The mechanical properties of earmuffs[1)]

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The physical properties of circum-aural hearing protectors, such as mass, clamping force and cup volume, have an influence on the attenuation performance of the device. This paper closely examines the physical and acoustic properties 39 of hearing protectors readily available to all users. The results indicate that attenuation increases with clamping force up to a limiting value of around 11 Newtons above which expected increases in attenuation are very small for large increases in clamping force. Likewise increasing the (newly introduced term) bulk of a hearing protector (volume, mass and cup elements) increases the attenuation but, as with clamping force a limit is reached where increased bulk increases discomfort and wearing difficulty.

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1 INTRODUCTION

In the hierarchy of hazard control in the workplace personal protective equipment (PPE) is seen as the last line of defence. This particularly applies to the use of hearing protectors and the control of noise exposure at work[1]. With consideration of the design and materials from which hearing protectors are constructed it is reasonable to assume that their acoustic performance, *ie* attenuation, will be somewhat dependent on their mechanical properties. This will be so particularly in the case of earmuffs with the mechanical properties under consideration such as cup mass; clamping force; the number and type of cups and cup liners and cup volume.

The mechanical action of earmuff clamping pressure, a function of clamping force and cushion surface area, has previously been shown to play a significant part in perceived comfort when wearing earmuffs[2]. The work reported here was a continuation from that starting point and set out to characterise a greater number of mechanical properties of circum-aural earmuffs and examine their relationship to the objective and subjective attenuation performance of the devices.

2 METHOD

2.1 Mechanical

This project involved the intensive study of the mechanical and acoustic (attenuation) properties of 39 sets of current production model earmuffs readily available in the market. The mechanical properties measured included: cup mass; cup penetrations; clamping force; cushion area; number of cups; number and type of cup linings; average outer cup thickness; and cup volume. Typical hearing protector cup construction is presented in Figs. 1 and 2. Figure 1 shows the components of a simple muff while Fig. 2 presents a more complex device.

While some of the mechanical parameters may seem obvious for clarity the details of measurement are provided here. Cup mass considered only the mass of the cup, including any included linings and/or sound absorbent material, without the head band or helmet if helmet mounted. Cup penetrations include any continuous 'hole' through the material of the cup. These penetrations are mostly made for a purpose and are effectively sealed through the use of grommets, flexible mounting hinges and the like, but they may allow a future acoustic leakage path and do require consideration here.

Clamping force was measured as required by Sec. 3.2.4 *Clamping force test* from combined *Australian – New Zealand Standard AS/NZS 1270: 2005 Acoustics – hearing protectors*[3]. Cushion surface area was measured as would be experienced around the ears. The measurement surface area and the calculation of clamping pressure were as described in earlier published work[2].

[1)] This work examines major mechanical properties of hearing protectors in relation to their acoustic attenuation.

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Fig. 1—Simple cup construction with three elements, from top (left to right), outer shell, inner foam lining and cushion.

The number of cups and cup linings are important as they significantly change the hearing protector construction. Some devices have more than one cup, with an outer cup and an inner cup commonly separated by a sound absorbent lining. The sound absorbent linings can consist of moulded, closed-cell foam, a simple 'cut outs' of closed- or open-celled foam. The cross-sectional thickness of the cups usually varies depending on the location on the cup usually being thicker at points that require greater structural strength. An average thickness was taken from several measurement points representing the overall surface of the shell.

Cup volume was determined by filling the empty hearing protector cup with an amount of a dry, small-grained material of known density. The full and empty mass of each cup was measured and the difference in mass divided by the density of the fill material provided the volume.

2.2 Acoustic

Acoustic properties consisted of various measurements of attenuation including the subjective attenuation using the methods as prescribed *AS/NZS 1270*[3] and the objective measure of insertion loss measurements in accordance with *ISO 4869-3*[4]. Subjective testing means using human test subjects and psycho-acoustic hearing test to determine octave band attenuation through the comparison of un-occluded and occluded hearing thresholds. The attenuation figures are then used to calculate a single figure attenuation performance according to the standard[3].

Calculation of the single figure attenuation performance (SLC_{80}) is conventionally carried out by using the mean minus one standard deviation (SD) of the subjective attenuations at each individual octave band. In this work it was thought desirable to remove the variability introduced to the performance figure through the inclusion of the SD, consequently only the mean octave band attenuation was utilised (SLC). While this performance figure may differ from that normally calculated the difference is slight and has been extensively discussed elsewhere[5,6].

Objective acoustic measurements were undertaken on the devices utilising an acoustic test fixture (ATF) following the requirements of ISO 4869-3. Measurements were carried out using a smooth ATF 'cheek' surface as described in the Standard and three other 'cheek' surfaces in an attempt to simulate possible sources of surface leakage under the cushion – cheek interface. The three surfaces consisted of: 1) a 5 mm rectangular grid pattern of lines 0.2 mm wide and 0.2 mm deep; 2) a second similar grid pattern this time with lines 0.4 mm deep; and 3) a smooth plate with a single radial line, 11 mm wide with a curved cross section of radius 10 mm. Surfaces 1) and 2) were intended to reflect different surface roughness between the cushion and the side of the head, while 3), the radial 'groove', simulated possible the temporo-mandibular joint leakage. Figure 3 illustrates the arrangement of ATF 'cheek' surface (2). As there were no significant effects found from the 'leakage' tests this work is not described here in any further detail.

Fig. 2—Complex cup construction with six elements, from top (left to right), outer shell, inner foam liner, inner shell, second inner foam liner, cup spacer and cushion.

3 RESULTS

The data was analysed by fitting two types of multiple regression model. Model 1 used a conservative approach, following the common recommendation to have at least 10 data points for each regression parameter to be estimated. Model 2 violated this recommendation; it had the potential to provide more detailed inferences, but its estimates were also expected to be less reliable.

For each of the two model types, five individual models were fitted, one for each of the following dependent variables: SLC on an artificial head (denoted SLC_{ATF}), SLC on humans (denoted SLC_{Hum}), low-

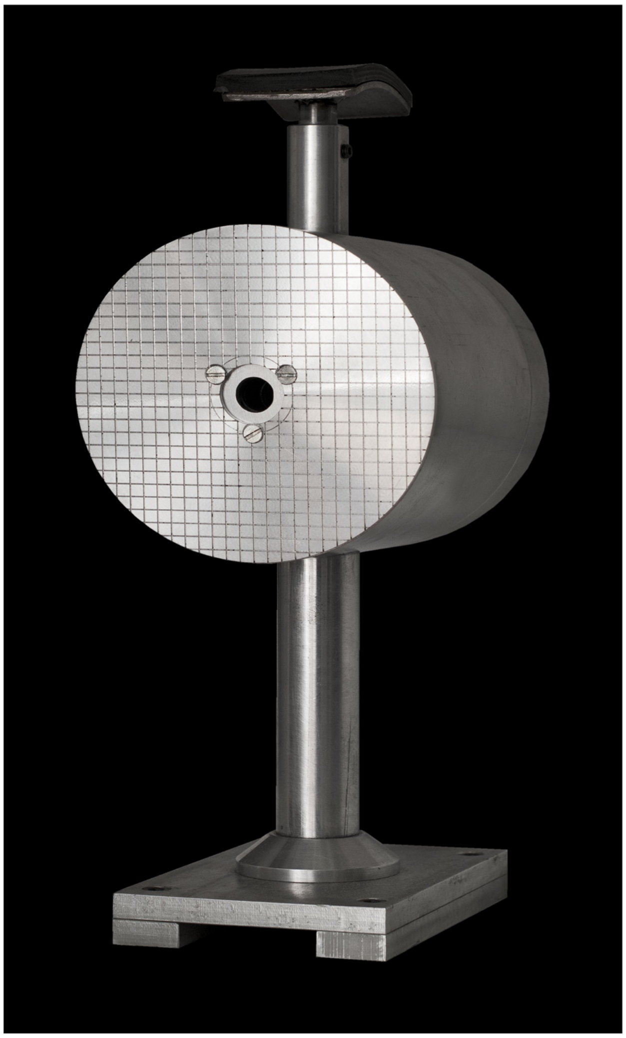

Fig. 3—Detail showing leakage path detail on the Acoustic Test Fixture with 0.4 mm deep cross hatching.

frequency attenuation on humans (average attenuation at 0.125, 0.25 and 0.5 kHz, denoted LFA_{Hum}), mid-frequency attenuation on humans (average attenuation at 1 and 2 kHz, denoted MFA_{Hum}), and high-frequency attenuation on humans (average attenuation at 4 and 8 kHz, denoted HFA_{Hum}).

The statistical analysis was performed using the statistical packages "*R*" (version 2.12.0)[7] and the additional packages "*rms*"[8] and "*ggplot2*"[9].

Table 1—p-values for Model 1.

	SLC_{ATF}	SLC_{Hum}	LFA_{Hum}	MFA_{Hum}	HFA_{Hum}
Force	0.50	<0.001	0.001	<0.001	0.53
Bulk	<0.001	<0.001	<0.001	<0.001	<0.001

The leakage variables were considered for Model 2, but in the end they were omitted. The 0.2 mm and the temporo-mandibular joint leakages have been omitted as their effect was minimal when compared to the effect of the 0.4 mm surface. The leakage over this surface demonstrated a significant positive effect (ie increased attenuation) for the ATF, which was not able to be explained.

3.1 Model 1

To reduce the total number of predictor variables, a single variable reflecting the "bulk" of a protector is introduced as a linear combination of several physical variables (overall cup mass, number of cup linings, number of inner cups, outer cup thickness, external cup volume, and cushion surface area). The coefficients for this linear combination are those of the first principal component, that is, the linear combination having maximum variance and therefore providing maximum differentiation between protectors. Specifically, bulk is defined to be: bulk = 0.50(overall cup mass) + 0.37(number of cup linings) + 0.45(number of external and inner cups) + 0.48(outer cup thickness) + 0.26 (external cup volume) + 0.33(cushion surface area). This is after standardising each variable (subtracting the mean then dividing by the standard deviation). There are no dimensions for bulk.

There were two main predictor variables determined for the model: clamping force and bulk. Because there was a strong expectation from previous work[2] that attenuation would be non-linearly related to clamping force, that predictor was represented as a restricted cubic spline[10] with three knots. For simplicity, bulk was represented as a linear term.

Table 1 shows the p-values for each predictor for *Model 1*. There was insufficient evidence to reject the null hypotheses of no association between clamping

Table 2—p-values for Model 2.

	SLC_{ATF}	SLC_{Hum}	LFA_{Hum}	MFA_{Hum}	HFA_{Hum}
Force	0.06	0.005	0.003	0.001	0.31
Cup mass	<0.001	0.01	0.01	0.008	0.003
Cup volume	0.15	0.62	0.23	0.47	0.41
Cushion area)	0.99	0.05	0.28	0.003	0.58
More than 1 lining	0.12	0.65	0.40	0.90	0.30

Table 3—Estimates and 95% confidence intervals for coefficients of the linear variables in Model 2. The coefficients represent the rate of change of the attenuation (dB) with respect to the parameter while controlling for other variables.

	SLC_{ATF} (dB)	SLC_{Hum} (dB)	LFA_{Hum} (dB)	MFA_{Hum} (dB)	HFA_{Hum} (dB)
Cup mass (gm)	0.17 (0.10, 0.25)	0.09 (0.02, 0.16)	0.11 (0.02, 0.19)	0.08 (0.02, 0.13)	0.12 (0.04, 0.19)
Cup volume (cc)	0.02 (−0.01, 0.05)	0.01 (−0.02, 0.04)	0.02 (−0.01, 0.05)	−0.01 (−0.03, 0.01)	−0.01 (−0.04, 0.02)
Cushion area (cm^2)	0.00 (−0.20, 0.20)	0.19 (0.00, 0.39)	0.12 (−0.10, 0.34)	0.24 (0.09, 0.40)	−0.06 (−0.26, 0.15)
More than 1 lining	−1.80 (−4.07, 0.47)	0.49 (−1.71, 2.69)	1.06 (−1.45, 3.57)	0.11 (−1.63, 1.84)	1.19 (−1.11, 3.48)

force and SLC_{ATF}, or between clamping force and HFA_{Hum}, but the other associations were highly statistically significant.

3.2 Model 2

For the second set of models, we included the predictor variables expected to have greatest association with attenuation. These were clamping force, overall cup mass, external cup volume, cushion area, and presence of more than one lining. Similarly as in Model 1 clamping force was represented as a spline with three knots, and presence of more than one lining was a binary variable. The other variables were continuous and were represented as linear terms.

Table 2 shows the p-value for each predictor variable and Table 3 shows the estimate and 95% confidence interval for the coefficients of the linear variables. The plots for the non-linear force variable were similar to those from Model 1 and are not shown. Overall cup mass had a statistically significant positive association with all five attenuation measures. For external cup volume and the number of linings, the null hypothesis of 'no association' was not rejected by statistical testing for any of the attenuation measures.

Table 4 contains adjusted R^2 values for Models 1 and 2. The adjusted R^2 values for both Models are similar for each measure except for SLC_{ATF}, with the difference for SLC_{ATF} appearing to be due to the strong association with cup mass. The lower adjusted R^2 values for high-frequency attenuation mean that there is more unexplained variation for high-frequency attenuation than for low- or mid-frequency attenuation. The reasons for this are not completely clear, but may be related to the difference in relative importance of different transmission paths for different frequency ranges.

Table 4—Adjusted R^2 values for the two sets of models.

	Model 1	Model 2
SLC_{ATF}	0.28	0.61
SLC_{Hum}	0.60	0.54
LFA_{Hum}	0.57	0.57
MFA_{Hum}	0.58	0.60
HFA_{Hum}	0.35	0.30

4 DISCUSSION

From Table 1, the null hypothesis of no association with force can be rejected for SLC_{Hum} but not for SLC_{ATF}. Using *Model 1*, when bulk remains constant, the predicted increase in attenuation when force increases from 9 N to 11 N is 3.0 dB for SLC_{Hum} and 1.3 dB for SLC_{ATF}. These results suggest that the flanking path is more important for SLC_{Hum} than for SLC_{ATF}. This makes sense, considering the regularity of the surface involved in the SLC_{ATF} measurement compared with the irregularity of human heads. The results also suggest that the flanking path is more important for low- and mid-frequency attenuation than for high-frequency attenuation.

The p-values in Table 1 indicate that the bulk variable has significant association with all five attenuation variables. The coefficient estimates for cup mass in Table 3 (0.17 dB/g for SLC_{ATF} and 0.09 dB/g for SLC_{Hum}) suggest that the transmission path through the cup is more important for SLC_{ATF} than for SLC_{Hum}, which complements the above inference that the leakage path is less important for SLC_{ATF} than for SLC_{Hum}.

The adjusted R^2 values for Models 1 and 2 are similar for each measure except for SLCATF, with the difference for SLCATF appearing to be due to the strong association with cup mass. The lower adjusted R^2 values for high-frequency attenuation mean that there is more unexplained variation for high-frequency attenuation than for low- or mid-frequency attenuation. The reasons for this are not completely clear, but may be related to the difference in relative importance of different transmission paths for different frequency ranges.

Table 3 shows that cushion area has significant association with mid-frequency attenuation, with greater area associated with greater attenuation. Because cushion area does not have statistically significant association with

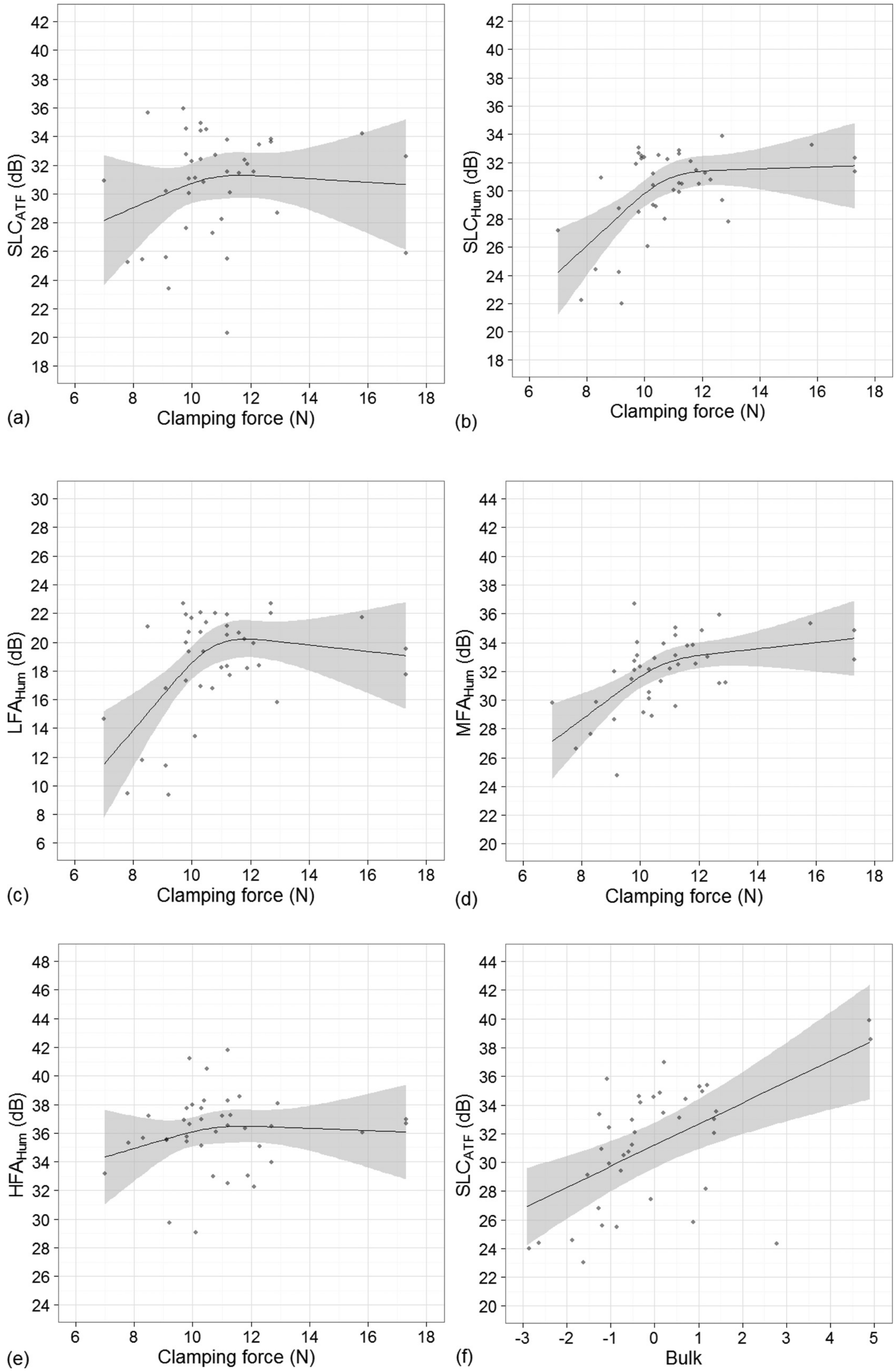

Fig. 4—(Continued on next page)

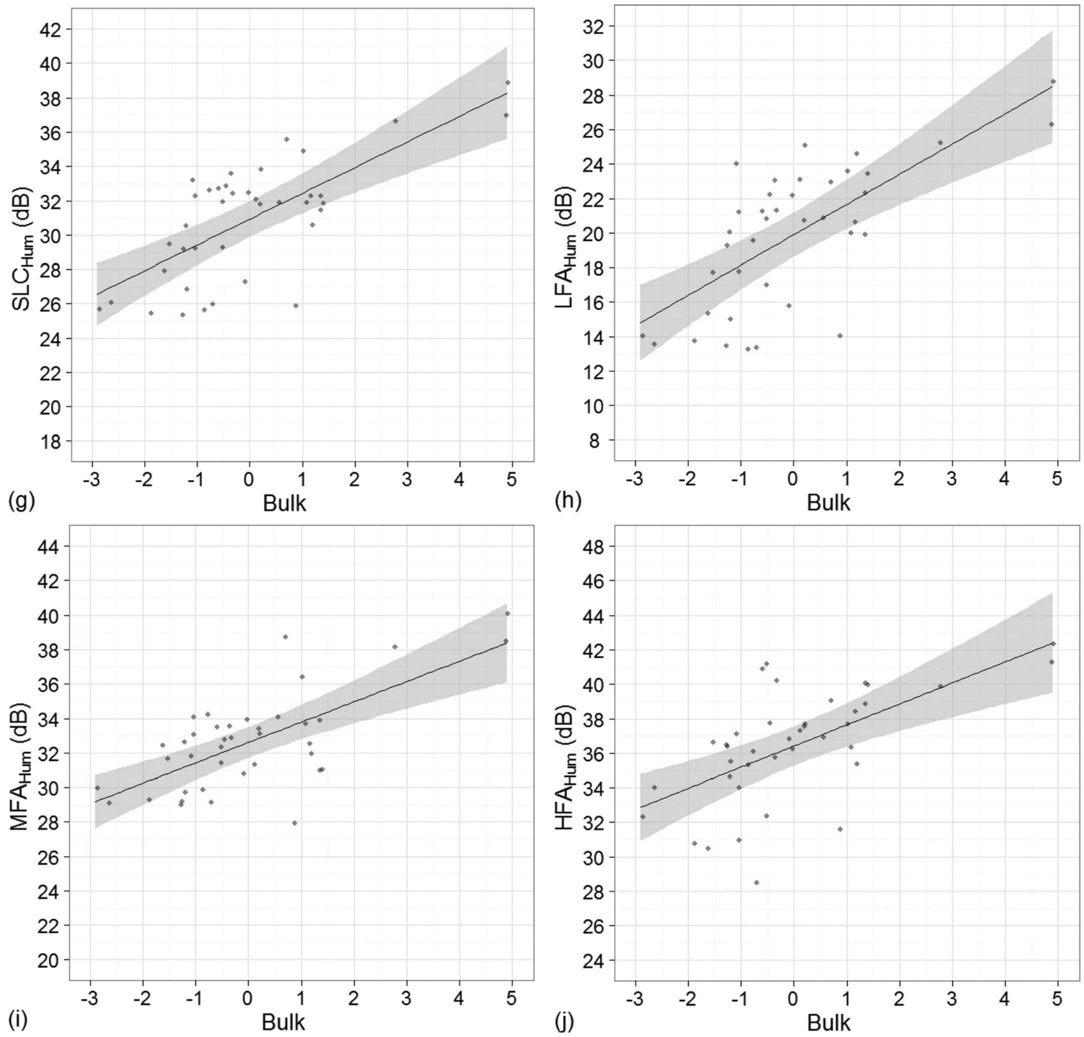

Fig. 4—Predicted mean attenuation (line) with pointwise 95% confidence intervals (grey band) as force varies with bulk held constant (a to e) or as bulk varies with force held constant (f to j), based on Model 1. The points show the observed attenuation values adjusted for the effects of bulk (a to e) or for the effects of force (f to j). Note: 1. In each plot, the line shows the predicted mean value of the attenuation variable as force (a to e) or bulk (f to j) varies, with the other predictor held constant at its mean value. The band shows point-wise 95% confidence intervals for these mean values. The points on each plot are a partial residual plot[11] with an appropriate vertical shift – they show the observed attenuation values after adjusting for the effect of bulk (a to e) or force (f to j). Note 2. SLC_{ATF} = SLC (overall attenuation) on an artificial head. SLC_{HUM} = SLC on (overall attenuation) human test subjects. LFA_{HUM} = low-frequency attenuation on test subjects (ave attenuation at 0.125, 0.25, 0.5 kHz). MFA_{HUM} = mid-frequency attenuation on test subjects (ave attenuation at 1.0 and 2.0 kHz). HFA_{HUM} = high-frequency attenuation on test subjects (ave attenuation at 4.0 and 8.0 kHz).

low- or high-frequency attenuation, the association with mid-frequency attenuation may be uncertain, however it is consistent with the previous inference that the leakage path is more important for the measurements on humans than for SLC_{ATF}.

From Figs. 4(a to e), a tentative conclusion can be made that if bulk is constant, increasing the clamping force above about 11 N results in little increase in attenuation. However, because the sample only contained three protectors with clamping force greater than 13 N, such a conclusion must be made with caution. If this tentative conclusion is accepted, a consequence may be that any increase in attenuation achieved by increasing the force above about 11 N is likely to be outweighed by the associated reduction in comfort accompanied by the increased force.

While it would be expected that the rate of increase of attenuation would also be reduced as bulk is increased at high values, Figs. 4(f to j) suggests that this did not occur to any great extent over the range of bulk values observed.

5 CONCLUSION

Generalising these results, the attenuation for human test subjects is seen to improve significantly with increasing clamping force up to about 11 N for wideband, low and middle frequencies. This relationship is not as significant for high frequency attenuation or for the wideband attenuation on the ATF. In all cases above around 11 N clamping force the rate of improvement is not as significant when compared to less than 11 N.

The bulk variable results imply that making the devices bigger (larger, heavier, more elements) will increase attenuation. This seems intuitive from an acoustic perspective. However there seems to be a physical limitation as increasing the bulk of a device will tend to make the resultant product more difficult to wear.

6 ACKNOWLEDGEMENTS

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