Guest editorial:

# Ultrasound in Air – guidelines, applications, public exposures and claims of attacks in Cuba and China

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## Abstract

This editorial introduces a Special Issue of the Journal of the Acoustical Society of America, on 'Ultrasound in Air'.

In this Special Issue, one paper covers ways of categorizing the ultrasonic regimes, and three papers cover human effects. One of those three, plus five others, constitute the six papers that report on the measured outputs of commercial devices. Two cover calibration, and the final three papers cover novel applications.

This editorial outlines the context in which these papers provide individual studies, including the development of technology and guidelines for safe exposure, and ending with an analysis of what is currently known about claims of sonic attacks on embassy staff in Cuba and China.

## I. Introduction

We are currently in the undesirable situation where a member of the public can purchase a $20 device that can be used to expose another human to SPLs that are >50 dB in excess of the Maximum Permissible Levels (MPLs) for public exposure[1-3]. Furthermore, there are also genuine questions regarding whether those MPLs are too permissive, particularly with regards to exposure of young people. When establishing those MPLs no data from young people was included. However, we know young people tend to have greater auditory acuity to low frequency ultrasound[4,5]. If this enhanced acuity were to correlate with an increased potential for adverse effects (this editorial will use this as a working hypothesis in the absence of direct evidence either way), then failure to include data from young people in setting MPLs could permit public exposures that generate adverse effects in the young. Data to improve the guideline MPLs are extremely difficult to obtain, because of: (i) the lack of appropriate observational/epidemiological data; (ii) the severe ethical questions that experimental studies involving human exposure would raise; (iii) the lack of calibration procedures for instrumentation and standardised measurement protocols; (iv) experimental difficulties that make transposition of some audio-frequency practices difficult; and (iv) the scarcity of accessible calibrated equipment and facilities for working in the low ultrasonic regime in air.

The increasing importance of ultrasound in air arises because the number of devices that expose members of the public (of all ages) to ultrasound in air (often tonal ultrasound) is increasing rapidly, at a rate that outpaces the guidelines[1]. Crucially, those guidelines were overwhelmingly based on small samples of adult males and designed to control occupational exposures. Occupational exposures differ from public exposures in that they occur in a workplace setting where (in principle) the subjects and their health histories can be known and monitored, the exposure levels (both instantaneous and cumulative) and duration can be measured, and protective measures can be put in place[1, 6]. Following the procedure used for noise exposure at hearing frequencies, the guidelines for ultrasound in air are expressed in terms of MPLs for third octave bands, which may not always be appropriate for tonal ultrasonic exposures[1].

Public exposure is particularly problematic because, unlike normal occupational exposure, the person deploying the device has no knowledge of the person who will be exposed as a consequence of the use of the device. Such ignorance covers age, medical history, duration of exposure and of any 'rest periods' between exposures. Furthermore, the person who is exposed may not know that this is occurring, and so cannot protect themselves (by moving away, wearing hearing protection, limiting exposure etc.)[1]. This is particularly important in a case like this, where many of the most at-risk individuals (children, some of whom will perceive the exposure) are expected to obey the directions of the adult in whose care they are (who in many cases will not be aware that an exposure is occurring).

Only one MPL for public exposure to ultrasound in air has ever been issued, in 1984, and that level was explicitly entitled as 'interim' because of lack of data[6]. It is based on subtracting a 'guestimate' 30 dB safety margin difference from the workplace MPLs (which, as stated above, are based on insufficient data) for the following reason:

> '*noting that the general population can potentially be exposed 24 hours per day and for the other considerations noted above, an added safety factor should be incorporated, at least as an interim measure until more definite data on adverse health effects of exposure to airborne ultrasound become available*'[6].

(Ironically, as will be shown below, some vendors of equipment that expose the public to ultrasound cite OSHA guidelines as allowing them to add, not subtract, 30 dB to the occupational exposures used in other countries[1,7-9]).

The '*more definite data*' mentioned in the above quote are now becoming available, although gathering it is a very difficult matter, for reasons explained in Section III. Nevertheless, it is vital that such data are obtained so that guidelines for MPLs can be based on evidence, to protect manufacturers, the public, employees and those deploying devices that emit ultrasound in air. Without such protection, the benefits of new technology will be compromised.

Most bodies setting guidelines for ultrasound have stated that the lower limit of the ultrasonic frequency band is 20 kHz. This is untenable[10], because by expressing MPLs in third octave bands, the national and international bodies who have issued guidance have (apparently without realising it) set MPLs down to 17.8 kHz (or thereabouts[11]), because the lower limit of the third octave band centered on 20 kHz is close to 17.8 kHz. ICNIRP's charter[12] separates its remit from the audiofrequency regime (that it must not cover), by setting a lower limit of 20 kHz for the ultrasonic range, and by doing so ensures that its MPLs extend down to 17.8 kHz. In the face of this contradiction, for the purpose of this Special Issue the lower limit of the ultrasonic range will be 17.8 kHz, and this author recommends[10] that, if a single frequency must be adopted for the lower limit of the ultrasonic range, it should be 17.8 kHz. That recommendation comes with the warning that use of a single frequency to define the ultrasonic range, whilst necessary for bodies with authorities over those ranges, should not be taken out of context, certainly not to the extent of stating 'humans cannot hear ultrasound, that is, sounds with frequencies above X Hz', because that does not reflect the great diversity in hearing acuity that is observed between individuals[1,5,10,]. It also becomes problematic when a device emits a continuum of sound that crosses the boundary between sonic and ultrasonic, causing each body (e.g. following the remit of its charter[12]) to consider only a proportion of the acoustic energy it emits when considering safety, and no organization considering the total emission[10]. It should be noted that departure from the 20 kHz mantra is not new: other authorities have suggested, as the lower limit for the ultrasonic regime, 10 kHz[13], 15 kHz[14], 16 kHz[15],[16] and 18 kHz[17]. One might argue that because frequencies 'above 16 kHz' were less well-characterized in terms of equal loudness and absolute threshold data (though this argument will date as new data are taken[4,5,18,19]), they could be considered 'ultrasonic'. However whilst MPLs continue to be expressed in terms of third octave bands, this argument inadvertently also argues, not for 16 kHz itself, but for the upper frequency limit of the third octave band centred on 16 kHz, to be the lower limit of the ultrasonic regime. Therefore both from low frequencies looking up (the equal loudness argument), and for high frequencies looking down (the ultrasonic MPLs ‘at 20 kHz’ cover the entire third octave band centred on 20 kHz), there are strong arguments for using 17.8 kHz as the lower limit of the ultrasonic range.

The first paper[11] in this special issue notes the peculiarity in defining ultrasound from the absence of two things, specifically that it ‘cannot be heard by humans’ and (particularly in the context of ultrasonic safety for humans) that it is a non-ionizing radiation[11]. It proposes that, particularly when addressing human safety, the ultrasonic regime be divided into three bands, following the example set for classifying ultraviolet radiation. Whilst the continuum of the spectrum and the presence of important exceptions is recognized, each band is characterized by the dominance of a given mechanism for producing bioeffects in a given medium. This is done to prevent a problem that has arisen in recent years, where for example manufacturers[20] of a device, uBeam (that purports to project ultrasound through air to charge phones etc., and would thereby expose members of the public to ultrasound of <100 kHz in air) make assurances that it is safe by stating that it complies with FDA regulations for the exposure of a fetus in the womb to >1 MHz ultrasound in liquid and soft tissue during the scanning of a pregnant woman. It would be inaccurate to suggest that the mechanisms by which the ultrasound in each case could possibly produce adverse bioeffects are the same. The manufacturers of uBeam for example state that:

> “*Ultrasound has been used safely for nearly 100 years. It has been studied extensively due to its use in medical imaging, and, unlike X-rays, there is no issue with a cumulative effect, meaning there is no risk of prolonged exposure to the uBeam system… 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... but we went a step further. If a person were to be exposed to the uBeam ultrasound source, 99.9% of the emitted ultrasound will bounce off the skin, which is the same occurrence as with fluorescent lights and*

> *rear parking sensors and other ultrasonic devices around us every day. Compare that with medical imaging, where the body absorbs most of the ultrasonic energy*"[20].

These claims occur so frequently from manufacturers and their representatives, that Leighton[10] entitled the opening sections of his article:

- 'How can ultrasound in air affect humans when more than 99% of the energy is reflected at the skin?';
- 'How can ultrasound in air affect humans when the incident energy in ultrasonic fields is low?';
- 'Ultrasonic safety is not an issue, because we have decades of experience on the safe use of ultrasound in fetal scanning'

At the heart of this is the fact that the tissues and mechanisms that the FDA regulations consider are the foetus submerged in amniotic fluid as it might be affected by ultrasonically-induced temperature rises, cavitation and radiation forces (no additional ill effects mediated by the hearing system are considered form these MHz exposures). In contrast, safety concerns regarding low frequency ultrasound in air must consider the hearing system in air, which is out-of-remit for the FDA guidelines cited in the uBeam quote. The same reflection coefficient relied upon in the uBeam quote also applies to sound at voice frequencies that, if sufficiently loud, can cause adverse bioeffects (e.g. hearing threshold shifts at a rock concert; compromised learning[21] and sleep[22] as a result of environmental noise). The human ear is designed specifically to be sensitive *despite* this >99% reflection at the skin.[23] As an extra note of caution, care must always be taken when comparing dB levels specific in water to those in air, and vice versa, as errors are frequently made, and published, because a one-to-one direct equivalence cannot be made.[23,47] It is vital that when safety arguments are made, they must be based on correct science, including the use of correct acoustical perspectives, to protect this rapidly expanding market, and those who undergo acoustic exposure as a result of it.

In this Special Issue, one paper covers ways of categorizing the ultrasonic regimes[11], three papers cover human effects[24-26], and six report on the measured outputs of commercial devices[24,27-31]. It is notable that measurements of commercial sources tend to focus on pest deterrents[24,30,31] (because they are inexpensive and produce high levels) and Public Address Voice Alarm (PAVA) systems[28-30] (because they recently came to light as inadvertent sources of ultrasound and are relatively common and accessible[1]). This means that the information on the levels emitted by most other commercially available sources come from manufacturers who rarely appear to access measurement equipment and procedures traceable back to national standards, and there is a lack of standardized procedures for conducting and reporting such measurements. Of the remaining papers in the Special Issue, two cover calibration[32,33], and the final three[34-36] cover novel applications. The Special Issue accepted 14 papers and rejected 7.

## II. Perspectives

The ultrasonic intensity at the ear of a member of the public depends on source power (and its time history), directionality, range and attenuation along the propagation path. Taking these factors into account, three types of source are notably common. Cleaning baths are a common source of occupational exposure, but are now penetrating the domestic market[15]. Probably the source that has been, over the years, responsible for giving most members of the public their most intense ultrasonic exposure in air is the pest scarer/repeller, a technology that has been sold for decades. In recent years, the advent of PAVA systems that emit ultrasound, usually at lower levels than pest scarers, have caused millions of exposures[1]. Despite these millions of exposures, only a minority of people have reported adverse effects. This may well indicate that the majority of adult humans will not have noticed adverse effects. Does this give us confidence in continuing to use the existing MPLs to protect the public? The reasons for revisiting the existing guidelines and approaches are that:

- Occupational guidelines should not be used for public exposure;
- If the variation in dB level for adverse effects resembles that for hearing thresholds at low ultrasonic frequencies, then protection of that minority should not be based on the response of the average adult, because with millions of public exposures annually the minority could constitute a large number of cases;
- A This illustrates a key point, that reliance on the average response for assessing the safety of the exposure of the public to ultrasound may not be adequate, since it might under-protect a minority that might include millions of individuals, and an important hypothesis (see above) suggests that young people could be over-represented in that minority.

The longevity of the pest deterrent market suggests that, despite some early conflicting reports as to their efficacy (reviewed in Ref. 1), modern users have confidence in the product. Certainly, by focusing on safety it is important not to suppress innovation and a market without warrant, but markets are in the long term harmed if not supported by appropriate guidelines, and enforcement of the same (which requires appropriate calibrations and measurement procedures, as discussed by Refs. 32 and 33). It would be wise to move the perspective from its current position to a wider viewpoint. Two examples of possible wider viewpoints are now described.

First, the discussion of widening perspective should include shifting from preventing adverse effects in the ‘average’ adult human to study instead sensitive subsets (as done in Refs. 25 and 26). Drever (writing in the context of hand dryers in public toilets[37,38]) introduces the term ‘auraltypical’ in place of the audiological term ‘otologically normal’. This follows the approach that characterise those not on the autistic spectrum as ‘neurotypical’, which also:

> *“refers to nonautistic people’s normality and implies their tendency to impose their understanding of normality on everyone else as correct and natural. Accompanying auraltypical hearing which we are trained to practice as acousticians, is the actual variety of (often less than ideal) hearing that we experience throughout a normal day and throughout our lives albeit to varying degrees (from the trifling experience of a temporary threshold shift or transient ear noise to intolerable pain from hyperacusis) which can be called auraldiversity”*[37].

Auraldiversity becomes an important concept in terms of public exposures.

Second, the widening perspective should also include discussion of the type of adverse effects covered. Subjective reports of headache, nausea, dizziness, tinnitus, and a sensation of ‘pressure in the ear’ are common, but have to date lacked the test of a double blind randomized controlled trial[1,10]. What safety aspects should we consider for an ultrasonic device? Suppose a given PAVA device at airports and sports stadia were to have been proven to have no direct adverse effects on humans, would we be correct in considering it out-of-remit before testing whether it produces an indirect problem by possibly compromising the performance of bomb search dogs?[10] On what range of adverse effects should MPLs for ultrasound in air be based? Certainly a narrowing of the range, as has happened in the past, is unjustified whilst we currently lack data on the range and prevalence of adverse reactions. Such narrowing was demonstrated in 2004 when the US Occupational Health and Safety Administration (OSHA) voted to adopt the recommendations from The American Conference of Governmental Industrial Hygienists (ACGIH)[39] who in turn set limits by restricting their perspective to consider avoiding only one specific adverse effect, 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*'. They chose to select MPLs by ignoring all other adverse effects (the ones listed above appear to set in at lower acoustic intensities, but can of course have non-acoustic causes), and by ignoring direct effects from the ultrasonic radiation itself, so that the only hazard that was to be avoided was one where the energy in subharmonics caused hearing loss: no other criteria were deemed relevant. Any potential for the primary ultrasonic frequency to cause hearing impairment other than through audio frequency subharmonics is ignored. This unorthodox approach was compounded by their publishing that, in their consideration, it would be possible to increase the allowable limits by 30 dB '*when there is no possibility that the ultrasound can couple with the body by touching water or some other medium*'[39] (one assumes the 30 dB is derived from the air/soft-tissue normal incidence pressure reflection coefficient). This would surely only be justified if all previous data on adverse effects used to derive the MPLs onto which 30 dB was to be added, had been derived with the subjects' heads immersed in water or in contact with transducers (which was not the case). The result of these twin recommendations by the manufacturers' association (ACGIH) was to give the USA the most permissive MPLs, by around 30 dB.[1,7-9]

## III. Applications

The applications discussed here generate ultrasound in air, and at frequencies below 100 kHz (usually 18-40 kHz). Other applications (from well-established fetal scanning to proposed applications like fingerprint detection[40]) are therefore out of scope of this Special Issue.

Technology that generated significant ultrasound in air became widespread in the 1960s and 1970s, for industrial purposes such as cleaning, welding and drilling, because of the advent of suitable transducers and amplifiers. Some proposed uses (such as sterilization[41]) for ultrasound in air, were not taken up. In the last decade the use of devices that emit ultrasound in air has undergone a renaissance because the cost and size of amplifiers has reduced, the cost of transducers has seen very large decreases, digital signal processing and control has become widespread, and mobile phone technology has placed into billions of pockets significant processing power, coupled to microphones and loudspeakers with the capability of operating up to approximately 22 kHz. The build quality of sources and amplifiers, and the procedures and equipment for calibrating sources and levels, has not kept pace with these innovative applications. The difficulties in obtaining new data caused bodies setting the many national and international guidelines to review the field and base new guidelines on the existing ones, reaffirming the consensus, rather than recognizing that these extant MPLs are based on a sparse dataset that the authors almost certainly never intended for use in this way. Notably, these guidelines were based on occupational exposures, and have not responded to the proliferation of public exposures.

The complexity of the exposure scenarios that guidelines need to cover has increased. The earliest guidelines considered simple occupational, in-air exposures, although data from workers and workplaces was usually contamination by high levels of voice-frequency exposure. Some devices have, like the pest scarers mentioned above, been in widespread use for decades. Pest scarers have been causing public as well as occupational exposures from their earliest days on the market, because of their deployment in parks, public buildings, railway stations etc. Other long-standing workplace technologies (such as ultrasonic cleaning baths) have only moved into the domestic market in recent years, as prices for domestic units decreased (e.g. for cleaning jewellery, dentures etc.). Placed for example in a kitchen, a domestic unit could expose all members of a household. Dental ultrasonics exposed the operator, in an occupational setting, to in-air ultrasound (with reports of reduced hearing sensitivity in dentists who use ultrasonic scalers[42]). In contrast, the dental patient's simultaneous exposure could not be considered occupational and includes bone-conduction as well as possible in-air exposure. Ultrasonic welders[27], drillers and cutters and similar industrial ultrasonic technologies show no current signs of making the transition to public use (see Maccà *et al.*[43] with updates noted in

Ref. 1). Other long-standing technologies include proximity warning systems (for example to assist drivers to park vehicles, or to act as triggers for opening automatic doors[44] in shops etc.).

Other devices, like the mobile phone charging example of in-air ultrasonic power delivery cited above, represent more modern applications. Some, like the 'acoustic spotlight'[45] and haptic feedback[46] systems, require high intensity beams to generate nonlinear effects.

To make sense of the range of scenarios in which humans encounter ultrasound in air, it is useful to refer to three categories[47] of exposure. Category 1 is labelled *Ultrasonic noise exposure*. This occurs when some process or device generates ultrasound as a by-product of its operation[1]. Historic examples include the jet engine (which was famously one of the earliest sources of complaint for causing 'ultrasonic disease', complaints that are undermined by the contamination of exposure by high levels of voice-frequency noise). The PAVA systems discussed above[1,28,30] also fall into this category. There have been anecdotal reports of low-level ultrasound from lighting, data projectors, smart screen multimedia projectors and other office equipment but no scientifically confirmed measurements. Dolder *et al*.[31] measure the interesting case of a new hairdryer that is advertised as being quieter because the manufacturer has increase the number of blades on the motor impeller in order to shift '*one tone within the motor to a sound frequency beyond the audible range for humans*'.

Category 2 is labelled *Unintended ultrasonic exposure*. This occurs when some process (such as an ultrasonic cleaning bath) requires the generation of a specific ultrasonic signal as key to completing its task, but in addition to insonifying its inanimate target, it also unintentionally exposes a human or animal to ultrasound[1]. This category includes ultrasonic levitation[48-51] systems, power delivery and battery charging systems[20], processing systems[52] (e.g. for foods[53] and clothes[54, 55]), ultrasonic beacons[56], and ultrasonic communication[34,35] systems. It also includes most ultrasonic warning[57], positioning[58] and tracking[59] systems (including bracelets to monitor hand positions[60]). The pairing of ultrasonics with mobile phones has generated some unusual applications, including the 'SilverPush' device[1] which, unbeknownst to the owner, uses their mobile phone microphone to track the online or TV content they watch from ultrasonic beacons embedded in the viewed content.

Although teeth are not strictly inanimate, it is convenient to include dental scalers, files and drills in this category.

Category 3 is labelled *Deliberate ultrasonic exposure*. This occurs when devices are designed to expose humans and/or animals to ultrasound in air (whether or not the target is the intended species or demographic) [1]. Category 3a consists of exposures made in order to ensure the device works but without intending any response from those exposed. Automated door opening systems[44] would give a transitory category 3a exposure to those passing through the door, but possibly a category 2 exposure for someone sitting in a waiting room or classroom chair nearby. Category 3b consists of exposures made in order to elicit a subjective response, such as for ultrasonic haptic feedback[46] systems. There is debate in the hi-fi entertainment industry as to the value of including the capacity to generate sounds above 20 kHz into the more expensive sound reproduction systems[61]. Pest deterrents[1,3,62,63] have probably been the most common high-power sources of public exposure, the level at the ear depending on range and directionality. These are measured in Refs 24, 30 and 31 of this Special Issue. Ultrasonic deterrents and weaponry form a special class of category 3 exposure, because the response sought is through deliberate generation of adverse effects[1], and so are discussed separately in Appendix A.

There are few measurements of the fields emitted by these devices, and indeed for some (e.g. Category 2's submerged algae removers[64]) one might reasonably expect the levels in air to be very low. The difficulty in obtaining reliable field and human response data for these devices will be discussed in Section IV.

## IV. Difficulties in obtaining data

In editing this Special Issue and reviewing the field, it has become clear that the quality of data and the metadata surrounding it, are crucial to making a way towards safely deploying ultrasonic emitters into air where humans can be exposed. Authors of the papers in this Special Issue all had their papers significantly improved by peer review, and were all encouraged to archive their raw data for readers to access openly. This was done to counter the current state of affairs, where we cannot access the raw data and calibrations on which current guidelines are based, which were made in circumstances that very often left questions unanswered.

### *(a) Difficulties in making measurements*

It is easy to read this collection and criticise the methodology, and quite rightly point out where studies fail to match the standards routinely achieved in voice-frequency studies by researchers following the appropriate standards (e.g. Ref. 65 ). It is clear that undertaking studies to that standard for ultrasound-in-air requires access to facilities that are not commonplace, and support via procedures and protocols which are in their infancy. For example, how many 'anechoic' chambers are certified up to 32 kHz?

There is a lack of developed metrology support available for the ultrasound range. The free-field frequency response of the microphone is very difficult to validate at ultrasonic frequencies in air, and only one or two laboratories globally have the necessary facilities. Others take the pragmatic approach of using electrostatic actuator methods that are not validated and require corrections often of unknown origin or quality, to obtain the free field response. In terms of measuring the output of commercial ultrasonic sources, surveying is sparse and levels stated by manufacturers are open to question because procedures for taking measurements traceable back to primary standards have only just been developed (see Ref. 32, this issue).

Whilst there is a large body of literature[1] reporting measurements made of workplace noise levels and human exposures during tests at frequencies in excess of 20 kHz, the perhaps understandable absence of archives of raw data and book-ended calibration tones means that an unknown proportion of exposures were contaminated by the effects (e.g. audible cues during testing; or cumulative workplace-induced hearing loss) of voice-frequency noise. Moreover, the strictest restrictions on tolerance may have come from instrument performance standards. The relevant standards[66,67] state that a Class 1 sound level meter should record frequencies up to and including the 16 kHz third-octave band, but that 12.5 kHz is the minimum frequency to which the frequency characteristics should be specified. While the performance acceptance limits in the standard[66] at 1 kHz are +/-1 dB, for the 20 kHz third-octave band (i.e. down to 17.8 kHz) they are from +3 dB to $-\infty$ dB for a Class 1 device, meaning that it could be capable of severely underestimating signal amplitudes above 17.8 kHz and still meet acceptance by the standard[1].

Common practices for voice-frequency measurements become sources of error at higher frequencies. The use of A-weighting is of course inappropriate for measurements above 17.8 kHz. Data acquisition systems commonly used for monitoring ultrasound by the public have sampling frequencies between 40-50 kHz (44.1 kHz for CDs, 48 kHz for some mobile phone apps etc.) so conclusions as to whether or not ultrasonic energy exists at frequencies greater than half the sampling frequency cannot be drawn from such measurements (indeed when the author was testing mobile phones for their ability to detect a chirp rising from 15-30 kHz, one mobile phone sampling at 48 kHz was found not to be equipped with anti-aliasing filters, causing wrap-around frequency errors). As another example, a 3D microphone grid with 5 cm spacing that is in routine use for <4 kHz source output measurement, is inappropriate at 20 kHz, and runs the risk of missing the central beam of an ultrasonic source, spatially aliasing the data, and suffering contamination from scattering by microphone stands etc. When the wavelength becomes this small (~1.7 cm at 20 kHz; ~0.86 cm at 40 kHz), scattering becomes more problematic, because: (i) of a weakening of the refraction effects that would, at lower frequencies, mitigate against scattering artefacts such as shadowing; (ii) phase changes rapidly with path distance, causing interference. Consequently, repeatability and reproducibility tests, and robustness against head movement, become more challenging because of scattering from stands, equipment, researchers moving around the room, the head and pinna[1] etc. Similarly whilst at voice frequencies a ½ inch microphone diaphragm (diameter ~0.13 cm) might easily be aligned to planar wavefronts so that the pressure oscillations across the diaphragm are in phase (at 8 kHz the wavelength in air is ~8.5 cm), it becomes more difficult to achieve such alignment as the frequency enters the ultrasonic range. Refs. 32 and 33 illustrate the extra considerations that must be taken because of these, and other, issues when considering calibration and procedures for ultrasound in air. Today's experimenters, whether measuring fields or human responses, have need of such careful analysis of the required procedures.

All these factors increase the need for a large number of test-retest repeat measurements, but the time required for this can become very large: consider that mapping a sound field at half-wavelength measurement points spaces a few millimetres apart just one time might require the microphone to be at 1000 different measurement points. At voice frequencies, fewer repeats would be required, the microphone spacing would be centimeters apart, and the microphones and calibrations sufficiently inexpensive to deploy dozens of microphones at one time. Calibrated ultrasonic microphones being so uncommon and expensive, if a test is conducted with one microphone on loan in an unfunded research topic, then measurements at thousands of points is not feasible. Therefore the mapping one might expect of voice-frequency sources is replaced by attempts to detect whether, at a likely location relative to the source where the ear of a member of the public might be present and might encounter the strongest emissions, those emissions exceed the MPLs[24, 28-31]. Similarly, audiological data from large populations that we have seen for voice frequencies, is replaced by case studies examining possible adverse reactions in potentially more sensitive individuals[24-26]. The voice-frequency goals to appropriately map fields and populations, is replaced in the ultrasonic regime with goals of spot-checking whether there are detectable cases of public exposures exceeding MPLs, or adverse reactions to similar fields that indicate whether there is a problem to be investigated. A notable exception to this is the work of Rodríguez Valiente *et al.*[5], who conducted high-frequency (9–20 kHz) audiometry reference thresholds in 645 healthy subjects, separating the results by age bracket, and included the 5th and 95th percentile when they tabulated the results. This is far more illuminating that simply tabulating the mean, median and standard deviation, because the variation in acuity even within a given age bracket is very great and the distribution unknown (especially in a small sample), and when public exposures of millions of people are considered, adverse effects in a small percentage can affect a large number of households and small businesses. Inter-subject variability appears to be considerably greater, and hearing thresholds appear to increase more rapidly with age, in the low frequency ultrasonic range than at voice frequencies. We do not have the data to link the hearing thresholds data in the low frequency ultrasonic range[4,5] to the potential for adverse effects, and the difficulty in obtaining those data is the topic of the next subsection.

### *(b) Difficulties in assessing adverse effects in humans*

The preceding section outlined the physical acoustics complexities of setting up an experiment involving human subjects and their response to ultrasound in air. The inclusion of human subjects presents additional problems, including head movement, choice of free field, headphone or in-ear source, greater scattering by the pinna (a source of person-to-person variation) and, for earphones, the method of calibrating the sound source in an appropriate ear simulator. The recruitment of individuals who represent that subsection of the public that might be more susceptible to adverse effects is difficult: many self-assessed sensitive individuals are reluctant to the point of refusing to travel to a testing centre, because of adverse effects they fear they will suffer on public transport (a mobile testing centre would greatly assist future research). Testing one potentially sensitive group to find the levels that elicit adverse reactions, would be unethical: some neonates, infants and children will in public places be exposed to pest scarers, Mosquito-like anti-loitering devices[68,69] and PAVA systems, whilst in the care of adults who are immune to adverse effects from these sources[1]. This presented perhaps the greatest challenge for this special issue, in that JASA requires compliance with ethical standards, so that exposures that can be generated by common commercial devices, could not be tested on even adult human subjects, let alone the young. Consequently the human data reported in this special issue shows marginal adverse effects, less than are reported elsewhere, potentially because the exposures are too brief, and too low-intensity, to elicit a statistically significant response in the small numbers of subjects that could be recruited.

### *(c) Recommendations*

Because of these difficulties (which arise primarily because we are extending to shorter wavelengths technology and procedures designed for the <8 kHz range) in addition to the recommendations given in Refs 1 and 10 for working in the ultrasonic regime in air, the following recommendations when conducting experiments are added:

- The spectral characteristics of filters (with appropriate attention paid to anti-aliasing filters, roll-off and guard bands), and the sampling frequency and frequency bin width/FFT size, must be stated explicitly, so that the spectral characteristics of the whole detector chain is known. A-weighting should not be used.
- Noise levels (background, platform etc.) should be stated, and tests undertaken to check whether the noise which appears to be acoustic is in fact electromagnetic in origin[44].
- The traceability of calibrations should be stated explicitly.
- Prior to experiment, a calculation should be done to estimate what can be achieved rigorously given the time the equipment (e.g. calibrated microphone on loan) and facilities (e.g. anechoic chamber) are available, the spacing of measurement positions, the directionality of the source field (and difficulty in locating the main beam), and the number of test-retest measurements that must be done to deal with repositioning and alignment errors. The full dataset allowing for these errors should be reported.
- A 'scatterer impact assessment' should be done prior to the experiment because in the field scatterers are likely to be important and possibly moving, and in the lab at ultrasonic

frequencies scatterers that are often neglected (walls of anechoic chambers, microphone stands, experimenter bodies) may become significant. Absorption (by air, scattering bodies etc., and the dependence on temperature, humidity etc.) should also be assessed prior to the experiment. These findings should be included in the data archive.

- If energy is detected in the third octave band centred on 20 kHz, measurements should also be made in the band centred on 16 kHz to check if the ultrasonic energy is associated with (e.g. via transients, harmonic or continuum emissions) sound signals at lower frequencies.
- All raw data should be archived in a manner robust against file obsolesce (for example, .txt tables would be preferable to Excel). Tests on human responses should indicate the mean, median, standard deviation, and the 5th and 95th percentiles. It should be explicitly stated what is being arithmetically treated in calculating these (e.g. a summation of dBs or rms pressures; subjective scores on subjective response etc.) and state the extent to which the data follows a Gaussian distribution. The meaning of any error bars (X% confidence intervals, standard deviation, standard error in the mean etc.) should be explicitly stated.
- Ethical approval appropriate for the journal should be obtained prior to measurement, taking into account the potential for adverse effects on all those exposed (subjects, researchers etc.).

## V. Conclusions

This first attempt to produce a Special Issue on the topic of Ultrasound in Air has highlighted difficulties in translating voice frequency practices and apparatus to use in the ultrasonic regime, and also highlighted neglected areas:

- Although there are a large number of devices (both established and newly-introduced) advertised, manufacturers did not take up the opportunity to put data forward for peer review;
- Measurements of devices by researchers tended to focus on pest scarers and PAVA systems, the former being inexpensive, and the latter relatively simple to locate in the field;

- No papers were submitted in a range of fields where airborne ultrasound in is important (e.g. zoology).

Ultrasonic signals are not difficult to generate and detect, so that today even smart phones can access the lower ultrasonic band (up to about 22 kHz). Furthermore, because ultrasound is a mechanical radiation, with high absorption (meaning significant ability to heat) compared to common EM radiation, and a low propagation speed (giving radiation pressures[47] 900,000 times greater times than achieved with EM waves of the same intensity in the long wavelength limit), and a propensity to generate nonlinearities[47], it is not difficult to demonstrate a range of effects in the laboratory, where ultrasound can affect physical objects (through heating, levitation etc.). However all the above effects are amplitude-dependent, and compromised if the signal is too weak at the target. Consequently whilst a wide range of prototype demonstrations can be produced covering a wealth of ultrasonic phenomena, subsequent commercialization of a phenomenon that is to be deployed where people and animals are exposed, requires data-driven guidelines that are properly supported by measurement procedures, calibrations and enforcement measures.

This Special Issue covers the perspective on where to place ultrasound in air in the wider ultrasonic field, calibration methods, the ultrasonic emissions generated by some commercial devices, and investigations into possible adverse effects.

The fact that ethical considerations preclude exposing people to the levels they can easily experience from an inexpensive commercially-available source, means that reports of adverse effects are almost entirely anecdotal. This, and the aforementioned scarcity of reliable independent measurements of source outputs and consequent reliance on manufacturer statements, means that in the absence of journal papers, articles such as this must with regret rely on citations to web pages. The one exception is found in the small number of scientific articles that measured levels and human responses in the field, or recorded human responses to inadvertent exposures whilst undertaking source level measurements. Whilst some older studies used sources that also emitted below the ultrasonic range

(Herman and Powell[15] measured "*81 dB in the third octave band centred at 12.5 kHz, 108 dB [SPL] in the 16 kHz band, and 96 dB in the 20 kHz band, five feet in front of a dog repeller, with reactions ranging "from no perception or no symptoms at all, to expressions of severe discomfort 40 feet from the source, in another room*"), Ueda *et al.*[2,3] reported variable (including strong) adverse reactions to purely ultrasonic pest repellents in a public area in the Tokyo Metropolis. In a restaurant, they measured 130 dB SPL under a 19 kHz source, and 90 dB SPL or more 14 m from the source. The multiple sources in a passage generated "*exceeded 100 dB [SPL] at all measurement points in the central portion of the passage. The questionnaire revealed that all 35 responders aged 20 to 50 can hear the sound generated and that more than half of them felt discomfort from such sound…*some responded that "my head may split" and "I will never come here again because of the pain in the ear."" [3].

Definitive statements are impossible, but a slim evidence base suggests the following (on weight-of-probabilities) regarding ultrasonic adverse effects in humans. One study[70] at extremely high intensities reports physical effects, specifically heating in human nasal cavities and on the skin between fingers as a result of accidental close-range exposure to very high intensities (>140 dB, probably 160-165 dB, re 20 µPa, at 20 kHz). At lower intensities, adverse psychological effects occur in only a subset of the population (susceptibility generally decreasing with age), are restricted to frequencies below ~30 kHz (data is too sparse to be specific), probably result from the extraordinary sensitivity of our hearing/balance systems, and can be difficult to separate from (and may be causally related to) adverse effects of anxiety and annoyance. This does not remove the need for protection, especially for increasingly common public exposures, where the exposure and exposed person are often uncharacterised.

Only one interim guideline from 1984 addresses maximum permissible levels (MPLs) for public exposure[1,6,71]. It is based on scant evidence, and may or may not be appropriate. All other guidelines relate to occupational exposure. These MPLs are a legacy of decades of copying previous guidelines, which were themselves based on inadequate sampling (usually a small cohort of adult men), and averaging practices which obscured the particular sensitivities of a subset of the population.

There is therefore a very strong case for revising and, if necessary, replacing existing guidelines, based upon evidence rigorously collected from appropriate age-specified cohorts, and appropriate consideration for the more sensitive members of the public (because data to date suggest that deviations from the average response may be very large, so that citing only the average may disenfranchise millions of people). Drever's concept of auraldiversity[37] may point to a more satisfactory approach. The potential benefits of new in-air ultrasonic technology (and protection from unintended ultrasonic leakage) will not be safely realised until we have secure guidelines, and measurement and calibration procedures. We also need clarity on when occupational MPLs are appropriate and when public ones should be used, and proper enforcement. We cannot continue in the situation where a $20 device on sale to the public, deployed and used in keeping with normal practice, can expose children to in excess of 50 dB above the current MPL, which is itself based on the average response of a small sampling of the adult population.

Nine decades of discussion about the safety of ultrasound in air have been plagued by sparse and anecdotal data. We are now in a position to act more logically. There is now strong evidence from blind trials[25] (supported by studies using commercial devices in lab[24] and field[1,3], and readily demonstrated by anyone that downloads a 'teen-tormentor' app onto their smart phone) that when a signal in the 20 kHz third octave band is played at modest volume in a room, that room can be populated with a cohort in which some will not hear it, and some will hear it and find it annoying, and some find difficulty in performing tasks. It would not be unreasonable (but yet unproven) to hypothesize that anxiety and stress from such responses could (at least sometimes) lead to headaches and other symptoms of the type often associated with exposure to ultrasound. MPLs for public exposure should be set at avoiding these symptoms in sensitive individuals (e.g. probably children), not at avoiding other symptoms (hearing threshold shift) in less sensitive (e.g. probably adult) subjects. That principle offers the opportunity of closing the argument for the 20 kHz third octave band, and further research could extend the principle to find the public MPLs for higher frequency bands, the starting point being designing studies for adverse effects based on the hearing threshold work[4,5].

Designing such studies is not simple, because of the ethical and practical considerations in deducing thresholds for these adverse effects in the most sensitive individuals. However by separating the issue into sounds that can be perceived and sounds that cannot, and on basing MPLs on the ability to produce these so-called ‘subjective’ effects as opposed to hearing threshold shifts, we have a structure that enables us to move forward.

This leaves one particular question remaining, which is the effect of exposures that cannot be perceived by anyone. Higher SPLs than could ethically be generated for the papers of this Special Issue will be required to address those, although again the focus should be on avoiding ‘subjective symptoms’, not hearing threshold shifts (assuming the latter require higher SPLs and longer exposures).

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## APPENDIX A – Ultrasonic weapons and the suggestions of ultrasonic attacks in Cuba and China

### A.I. Ultrasonic deterrents

The topic of ultrasonic deterrents and weapons was reviewed in Ref 1. These devices are inexpensive, widely advertised and readily available. They are specifically designed to produce an adverse effect. Their safety is never discussed in the context of the one existing MPL for public exposure[6] (70 dB SPL re 20 µPa for third-octave band 17.8-22.4 kHz; 100 dB SPL re 20 µPa for the third octave bands centred on 25-100 kHz). Some are marketed specifically against young people, notably teenagers, e.g. as anti-loitering devices[1,68].

Anecdotal reports of adverse effects are common on the web, for both anti-teenager devices (some of which emit below 17.8 kHz), and pest deterrents (e.g. repellers[24,30,31] anti-barking devices[72]). However, ethical constraints limit the extent to which the scientific community are able to conduct controlled double-blind studies and report them in the peer-reviewed scientific literature. In the absence of such tests, it is relatively simple to envisage how symptoms associated with anxiety/annoyance/stress (headache, dizziness, inability to concentrate, migraine etc.) could follow from audible exposure to the levels of ultrasound generated close to a pest deterrent: here the path from ultrasound to symptom requires first that the ultrasound produces anxiety/annoyance/stress. It is more difficult to propose mechanisms by which the reported adverse effects are directly caused by ultrasound without a mechanistic route via acoustically-induced anxiety/annoyance/stress, and without the signal being audible to the subject, although it is possible to construct untested strawman mechanisms[1]. In this environment devoid of peer-reviewed double-blind testing, it is difficult to believe, in the absence of evidence, claims from members of the public that their neighbors have constructed ultrasonic weapons that cause severe adverse reactions, and hearing threshold shifts, through house walls, and when projected over long distances, particularly if done so without the neighbors harming themselves. On the other hand, there is nothing to stop an adult deploying a commercial pest scarer (that is inaudible to them) close to a boundary fence of a neighbor who has children, who may or may not experience adverse effects, especially if they perceive it to be audible and loud. In another scenario, one can easily annoy some teenagers in a room by playing low ultrasonic frequencies from a phone or laptop using one of many downloadable apps.

This brings us to an issue of current debate, that of whether ultrasonic weaponry was deployed against Embassy staff in Cuba and China.

### A.II. The reports of an attack on the US Embassy in Cuba

On 9 August 2017, the US State Department suggested the possibility that an attack had occurred between November 2016 and Fall 2017. As time passed, information and possible misinformation came out. It seems established that in December 2016, around 80 staff visited the medical facility at the US Embassy in Havana with a wide range of complaints, and there were some verbal descriptions of unpleasant sounds. The US authorities believed these were associated with exposures and residences and hotels in November and December 2016. Around March 2017, an exercise was conducted that removed 64 of those individuals who complained from inclusion in this examination, leaving 16. There is very little information on this down selection, but it is key if one then claims there are trends evident in the remaining 20% after 80% have been dismissed as outliers. A review was conducted by the US authorities in July 2017, and the field (in terms of timelines and populations) was expanded, which found another 8 individuals fitting the pattern that selected the previous 16. Again, there is little information of how this expansion was done, because it is important to know not only how many were included in it (8), but also how many were discarded as not fitting the pattern, if one is to assess whether that pattern is valid for the narrative constructed around it. Those 16+8 cases were then sent to the Department of Neurosurgery and Center for Brain Injury and Repair, Perelman School of Medicine, University of Pennsylvania, who conducted a wide range of tests. It is possible that no physical acoustician was involved. This picture was divulged in parts from August 2017 to January 2018.

In August 2017 the Associated Press (AP), who led on the reports, stated that the sound was inaudible, placing the issue in the remit of this Special issue (according to many references[73,74]: '*the diplomats had been exposed to an advanced device that operated outside the range of audible sound and had been deployed either inside or outside their residence*'). On 13 October 2017, an audio recording of the sound was revealed[75], in a report that was subsequently covered by others with the following contradiction, which has gone unchallenged:

> *"The recording -- obtained by The Associated Press and released on Thursday -- is the first publicly reported audio sample said to be related to attacks that, according*

> *to a US official, may have involved the use of an acoustic device. The device was so sophisticated, it was outside the range of audible sound, the official said. And it was so damaging, the source said, that one US diplomat now needs to use a hearing aid*".[76]

These reports were accompanied by pseudo-scientific analysis based what appears to be visual analysis of the spectrogram. The AP signals consisted of unremarkable broad peaks at 6-9 kHz (Figure 1). The amplitude is not known, and AP reports that '*Americans affected in Havana reported the sounds hit them at extreme volumes*'[75] (although these amplitude data appear to be restricted to the subjective recollections of those annoyed by it).

AP also stated[75] that it was possible that '*Individuals who have heard the noise in Havana confirm the recordings are generally consistent with what they heard*'. They also stated (without evidence either way) that it was possible that energy might have been present at frequencies outside of the sensitive range of the detector, saying: '*Those frequencies might be only part of the picture. Conventional recording devices and tools to measure sound may not pick up very high or low frequencies, such as those above or below what the human ear can hear. Investigators have explored whether infrasound or ultrasound might be at play in the Havana attacks*'[75].

By December 2017, Associated Press reported that '*Doctors treating the U.S. embassy victims of suspected attacks in Cuba have discovered brain abnormalities*'[77]. The first reports of 'white matter tract' changes surfaced. The absence of hard facts, particularly on the purported acoustic exposures and the evidence trail that led from these symptoms to reports of acoustic weapons, and the lack of balance in assessing the meaning of what must at first sight have appeared to be alarming medical terms, led to speculation in the media and political arenas that should have been tempered by the presence of contradictory reports.

The 'sonic attacks' were given significantly more political weight when Senator Marco Rubio stated that '*It's a documented FACT [sic] that 24 U.S. govt officials & spouses were victims of some sort of* *sophisticated attack while stationed in Havana*', as reported by the Miami Herald[78] on 7 January 2018. The following day CBS Miami[79] reported that Rubio was going to set up Senate Hearings entitled 'Attacks on U.S. Diplomats in Cuba: Response and Oversight', and that these 'attacks' had caused:

> '*changes to the white matter tracks that allow different parts of the brain to communicate. Victims have reported damage to their hearing, vision, balance and memory. Meantime Secretary of State Rex Tillerson, while in Belgium, said he is convinced the incidents were targeted attack*s'.[79]

The day after that, Rubio speculated on the reasons behind the 'attack'[80]. In the subsequent Senate hearings[81] in January 2018, prior to hearing from Dr. Charles Rosenfarb, the Chief Medical Officer for the United States State Department, Rubio summarized the state of affairs. According to his testimony, as early as November 2016, events occurred at diplomatic residences, and later at hotels (the Hotel Capri and the Hotel Nacional de Cuba). Sufferers visited the medical facility at the Embassy in December 2016 and January 2017. In the words of Rubio[81]:

> '*From February through April 2017 there was an evaluation conducted of 80 members of the Embassy community. Sixteen of these were identified with symptoms and medically verifiable clinical findings of some combination similar to what you would see in patients that have had mild traumatic brain injury or concussion*'.

After Rubio's introduction, the ranking member of the Foreign Relations Subcommittee on Western Hemisphere, Sen. Non Menendez, opened his comments in a way that emphasized the word 'attack' repeatedly, starting with:

> *'Thank you Mr Chairman and I appreciate that we are starting the year with a much-needed hearing on the brazen <u>attacks</u> on our diplomats in Cuba, and I'd ask that my full statement be included in the record. It's unfortunate that since the news of these bizarre and vicious <u>attacks</u> broke late last summer, we have not seen more public*

> *outcry against the Cuban government for whatever scope of ownership it has over these attacks, or more accountability for the health and well-being of our diplomats, some of whom continue to suffer lingering health conditions form these attacks'.*

The hearings were told that in August 2017 the Brain Injury Centre at the University of Pennsylvania re-evaluated these 16, plus 8 additional individuals who had 'similar findings'[82] (8 Canadians stationed in their Cuban Embassy reported symptoms) [83]. Rubio[81] described these 24 as having '*some combination of the following symptoms: sharp ear pain, dull headaches, ringing in one ear, vertigo, visual focusing issues, disorientation, nausea and extreme fatigue*'. February 2018 saw online publication of a paper[82] and editorial[84] in the March 2018 issue of the *Journal of the American Medical Association* on the University of Pennsylvania findings, which will be summarized below. However, the report critically lacked the context and machinery to counterbalance the media interest in such newsworthy and potentially alarming findings, and the accompanying editorial[84] was not blind to this problem, noting that when publishing case reports and case series in general, '*the fundamental etiology and pathophysiologic mechanism underlying the clinical phenomena are not yet fully understood, but the clear description of potentially pertinent data serves as a foundation on which other clinicians and investigators can build*'. [84] The problem here is that Swanson *et al*.[82] have published no raw data for other investigators to check, and the approach of publishing material that sounds alarms without the possibility of independent testing, continues to build an edifice that has its foundations in the 'ultrasonic death ray' [1,85] and 'ultrasonic sickness'[1,86,87] reports of the 1950s, which have never moved on from the bricks and mortar of anecdote, and retrospective case studies and case series without etiology.

### A.III. The report from the Brain Injury Centre at the University of Pennsylvania

In their journal article, Swanson *et al*.[82] reported on a retrospective case series study that was referred onto them after an initial evaluation. They confirmed that the sufferers reported that the signals were audible, and 'emanating from a distinct direction'. Initial triaging of 80 embassy community members elsewhere had identified 16 people '*with similar exposure history and a constellation of neurological signs and symptoms commonly seen following mild traumatic brain injury, also referred to as concussion*'. With 8 additional candidates identified later, these 24 individuals were on average examined 203 days (range, 3-331 days; median, 189 days; interquartile range, 125 days) after the suspected exposure. Swanson *et al.*[82] reported that from the 21 (11 women and 10 men, with a mean age of 43 years) who completed multidisciplinary evaluation, that "*Persistent symptoms (>3 months after exposure) were reported by these individuals including cognitive (n = 17, 81%), balance (n = 15, 71%), visual (n = 18, 86%), and auditory (n = 15, 68%) dysfunction, sleep impairment (n = 18, 86%), and headaches (n = 16, 76%). Objective findings included cognitive (n = 16, 76%), vestibular (n = 17, 81%), and oculomotor (n = 15, 71%) abnormalities. Moderate to severe sensorineural hearing loss was identified in 3 individuals. Pharmacologic intervention was required for persistent sleep dysfunction (n = 15, 71%) and headache (n = 12, 57%). Fourteen individuals (67%) were held from work at the time of multidisciplinary evaluation. Of those, 7 began graduated return to work with restrictions in place, home exercise programs, and higher-level work-focused cognitive rehabilitation*".[82]

There are important threads to pull together here:

- The reports are on a subset of sufferers (16 out of 80; with a further 8 added from an additional pool of unknown size). The majority of sufferers were not included in the count in calculating the statistics stated above: the majority were, effectively, handled as outliers. Swanson *et al.*[82] appear to have had no choice here, because they only became involved once this down-selection had occurred. Details on this down selection are insufficient to assess whether the appearance of a pattern after down selection is valid.
- Many reports indicated that there was audible sound. Reports that it was outside the range of human hearing are misleading where they suggest a purely covert exposure. Audio frequency sensations in humans can arise from several sources. Very often they are just what they appear to be, directly generated audio frequency sound fields. However, other options

exist. They can be the result of tinnitus. It is possible to produce audio-frequency sound through the nonlinear mixing of two ultrasonic fields, as in the acoustic spotlight[1,45] mentioned in section III (an extension to the ultrasonic regime of the submariner's parametric sonar[47]). Such mixing can also occur accidentally[88] (i.e. by placing two pest deterrents in close proximity). Audio-frequency signals that are not detected by people, but picked up by electronic monitoring equipment, could be the result of electromagnetic pickup, and never sound at all, for which a test can easily be conducted[44]. It is possible that the audible signal recorded by AP may have been accompanied by ultrasonic energy, but there is no evidence of this. Whether any of the above possibilities relate to the sound recorded by AP in Cuba is speculation, without evidence. What is crucially missing from the AP recording is any assessment of the amplitude of the signal, and this is crucial. If the reports by AP (that sufferers identified the data in Figure 1 as the offensive sound) are correct, then the audible component is at 6-9 kHz. Exposure to a sound at 6-9 kHz that is capable of producing adverse effects more than 200 days later, including hearing loss, is not an uncertain or marginal signal: it would have been extremely, unforgettably loud. Whilst AP notes that sufferers recall the sound as having '*extreme volumes*'[75], its elusiveness, and reports that it could be confined to some parts of the room[75], and the fact that AP stated their clip had '*been digitally enhanced to increase volume and reduce background noise*'[75], possibly suggest that the sound might have been less loud than those which are commonly accepted to represent clear hazard. Lack of information on the amplitude of this AP sound is crucial, because it not only affects human response, but also the degree to which the recording equipment might introduce distortions. Exposure limits are based on the level and duration of exposure, but the key finding that the exposure was audible and unpleasant, if AP reports are correct, mean it is possible to surmise a short exposure, since subjects would move away from the source (one reason why 'ultrasonic attacks' have carried such fascination since the first unfounded anecdotes of the 1950s, is that exposure is covert, so that the subject is not aware of the need to protect themselves). Table 1 indicates some exposure levels from OSHA[89], NIOSH[90] and the EU Parliament[91]. Given that these levels are predicated on avoiding adverse effects, then questions must be raised as to how the AP signal could have been sufficiently loud to cause the cited effects up to 331 days after exposure, yet still need amplification to reduce the masking effect of background noise. Without testimony from the sufferers, or better yet calibrated acoustical measurements, it is hard to be conclusive, but the published evidence does not support the narrative of an acoustical attack.

- With the exception of permanent hearing threshold changes (which have only been associated with long term occupation ultrasonic exposure in the presence of significant levels of voice frequency noise), all reports of ill effects attributed to ultrasonic exposure indicate that the symptoms disappear when the source of exposure is removed, yet the Swanson *et al.* tested individuals an average of 203 days after the suspected exposure and stated that '*most patients referred following suspected exposure in Havana exhibited significant impairment that persisted for months with no significant improvement in multiple cases until rehabilitation was initiated*'. Furthermore, at 43, the average age is older than one might expect for exposure to ultrasound, and for exposures in the home one might expect the most easily detectable symptoms to manifest in the young.
- What led to suggestions that this might be ultrasonics, or some other form of sonic attack? There were many assertions that this was the case, but it is important to explore the route by which this connection was made. The diversity of complaints made by the original 80 staff have never been published, and although there were third hand reports of auditory effects, unusual sounds and hearing loss, and the 'subjective symptoms' that are commonly (in anecdotally) associated with exposure to ultrasound that have caused adverse effects, there is no scientific evidence on this published to allow us to work out the correlation between the reports of the original 80, the wider field of people examined in August 2017, and those whom the authorities claim were 'attacked'.

- What led to suggestions of brain injury'?

The final question in the preceding list is vital. The two most emotive words commonly used in discussion of the situation in Cuba, and now China[92], by the media and politicians, is 'attack' and 'brain'. Use of these is so unsupported by the current evidence that their omission from the discussion would be helpful. Consider the entirety of the comments by Swanson *et al*. [82] on the 'white matter' issue:

> *"MRI neuroimaging was obtained in all 21 patients. Most patients had conventional imaging findings, which were within normal limits, at most showing a few small nonspecific T2-bright foci in the white matter (n =9, 43%). There were 3 patients with multiple T2-bright white matter foci, which were more than expected for age, 2 mild in degree, and 1 with moderate changes. The pattern of conventional imaging findings in these cases was nonspecific with regard to the exposure/insult experienced, and the findings could perhaps be attributed to other preexisting disease processes or risk factors. Advanced structural and functional neuroimaging studies are ongoing."* [82]

Political and media reporting ignored the cautionary note in the last 2 sentences of the above, on the associated etiology, the lack of evidence of causation and the possibility that the detected white matter (which could have a myriad of potential causes that do not require an attack) is the result of pre-existing disease. Also lost was the broader context, specifically that these foci were found in only 3 of the group after downselecting from the original 80 US cases considered in March 2017 plus an unknown number of other cases that were considered when the search was broadened to find an additional 8. The 'white matter' phrase was taken out of context and quoted by non-experts. When coupled to the suggestion of a covert attack by a radiation with which the public has no familiarity, and for which most commentators had no body of expert literature on which to draw, the resulting narrative is unduly alarmist. The opposing commentary of Bartholomew and Zaldívar Pérez[93] provides a useful alternative starting point for assessing the presence or not of an acoustic attack.

However, the most damning indictment of the evidence supporting brain injury, comes from the fact that the statistical analysis used by the Brain Injury Centre at the University of Pennsylvania[82] is unorthodox, indeed unacceptable. It is far more likely to indicate that a candidate has suffered an adverse effect than the methods usually used. It provides no etiology, and so cannot be used to make an evaluation of whether ultrasound was used in an attack, and certainly produce no evidence at all that it was. There could be no possibility of a control group or calibrated acoustical field measurements of the type required to determine adverse reactions, no reactions, and nocebo effects[25,26]. Della *et al.*[94] criticise Swanson *et al.* [82] for supplying only percentiles and not the raw data, and providing no demographic data. It is entirely possible that these elements may have been out of control of Swanson *et al.* [82]. However Della *et al.*[94] also criticise Swanson *et al.* [82] for choices that surely were in their control, of using only a psychometric approach, and of selecting performance below the 40th percentile as the threshold for an ‘abnormal’ result, so high as to give numerous false positives (a criterion where 5% of the normal population would be expected to ‘fail’ the test is more usual).

Let us look at the results in executive function (the processes, controlled by the frontal lobe of the brain, that allow an individual to manage themselves and their resources, including for example working memory, self-control, flexibility in thinking, planning, paying attention etc.). Only 6 of the 21 people who agreed to be examined by the Brain Injury Centre completed all 37 tests; and 6 of these tests assessed the executive function. Swanson *et al*.[82] decided that failure in at least one of these 6 tests would allow them to classify an impairment in executive function[94], and indeed the Penn State team stated that, for all 6 of the people that completed the tests, ‘Impairments were found in executive function’. On the face of it, according to the Penn State criteria, 100% of those who complained of the attack and were tested were found to have impaired executive function, a statement which alarmed politicians and media outlets. However, from a statistical point of view, this is exactly what would be expected in the normal population who had not been to Cuba. To be specific, if the failure criterion of each testis set at the 40th percentile, the chance of a normal, unimpaired individual passing that test is 0.6 (i.e. 1-0.4). The chance of a normal individual passing all 6 tests (assuming the results are statistically independent of one another, which may not be the case) is $0.6^6$ =0.047, i.e. 4.7 percent. Therefore there is a 95.3 percent chance of a normal individual failing one or more test and so being classed as impaired in executive function. This puts a very different perspective on the political and media interpretations which took the Penn State tests to mean that all those exposed to the 'attack', who completed testing, were found to be impaired in their executive brain functions.

Della *et al*.[94] reanalyse what data they could access from the University of Pennsylvania[82] study, only this time choosing a criterion based on the 5th centile 'as it is custom in clinical neuropsychology'. They found fewer test failures, and those failures occurred with no systematic pattern making a neuropsychological diagnostic interpretation impossible. Della *et al*.[94] note that discerning such patterns is a core competence in neuropsychology because performance of an individual in a given test is not illuminating.

### A.IV. A process of elimination

There is a process of elimination, a series of questions that must be asked, before one attributes symptoms to an ultrasonic weapon. There is no doubt that sufficiently intense ultrasonic signals can cause adverse effects in humans. There is far greater doubt as to whether the symptoms presented by an individual are caused by an ultrasonic weapon. As a rough generalization, once adverse effects occur, the greater the intensity of an ultrasonic signal (and the lower its frequency in the ultrasonic range), in general the more serious the symptoms, although susceptibility varies enormously from person to person and is very difficult to predict.

Careful judgement needs to be deployed, especially if evidence is scarce, particularly given the weight of inexpert assessment on the internet. At one extreme, some will state that ultrasound could never cause damage to humans because the intensity of acoustic waves is generally low, and because acoustic waves are almost entirely reflected from the skin. Both points are true but misleading because they neglect the particular sensitivity of the ear and hearing/balance organs (as illustrated by the fact that both points are equally true of sound in the audible frequency range, which we know can cause annoyance and hearing damage if sufficiently loud)[10]. At the other end of the spectrum the internet holds many anecdotal reports, ranging from ultrasonically-induced distraction to extreme harm. The peer reviewed literature contains reports of heating, exacerbated by hair, there being rare reported cases of heating, and even death[95-97], in insects and rodents in excess of 140 dB re 20 µPa, and heating[70,98,99] in human nasal cavities and on the skin between fingers as a result of accidental close-range exposure to very high intensities (>140 dB, probably 160-165 dB, re 20 µPa, at 20 kHz). Such beams are difficult to generate and would not sustain that intensity over long distances. Not enough peer-reviewed evidence exists to be conclusive, but the literature to date suggests that the effects at several metres distance from, say, pest scarers[1,13-15,24,25,43,1,3,63] can be painful, and certainly distracting, in a minority of the population, signals to which the majority (averaged over all ages) are immune. The reports in this Special Issue by Fletcher *et al.*[25,26] found that, to suffer adverse reaction to a signal in air in the ultrasonic (>17.8 kHz) regime, the individual needed to be able to hear the signals. This is not to rule out the possibility of effects from longer or more intense inaudible signals (and indeed we know heating can occur with intense beams, as outlined above), but Fletcher *et al.* [25,26] were looking to excite the mechanisms that produces what have been termed 'subjective' effects (headaches, nausea, failure to perform tasks etc.) within exposure limited by strict ethical guidelines.

Ultrasound would therefore be an odd choice of weapon to produce an adverse reaction in an adult, because the effect is very variable from person to person, and therefore unpredictable, and adults (possibly middle-aged males) would be least sensitive to the signal. The above-mentioned ability of solids to scatter ultrasonic beams, make them unlikely choices to penetrate walls or windows. Strong ultrasonic beams do not propagate well to range, the absorption in air being exacerbated if the beam is strong enough to cause nonlinear effects[47], and the source would need to be large or distributed with phase control to keep the energy within a narrow main beam.

Therefore if somebody were to turn up with some or all of the symptoms associated with modest ultrasonic exposure in air (nausea, headache, fatigue, migraine, tinnitus, dizziness, anxiety, annoyance, failure to concentrate), the above challenges to attributing these to ultrasound mean that there is a process of elimination that should be gone through. First, there is an immediate need to rule out drugs, poisoning, pathogens and anxiety before suggesting these symptoms were caused by ultrasound. Bartholomew and Zaldívar Pérez[93] suggest mass psychogenic illness, which Swanson *et al*.[82] argue against.

Despite this, the stories of an ultrasonic attack persist, so let us suppose that the above sources have been ruled out, and even that ultrasound has been detected at the location of the presumed attack (hopefully by a calibrated detector). Even then it is not possible to conclude that the ultrasound wave was produced by a weapon. The second stage of elimination would then be to rule out accidental exposure by the products which expose the public to ultrasound[1]: pest deterrents, anti-loitering devices, PAVA systems, etc. – mobile phones alone have an impressive rate of bringing new ultrasonic signals close to the head through insect deterrents[100], proximity sensors[101], and a host of apps to annoy teenagers etc.

Therefore, before the event in Cuba can be attributed to an ultrasonic weapon, it must first be attributed to ultrasound. If this is done, one further step is required in the process of elimination, and that is to rule out accidental ultrasonic exposure.

### A.V. How ultrasonic attack stories arise

Ultrasound as a weapon can be unpleasant at close ranges, but there are far more unpleasant weapons. Its potential to be used covertly, to generate a range of puzzling effects, and the difficulty in linking cause to effect, and the occurrence of tinnitus in large numbers of people, has caused it to be the subject of rumour for decades, attracting the media and those with genuine symptoms but no alternative explanation. Caution is required because so many other things (increasing public exposure to ultrasound; poisoning; pathogens; drugs; anxiety) can cause a similar set of symptoms. Therefore making an unjustified claim of the deliberate use of an ultrasonic weapons without ruling out all these other possibilities, is rash.

Rumours about ultrasonic weapons have been compounded by confusion with non-ultrasonic acoustic weapons, such as the LRAD devices[1,102,103] which emit at around ~2.5 kHz and were ostensibly designed for long range communication, but have been deployed for crowd control[104]. An attack by an LRAD would not be ultrasonic, and so is out of the remit of this Special Issue. However the likelihood of a commercially-available device like an LRAD being deployed to target someone in a building at distance, is far greater than the likelihood of successfully completing the development work for an ultrasonic device to do the same task. An LRAD attack, however, would not be as elusive to pin down as the Cuban incident appears to be. If an LRAD was indeed deployed, speculation about the role of ultrasonics is misleading.

Given the limited information present, association of the Havana incident with acoustic exposure seems to have occurred because: (i) nearly all of those studied by Swanson *et al*. [82] reported '*directional audible and/or sensory phenomena that was followed by the development of a consistent cluster of neurological signs and symptoms*', yet (ii) Swanson *et al*. [82] were unable to attribute these to any known medical cause (viral, chemical, collective delusional disorders, though these were not systematically excluded); and (iii) '*individuals experienced unilateral ear pain and tinnitus after exposure, and some were later detected to have a unilateral peripheral vestibulopathy (along with central vestibular dysfunction)*'. These symptoms are not consistent with known causes, and the appearance of auditory/vestibular cues and symptoms might have suggested an acoustic cause. However ultrasonically-generated symptoms do not benefit from the long medical history of correlation with symptoms and measurables, that infection and chemically induced symptoms possess, that enabled them to be ruled out as causes. Taken as a whole, some aspects of the limited reports available suggest the source of problem was not ultrasonic.

The topic of the potential of adverse effects on humans from ultrasound has been plagued by six decades of poor reporting: unverified anecdotes making it impossible to sort any potentially useful information from misleading information; reports based on measurements with poor or non-existent calibrations; exposures contaminated with voice-frequency noise which may dominate any adverse reactions; decisions based on agendas rather than data (as on use of the ACGIH suggestions to shape OSHA guidelines, described above); lack of double blind testing to sort out causality in any human effects or responses that are observed. The Cuban event contained all the above, and added to it consequences of running a battery of sophisticated tests, and expressing the results in a highly respected peer-reviewed journal using phrases that, taken out of context, will be alarmist. A powerful driver to the momentum these 'ultrasonic death ray' stories have had since their inception[1,85] in the 1950s has been the impression that the exposures are covert (a statement that US officials believed the attack to involve a 'covert sonic device' appeared frequently in the media from as early[105] as August 2017). A covert attack brings the fear of having an unknown history of exposure, and no sensory cues to warn that there is a current exposure that requires protective measures. Coupled with the absence of history of past confirmed cases by which those exposed, and their doctors, can assess the progression of any adverse effects and route to recover, the introduction of a possible covert acoustic attack into the Cuban narrative could only lead to a fearful response, which we know can lead to symptoms[26]. This foreseeable result should have been balanced against the paucity of data linking acoustic conditions in Cuba to the reported symptoms.

### A.VI. Conclusions

It is possible to generate adverse effects in some individuals using low frequency ultrasound. It is a simple matter to irradiate a group of people in a given room, but ultrasound in air is not a long range weapon.

Currently everything in the evidence points away from labelling the events in Cuba and China as being ultrasonic attacks that causes brain injury. These terms are emotive and misleading. First, the only evidence that this is sonic, let alone ultrasonic, is indirect testimonies that have not been published, and as someone who deals will anecdotal reports of ultrasonic attacks, there needs to be much greater weight of evidence before this is termed "sonic". Second, as someone who has investigated many purported claims of ultrasonic attacks, I have never found one to be an actual attack. They were either not sonic, or if they were, were accidental exposures. Third, references to brain injury caused by such an attack do not reflect the evidence in the scientific and medical tests that were conducted on the people who were examined.

Attempts to fit the evidence to the narrative of an ultrasonic attack that caused brain injury produces anomalies. The detection of symptoms hundreds of days after exposure ceased does not coSnform to with what is known of adverse effects of ultrasound in air. The way the 24 individuals were selected for testing, the criteria for failure of a test, the drawing of conclusions based on a given test, demand further explanation and justification. The selection of a radiation whose effect is unpredictable and to which adult males are probably the most robust, would be curious.

At best, statements of sonic attacks causing brain injury are speculative and premature, and the evidence to date points away from these conclusions.

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| Exposure Time | A-weighted dB level (OSHA) re 20 µPa | A-weighted dB level (NIOSH) re 20 µPa | EU Parliament A-weighted dB level re 20 µPa | | |
|---|---|---|---|---|---|
| | | | *Lower Exposure Action: hearing conservation program must be placed in effect* | *Upper Exposure Action: exposure levels at work must be lower than this* | *Exposure Limit: Breach of these levels has serious consequences for company* |
| 8 hours | 90 | 85 | 80 | 85 | 87 |
| 4 hours | 95 | 88 | 83 | 88 | 90 |
| 2 hours | 100 | 91 | 86 | 91 | 93 |
| 1 hours | 105 | 94 | 89 | 94 | 96 |
| 30 minutes | 110 | 97 | 92 | 97 | 99 |
| 15 minutes | 115 | 100 | 95 | 100 | 102 |
| | 115 for < 15 minutes | 115 for 28 s<br>130-140 for <1 s | 98 | 103 | 105 |
| Maximum allowable instantaneous peak | 140 | 140 | 135 | 137 | 140 |

*Table 1. Various occupational exposure levels for selected durations (not comprehensive) from OSHA*[89]*, NIOSH*[90] *and the EU*[91]*. It should be noted that the use of A-weighting, as here, is inappropriate for signals in excess of the 20 kHz third octave band, and possibly for signals in the 16 kHz third octave band if the mechanism and type of adverse effect are difference from those identified by these agencies as requiring protection at voice-frequencies.*

FIGURES

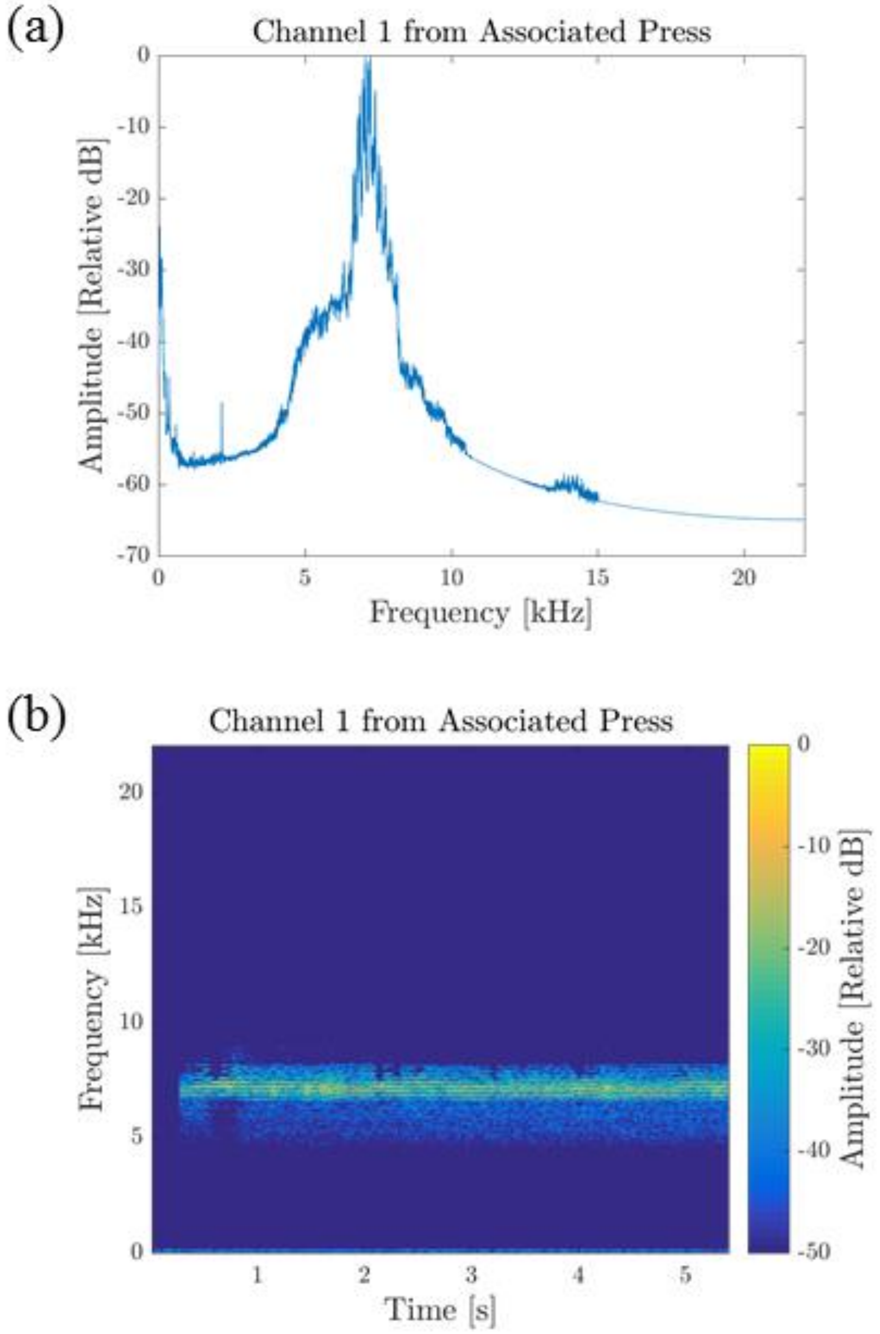

*Figure 1. Analysis of the recording published by Associated Press[75] of the possible disturbing sound detected in Cuba. There is no amplitude calibration.*