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Technical note

Measurement of hearing protector insertion loss at ultrasonic frequencies

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Abstract

The preferred method for assessing the attenuation of hearing-protective devices (HPDs) involves real ear attenuation at threshold (REAT) determinations, usually obtained in accordance with ANSI Standard S12.6-1997 or ISO Standard 4869-1, where measurements are normally made in the range 125–8000 Hz. In certain circumstances, the use of an acoustic test fixture (ATF) with built-in artificial ears is an acceptable substitute for subjective testing. In this case, the metric obtained is "insertion loss"; the difference between the open-ear and occluded-ear sound levels measured using the ATF microphone. REAT attenuations are not generally interchangeable with insertion loss measurements; however, their similarity often promotes data comparison. Experience has shown that subjective thresholds obtained above 8000 Hz are highly variable due primarily to decreased hearing sensitivity and to the complexity of high-frequency wave patterns. With an ATF, measurements may be carried out over an extended frequency range while minimizing the problems associated with subjective evaluations. In this study, the high-frequency insertion loss of two earmuff and three earplug HPDs was measured objectively at frequencies up to 22.4 kHz. One of the earplugs provided consistently better performance than the other devices for both grazing and direct sound incidence. In addition, two lightweight materials (copier paper and foamcore sheeting) were evaluated for high-frequency noise reduction when placed in the direct path between the sound source and the artificial ear of the ATF. Of these, the foamcore was the more effective barrier. Crown copyright © 2000 Published by Elsevier Science Ltd. All rights reserved.

Keywords: Ultrasound protection; Hearing protective device (HPD) performance; High frequency HPD insertion loss; Acoustic test fixture (ATF) measurements

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1. Introduction

The term "ultrasound" implies a sound that cannot be heard because its frequency is above the range of human hearing, yet the allocation of the minimum frequency boundary applying to the ultrasound region continues to be debated. For example, the International Electrotechnical Commission (IEC) [1] and the International Non-Ionizing Radiation Committee [2] consider sound at frequencies above 20 kHz to be ultrasound. However, other organizations such as the Association Française de Normalisation (AFNOR) [3], Health Canada [4] and the World Health Organization (WHO) [5] suggest that 16 kHz is an appropriate lower limit. The American Conference of Governmental Industrial Hygienists (ACGIH) [6] specifies 10 kHz as the minimum ultrasound frequency.

Several studies of typical industrial ultrasound sources such as immersion cleaners and welders [7–9] have shown that the usual operating frequency of the ultrasound transducers is about 20 kHz, that is, beyond the audible range for the majority of a user population. A problem peculiar to certain ultrasound processes involves the accidental generation of audible noise. In cleaners, for example, cavitation in the vicinity of the transducer causes small bubbles to form in the fluid adjacent to the transducer which grow, become resonant, then implode upon themselves. A byproduct of this process is the generation of an unpleasant time-varying sound over a band of audible frequencies below the excitation frequency. The associated sound levels are often sufficient to pose a noise hazard.

Health hazards resulting from exposure to ultrasound such as nausea, vertigo and fatigue (collectively termed ultrasound sickness) have been recognized for many years, both in situations where the energy is transmitted either directly to human tissue or indirectly through the air [4]. The recognition of these hazards is reflected in the existence of several standards and regulations issued by governmental and health agencies in various countries [4–6]. Some of these set limits for exposure to air-transmitted ultrasound intended to minimize the risk of sustaining ultrasound sickness. In contrast to the hazard assessment of audible sound which involves A-weighted level and duration data, most specify acceptable at-ear levels in high-frequency one-third octave bands, typically over the range of 12.5 to 20 kHz, without reference to the duration of exposure.

In general, the minimization of hearing loss and other negative effects of sound exposure are achieved either through a reduction in noise level to which an individual is exposed, or through a reduction in the time of exposure. The former is preferably achieved by appropriate engineering controls, but more often through the use of personal hearing protection.

The preferred method for assessing the performance of hearing-protective devices (HPDs) is the real ear attenuation at threshold (REAT) procedure given in ANSI S12.6-1997 [10] and in ISO 4869-1 [11]. Measurements according to these standards are typically performed over the range of 125 to 8000 Hz. Other than the work of Berger, who in 1984 provided a summary of REAT data at 16 kHz and below for several HPDs [12], there are few commercial data available describing the noise reduction characteristics of HPDs in this frequency range. Given the abundance of ultrasound devices in the workplace, there is a clear requirement to improve the methodology whereby high-frequency attenuation may be quantified to ensure that adequate ear protection is being provided for ultrasound-exposed individuals.

The use of an acoustic test fixture (ATF) fitted with artificial ears is gaining acceptance [13] as a substitute for REAT evaluations in screening and in performance comparisons, due to the distinct advantages of time and cost effectiveness. Of particular interest in this study was the ease with which measurements may be carried out at frequencies above 8000 Hz, where experience has shown that subjective data are highly variable. The characteristic that is measured is "insertion loss", taken as the difference in the sound level at the ATF microphone when the ATF is subjected to the same sound field with and without the protector in place. For comparison with REAT data, ATF-based results should be compensated for the effect of physiological noise and the bone conduction pathways, which exist in real observers. This can be done using a mathematical model developed by Schroeter and Poesselt [14]. The objective of this study was to measure the high-frequency insertion loss of selected hearing protectors using an ATF.

2. Procedure

2.1. Samples for testing

The following HPDs and materials were tested for their high-frequency insertion loss properties. The materials, (f) and (g), were included in the samples to test the concept that ultrasound may be easily controlled by materials known to be ineffective at lower frequencies.

(a) Bilsom Viking Earmuff.
(b) Peltor Comfort H10A Earmuff.
(c) Aearo Company (Cabot Safety) E-A-R Classic Earplug.
(d) Aearo Company (Cabot Safety) E-A-R E-Z-Fit Earplug.
(e) Willson EP-100 Sound Silencer Earplug.
(f) Sheet of standard bond 20 pound letter-size copier paper.
(g) Sheet of foamcore, a lightweight foam layer faced on both surfaces with heavy coated paper, 40×40 cm×6 mm.

2.2. Acoustic test fixture

The ATF headform used in this study was the binaural implementation of a mannequin with one instrumented ear designed and fabricated by the Institute of Biomedical Engineering, University of Toronto, under contract to DCIEM [15]. Features of both mannequins include circumaural areas, pinnae, and auditory canals fabricated with simulated skin and tissue that retain the correct dynamic mass and textural properties of human flesh. The auditory canals are terminated in Zwislocki type DB100 couplers and Brüel & Kjær type 4134 microphones that together emulate the acoustic impedance of human ears. The torso supporting the headform was mounted on a telescoping stand such that the artificial ear was located 150 cm above the floor.

In this study, the binaural ATF was located within a large semi-reverberant room between two sound-absorbent office screens measuring 1.9 by 1.8 m. These were arranged in a non-parallel manner as shown in Fig. 1 to discourage the formation of close-in standing waves. Potentially reflective pathways from the room boundaries were ignored.

2.3. Instrumentation

The test signal for this experiment was pink Gaussian noise (equal energy per octave) generated by a Brüel & Kjær type 2133 digital signal analyzer. This signal was amplified by a Bryston type 2B power amplifier that in turn drove the ultrasound source, a horn-loaded Motorola piezoelectric loudspeaker, type KSN 1016A, capable of producing 1/3 octave-band sound levels of the order of 100 dB at the ATF. The signal from the microphone mounted in the Zwislocki coupler in the left ear of the AFT was fed back to the Brüel & Kjær analyzer to obtain measurements in 1/12 octave bands from 5.79 to 22.4 kHz. For display purposes, the data were combined into the corresponding 1/3 octave bands from 6.3 to 20 kHz.

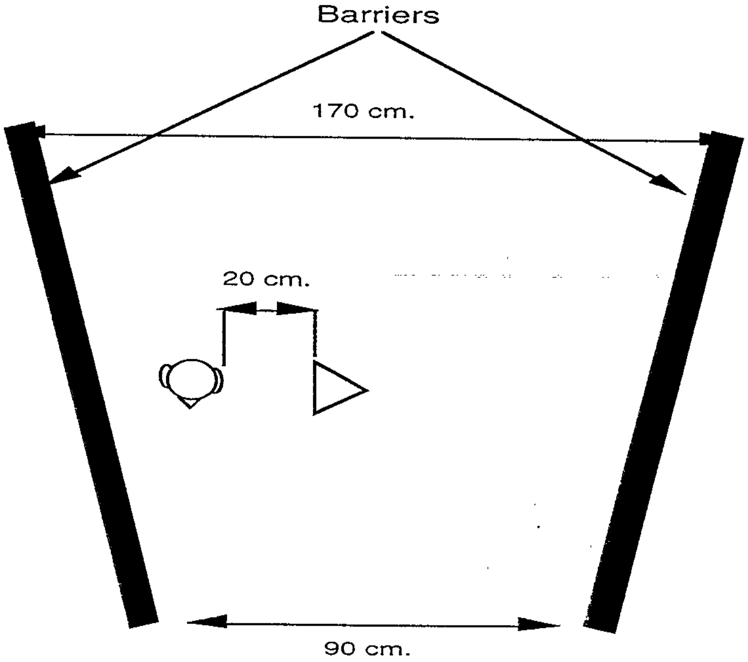

Fig. 1. Arrangement of barriers, ATF and ultrasound source for direct incidence measurements.

2.4. Measurement technique

Two separate series of measurements, one for direct and one for grazing incidence, were performed with the ATF. For direct incidence, the ultrasound source was placed beside the ATF, facing the ear canal at a distance of 20 cm, as shown in Fig. 2. In the grazing incidence series, the sound source was positioned 30 cm in front of the ear canal of the ATF, offset by 10 cm from the saggital plane such that the sound path was tangential to the side of the mannequin headform, as shown in Fig. 3.

Each measurement series was preceded by the acquisition of an open-ear spectrum measurement (when the ear of the ATF was not occluded). Separate measurements were then obtained for three fittings of each HPD for direct and grazing incidence, the fittings being carried out alternately by the authors. At each 1/12 octave-band frequency, the insertion loss was calculated as the difference between the open-ear spectral levels and the occluded levels for each HPD. The residual noise level at the ATF ear was monitored with the ultrasound source turned off to ensure that the accuracy of measurement was compromised neither by a low signal-to-noise ratio nor by insufficient stimulus amplitude.

In an additional test, the sheet barrier materials were placed across the direct sound path at the median point between the ultrasound source and the ATF ear. The sound reduction obtained from spectral differences is the result of a single ad-hoc measurement, and is not represented as a rigorous evaluation of transmission loss.

Fig. 2. Relationship of ATF and ultrasound source for direct-incidence measurements.

3. Results

The results of this study are provided in Tables 1–8; the open-ear spectra are given in Table 1 and the resulting insertion loss for each HPD in Tables 2–6. The mean insertion losses calculated for the HPDs and the sound reduction results of the barrier measurements are shown in Tables 7 and 8. For purposes of comparison, the mean values of insertion loss across fittings with direct and grazing incidence are summarized graphically in Figs. 4 and 5, respectively. Similarly, the results of the barrier assessment are given in Fig. 6.

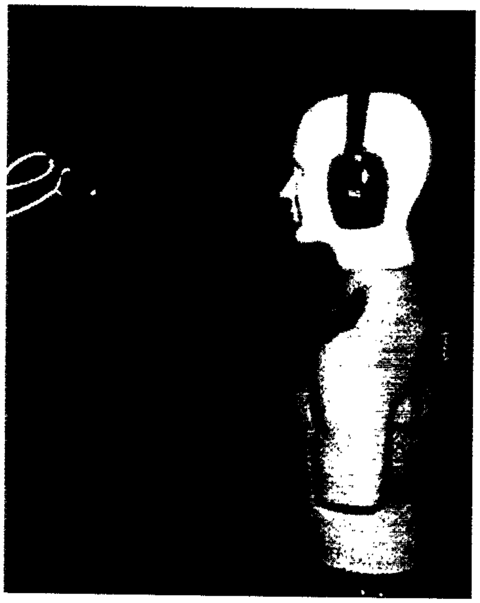

Fig. 3. Relationship of ATF and ultrasound source for grazing-incidence measurements.

Table 1
Open-ear (non-occluded) sound levels in dB at the ear of the ATF

1/3 Octave-band centre frequency	Direct incidence	Grazing incidence
6.3 kHz	104.2	90.2
8 kHz	97.5	80.4
10 kHz	91.9	89.6
12.5 kHz	101.3	105.6
16 kHz	106.0	101.1
20 kHz	92.7	83.4

4. Discussion

4.1. HPD insertion loss

A review of the data presented in Figs. 4 and 5 shows a considerable variation in insertion loss across devices and across direction of incidence. Nonetheless, in this study, the Aearo E-A-R E-Z-Fit earplug consistently appeared to provide the greatest overall insertion loss, regardless of frequency or direction of sound incidence.

Table 2
Insertion loss in dB for three fittings of the Bilsom Viking earmuff

1/3 Octave frequency	Direct incidence			Grazing incidence		
	Fit 1	Fit 2	Fit 3	Fit 1	Fit 2	Fit 3
6.3 kHz	46.3	47.0	47.4	29.3	31.8	19.8
8 kHz	45.8	45.0	44.5	27.4	33.8	24.8
10 kHz	43.3	46.6	44.6	33.8	43.3	35.5
12.5 kHz	48.1	51.9	44.9	48.0	49.3	34.2
16 kHz	54.1	55.1	52.1	33.7	47.9	45.0
20 kHz	48.5	54.4	46.7	38.5	37.5	46.6

Table 3
Insertion loss in dB for three fittings of the Peltor Comfort H10A earmuff

1/3 Octave frequency	Direct incidence			Grazing incidence		
	Fit 1	Fit 2	Fit 3	Fit 1	Fit 2	Fit 3
6.3 kHz	45.2	43.3	48.0	30.5	32.0	31.6
8 kHz	41.7	43.9	43.4	21.6	20.9	21.0
10 kHz	44.5	42.6	48.5	39.5	39.3	37.7
12.5 kHz	42.3	42.2	43.7	48.2	39.2	42.9
16 kHz	50.8	47.9	47.9	44.8	39.0	31.4
20 kHz	49.0	48.4	47.3	47.1	31.7	28.2

Table 4
Insertion loss in dB for three fittings of the Aearo Company (Cabot safety) E-A-R Classic earplug

1/3 Octave frequency	Direct incidence			Grazing incidence		
	Fit 1	Fit 2	Fit 3	Fit 1	Fit 2	Fit 3
6.3 kHz	53.2	55.1	51.3	46.8	48.7	44.0
8 kHz	52.0	58.8	51.9	44.1	40.5	44.8
10 kHz	48.6	51.5	46.5	53.3	50.1	53.3
12.5 kHz	45.0	47.0	33.0	42.5	43.5	43.0
16 kHz	47.1	35.6	48.9	37.1	41.0	45.6
20 kHz	49.9	41.7	47.2	45.7	44.5	45.0

Across HPDs, there was also a general trend toward higher performance with direct incidence and relative independence from frequency, whereas with grazing incidence, there was a trend towards maximum insertion loss at 12.5 kHz. Moreover, without exception, refitting the HPD resulted in considerable variation (see Tables 2–6). It was assumed that the fine structure of the high-frequency sound excitation field was easily disrupted by slight physical differences in the fitting of the protective devices.

Support for the relevance of the objective procedure for measuring extended-frequency insertion loss was obtained by comparing these data with subjective measurements

Table 5
Insertion loss in dB for three fittings of the Aearo company (Cabot safety) E-A-R E-Z-Fit Earplug

1/3 Octave frequency	Direct incidence			Grazing incidence		
	Fit 1	Fit 2	Fit 3	Fit 1	Fit 2	Fit 3
6.3 kHz	51.6	52.9	53.2	48.8	51.5	50.8
8 kHz	55.6	56.8	57.1	42.2	50.4	50.7
10 kHz	50.5	57.1	52.4	49.1	52.5	54.8
12.5 kHz	55.5	50.8	58.2	59.7	64.1	60.9
16 kHz	62.1	58.1	63.2	58.8	62.0	61.8
20 kHz	63.2	60.8	64.1	53.5	62.5	64.2

Table 6
Insertion loss in dB for three fittings of the Willson Sound Silencer earplug

1/3 Octave frequency	Direct incidence			Grazing incidence		
	Fit 1	Fit 2	Fit 3	Fit 1	Fit 2	Fit 3
6.3 kHz	45.1	49.0	45.6	25.6	45.7	45.5
8 kHz	42.4	44.0	33.0	16.9	34.5	35.0
10 kHz	37.5	30.4	26.4	27.8	39.8	32.1
12.5 kHz	47.9	45.0	30.1	31.4	54.8	44.1
16 kHz	53.9	52.6	32.5	21.8	47.0	51.3
20 kHz	48.0	45.7	39.6	23.9	33.6	42.5

Table 7
Mean HPD insertion loss and material sound reduction in dB with direct sound incidence

1/3 Octave frequency	Bilsom Viking	Peltor Comfort	Aearo Classic	Aearo E-Z-Fit	Willson Silencer	Copier paper	Foam core
6.3 kHz	46.9	45.5	53.2	52.6	43.2	8.7	23.9
8 kHz	45.1	43.0	54.2	56.5	39.8	12.2	17.7
10 kHz	44.8	45.2	48.9	53.3	31.4	11.2	21.5
12.5 kHz	48.3	42.7	42.0	54.8	41.0	13.4	31.4
16 kHz	53.8	48.9	43.9	61.1	46.3	13.4	30.8
20 kHz	49.9	48.2	46.3	62.7	44.4	16.3	33.9

reported by Berger [12], as shown in Fig. 7. It has been assumed that the large-volume foam-cushion earmuff measured in Berger's study was similar in performance to the Peltor H10A, and that the E-A-R Classic samples were identical across studies. Berger's data were collected in accordance with ASA STD 1-1975; this implies that his measurements were made in a diffuse noise field. To better approximate that condition in this study, the direct and grazing incidence data were averaged to produce

Table 8
Mean HPD insertion loss and material sound reduction in dB with grazing sound incidence

1/3 Octave frequency	Bilsom Viking	Peltor Comfort	Aearo Classic	Aearo E-Z-Fit	Willson Silencer	Copier paper	Foam core
6.3 kHz	27.0	31.4	46.5	50.4	38.9	10.2	18.4
8 kHz	28.7	21.2	43.1	47.8	28.8	10.7	13.9
10 kHz	37.5	38.8	52.2	52.1	33.2	13.4	22.3
12.5 kHz	41.4	43.4	43.0	61.6	43.4	13.1	29.5
16 kHz	38.0	38.4	41.2	60.9	40.0	10.9	32.7
20 kHz	31.5	35.7	45.1	60.1	33.3	13.9	26.8

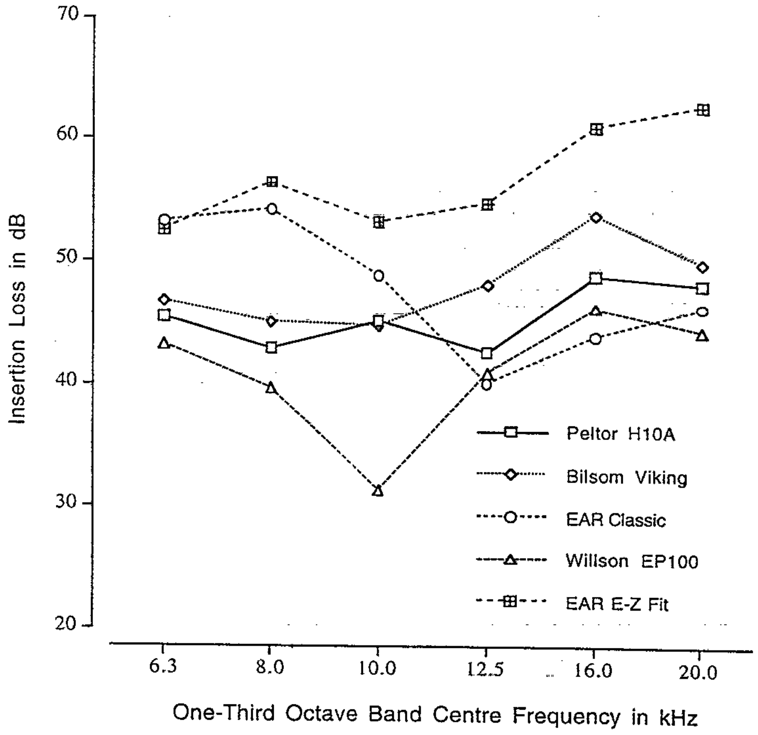

Fig. 4. Mean high-frequency hearing-protective device insertion loss with direct (lateral) source incidence.

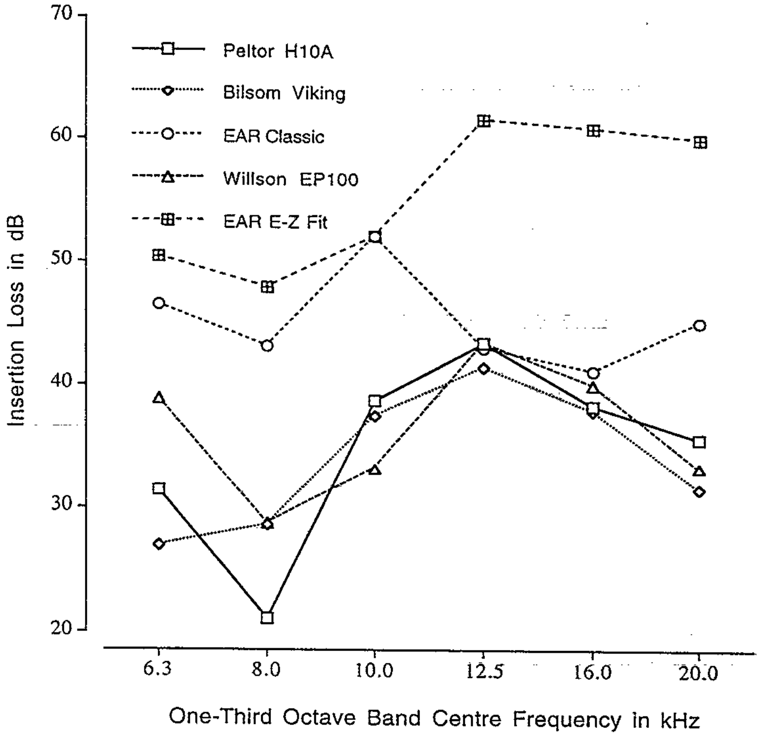

Fig. 5. Mean high frequency hearing-protective device insertion loss with grazing (frontal) sound incidence.

the insertion loss spectra shown in Fig. 7. It is acknowledged that the subjective result was the mean of 10 subjects measured three times ($n = 30$), whereas in the current study only three repeat measurements were performed.

In general, the objective data were more optimistic than those obtained by subjective means. This result might be expected, given the subjective (REAT) limit imposed by approaching the bone conduction threshold, which has also been plotted in Fig. 7. In this experiment, the insertion loss measurements exceeded the bone conduction threshold at several frequencies, as shown in Fig. 7, particularly in the case of the earplug. With the earmuff, objective/subjective differences were greatest at the higher frequencies where the bone conduction threshold was exceeded. Thus for both devices, inclusion of an allowance for bone conduction in the insertion loss data would have improved the agreement between the data sets.

4.2. Sound reduction due to barrier materials

The data of Fig. 6 indicate that losses due to the presence of very light materials can be significant in ultrasound fields, despite insufficient mass to be effective for this purpose at lower frequencies. Although these results may be of academic interest,

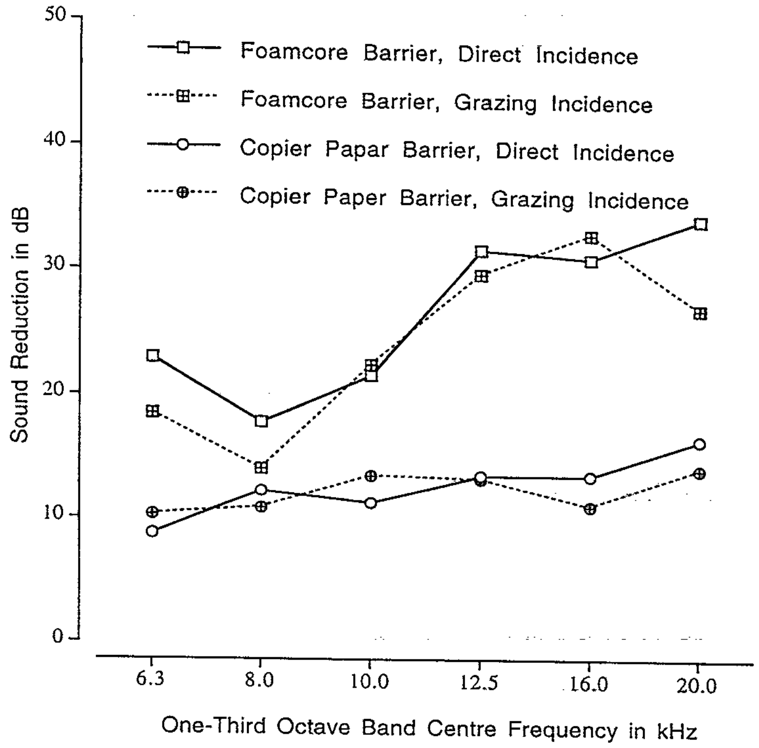

Fig. 6. Direct- and grazing-incidence high-frequency sound reduction due to copier paper and foamcore barrier materials placed across the direct sound path.

commercially available products such as enclosures or acoustical screens and curtains are much more effective at reducing ultrasound exposure.

4.3. *Implications for hearing protection from ultrasound sources*

The effect of personal protection on ultrasound exposure can be calculated as shown in the example of Table 9. In this instance, the actual noise spectrum produced by an ultrasonic cleaner at the operator's position [7] has been reduced by using the mean values obtained for one of the less effective HPDs assessed in this study, averaged across directions of incidence.

The resulting levels can be compared with hearing conservation criteria intended for use with ultrasound. For example, Parrack [16] has suggested that no exposure be permitted if the 20 kHz 1/3 octave band level exceeds 105 dB (considering that a hazard may exist due to sub-harmonic energy accidentally generated by ultrasound equipment), whereas, the hearing damage threshold is thought to be about 140 dB. For avoidance of the symptoms of ultrasound sickness (vertigo, nausea, fatigue, etc.) Acton and Carson [17] have proposed that the power summation of the levels in the 12.5 and 16 kHz 1/3 octave bands should not exceed 78 dB. In the case of the Lewis cleaner, the noise emission levels are considered sufficient to cause symptoms of ultrasonic sickness. An HPD providing the relatively modest performance given Table 9 would still be expected to afford the user a safety margin exceeding 20 dB in reducing the noise of this device. The data suggest that foamcore should also provide adequate protection in this instance, but with a reduced margin of safety.

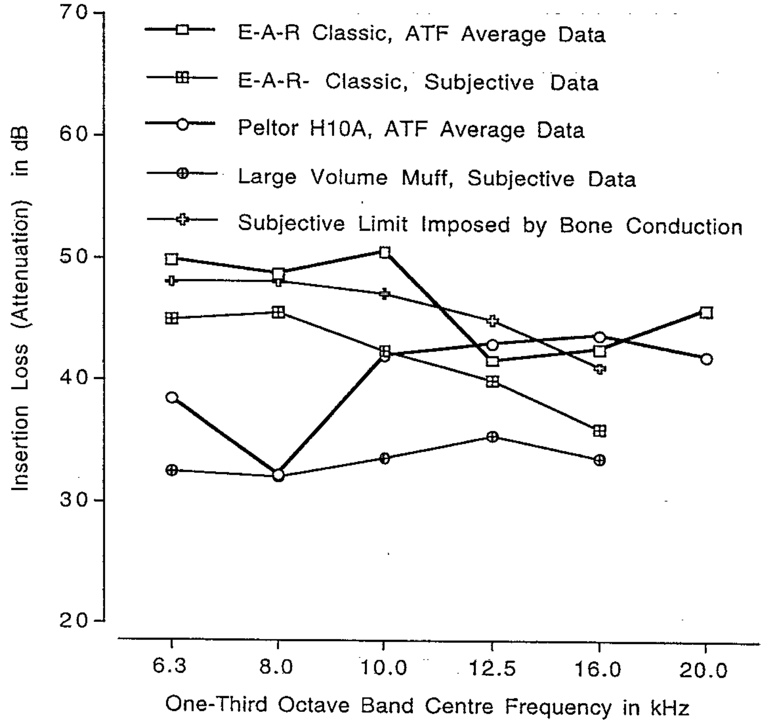

Fig. 7. A comparison of extended-frequency range insertion loss data obtained with an ATF (physical data from current study) with subjective attenuation data obtained by Berger [12].

Table 9
Estimated at-ear sound levels at the operator position of a Lewis type L/C 136H ultrasonic cleaner, assuming the use of Willson Sound Silencer earplugs

1/3 Octave band centre frequency	Lewis ultrasonic cleaner noise	Willson Silencer mean insertion loss	Estimated at-ear levels
6.3 kHz	64	41.1	22.9
8 kHz	71	37.7	33.3
10 kHz	75	32.3	42.7
12.5 kHz	56	42.2	13.8
16 kHz	97	43.2	53.8
20 kHz	103	38.9	64.1

5. Conclusions

The efficacy of using an ATF for the measurement of HPD insertion loss at ultrasonic frequencies has been demonstrated in this study. It has also been shown that a hearing-protective device providing moderate performance at high frequencies would be capable of protecting the hearing of noise-exposed individuals with a wide margin of safety in certain work environments containing ultrasound. Barriers with insufficient mass for effective control of low frequency sound may function well in ultrasound control applications.

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