Airborne ultrasonic standards for hearing protection, 2008

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INTRODUCTION

The American Conference of Governmental Industrial Hygienists (ACGIH) increased the threshold level Values (TLVs) for airborne ultrasound and these levels were adopted by Occupational Safety and Health Administration (OSHA) in 2003. The European community, Australia and Canada have retained the more stringent levels that stemmed from reports of “ultrasonic sickness” in the 1960s. Ultrasound can be solely airborne, or it can be fluid and/or solid-coupled. The substantial impedance mismatch between the air and the body prevents absorption of most of the airborne ultrasound energy. When airborne ultrasound impacts on human skin, less than 0.1 % of the energy is absorbed (Wiernicki & Karoly 1985). Partially on this basis, the ACGIH voted to raise the TLVs by 30 dB; unless solid or liquid coupling is also possible allowing increased transmission through these paths into the body. A source of risk in industrial applications is the unintended transfer of acoustic energy into the human operator through solid or liquid coupling.

Current exposure standards are based on the concept that detectability and the potential for damage to hearing are related. The current ACGIH TLVs, accepted by OSHA, offer guidelines based on two lines of argument: the bottom up approach addressing detectability of directly coupled ultrasound and the top down approach based on evidence of damage from exposure.

The current ultrasonic standard has four components:

- TLVs for high audio frequencies (10-20 kHz) in air and in water,
- TLVs for airborne ultrasound (25-100 kHz) without coupling to other media (i.e., fluid, substrate),
- TLVs for airborne ultrasound with coupling to other media,
- TLVs for waterborne ultrasound (25-100 kHz) with full body coupling.

Because of the nature of ultrasound propagating in three possible media, one or more of three types of analysis are required, i.e., airborne sound pressure level up to 100 kHz, water sound pressure up to 100 kHz and high frequency vibration. The current ultrasonic TLVs are presented in Table 1.

Table 1: The current ACGIH and OSHA standard

Frequency	Measured in Air in dB re: 20 µPa; Head in Air		Measured in Water in dB re: 1 µPa; Head in Water
Mid-Frequency of Third-Octave Band (kHz)	Ceiling Values	8-Hour TWA	Ceiling Values
10	105[A]	88[A]	167
12.5	105[A]	89[A]	167
16	105[A]	92[A]	167
20	105[A]	94[A]	167
25	110[B]	--	172
31.5	115[B]	--	177
40	115[B]	--	177
50	115[B]	--	177
63	115[B]	--	177
80	115[B]	--	177
100	115[B]	--	177

[A]*Subjective annoyance and discomfort may occur in some individuals at levels between 75 and 105 dB for the frequencies from 10 kHz to 20 kHz especially if they are tonal in nature. Hearing protection or engineering controls may be needed to prevent subjective effects. Tonal sounds in frequencies below 10 kHz might also need to be reduced to 80 dB.*

[B]*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. [When the ultrasound source directly contacts the body, the values in the table do not apply. The vibration level at the mastoid bone must be used.] Acceleration Values 15 dB above the reference of 1g rms should be avoided by reduction of exposure or isolation of the body from the coupling source. (g = acceleration due to the force of gravity, 9.80665 meters/second; rms = root-mean-square).*

Source: ACGIH® Worldwide. 2003 TLVs® and BEIs®: Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices, p.107. 6500 Glenway Ave, D7 Cincinnati OH, USA 45211-4438

The ceiling value increase from 110-115 to 140-145 dB SPL for 25-100 kHz displayed in Table 1 reflect the philosophy that the prior TLVs were too stringent, based on the impedance mismatch between skin and airborne ultrasound. The higher TLVs are below the level Parrack (1966) reported temporary threshold shifts. Possible elevation of the thresholds was a topic of a conversation on ultrasonic auditory effects among Drs. Henning von Gierke, Daniel Johnson and the author in the late 1990s at National Institute of Safety and Occupational Health (NISOH). The elevated TLVs are only applied if there is no possibility that the ultrasound can couple to the body through water or some other medium. If there is coupling, the TLVs are 110-115 dB SPL for 25-100 kHz. Ultrasonic energy in the coupling medium is not measured. The possibility of coupling alone triggers the lower TLVs; with no coupling, the TLVs are 140-145 dB.

Table 2: TLVs with no fluid or substrate coupling possible

Mid-Frequency of Third-Octave Band (kHz)	Ceiling Values
25	140 dB SPL
31.5	145
40	145
50	145
63	145
80	145
100	145

If there is coupling in a medium other than air, i.e. fluid or substrate, or the *potential* for coupling, then lower ceiling values apply. The measure is sound pressure level in air, and the assumption is made that the airborne sound pressure levels are an indirectly related to possible coupling energy.

Table 3: TLVs when fluid or substrate coupling is possible

Mid-Frequency of Third-Octave Band (kHz)	Ceiling Values
25	110 dB SPL
31.5	115
40	115
50	115
63	115
80	115
100	115

There may be circumstances when the source of the ultrasound directly contacts the body. Under these circumstances the TLVs are not to be used since the main ultrasonic exposure is not airborne. “When the ultrasound source directly contacts the body, the values in the table do not apply. The vibration level at the mastoid bone must be used. Acceleration Values 15 dB above the reference of 1g rms should be avoided by reduction of exposure or isolation of the body from the coupling source. (g = acceleration due to the force of gravity, 9.80665 meters/second; rms = root-mean-square).”

The measurement of choice is the vibration level at the mastoid bone. Acceleration values 15 dB above the reference of 1g rms should be avoided. This value is based on subjective detection of ultrasound applied to the head or neck as vibration (Lenhardt et al. 1991). The goal it to limit exposure to levels below detectability.

There is no standard guidance on making acceleration measurements on the head for high frequencies. For example, measurements could be made on either mastoid or both (Lenhardt et al. 2002). The occiput is another potential measurement site. Bone conduction levels are measured as force (mass X acceleration) for the audiometric frequencies (< 6 kHz). Caution should always be exercised in that slight movement (a few mms) of the accelerometer on the mastoid may alter the vibration value by a few dB due to complicated head geometric interactions with ultrasound. The highest acceleration value should be used as a reference after multiple replications (3X).

The forth area of concern is the risk of ultrasonic exposure underwater as reported as early as the the1950s (Deatherage et al. 1954). The measure of ultrasound in water medium involves a different acoustic impedance and a different reference value than in air; hence the levels are much higher. The reference intensity in water is 1 µPa which is 26 dB higher than 20 µPa, the air reference. The differences in medium densities account for approximately 36 dB; thus the difference for two tones of equal intensity in air and water will be approximately 62 dB. With full body coupling, the air values in Table 1 are used as the first approximation. These ceiling values are converted to water sound pressure levels by adding 62 dB. Thus at 25 kHz the air reference (with coupling to another medium) is 110 dB SPL (air) which is equivalent to 172 dB SPL (water). There is good agreement with near detectablity and the TLV at 50 kHz and exceeding the TLV has resulted in long term tinnitus (Deatherage et al. 1954). Deatherage et al. (1954) is the only reference to waterborne ultrasound producing tinnitus after numerous suprathreshold exposures in an attempt to assess loudness. No hearing loss was reported in this study but the authors suggested that tinnitus may be an early sign of ear damage. The air and water medium data are presented in Table 4.

Table 4: Ultrasound exposure in air and water (with coupling)

Frequency	**Measured in Air in dB re: 20 µPa; Head in Air**		**Measured in Water in dB re: 1 µPa; Head in Water**
Mid-Frequency of Third-Octave Band (kHz)	**Ceiling Values**	**+**	**Ceiling Values**
10	105	62	167 dB SPL
12.5	105		167
16	105		167
20	105		167
25	110		172
31.5	115		177
40	115		177
50	115		177
63	115		177
80	115		177
100	115		177

METHOD

The revision of the ACGIH TLVs, accepted by OSHA, was based on the bottom up approach of setting a coupled ultrasonic exposure near sensory detectability and the top down approach based on evidence of damage from ultrasonic exposure. This review is the author's and does not necessarily represent the position of the ACGIH.

The focus is only on any current evidence that airborne ultrasound may pose a risk to hearing. To assess risk, an indirect method will be applied which includes:

- understanding the hearing processes / hearing organs, and
- the types of physical ultrasound measurements relating to hearing detection and non-auditory effects.

RESULTS

The bottom up approach of setting the coupled ultrasonic exposure near sensory detectability remains unchanged. For direct contact with the source, the TLV is 15 dB above 1g rms; which is about 5 dB below average threshold at 25 kHz (Lenhardt et al. 1991). The underwater TLV at 50 kHz is approximately 11 dB below threshold (Deatherage et al. 1954).The top down approach to assessing risk is based on evidence of ear damage from ultrasound. In the only such report of ultrasonic hearing damage, Grzesik and Pluta (1986) compared audiometric tests performed twice, three years apart in workers exposed to airborne ultrasound. Thresholds from 13 to 17 kHz revealed an average increase of 2-5 dB, beyond the hearing loss corrected for aging. The highest permanent threshold shifts were in the highest audible frequencies. This was interpreted as the cochlea was susceptible to hearing loss at the highest frequencies. More recently, workers exposed to ultrasonic welders, beyond the safe limit at 10-40 kHz, for 3-13 years, have revealed no progressive hearing loss in the 2-6 kHz range. Ultrasonic welders and lace sewing machines are a major source of intense airborne ultrasound (Pawlacyk-Luszczynska et al. (2007a, b).

If contact ultrasound, centered at either 26 or 39 kHz, is applied directly to the head at five dB sensation level (SL), air conduction thresholds from 12 to 18 kHz are increased by 2-29 dB (Lenhardt 2003) paralleling the pattern of permanent hearing loss reported by Grzesik and Pluta (1986) but to a greater degree. When the ultrasonic noise was terminated, normal threshold were again recorded, thus there was only a temporary effect in the cochlea (Lenhardt 2003). Kee et al. (2001) performed the inverse experiment by mixing 20 and 24 kHz tones (5 dB SL) and narrow-bands of audio noise (3-6, 6-9, 9-12, 12-15, 12-18 kHz) at 10-40 dB SL. Distortion product otoacoustic emissions (DPOAEs) were obtained prior to and following the task; there was no change after ultrasonic stimulation. The ultrasonic tones masked the audio noise for only the higher frequency bands. These masking experiments indicating interaction of ultrasound with high audio frequencies (12-18 kHz) is consistent with the pitch matching of ultrasound with high frequency audio tones (Lenhardt et al. 1991; Lenhardt 2003) and thus ultrasound activates first few mm (<4) of cochlear base.

Wilson et al. (2002) reported audiograms in dental hygienists, who used ultrasonic scalers. There was loss of hearing at 3 kHz but not at conventional higher and lower audiometric frequencies. The spectra of ultrasonic drills were broad with the most energy in the 40 kHz range peaking at 80-89 dB SPL (Sorainen & Rytkönen (2002). Noise intensity was measured up to 82 dB A. Thus, the loss at 3 kHz may not be solely due to ultrasound. Further, ultrasonic hearing may be a more common phenomenon that first realized. A series of experiments have been carried out indicating that subjects respond behaviorally and physiologically (electroencephalograms and imaging) to the airborne ultrasonic components in some pieces of music (Oohashi et al. 2000, 2006). The auditory ultrasonic pathway for music was not specified. Ultrasound was subsequently found to pass first through the eyes and brain then into the inner ear (Lenhardt 2007a). The eye is a mechanical structure capable of ultrasound propagation (Görig et al. 2006) and eye conduction of airborne sound could nicely explain hearing loss and tinnitus in young workers exposed to intense ultrasound reported more than 40 years ago (Parrak 1966). Acoustic impedance (Z) is a function of density (kg/m^3) and ultrasonic velocity (/m^{2}s). The transmission coefficient (TC) of air (1.29 kg/m^3) to the skull (1,900 kg/m^3) is 59 dB. The TC from air to the eye (1,090 kg/m^3) is 33 dB. The eye density is approximate the same as brain and the cochlear fluids (1,004 kg/m^3) suggesting little attenuation inside the head. The frequency response of the eye is ultrasonic with a pass band from about 25 to 60 kHz. There remains only one report of some modest very high frequency hearing loss as a possible result of intense airborne exposure. However, now there is evidence that the eye is a window to the ear for airborne ultrasound, the high impedance of skin may not be as solid foundation for TLVs as previously argued.

DISCUSSION

The US OHSA accepted the ACGIH recommended limits to prevent possible hearing loss caused by subharmonics of the ultrasonic frequencies rather than the ultrasonic sound itself. The masking data suggests ultrasound can directly affect the base of the cochlea. It was von Gierke (1950) who first proposed that audible subharmonics of ultrasound and the middle ear (air volume and/or ossicular displacement) were somehow involved in the response of workers to ultrasonic exposure. Displacement of the round and oval windows as release mechanisms for eye induced brain vibration could certainly interact with the ossicular chain, producing audio components that are detectable. Dallos and Linnell (1966) demonstrated intense stimulation can induce subharmonics at the eardrum, but not for ultrasound in humans. Contact ultrasound, at a comfortable level of 15 dB SL, will not produce subharmonics in the canal (Staab et al. 1997). Thus, threshold shifts in the high audio frequencies (10-20 kHz) could be due to high audio noise, ultrasonic subharmonics, ultrasound itself (via the eye) and even lower spectra noise. Because of this ambiguity, the TLVs for high audio frequencies are probably appropriate using time weighted averages (TWAs) at 88-94 dB (Table 1). Some fraction of workers may experience subjective effects between 75-105 dB, thus hearing protection, engineering controls (reflection or absorption barriers) and goggles may be needed. A novel vacuum earplug which distends the eardrum outward and damps the ossicles would attenuate possible ultrasonic subharmonics (Lenhardt 2007b). Worker exposure maintained under the TLVs should prevent adverse effects on their hearing and ability to understand speech. Nonetheless, a review of the high audio frequency ceiling values and possible adjustment might be considered if future evidence supports any increased hearing risk.

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