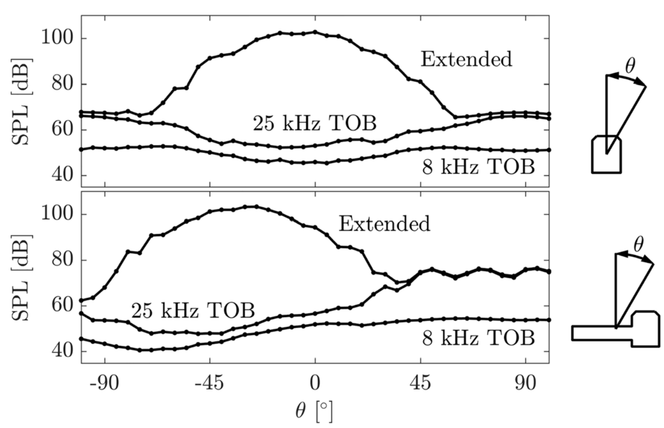


FIG. 11. Directivity of hairdryer 2 taken at 5° increments for the extended SPL and the TOBs of the two prominent tones: Top—horizontal directivity, Bottom—vertical directivity.

The levels measured from commercial pest deterrents seem to justify concern over public exposure to devices operating in the VHFS or US bands. Since the guidelines in question are themselves "interim" there is insufficient information to determine whether the devices pose a threat to public health.[1] As these guidelines are being exceeded by commercially available units and the data set underlying safety guidelines is minimal,[1] it is recommended that future research focus on the annoying and possibly damaging effects of VHFS and US deterrent devices. Care needs to be taken that the precise weighting used, including high-frequency cutoffs, are reported for all measurements. This study did not conduct measurements off-axis and as such it is possible that higher levels may be produced. It is recommended that future research look at the directivity of these types of sources. Many laboratories are limited in their testing resources in the US band and may need to invest in new equipment. In order to properly characterize these sources, laboratories need microphones capable of resolving these high-frequencies, positioning systems capable of mapping sound fields at sub-wavelength resolution, and facilities certified for the band.

Given the propensity for ultrasonic signals to scatter, consideration must also be given to the mounting and room in which the measurements are made; whilst anechoic conditions are favored to give reproducible tests free of artifacts, *in situ* exposures might be critically influenced by such artifacts (pest deterrents mounted against a concrete wall, for example, potentially doubling the exposure levels). Realistic ranges should also be considered. While a uniform 1.7 m on-axis test range was used here, in practice the exposure position for pest deterrents might be further away, and for hairdryers might be considerably closer to the source, and often none of these exposures will be on-axis *in situ*. The case of the hairdryer illustrates that, for a given device, there may be multiple considerations: if used in a professional salon, the hairdresser might get many hours of exposures every working day, at a range of 50 cm and from behind the device, and be subject to occupational guidelines; in contrast, the customer would be subject to public exposure guidelines, and in the salon receive a shorter exposure from in front of the device at a range of 15 cm once every few weeks (but may receive additional exposures from a similar hairdryer at home).

As a consequence of the variation in hearing threshold discussed in Sec. I, a member of the public might or might not be aware of their exposure. If they are able to hear the source, it may be inaudible to an authority figure to which the source is reported. Further, class 1 SLMs have acceptance limits[38] of $+3$ dB to $-\infty$ dB in the 20 kHz TOB so a person with certified acoustic measurement equipment may indicate that no problem is present. Therefore, the complaints by individuals who suffer from exposure may be dismissed by those in authority. Further research and public awareness can help resolve such problems.

Ideally these measurements would have been compared against those published by manufacturers. Except for the levels cited in this paper, manufacturers published frequency information and omitted amplitude measurements. Leighton[1] recommended that "Manufacturers should provide: a statement of the source level and spectral content (measured using international standard procedures and calibrations traceable back to primary standards) of the output of VHF/US emitters if above a yet-to-be-determined spectral level; a statement of the purpose of the sound; and an assessment of the levels when deployed in the field." In order for reliable comparison all measurements must state the type and values of the low-pass filter used. The weighting must be explicitly stated. The U and AU-weightings must not be used for VHFS/US sources. Allowing the use of these weightings would allow devices to pass guidelines by adding energy to their signals.

## VII. DATA ACCESSIBILITY

All data supporting this study are openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D0190.


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[1]T. G. Leighton, "Are some people suffering as a result of increasing mass exposure of the public to ultrasound in air?," Proc. R. Soc. London A **472**, 20150624 (2016).

[2]ellipticlabs products, http://www.ellipticlabs.com/products/ (Last viewed 20 July 2017).

[3]G. Wilson, T. Carter, S. Subramanian, and S. A. Brewster, "Perception of ultrasonic haptic feedback on the hand: Localisation and apparent motion," in *Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems* (ACM, Toronto, Ontario, Canada), 1133–1142 (2014).

[4]T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, "UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces," in *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (ACM, St. Andrews, Scotland, UK), 505–514 (2013).

[5]S. Jenni-Eiermann, D. Heynen, and M. Schaub, "Effect of an ultrasonic device on the behaviour and the stress hormone corticosterone in feral pigeons," J. Pest Sci. **87**, 315–322 (2014).

[6]T. G. Leighton, "Comment on 'Are some people suffering as a result of increasing mass exposure of the public to ultrasound in air?,' " Proc. R. Soc. London A **473**, 2060828 (2017).

[7]M. D. Fletcher, S. Lloyd Jones, P. R. White, C. N. Dolder, T. G. Leighton, and B. Lineton, "Effects of very high-frequency sound and ultrasound on humans. Part I: Adverse symptoms after exposure to audible very-high frequency sound," J. Acoust. Soc. Am. **144**(4), 2511–2520 (2018).

[8]W. I. Acton and M. B. Carson, "Auditory and subjective effects of airborne noise from industrial ultrasonic sources," Br. J. Ind. Med. **24**, 297–304 (1967).

[9]C. P. Skillern, "Human response to measured sound pressure levels from ultrasonic devices," AIHA J. **26**, 132–136 (1965).

[10]B. A. Herman and D. Powell, "Airborne ultrasound: Measurement and possible adverse effects," *US Department of Health and Human Resources, HHS Publication (FDA)*, No. 81-8163 (1981), pp. 1–12.

[11]A. Rodriguez Valentine, A. Trinidad, J. R. Garcia Berrocal, C. Gorriz, and R. Ramirez Camacho, "Extended high-frequency (9–20 kHz) audiometry reference thresholds in 645 healthy subjects," Int. J. Audiol. **53**, 531–545 (2014).

[12]P. G. Stelmachowicz, K. A. Beauchaine, A. Kalberer, and W. Jesteadt, "Normative thresholds in the 8- to 20-kHz range as a function of age," J. Acoust. Soc. Am. **86**, 1384–1391 (1989).
[13]D. M. Green, Gerald Kidd, Jr., and K. N. Stevens, "High-frequency audiometric assessment of a young adult population," J. Acoust. Soc. Am. **81**, 485–494 (1987).
[14]D. Moore, L. Hunter, and K. Munro, "Benefits of extended high-frequency audiometry for everyone," Hear J. **70**, 50–52 (2017).
[15]K. Ashihara, K. Kurakata, T. Mizunami, and K. Matsushita, "Hearing threshold for pure tones above 20 kHz," Acoust. Sci. Technol. **27**, 12–19 (2006).
[16]K. Ashihara, "Hearing thresholds for pure tones above 16 kHz (2007)," J. Acoust. Soc. Am. **112**, 52–57 (2007).
[17]K. R. Henry and G. A. Fast, "Ultrahigh-frequency auditory thresholds in young adults: Reliable responses up to 24 kHz with a quasi-free-field technique," Audiology **23**, 477–489 (1984).
[18]M. D. Fletcher, S. Lloyd Jones, P. R. White, C. N. Dolder, T. G. Leighton, and B. Lineton, "Effects of very high-frequency sound and ultrasound on humans. Part II: A double-blind randomized provocation study of inaudible 20-kHz ultrasound," J. Acoust. Soc. Am. **144**(4), 2521–2531 (2018).
[19]B. W. Lawton, "Exposure limits for airborne sound of very high frequency and ultrasonic frequency," ISVR Technical Report No. 224, University of Southampton, Southampton, UK (2013), pp. 1–16.
[20]M. Ueda, A. Ota, and H. Takahashi, "Investigation on high-frequency noise in public space," in *Inter.noise 2014*, Melbourne, Australia (2014).
[21]P. Mapp, "Ultrasonic surveillance monitoring of PA systems, A safety feature of audible hazzard?," Proc. IOA **38**, 1–16 (2016).
[22]M. D. Fletcher, S. Lloyd Jones, P. R. White, C. N. Dolder, B. Lineton, and T. G. Leighton, "Public exposure to ultrasound and very high-frequency sound in air," J. Acoust. Soc. Am. **144**(4), 2554–2564 (2018).
[23]T. Jenny and B. E. Anderson, "Ultrasonic anechoic chamber qualification: Accounting for atmospheric absorption and transducer directivity," J. Acoust. Soc. Am. **130**, EL69–EL75 (2011).
[24]ISO, 3745:2012: *Acoustics—Determination of Sound Power Levels and Sound Energy Levels of Noise Sources Using Sound Pressure—Precision Methods for Anechoic Rooms and Hemi-Anechoic Rooms* (International Organization of Standards, Geneva, Switzerland, 2012).
[25]D. T. Blackstock, "Radiation from a baffled piston," in *Fundamentals of Physical Acoustics* (Wiley, New York, 2000), p. 451.
[26]ISO, 9614-1:2009: *Acoustics—Determination of Sound Power Levels of Noise Sources using Sound Intensity Part 1: Measurement at Discrete Points* (International Organization of Standards, Geneva, Switzerland, 2012).
[27]ISO, 9614-3:2009: *Acoustics—Determination of sound Power Levels of Noise Sources Using Sound Intensity Part 3: Precision Method for Measurement by Scanning* (International Organization of Standards Geneva, Switzerland, 2009).
[28]T. G. Leighton, "What is ultrasound?," Prog. Biophys. Mol. Biol. **91**, 3–83 (2007).
[29]Dyson, "Technology | Dyson Supersonic™ Hair Dryer," https://www.dyson.co.uk/hair-care/dyson-supersonic-technology.html (Last viewed 13 January 2018).
[30]M. L. Lenhardt, "Airborne ultrasonic standards for hearing protection," in *9th International Congress on Noise as a Public Health Problem (ICBEN)* (2008).
[31]OSHA, "OSHA technical manual, Section III: Chapter 5—Noise measurement," U.S. Department of Labor, Occupational Safety and Health Administration (2015).
[32]NIOSH, "Criteria for a recommended standard: Occupational noise exposure," U.S. Department of health and human services, Centers for Disease Control and Prevention, Publication No. 98-126 (1998).
[33]European Parliament, "Directive 2003/10/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)," European Agency for Safety and Health at Work (2003).
[34]ICNIRP, "Interim guidelines on limits of human exposure to airborne ultrasound," Health Phys. **46**, 969–974 (1984).
[35]ISO 1999:2013: *Acoustics—Estimation of Noise-Induced Hearing Loss* (International Organization of Standards, Geneva, Switzerland, 2013).
[36]ACGIH, "ACGIH threshold limit values (TLVs) and biological exposure indices (BEIs)," *American Conference of Governmental Industrial Hygienists (ACGIH)*, Cincinnati, OH (2012).
[37]C. Q. Howard, C. H. Hansen, and A. C. Zander, "A review of current airborne ultrasound exposure limits," J. Occup. Health Saf. Aust. New Zealand **21**, 253–257 (2005).
[38]British Standards Institution, BS EN 61012-1998: *Filters for the Measurement of Audible Sound in the Presence of Ultrasound* (1998).
[39]British Standards Institution, BS EN 61672-1: *Electroacoustics—Sound Level Meters Part 1: Specifications* (2013).
[40]M. R. Stinson and B. W. Lawton, "Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution," J. Acoust. Soc. Am. **85**, 2492–2503 (1989).
[41]H. E. Bass, L. C. Sutherland, A. J. Zuckerwar, D. T. Blackstock, and D. M. Hester, "Atmospheric absorption of sound: Further developments," J. Acoust. Soc. Am. **97**, 680–683 (1995).
[42]H. E. Bass, L. C. Sutherland, A. J. Zuckerwar, D. T. Blackstock, and D. M. Hester, "Erratum: Atmospheric absorption of sound: Further developments," J. Acoust. Soc. Am. **99**, 1259–1259 (1998).
[43]Balcony Guard product page https://bird-x.com/bird-products/electronic/ultrasonic/balcony-gard/ (Last viewed 5 January 2018).
[44]Mosquito mk4 product page, https://www.compoundsecurity.co.uk/security-equipment-mosquito-mk4-anti-loitering-device (Last viewed 29 July 2017).