Dependence of acoustic attenuation of hearing protectors on incident sound level

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ABSTRACT The relationship between incident sound level and acoustic attenuation for four types of earplug and four types of earmuff have been investigated using freshly prepared and instrumented cadaver ears. Pure tones and 1/3-octave bands of random noise in the frequency range 125–8000 Hz were employed as steady-state stimuli with sound pressure levels between 75 and 125 dB. Impulses with peak sound levels in the range 135–175 dB(P) were also presented. For the steady-state signals employed, the eight hearing protectors have been shown to have constant attenuation characteristics over the range of incident sound levels investigated. This was also the case for the six conventional protectors (with intentionally linear characteristics) for the impulse stimuli. The two intentionally amplitude-sensitive protectors provided attenuation which increased with incident sound level for impulse noises. Comparison of the protector attenuation–frequency characteristics determined for steady-state sounds shows good agreement with those obtained from subjective (threshold shift) national standard measurement procedures. It may be concluded, therefore, that the six conventional hearing protectors studied here have attenuation characteristics that are equal for incident sound levels at about 40 and 75 dB, and that they are constant for levels between 75 and 175 dB. Consequently, the results of national standard threshold-shift procedures, although measured at low sound levels, may be applied with confidence to occupations where hazardous high-level noises are present.

With increasing dependence being placed by industry on personal hearing protection as a means of reducing hazardous noise exposure, there has been a growing need for accurate measurement of their acoustic attenuation characteristics, so that reliable selection of the appropriate protectors may be made for a particular noise environment. A number of experimental techniques are available for evaluating hearing protectors (Whitham and Martin, 1976), but the one usually employed is the real-ear at threshold method. This technique forms the basis of the American standard ASA Z24.22:1957 (American Standards Association, 1957), the British standard BS 5108: 1974 (British Standards Institution, 1974), and the new American standard ASA STD-1: 1975 (Acoustical Society of America, 1975) among others. As the method relies on determining the difference between the binaural free-field thresholds of hearing of human subjects with and without the protectors in question, it necessarily measures

attenuation at low incident sound levels. It does not permit examination of the variation of attenuation characteristics with increasing sound levels, neither does it allow the attenuation of impulse noises nor the characteristics of non-linear amplitude-sensitive protective devices to be evaluated. Furthermore, the accuracy of the technique at low test frequencies is doubtful, where subjective physiological noise may artificially enhance the measured attenuation. Nevertheless, the method still remains the most acceptable for national standard measurements.

At present, protector attenuation data obtained by this standard laboratory measurement technique at low incident steady-state sound levels are applied to practical occupational situations where hazardous high levels of noise are present and where, quite commonly, impulse noise is also present to a greater or lesser degree. It is therefore most important that the relationships between attenuation and incident sound level, for both steady-state and impulse sounds, are examined over a range including the hazardous noise levels found in industry. If it can be

Received for publication 8 February 1978

Accepted for publication 28 July 1978

shown that protector attenuation characteristics are essentially constant over this range, then attenuation data obtained in the laboratory may be applied with confidence to the industrial situation.

The use of an artificial ear or head to examine these particular protector characteristics is an appropriate measurement technique. However, the problems of simulating accurately the many complex dynamic, physical and acoustical properties of the human head and external ear canal have not been completely solved so far.

In order to overcome these problems, while still retaining the versatility and flexibility of an 'artificial head' approach, freshly prepared and instrumented cadaver ears have been used. A small measurement microphone is introduced through the postero-superior wall of the deeper bony part of the cadaver external meatus, so that its diaphragm is flush with the meatus wall external to the intact eardrum. This enables the sound level in the region of the eardrum to be measured under various experimental conditions.

This paper describes measurements, carried out using this technique, of the attenuation-frequency characteristics of eight hearing protectors for pure-tone, 1/3-octave bands of random noise and impulses, with sound levels in the range 75–175 dB. The linearity of attenuation characteristics of the protectors, of which two are amplitude-sensitive devices, was examined over this range, and average attenuation data were compared with the results of standard subjective tests. The acoustical characteristics of the unoccluded ear canal were also assessed.

Methods

Measurements were carried out on the ears of nine cadavers in the post-mortem room of the mortuary at Southampton General Hospital. This room constituted a semi-reverberant sound field during testing.

PREPARATION OF CADAVER EARS

Cadavers were tested following the course of a normal post-mortem examination, which involved the removal of the skull roof and brain, thus giving access to the internal aspects of the skull. The preparation technique has been described by Forrest and Coles (1969) and was briefly as follows.

Any cerumen in the ear canal was removed and the eardrum examined for normality of appearance and mobility. The acoustic impedance at the eardrum was measured using the Grason-Stadler type 3 acoustic impedance bridge designed by Zwislöcki (1963) and evaluated by Bicknell and Morgan (1968).

A metal sleeve was then inserted from within the cranial cavity through a hole drilled downward and slightly anteriorly through the squamopetrous suture so that the lower end of the sleeve was flush with the skin of the meatus just lateral to the eardrum. The sleeve fixture was made strong and airtight with dental cement further surrounded with plasticine. A tightly fitting Bruel and Kjaer quarter-inch condenser microphone was then inserted into the sleeve so that its diaphragm was flush with the external meatus wall (Figure 1). To reduce the possibility of damage to the delicate microphone diaphragm during its insertion, a dummy microphone was used as an obturator to remove any debris in the sleeve.

EQUIPMENT

Electronic equipment used for the generation, recording and analysis of the acoustic stimuli employed during the experiment was set up in the post-mortem room (Figure 2).

Pure tones were generated by a Bruel and Kjaer beat frequency oscillator, type 1022, and amplified by a Quad power amplifier, type 303, before being presented by a Goodmans Magnum K loudspeaker. A Bruel and Kjaer random noise generator, type 1405, and filter set, type 1615, produced 1/3-octave bands of random noise which were then amplified and transduced by the loudspeaker. Impulse noises were generated with a starting pistol using either 0.22 or 0.32 inch cartridges.

Acoustic signals both inside and outside the cadaver ear were picked up by two Bruel and Kjaer $\frac{1}{4}$ -inch condenser microphones, type 4136, and associated pre-amplifiers. During pure-tone stimulation the signals from the two microphones were analysed on Bruel and Kjaer audio-frequency analysers type 2107, and Bruel and Kjaer microphone amplifiers, type 2604 and filter sets were used when 1/3-octave bands of random noise were presented. Impulse noises were recorded on a two-channel Tektronics storage oscilloscope, type 564, in the form of sound pressure-time waveforms which were then photographed with a Polaroid oscilloscope camera. A third microphone and amplifier were used to trigger the oscilloscope. All measurement equipment was calibrated with a Bruel and Kjaer piston-phone type 4220 before measurements were made, and this was checked at various times during each session.

EXPERIMENTAL PROCEDURE

After preparation and instrumentation of the cadaver ear with the internal microphone (microphone A in Figure 2), the external microphone (microphone B) was set up at a distance of 150 mm from, and

Fig. 1 Cadaver ear instrumented with 1/4-inch condenser microphone. After Forrest and Coles (1970).

Fig. 2 Stimulus-generating and analysis equipment.

directly in line with, the cadaver ear canal. This position was standardised for measurements of both earplugs and earmuffs to minimise any variations in the incident sound field, such as reflection and diffraction effects, which might have been caused by

the presence of earmuff shells, and to allow direct comparison between measurements on different types of protector.

The sound levels were measured at positions A and B for pure tones and 1/3-octave bands of

Table 1 *Characteristics of hearing protectors evaluated in the study*

Code	Type	Characteristics
A	Earplug	Prefabricated solid plastic.
B	Earplug	Semi-disposable plastic foam.
C	Earplug	Prefabricated plastic, non-linear device.
D	Earplug	Non-linear valve in rubber capsule.
E	Earmuff	Symmetric plastic shells, foam-filled cushion seals.
F	Earmuff	Symmetric plastic shells, foam-filled cushion seals.
G	Earmuff	Asymmetric plastic shells, liquid-filled cushion seals.
H	Earmuff	Asymmetric plastic shells, liquid-filled cushion seals. Mechanical valve.

random noise with centre frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300 and 8000 Hz for incident sound levels varying in steps of 10 dB in the range 75–125 dB. Similar measurements were also made at these positions using impulses with peak sound levels in the range 135–175 dB(P). This range was obtained by using 0.22 and 0.32 inch cartridges and by varying the distance between the starting pistol and the cadavers for the eight different types of hearing protector described in Table 1, although time limitations in the post-mortem room precluded examination of all signal and ear conditions for all the cadaver ears. The sound levels at the two microphone positions were also measured on the nine cadaver ears in the unoccluded condition (without fitted protector).

In all, 3825 measurements of acoustic attenuation were made for steady-state stimuli at the different test frequencies and 170 measurements of attenuation were made for impulse stimuli.

Transmission loss and insertion loss

In general, measurements of the sound levels at microphone positions A and B, with and without a

protector occluding the ear, allow three separate but interdependent quantities to be deduced. These are the transmission loss of the hearing protector, the transfer function of the open ear, and the insertion loss of the protector. They may be defined in terms of the three measurements, diagrammatically represented in Figure 3, where A is the measured sound level at the eardrum with the ear unoccluded, A' is the sound level at the eardrum with the ear occluded by a protector, and B is the external sound level measured at a point 150 mm from the entrance to the ear canal:

Protector transmission loss:

$$TL = B - A' \quad (i)$$

Transfer function of open ear:

$$TFOE = B - A \quad (ii)$$

Protector insertion loss:

$$IL = A - A' \quad (iii)$$

Both transmission loss and insertion loss are measures of attenuation but, from a practical viewpoint, the insertion loss is the more important. This is the measure evaluated by standard subjective procedures and is the value most relevant to the wearer in industry in the context of hearing conservation. It provides a measure of the reduction in sound level at the eardrum which occurs when a protector is fitted to the ear.

Time limitations, and attempts to reduce errors caused by repeated refitting of the protector, precluded direct measurement of the insertion loss of each protector; however, this was deduced from its transmission loss and the transfer function of the open ear, as follows:

Subtraction of equation (ii) from equation (i) gives:

$$TL - TFOE = A - A' \quad (iv)$$

which, from equation (iii), gives

$$IL = TL - TFOE \quad (v)$$

Fig. 3 *Measurements in the occluded and unoccluded experimental conditions.*

Thus the insertion loss of a protector may be deduced by subtracting the transfer function of the open ear from the transmission loss of the protector. In practice TFOE is generally negative (a gain) and is therefore added to the transmission loss to give the insertion loss.

Hearing protectors tested

The general characteristics of the hearing protectors tested are summarised briefly in Table 1. Of the four earplugs tested, two (C and D), were intentionally non-linear amplitude-sensitive devices intended for protection against gunfire noise, while allowing steady-state sounds to be partially transmitted. Earmuff H had an externally adjustable valve on each shell, which in the open position was intended to act as a non-linear device for protection against gunfire and in the closed position acted like a normal earmuff. Both open and closed valve conditions were evaluated for this protector.

As far as possible, test hearing protectors were fitted to cadaver ears in a similar manner to that for normal live subjects. Earmuff shells were placed over both ears with the tensioning headband over the top of the head, while the correct size of earplug was individually fitted to the ear canal where this was appropriate.

Results

The sex and age at death of the cadavers tested are noted in Table 2 together with the ear on which measurements were made. The mean age at death of the cadavers was 67 years.

Measurements of eardrum impedances with the Zwislocki acoustic bridge showed that the impedance components, resistance and reactance of the unprepared ears all came within clinically accepted normal limits for live ears. In addition, instrumentation of each cadaver ear with the condenser microphone did not alter these values sufficiently to reach statistical significance. Thus, in the context of this study, each instrumented cadaver ear canal was

assumed to act acoustically in an approximately similar manner to that of a live human ear.

To ensure that acoustic and vibration pathways to the measurement microphone, other than those of interest, were minimised by the preparation technique, each cadaver ear was fitted with a good ear-plug and good earmuff and the attenuation of this combination was determined. Both protectors were very carefully fitted to obtain maximum attenuation. In all cases the resulting attenuation was found to be greater than that measured for individual protectors at all test frequencies. It was thus concluded that attenuation data for individual protectors was not influenced significantly by possible spurious microphonic effects caused by vibration of the internal measurement microphone or its pre-amplifier, nor by sound passing through the floor of the cadaver skull.

MEASUREMENTS IN THE UNOCCLUDED EXPERIMENTAL CONDITION

The results of measurements made on cadavers with the ear unoccluded by any protectors provide a measure of the acoustic transfer characteristics of the human ear between a point adjacent to the eardrum and the external sound field, as well as factors to correct transmission-loss measurements to insertion-loss values. It is the insertion-loss of a protector which is of greater interest when comparing attenuation data observed here with that derived by other subjective standard measurement techniques.

In the case of the steady-state stimuli the attenuation (the experimental measure of the acoustical transfer characteristics) of the unoccluded ear was found to be constant with external sound level over the range studied, as shown by linear regression analyses undertaken at each test frequency. Consequently, the data were combined to give estimates of the mean value at each test frequency. Figure 4 shows the means and standard deviations of the attenuation for pure tones and for 1/3-octave bands of random noise, each point being the mean of 37 measurements. Figure 4 shows that there is a gain in the system above 500 Hz, which is maximally about 10 dB in the case of pure tones between 2 and 6 kHz and maximally about 13 dB for the 1/3-octave band of random noise centred on 2 kHz.

The observed gain is assumed to be caused by resonances in the external ear and ear canal and may be regarded as quite substantial. Certainly, a hearing protector must overcome this gain before actually providing attenuation of the sound reaching the eardrum. This presumably is achieved, partly by its actual presence on or in the ear, thereby reducing and possibly changing these resonances, and partly by acting as a simple acoustic barrier.

Table 2 Sex, age at death and ear tested of cadavers used in the study

Cadaver serial no.	Age at death	Sex	Ear tested
1	71	M	R
2	65	M	R
3	59	M	L
4	70	M	L
5	54	F	R
6	63	M	R
7	87	M	L
8	71	M	L
9	60	F	L

Fig. 4 Transfer characteristics of unoccluded ear for steady-state stimuli.

In the case of impulse-noise stimuli, a linear regression analysis of 17 measurements of attenuation produced a correlation coefficient which was not significant. Consequently, as in the case of steady-state stimuli, the transfer characteristics of the unoccluded ear may be regarded as constant with incident peak sound level over the range 135–175 dB(P). The mean attenuation (reduction in peak level) was found to be -11.1 dB with a standard deviation of 3.03 dB. Thus a gain of 11.1 dB in the initial peaks of impulses was observed and this is entirely consistent with the results for steady-state stimuli. This is to be expected, as the frequency spectrum of the impulse noise is generally broad-band over the frequency range of interest, with considerable energy at the higher frequencies.

Forrest and Coles (1969) carried out similar measurements on unoccluded cadaver ears using pure tones and impulses. Their pure-tone data are compared with the results of the present study in Figure 4. There is reasonably close agreement between the two studies except at 3 and 4 kHz, where Forrest and Coles' results indicate a dip in the transfer function. This is probably attributable to the fact that they placed the external measurement microphone 'close to the meatus entrance just in front of the tragus', whereas it was placed 150 mm

away from, and normal to the entrance to, the ear canal in the present study. This probably also explains the lower mean gain figure of 4 dB for impulse noises reported by these authors, compared with the 11.1 dB mean gain observed in the unoccluded condition in the present study.

LINEARITY OF ATTENUATION CHARACTERISTICS WITH INCIDENT SOUND LEVEL FOR STEADY-STATE STIMULI

The attenuation characteristics of the eight hearing protectors were determined in terms of transmission losses for pure-tones and $1/3$ -octave bands of random noise with incident sound levels between 75 and 125 dB. Attenuation linearity was examined for the results at 250, 1000, 4000 and 8000 Hz. At each test frequency, linear regressions of the attenuation data with incident sound level were deduced for individual cadaver ears. Of interest here is the gradient of the regression line, which should be zero if attenuation does not change with incident sound level, or have a value significantly different from zero if it does. Mean values of the gradient were determined for each protector and test frequency for pure-tone stimuli and $1/3$ -octave bands of random noise. Each estimate of the gradient was the mean value for the results of at least four cadaver ears, and the value for each cadaver ear was based on between four and eight individual data points. It was found that all values of the gradient were small, varying between -0.14 and 0.15 with a mean of 0.036 .

Student's t tests (Snedecor and Cochran, 1973) were carried out to establish which were significantly different from zero; of the 72 estimates of the gradient, only five were significantly different from zero at the 5% level and only one at the 1% level of significance. As both these are close to the number expected to occur by chance alone, it is concluded that all the hearing protectors considered generally provide attenuation which is constant with incident sound level for the range of steady-state sounds examined here.

ATTENUATION-FREQUENCY CHARACTERISTICS FOR STEADY-STATE STIMULI

Having established the linearity of acoustic attenuation with incident sound level over the range so far considered, it is now permissible to reduce the available attenuation data for each protector to a single mean value at each test frequency. Thus, each estimate of the mean attenuation for a particular test frequency is based on approximately 20 measurements of the attenuation made over the range 75–125 dB.

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Figs 5-13 Attenuation characteristics of hearing protectors A, B, C, D, E, F, G and H for steady-state stimuli.

Figures 5–13 show the mean attenuation–frequency characteristics of the eight protectors for pure-tones and 1/3-octave bands of random noise. The basic measurement was the transmission loss of each protector, shown in the Figures, together with these data corrected to the insertion loss for each protector using the information given in Figures 4a and b.

As a comparison, attenuation data measured by national standard subjective procedures are also shown in the Figures where appropriate and available (Martin, 1977). Pure-tone attenuation data are compared with those obtained from measurements following the American subjective standard ASA Z24.22:1957 (American Standards Association, 1957) which itself uses pure-tone stimuli, while the attenuation values determined with 1/3-octave bands of random noise are compared with results of the British Standard BS 5108:1974 (British Standards Institution, 1974), which also uses these noise stimuli.

LINEARITY OF ATTENUATION CHARACTERISTICS WITH INCIDENT SOUND LEVEL FOR IMPULSES

As in the case of steady-state stimuli, the basic measure of attenuation was the transmission loss of

Fig. 12

Fig. 13

each protector. This is defined here as the difference in decibels between the peak sound pressure levels of the high initial peaks of the impulse sound pressure waveforms recorded by microphones B and A. Between 13 and 21 measurements were made of attenuation for each of the nine hearing protector conditions over the range 135–175 dB(P).

The linearity of attenuation with incident peak sound level was examined, as before, in terms of linear regression between these two quantities for each protector. The number of measurements, the gradient of the regression equation and the regression

correlation coefficient are given in Table 3 for each protector. Student's *t* tests of the significance of the correlation coefficients were also carried out. As indicated in Table 3, with the exception of results for earplugs C and D, and earmuff H in the open condition, the correlation coefficients are not significant. This shows that the six protectors that are intended to have linear attenuation characteristics do, in fact, have such characteristics for impulse sounds in the range 135–175 dB(P). The two intentionally non-linear earplugs C and D provide linear regressions with significant correlation coefficients ($p < 0.001$), thus vindicating the manufacturers' claims for these devices.

The one borderline case is earmuff H which, in the open valve condition, produced a mean gradient with a correlation coefficient having a significance level of approximately 0.06. One possible explanation for this intentionally non-linear condition providing such a comparatively low regression line gradient is that these earmuffs are primarily intended for use in very high levels of noise produced by heavy gunfire, and not by small-arms fire as in this study. Consequently, the peak sound levels produced here may not have been sufficiently high to operate the valve effectively.

The non-linear attenuation characteristics of earmuff H and earplugs C and D are shown in

Table 3 Relevant results of linear regression analyses of attenuation with incident peak sound level for impulses in the range 135–175 dB(P)

Hearing protector	Number of measurements	Gradient (m)	Correlation coefficient (r)
A	16	0.109	0.229
B	14	-0.014	-0.024
C	13	0.430	0.95*
D	21	0.314	0.51*
E	19	0.110	0.217
F	20	0.025	0.044
G	18	0.024	0.037
H			
valve open	14	0.22	0.51**
valve closed	17	0.135	0.190

* $p < 0.001$; ** $0.1 > p > 0.05$

Figures 14, 15 and 16 respectively, in which the individual points are plotted in terms of the measured transmission loss. The regression equation is plotted for the data in each case. These Figures also show the insertion losses of the protectors. As before, these data are derived from the results of the unoccluded condition for impulse noises.

The results reported by Forrest (1969) obtained by similar experiments are also given in Figures 15 and 16 for earplugs C and D. There is good agreement between the transmission loss values reported by Forrest and those observed in the present study, with less than 5 dB difference between the two lines for both earplugs within the range of impulses considered.

ATTENUATION CHARACTERISTICS FOR IMPULSE NOISE

With regard to the six hearing protectors shown to have linear attenuation characteristics for the range of impulses studied, the individual transmission loss data points may now be combined to give an estimate of the mean value for each of these protectors. The means and standard deviations of the attenuations of these protectors are given in Table 4, together with the derived insertion loss values.

Discussion

RESULTS FOR STEADY-STATE STIMULI

In general, all eight hearing protectors appear to

Fig. 14 Variation of attenuation with incident peak sound level of earmuff H with valve open for impulse noise stimuli.

Fig. 15 Variation of attenuation with incident peak sound level of earplug C for impulse noise stimuli.

Fig. 16 Variation of attenuation with incident peak sound level of earplug D for impulse noise stimuli.

provide substantially constant acoustic attenuation characteristics over the range of incident sound levels between 75 and 125 dB. This is in fact the most important range for practical industrial hearing conservation purposes.

However, protectors are usually evaluated in the UK by one of the national standard subjective test procedures, such as BS 5108:1974 (British Standards Institution, 1974) or ASA Z24.22:1957 (American Standards Association, 1957), which involve low incident sound levels in the region of 0–40 dB SPL; therefore the question remains of attenuation linearity between these ranges (between about 40 and 75 dB) and whether attenuation data from standard tests are directly applicable to hazardous noise levels. Examination of the differences between attenuation data obtained by these standard procedures and those from the present study may provide further information on attenuation linearity over this range.

Figures 5, 6, 9, 10 and 11 compare the attenuation (insertion loss) data obtained in the present study

Table 4 Means and standard deviations of transmission losses of linear hearing protectors together with insertion loss values, for impulse noises over the range 135–175 dB (P)

Hearing protector	Number of measurements	Transmission loss (dB)		Mean insertion loss (dB)
		Mean	Standard deviation	
A	16	14.0	6.25	25.1
B	13	27.3	5.84	38.4
E	19	21.0	4.39	32.1
F	20	27.9	4.83	39.0
G	18	28.7	6.46	39.8
H				
valve closed	17	31.7	6.18	42.8

with those from the two national standard procedures, and there is generally good agreement between them. Figure 17 shows the differences in attenuation between results of the two approaches, expressed as the average differences for the five hearing protectors. These are plotted separately for the pure tone and 1/3-octave band random noise comparisons. Positive differences indicate that the results of the standard subjective procedures are greater than those obtained from cadaver ear measurements. There is little difference between these comparisons, both curves following a similar pattern. In general, the subjective standard procedures give attenuation values which are greater, on average by 3.5 dB, than those observed in the present study for the lower test frequencies between 125 and 1000 Hz. On the other hand, for test frequencies of 2000 Hz and above, the reverse tends to occur, where the present data from cadaver ears are on average 3.1 dB greater than those measured with the standard subjective procedures. These are small differences, considering the diverse nature of the experimental procedures involved in these comparisons. Nevertheless they are, in the main, explicable in terms of known auditory physiological phenomena.

The former observations for frequencies below 1000 Hz may be explained in terms of the artefact introduced into the standard subjective (threshold shift) methods because of the enhancement of physiological noise by the presence of the protector. In this regard, the data measured in the present experiment may be considered to be nearer the true attenuation provided by hearing protectors. Similar differences of the order of 3–5 dB have been reported by Webster (1955) and Weinreb and Touger (1960) in the case of comparisons between the American standard method and loudness-balance and insert

Fig. 17 Differences between mean attenuation values obtained by national standard procedures and mean insertion losses measured on cadaver ears, averaged over results for protectors A, B, E, F and G. Results of ASA Z24.22:1957 are compared with pure-tone data, and results of BS 5108:1974 are compared with 1/3-octave band random-noise values. Positive difference indicates result of standard test is greater.

microphone techniques. Anderson and Whittle (1971) investigated in considerable detail the differences between hearing thresholds determined using free-field and earphone-generated signals. They reported that the difference varied monotonically between about 15 dB and zero over the frequency range 100–1000 Hz, and concluded that it was caused by physiological noise of vascular origin generated in the external ear canal. They also showed that the level of physiological noise was inversely proportional to the effective volume of the occluding device. Furthermore, the presence of an earplug in the ear canal will enhance the noise by providing additional sound-radiating surfaces. Thus, it may be concluded that the differences between subjective free-field threshold measurements of protector attenuation and those employing objective techniques are likely to be greater for earplugs than for earmuffs. This is exemplified by the relatively large differences between data from standard subjective and cadaver ear procedures observed at the lower test frequencies for earplug B shown in Figure 6.

The fact that the results of the present study are, on average, slightly lower than those obtained from the standard subjective procedures for test frequencies above 1500 Hz may be explained by the ultimate limitation of attenuation provided by bone conduction in the latter more realistic situation. Incident sound will reach the inner ear via the bones and tissue of the head as well as by air conduction. According to Tonndorf (1972) there are three main routes by which bone-conducted sound may reach the cochlea: (i) by vibration of the ear canal walls; (ii) by inertial vibrations of the ossicles, and (iii) by mechanical distortion of the cochlear walls. Thus, in the present study the internal microphone would pick

up the first of these signal routes, and possibly some portion of the second via vibration of the eardrum, but not the third. Consequently, these secondary paths are not completely accounted for in the present measurement technique, whereas they will obviously be included in experiments with live subjects. Nevertheless, the present technique does take more account of these secondary conduction paths than do conventional artificial ear or head measurement procedures.

Perhaps the most important conclusion to be drawn from this part of the study is that, notwithstanding explicable average differences of the order of ± 3 dB, the attenuation data measured by national standard procedures are in very good agreement with those obtained in the present study. Consequently, protector attenuation would also appear to be constant for incident sound levels between 40 and 75 dB. Furthermore, the results of standard low-level threshold shift techniques may be applied with confidence to industrial situations where high levels of noise occur. Likewise, the calculations recommended by the *Code of Practice for Reducing the Exposure of Employed Persons to Noise* (Department of Employment, 1972), for deducing the sound level inside a protector for a particular noise environment, allow adequate protection to be chosen with the same degree of confidence.

In general, the present measurement technique provides a more realistic estimate of protector attenuation than the standard free-field threshold shift procedures at the lower test frequencies. However, because of bone conduction they are less realistic at the higher test frequencies. It has been suggested by Shaw (1976), and is apparent from the present data, that in practice bone conduction does

tend to limit protector attenuation at 2000 Hz and above. This is the important frequency range as regards practical hearing conservation. It may therefore be concluded that data obtained from objective methods of evaluating hearing protectors (such as an artificial head, an insert microphone and, to a lesser extent, instrumented cadaver ears) should be treated with some caution at these higher frequencies. Additional corrections or modifications to objective measurement techniques may be necessary in the future in the case of such procedures, if realistic estimates of attenuation are to be obtained. Moreover, the general agreement between results of national standard procedures and the present insertion-loss data indicates that it is the latter measurement rather than transmission loss which should be determined by such objective techniques.

RESULTS FOR IMPULSE NOISE

Of the nine hearing protector conditions evaluated, the six with intentionally linear characteristics have been shown to provide constant attenuation for impulses with peak sound levels in the range 135–175 dB(P). This result, coupled with the results for steady-state sounds, extends the range of measured attenuation linearity to include incident sound levels between 75 and 175 dB. Consequently, as discussed above, the general inference is that these protectors provide attenuation which appears to be approximately constant over the range of incident sound levels between about 40–175 dB.

The two earplugs which are designed to be amplitude-sensitive for impulse noise, earplugs C and D, shown in Figures 15 and 16 respectively, have significantly non-linear attenuation characteristics. Earplug C provides attenuation (insertion loss) which appears to vary monotonically from about 18 dB for an incident peak sound level of 135 dB(P) to 35 dB for incident sound at 175 dB(P). Similarly, attenuation of earplug D varies from about 20–34 dB over this range of incident peak sound levels. Earplug C seems to be slightly more efficient in this respect, as the gradient of the regression line is 0.43 as opposed to 0.31 in the case of earplug D. Although earplug D is designed to be amplitude-sensitive by means of a flutter valve, it seems unlikely that the inertia of the valve would allow it to close sufficiently quickly to be effective (Forrest and Coles, 1969). If the valve did operate as intended, some form of step function or discrete change in the attenuation–peak sound level characteristic (Figure 16) might be expected at some critical value of incident sound level. This has not been observed for the range of sound levels studied here. Nevertheless the earplug is non-linear and it seems more likely that the mechanism producing

this effect is similar to that operating in earplug C. Acoustic flow through the orifices in the valve mechanisms becomes more turbulent, and resistance to flow increases, as the incident peak sound level increases. The effective diameter of these orifices may be slightly larger than the orifice in earplug C, which would account for the lower gradient of the regression line in the case of earplug D.

The results of the present study for these amplitude-sensitive earplugs compare well with the attenuation data for these devices reported by Forrest (1969). Forrest obtained slightly lower gradients for the regression lines than were found in the present study and this is probably attributable to differences in experimental technique, such as the position of the external measurement microphone and earplug-fitting procedures.

In the present study, attenuation has been defined as the change in the initial peak level of the impulse measured outside and inside the protector. This measure of attenuation is, of course, not frequency-specific. Nevertheless, as much of the sound energy in the initial peak of the impulse will be in the higher frequency range where the greater attenuation of the protectors is located, this measure of attenuation probably indicates the maximum attainable, because of the higher frequency content of that part of the impulse waveforms involved in this analysis.

Conclusions

The measurement approach employed, although by no means amenable to standardisation, provides a more useful and accurate representation of the real situation than many other objective and semi-objective techniques. In particular, it takes account of more of the bone and tissue conduction paths in the human head than do other objective methods, while also allowing impulse stimuli to be investigated, which cannot easily be achieved in subjective procedures.

The relationships between acoustic attenuation and incident sound level for the eight protectors studied have been shown to be essentially linear for pure tones and 1/3-octave bands of random noise having sound levels in the range 75–125 dB. In the case of the six intentionally linear protectors, this was also shown to be the case for impulses with peak levels in the range 135–175 dB(P).

A comparison between the attenuation–frequency characteristics for steady-state sounds measured here, with those derived from subjective national standard procedures, shows good agreement between the two. This agreement provides a further known point of equal attenuation on the incident sound level scale in the region of 0–40 dB. Thus, it may

be concluded that the intentionally linear hearing protectors studied here have essentially constant attenuation characteristics for incident sound levels, at least between about 40–175 dB.

This result is of particular importance, as it implies that the results of the national standard threshold shift procedures, although measured at low sound levels, may be applied with confidence to industry where hazardous high-level noises are present.

The author wishes to acknowledge and thank Mr C. S. Munn for assistance in undertaking the measurements, Mr G. Knebel for the initial preparation of cadavers, and Dr R. A. Goodbody, Pathologist in Charge at Southampton General Hospital, for providing the general facilities of the mortuary and permission to carry out the work there. The research was funded by the Science Research Council, Grant number B/SR/95560, whose support is gratefully acknowledged.

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