EAR CANAL MODELLING AND CATEGORISATION FOR IMPROVED OBJECTIVE HEARING PROTECTOR PERFORMANCE TESTING

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1 INTRODUCTION

1.1 The Problem

There is wide range of shapes and sizes of the human outer ear, in particular, the ear canal. Even so, the auditory meatus is commonly modelled as a cylindrical tube of approximately 3 cm in length. In fact dummy heads used for objective acoustic testing, such as the new KEMAR[1], still model the ear canal as a straight tube. However, many researchers have found this approximation too crude for some applications; such as the investigation of sound pressures at the ear drum with an in-situ hearing aid[2] or, in the case of this particular study, ear plug fit. There can be a serious effect on performance when ear plugs, or any type of hearing protection device (HPD), do not fit correctly.

1.2 Ear Plug Types

The use of earplugs is becoming more and more prevalent with the growth of portable audio devices, more sophisticated military in-ear devices and better promoted hearing protection schemes. For a hearing protector, an earplug is usually more attractive, as they are considerably lighter than their earmuff counterparts and do not suffer from air leaks due to hair or eye glasses. Earplugs that are formed from the ear impression of a user, custom moulds, are an attractive solution due to their quality and consistency of fit. Unfortunately, these devices are relatively very costly and their attenuation is usually modest. Standardised earplugs are significantly cheaper and can out-perform custom moulds. However, they are more susceptible to ill fitting due to the variability of inter-subject physiology and intra-subject fit (i.e. plugs may become loose whilst worn – see Figure 1).

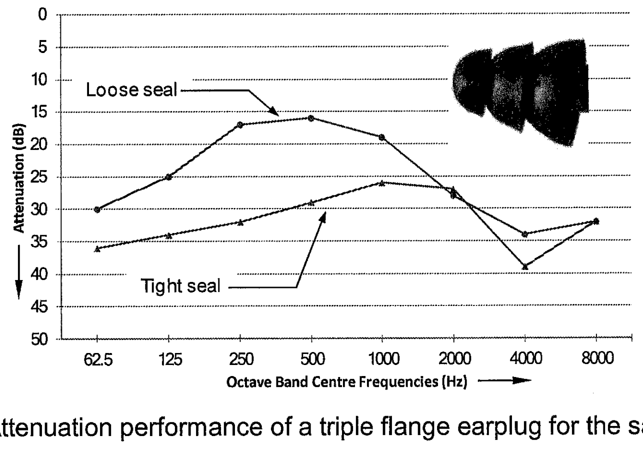

Figure 1 Attenuation performance of a triple flange earplug for the same subject

The foam earplug has chiefly overcome the issue of a diverse population by manufacturing a one-size-fits-all device (or more specifically 'one-size-fits-most') that expands in the ear canal to fit the user. When it does so, wearers of foam earplugs usually report high levels of comfort and attenuation. However, it is not always easy to achieve a good fit (hence performance is reduced), as these products need to be compressed prior to inserting into the ear canal. This not only has issues with particular canal shapes, especially ones with a sharp first bend, but also is not suitable for dirty environments or where manual dexterity would be an issue, for example riding in a moving vehicle.

1.3 Ear Plug Performance Testing

The current and well-tested method for measuring the attenuation of hearing protection devices (HPD), in particular earplugs, is to use Rear Ear at Threshold (REAT) where a hearing threshold test is performed in a controlled, low noise environment. The difference between protected and unprotected threshold scores indicates the insertion loss of the device. This method can correlate to field tests, and takes into account the physiology of the subject, bone conduction, ease of insertion and comfort. However, these tests are very time consuming and costly, so are usually not readily available in the commercial sector; therefore reliable objective measures are highly desirable.

Acoustical Test Fixtures (ATF) or commonly known as 'dummy heads', remove the need for subjects so, conceptually at least, they are a very attractive means of testing hearing protectors due to a much quicker and efficient testing regime with high levels of repeatability and reproducibility. For an ATF to be useful for earplug testing there needs to be simulated ear canal and eardrum. However, an ATF that can simulate the complex hearing process and large inter-subject variability has hitherto proved elusive. For example, no ATFs give sufficient variation in the geometry of the ear canal, indeed a straight 'average' canal is normally used. Hiipakka[3] used a dummy head called Dadec (dummy head with adjustable ear canals) that used a canal made from a material that could be compressed and bent into shape. Measurements were taken to describe the frequency response of the ear canal, although no attempt was made to mimic human ear canal types. In fact, there is very little in the literature that describes ear canal 'types' so that they can be modelled more accurately, either physically or numerically.

1.4 Acoustics of the Outer Ear

The frequency response of the outer ear (hereafter assumed to be the eardrum and ear canal for the purposes of this study) is more formally known as the transfer of the open ear (TFOE). This has been a common descriptor of the morphology of the outer ear and can be described as the ratio of sound pressure at the eardrum with the free field sound pressure. The free field sound pressure is usually measured at the centre of the head but with the head absent. The transfer function of the ear reveals the outer ear's natural amplification properties mainly due to resonances in the ear canal with its ¼-wavelength resonance leading to an increase of at least 10 dB at 2 – 4 kHz. The TFOE for individuals can vary considerably due to the wide variation in canal sizes and shapes.

2 EAR CANAL VARIABILITY

Details of the ear need to be known in order for the ear canal to be modelled effectively and to fully understand the interface between an in-ear device, the ear canal and ear drum.

2.1 Ear Canal Morphology

The ear canal is not a straight tube terminated by the eardrum at right angles, but twists and turns with the ear drum terminating obliquely. There are usually two bends within the ear canal, one near the entrance and one near the fleshy / bony junction.

2.1.1 Full Canal Moulds

The first significant study of the inter-subject variation of the outer ear was by Lawton[4] who examined full ear canal moulds from thirty-nine cadavers. Examination of the moulds revealed that there can be a significant departure from the idealised straight canal.

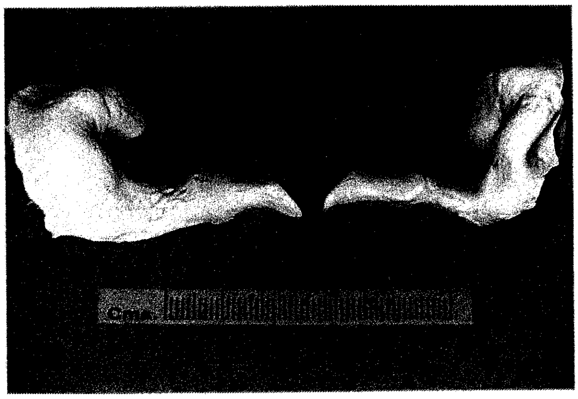

Figure 2 Photographs of complete moulds from different subjects from Lawton[5]

Figure 2 clearly shows a smooth inner osseous section and rough outer cartilaginous section of the ear canal. The change in cross sectional area along the canal, sometimes referred to as the 'area function'[13], can be easily seen, as well as relative notional canal diameter Furthermore, the tilted orientation of the eardrum and the umbo are evident. Curvature can be particularly prominent and is highlighted in Figure 3.

Figure 3 The inner bony portion of the ear canal showing the second bend and curvature

From the Lawton study, the averaged canal profiles for men and women were grouped into long and short canal lengths which showed that there is a constriction near the fleshy / body junction (even with averaged data). The presence of this constriction and the steepness of the first bend have ramifications for the quality of earplug fit. This hints at the conclusion that one size may not fit all with generic sized earplugs and not only are different widths potentially required but possibly different lengths.

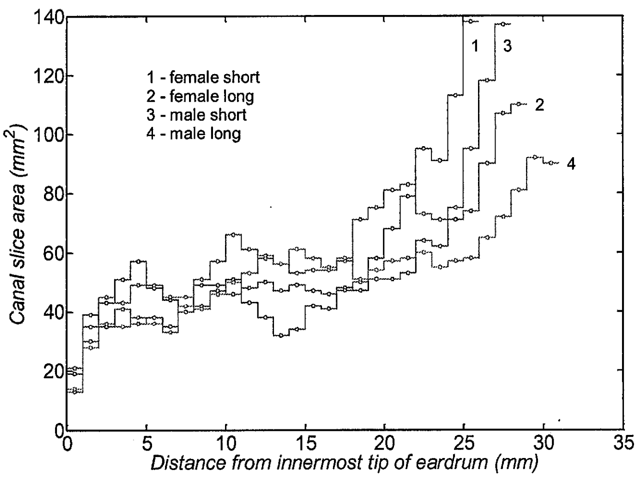

Figure 4 Summary of Lawton canal profile data where the cross section of full ear moulds were measured every 1mm.

Specifying the cross sectional areas of the canal for a straight 'central' axis do not give the true area function of the ear canal. Stinson[13] described the canal's central axis as the s–axis which describes the canal's geometry more accurately (Figure 5).

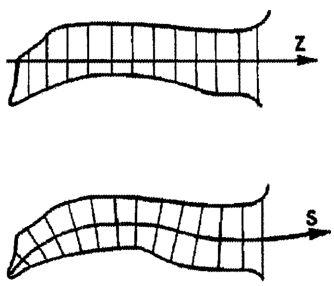

Figure 5 Comparison of the straight and curved axes used to describe ear canal geometry

2.1.2 Partial Canal Moulds

As part of an earlier work[6], partial ear canal moulds were taken for the purpose of fabricating custom moulded ear plugs. Figure 6 shows ear impressions for men (top two rows) and women (bottom row). On close inspection there is a general difference in size although some men's impressions have similar dimensions to women (top right is an example). Interestingly, the only 'straight' canal is second from the left on the bottom row. Needless to say, this subject had no issues with ear plug fit at all but it was interesting to see that the straight canal is far from the norm and, in this case, is the exception. In fact, some candidates, who had difficulty inserting plugs, had a very steep first bend – particularly second from right on the top row and bottom right.

Another striking feature of the ear impressions is the difference between left and right canals, which is evident in almost every impression.

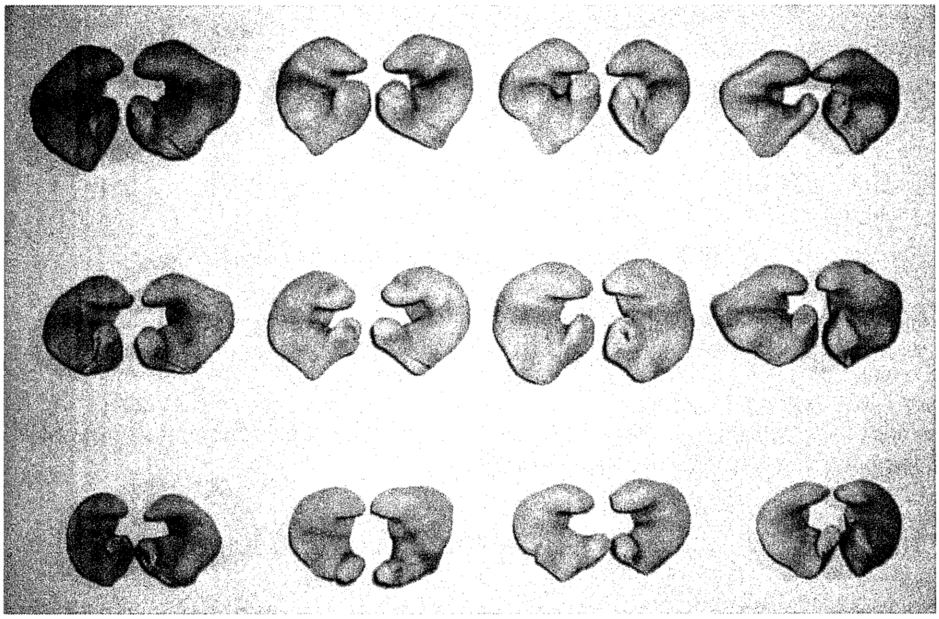

Figure 6 Ear impressions taken for custom ear moulds

3 EAR CANAL MODELLING

The variations in size and shape between individual ear canals have been shown to be considerable, with very few examples resembling the simplified cylindrical model. It is true that for wavelengths much larger than the canal dimensions, the exact geometry is not important, acoustically. However, the fit of in-ear devices will, in most part, depend upon the morphology of outer ear, especially the initial, fleshy part of the canal as well as the transitions from concha to canal. Furthermore, if earplugs form part of a communication system used in high noise environments, then the higher frequencies, say 6 – 8 kHz are important for speech intelligibility, and so need to be accounted for. Audio in-earphones (fitted with a transducer) would require an even higher frequency range, so the effect of the canal geometry should be investigated.

There are many methods of modelling the ear canal with various amounts of approximation. A compromise between ease of use and accuracy is the 2 Port method where the continuous curvature of the canal is simulated using a discrete number of cylindrical elements. This method is robust even when a relatively modest number of elements are used.

3.1 2-port model description

Electrical, mechanical and acoustical systems can be described by using electrical elements[7]. However, block diagrams are usually more efficient at conveying the operation of a complicated set of components – the so-called 'black box'. A complete system can then be conveniently represented by a connection of black boxes. Each block box will have a pair of input and output terminals, hence called four pole or two port terminal networks[8].

The advantage of the two-port method is that each element can be represented simply by a 2 x 2 transmission matrix (T-matrix). The whole system can be easily realised by a single matrix which is the product of all the T-matrices. This way, the relationship between the system input and output is easily determined without reference to any intermediate internal variables[9]. The main drawback with the two port method is the fact that the system is comprised of 'black boxes' so that exact internal operation is not described. However, the two port method also allows the ability for models of hearing devices[10] (for example) to be 'bolted on'; thus giving a complete model of the in-ear device and outer ear.

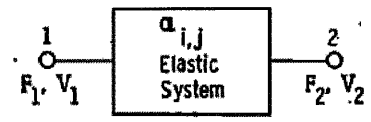

Figure 7 Two port linear elastic system (from Molloy)

3.2 Acoustics of a single cylinder

A single cylindrical waveguide can be thought of a rigid, lossless tube that is driven pistonically. The incident and reflected sinusoidal acoustic waves combine to give constructive and destructive pressure and velocity patterns within the tube. The input and output pressures and velocities describe the acoustics of the cylindrical waveguide.

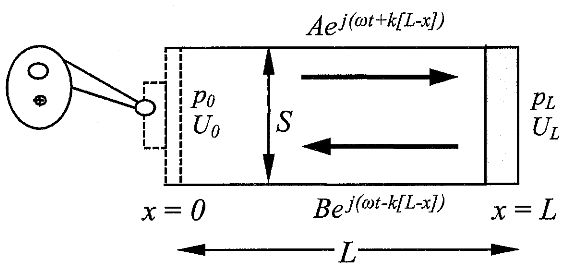

Figure 8 Piston driven waveguide with constant cross sectional area

The pressure and volume velocity at the entrance ($x = 0$) and termination ($x = L$) of a cylindrical duct is then described by Equation (1) where symbols have their usual meaning.

$$\begin{Bmatrix} p_0 \\ U_0 \end{Bmatrix} = \begin{bmatrix} cos(kL) & j(\rho_0 c/S)sin(kL) \\ j\dfrac{1}{\rho_0 c/S}sin(kL) & cos(kL) \end{bmatrix} \begin{Bmatrix} p_L \\ U_L \end{Bmatrix} = T \begin{Bmatrix} p_L \\ U_L \end{Bmatrix} \qquad (1)$$

3.3 Modelling the ear canal

The ear canal can be thought of as a waveguide of arbitrarily changing cross sectional area along its length, with rigid, lossless walls and so can be modelled by using simpler geometries such as a cylindrical duct. Due to the straight walls of a cylinder, wavefronts cannot diverge spherically and thus sound is propagated via plane waves. As the dimensions of the human ear canal are small compared to wavelength, then the plane wave model holds for most of the audio spectrum. This method has been successfully utilised in the modelling of horn loudspeakers[11] and described in modelling the ear canal itself[12]. Thus the ear canal can be described as the concatenation of cylindrical element of changing cross sectional area.

For multiple, *N*, concatenated cylinders with differing radii, the overall transfer matrix of the complete waveguide, *T*, is formed from the product of each cylinder with differing cross sectional areas, *S*.

3.4 Setting up the ear canal model

In order to model the ear canal, data from Lawton's[4] moulds were used. The continuous area functions (canal profiles) are shown in a later paper by Stinson and Lawton[13]. From the area functions, the incremental cross sectional areas were noted at every 1 mm from the 'end' of the canal along the *s* axis.

Also, canal profile data was taken from the study by Egolf et al.[14] The cross sectional areas were taken at 1 mm increments, like Lawton, and, also like Lawton, took the dimensions perpendicular to the x-axis. Due to issues of the measurement systems employed by Egolf et al, data for the first few cross sectional areas had to be extrapolated for this study.

3.4.1 Validating model with previous work

The measured and modelled pressure distribution in a replica ear model used by Stinson[15] was compared with the transmission matrix method for a single frequency. A pressure distribution plot for a straight cylindrical pipe is also shown for comparison (Figure 9).

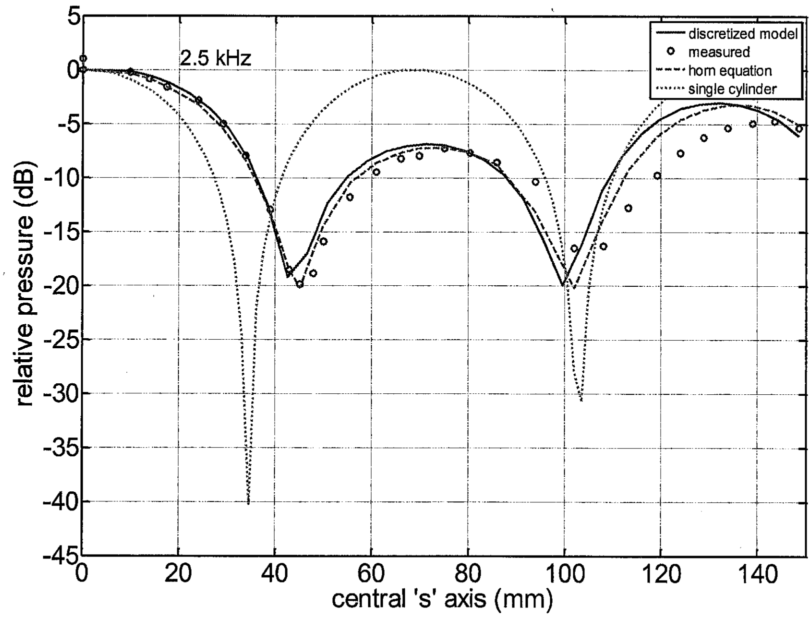

Figure 9 Pressure distribution in replica ear canal adapted from Stinson[15]

The replica canal used by Stinson was made bigger to aid accuracy of measurements and included a waveguide to ensure plane wave propagation; hence the dimensions along the x-axis are somewhat larger than a real canal. The up-sized replica meant that the reported frequencies need to be multiplied by 2.56 and the dimensions divided by 2.56 to compare to a real human canal. Therefore the pressure distribution shown in Figure 9 relates to 6.4 kHz.

The discretized matrix model compares favourably with the more analytical modified horn equation method which in turn agrees well with the measured pressure values within the replica canal. The error between the measured and the modelled data seems to increase with distance so could be a cumulative error due to accuracy of the measurement position. It is interesting to compare the pressure distribution assuming a single cylindrical canal with a rigid end. The pressure maximum and minima are not accurately described nor is the amount of absorption due to the eardrum which is evident in the disparity in the amplitudes of the pressure minima.

4 EAR CANAL CATEGORISATION

Even though there is limited raw data available, an attempt has been made to categorise the ear canal shape so that simulations, either using dummy heads or computer models, can be improved and correlate more to real canal shapes that the cylindrical tube.

From the various canal geometries the input impedance was calculated using the transmission matrix technique. The first two resonances were picked out and plotted as a scatter plot with f1 forming the x-axis and f2 the y-axis. From the two dimensional scatter plot, an attempt was made to cluster the data so that canal 'types' could be realised.

4.1 Using 'straight' canal data

Clustering algorithms were initially tested using fake straight canal data for a short length canal of 23mm and a long length of 31mm. Random lengths within ±2mm were generated for each, with the resulting input impedances shown in the figures below.

Plotting the first two resonances against each other resulted in some obvious clustering along a central line due to the predicable nature of the resonances.

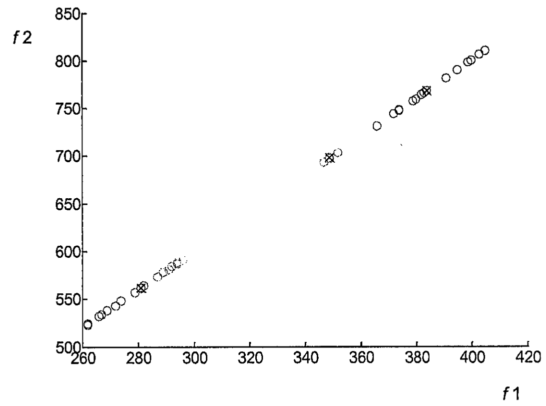

Figure 10 Clustering of two distinct groups of straight canal length

The fake data shows that there can be the possibility of clustering with the long canals bottom left and the short canals top right.

4.2 Real Canal Data

Twenty canal profiles were used with five (Lawton[4] and Egolf[14]) using the straight axis and fifteen (Stinson & Lawton[13]) using the curved s axis.

Several clustering methods were used but it was found that a Distribution based clustering method worked well. Distribution based clustering relates data that are part of the population of a certain distribution. This is a powerful and sometimes complex method but the distribution of the data should be known. As the ear canal data is from a human sample then a Gaussian distribution has been assumed (although the sample of 20 was small).

When the distribution algorithm was implemented there was a suggestion that there may be two sets of data orthogonal to each other (Figure 11).

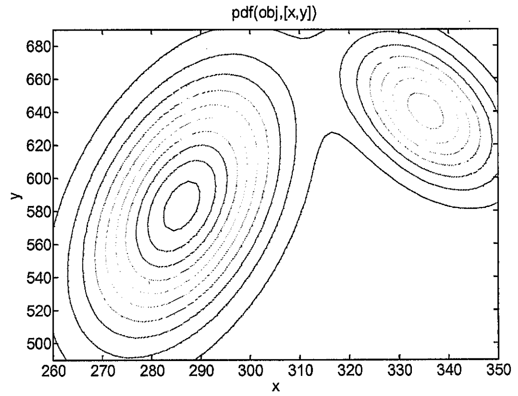

Figure 11 Distribution contours

The original scatter plot was re examined and some of the extremes of the two orthogonal axes where annotated.

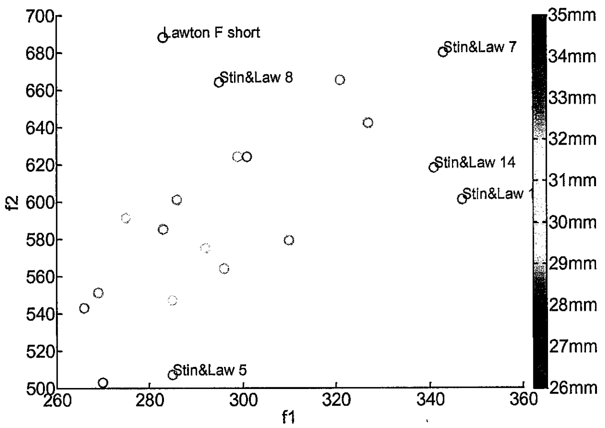

Figure 12 Annotated scatter plot

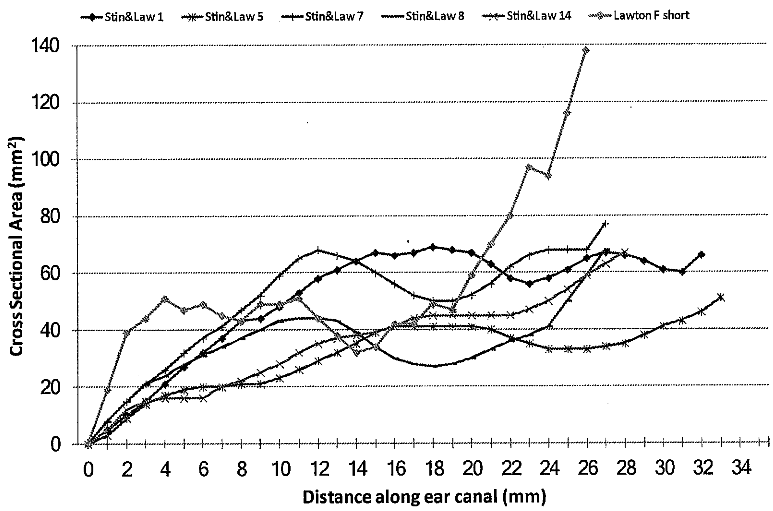

Figure 13 Canal profiles highlighted in Figure 12

By plotting the canal profiles for the datasets highlighted in Figure 12 a visual inspection could be made. Certainly Stin&Law1 and Sin&Law14 are relatively straight canals with no sharp bends while LawtonFshort and Stin&Law1 seem more tortuous with steeper local changes in cross section area. It should be noted, however, that the s axis method will give a relatively smoother area canal function compared to the straight axis.

A somewhat brief overview of clustering has shown that a relatively simple two dimensional clustering method shows the possibility that ear canals can be grouped. Further studies could reveal multi dimensional components that could describe ear canal characteristics more accurately.

5 CONCLUSION

Details of the ear need to be known in order for the ear canal to be modelling effectively and to fully understand the interface between an earplug and the ear canal (for example). The canal is not a straight tube terminated by the eardrum at right angles but twists and turns with the ear drum terminating obliquely. There are usually two bends within the ear canal, one near the entrance and one near the fleshy / bony junction. Examination of a full ear canal moulds and in-vivo ear impressions (partial canal moulds) reveals that there can be a significant departure from the idealised straight canal often used to model the auditory meatus. The presence of a constriction near the fleshy / body junction and the steepness of the first bend have ramifications for the quality of earplug fit.

Using the geometries of ear canal moulds from various studies, models of the ear canal were generated from cascading cylindrical elements. The transmission matrix method uses acoustic two-ports which are 'black boxes' that can describe the input / output of any electrical, mechanical or acoustical element(s). The two-port element is described by a 2 x 2 'transmission' matrix. The advantage of the transmission matrix method is that a whole system can be described by simply multiplying all the transmission matrices together. Furthermore, the two-port method also allows the ability for models of hearing devices to be 'bolted on'; thus giving a complete model of the HPD/transducer and outer ear. Transmission matrices have been used to describe many systems such as waveguides of arbitrary cross section including horn loudspeakers, where sufficient number of elements yields excellent results. Results were also compared with a physical replica model of the ear canal from previous research. In that study, the curvature and change of cross section were modelled using a modified horn equation. The discretized two-port method agreed very closely with the more analytical approach, with both methods agreeing with measurement (allowing for some minor measurement/replica inaccuracies).

The model was then extended to represent twenty ear canal profiles that could be gleaned from the literature. The input impedance was plotted for each canal with the first two resonances plotted on a scatter graph, f1 and f2. Some elemental clustering methods were employed to ascertain whether ear canal morphology could be grouped. It seems from this initial research that canal types could be classified by length and curvature although the amount of tortuosity was not quantified.

6 FURTHER WORK

The discretized transmission matrix ear canal model works well but needs to be refined to include: leaks, shear compliance of the canal / plug interface, bone conduction and more sophisticated models of the ear drum. Two-port models of the ear plug[10] can be used to define a complete plug / canal model and be compared to REAT data. The model could be then be extended to represent other HPDs and devices with transducers such as earphones and active noise reduction (ANR) devices.

This study has shown that ear canal types may be classified in length and rate of change of cross sectional area. Further work is required in defining curvature. More data of existing full length moulds is required. The classification needs to be extended to group curvature, transition flare of concha / canal entrance (rate of change of cross sectional area) and steepness of first bend. More investigation into clustering methods are required where Principal Component Analysis (PCA) could be a powerful method that allows many dimensions to be extracted from data.

Physical modelling with acoustical test fixtures and numerical modelling, would therefore be greatly enhanced if a discrete number of canal 'types' could be used.

Research could then be extended to classify partial moulds from *in vivo* ear impressions used for custom moulds. This would be especially beneficially for the sizing of non-custom plugs and to further investigate fitting issues with earplugs.

7 REFERENCES

[1] G.R.A.S. 'Instruction Manual - 45CB Acoustic Test Fixture According to ANSI S1242', (2012).

[2] P. A. Johansen, 'Measurement of the Human Ear Canal', Acustica, 33(5):349–351 (1975).

[3] M. Hiipakka, Measurement Apparatus and Modeling Techniques of Ear Canal Acoustics, MSc Thesis, Helsinki University of Technology (2008).

[4] B. W. Lawton, The dimensions of the human ear canal, Report No. 83/15, ISVR, Southampton, England (1983).

[5] B. W. Lawton, Personal Communication (2012).

[6] J. J. Braiden, Earplug Performance Testing and Ear Canal Modelling, MSc Thesis, University of Salford, UK (2012).

[7] L. L. Beranek, Acoustics, McGraw Hill, New York (1954).

[8] C. T. Molloy, 'Use of Four-Pole Parameters in Vibration Calculations', J. Acoust. Soc. Am., 29(7):842–853 (1957).

[9] M. Lampton, 'Transmission Matrices in Electro-Acoustics', Acustica, 39(4):239–251 (1978).

[10] P. Hiselius, 'Acoustic modelling of earplugs', Acta Acust. United Acust., 92(1):135–138 (2006).

[11] D. Mapes-Riordan, 'Horn modeling with conical and cylindrical transmission-line elements' J. Audio Eng. Soc., 41(6):471–483 (1993).

[12] M. Joswig, 'Impulse response measurement of individual ear canals and impedances at the eardrum in man', Acustica, 77:270–282 (1993).

[13] M. R. Stinson and B. W. Lawton, 'Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution', J. Acoust. Soc. Am., 85(6):2492–2503 (1989).

[14] D. Egolf et al. 'Quantifying Ear-Canal Geometry with Multiple Computer-Assisted Tomographic Scans', J. Acoust. Soc. Am., 93(5):2809–2819 (1993).

[15] M. R. Stinson, '"The Spatial-Distribution of Sound Pressure Within Scaled Replicas of the Human Ear Canal', J. Acoust. Soc. Am., 78(5):1596–1602 (1985).