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An Experimental Study on Multiple Acoustic Venting for Hearing Aid Applications

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Summary

Providing adequate relief from the occlusion effect while avoiding gain-limiting acoustic feedback continues to be a major issue in hearing aid design and fitting. Traditionally fitting of a parallel vent is often seen as a trade-off of occlusion performance for increased feedback effects. This paper explores the possibility of using multiple small acoustic vent paths in hearing aid design and provides an understanding of varying vent number and size on acoustic transmission through a vent system. The sound transmission properties of multi-vented samples have been tested in a custom 2 cc coupler. Results show, with increasing vent number and vent diameter there is an upward shift in vent associated resonance. Decreasing vent number decreases the magnitude of the vent resonances observed. In general, smaller vents require greater area to exhibit similar low frequency transmission properties but are less prone to vent associated Helmholtz resonances. High frequency attenuation important for feedback performance is found to be dependent on total vent area but not on the size of the vents used. We would expect multiple vented earmoulds to have similar feedback performance to traditional single vented samples with the same area of venting. Occlusion performance may be poorer than a single large vent, however multiple acoustic venting may provide greater design flexibility with regard to space in the ear canal.

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1. Introduction

Studies of adults aged 17 to 80 years and 15+ years in the UK and Australia respectively indicate that approximately 1 in 6 people suffer from some form of hearing loss [1, 2]. However approximately 75 to 80% of people who could benefit from hearing aids do not use them [3, 4]. Studies considering the satisfaction of hearing aid users have identified issues such as maintenance, cost, feedback, occlusion, performance in noisy environments, comfort and issues to do with manual dexterity as barriers to hearing aid use [5, 6, 7]. Cox and Alexander [5] developed a Satisfaction with Amplification Daily Life (SADL) scale that considered factors that affect overall hearing aid satisfaction. The lowest satisfaction was shown when users had hearing aid related problems with performance, such as feedback, usage with phones and background noise. Dynamic Assessment of Hearing Aids (DAHA) has shown similar trends to the SADL with lower user satisfaction with communication on most phones, conversation in groups, whistling/squealing, cost, maintenance and distortion [7]. While development of hearing aids through digital signal processing continues and may address some of these current issues with performance and sound quality, an understanding of physical hearing aid design and its effect on acoustic performance is also important. Particularly important in hearing aid design are occlusion and acoustic feedback and the relationships that exist between them. In acoustic design of hearing aids occlusion and feedback are opposing design constraints in that increasing vent size reduces occlusion while increasing chances of feedback. Recent developments in hearing aid design have seen a trend from custom made earmoulds to hearing aids with thin diameter tubing and non-custom silicone domes. The primary benefit of these aids is their non-occlusion characteristics when used with open domes.

The occlusion effect (OE) is the perceived increase in low frequency sounds of a speaker's own voice when the ear canal is blocked or closed off. During speech, low frequency sound energy is transduced through the condyle of the jaw to the medial bony portion of the external ear canal. This bone conduction occurs whether or not the ear canal is occluded, but occlusion blocks the escape of the airborne sound and causes a build up of these low frequency sounds increasing the wearer's perception [8, 9, 10]. Those with good low frequency hearing are mostly likely to experience these own voice problems with occluding devices.

The traditional method to reduce occlusion is to provide a pressure equalising vent path within the earmould to allow some low frequency sound out. However venting

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is also a major acoustic feedback path in hearing aid design and limits available gain important for speech recognition. Acoustic studies on traditional parallel vents and other variations such as reverse horn, side branch vents and non-occluding soft silicone ear tips have shown occlusion effects to be roughly linear with the log of acoustic mass of the vent [11, 12, 13, 14, 15, 16]. Acoustic mass is a measure of the inertia of the column of air in the vent. For cylindrical vents this is equal to the mass of air in the vent divided by the cross-sectional area squared with the addition of end corrections. It has been shown that, wider and shorter vents provide more occlusion relief with the best results from non- occluding soft ear tips [11, 12, 13, 14, 15, 16]. However this occlusion relief comes with an increased risk of feedback and thus a decrease in available gain. From a practical point of view reducing hearing aid vent length is not always an option. As such, traditional hearing aid fitting involves finding a vent that is as large as possible to minimize occlusion without compromising high frequency gain needed for the individual. This can be assessed using probe tube microphone real ear measurements. Sound pressure inside the ear canal can be compared with the incident sound pressure outside the ear across the frequency band typically between 200 and 1000 Hz. The extent to which an earmould blocks incident sound can be measured via real ear occluded response (REOR). The REOR can be obtained with the hearing aid in situ but turned off and compared to the unaided and/or aided condition to measure vent contribution to the acoustic response. The REOR is a measure of the degree to which sound is transmitted to the ear not a measure of bone conduction occlusion effects.

The last ten years has seen the development and now high market penetration of "open-fit" hearing aids made possible through the use of digital feedback management [17, 18]. Opening fitting hearing aids such as receiver-in-the-aid RITA and receiver-in-the-ear RITE or receiver-in-the-canal RIC provide minimal blocking of the ear canal to improve occlusion performance and rely on effective electronic feedback management to avoid feedback issues. However digital feedback cancellation has practical limits on the additional gain made available which restricts open-fit hearing aids to those with mild to moderate hearing loss [17, 18]. Entrainment artefacts introduced by digital feedback management also may have a negative impact on sound quality, particular for tonal inputs such as music [19, 20]. While these open fitting devices have much improved occlusion and own voice characteristics significant performance concessions must be made in areas of feedback and the effects of the digital feedback management methods employed. As a result open fitting hearing aids are not able to provide the amplification and sound quality needs of many hearing impaired individuals.

This study focuses on the possible value of using a larger number of smaller vent paths as opposed to a single larger vent path. In terms of venting, the optimal solution would be one that enables transmission of low frequency occlusion sounds out of the ear easily while attenuating high frequency sounds related to acoustic feedback. Narrow acoustic channels have been used effectively in earplug design in order to attenuate high frequency noise through increased resistance due to viscothermal effects [21, 22]. Furthermore increased acoustic resistance due to smaller vent size may potentially dampen vent resonance and decrease occlusion. Thus multiple small vents present a potential solution for reducing occlusion while limiting leakage of high frequency sounds responsible for feedback. By expanding beyond the traditional understanding of an acoustic vent as a single tube running from hearing aid base plate to end plate, to a system of multiple venting paths we may be able to obtain a hearing aid system that provides improved acoustic performance and is easier to fit to specific acoustic needs of each individual.

2. Method

2.1. Test coupler and samples

In order to assess only the effects of the venting channel on acoustic performance a coupler testing method was used. A custom 2 cc coupler was created to mount test samples with varying vent diameter and number (Figure 1).

The coupler was designed to provide a 2 cc volume of air between the microphone and mounted sample. In order to provide a tight seal on the ½-inch microphones used an EVA packing foam with a density of 0.11 g/cm^3 was used. This forms a type of custom 2 cc coupler similar to standard 2 cc couplers specified in ANSI S3.22-2003, which is used for the testing and verification of hearing aids [23]. The custom coupler allowed the effects of venting and vent associated resonance to be studied, while removing some variability associated with real ear microphone measures.

A non-standard coupler was used in this case as standard couplers are designed to be tested without venting either by directly connecting to hearing aid receivers (HA-2 type) or by recommending vents be closed with a clay or putty (HA-1 type) [23]. Furthermore, the proposed custom coupler design provides more space to test the principle of multiple venting without the concerns of the physical limitations of space on the earmould or hearing aid faceplate.

Five samples with vent diameters of 1, 0.8, 0.6, 0.5 and 0.4 mm were tested. The test blocks were machined into 9 mm thick Perspex rounds, 34 mm in diameter with 30 vents (Figure 1b). Samples were tested with all vents open and then tested with vents progressively blocked with putty in a symmetrical pattern towards the centre. A central hole was made to accommodate a 25 mm length of medium #13 hearing aid tubing with an internal diameter of 0.076 inches (1.93 mm).

2.2. Simulated insertion gain

Measurements of the effect of external sounds entering the coupler was conducted using a Fonix 6500-CX hearing aid test box. A swept tone signal was generated at 75 and 90 dB SPL and the levels at the ½ inch test microphone in the coupler were recorded. A behind-the-ear (BTE) style

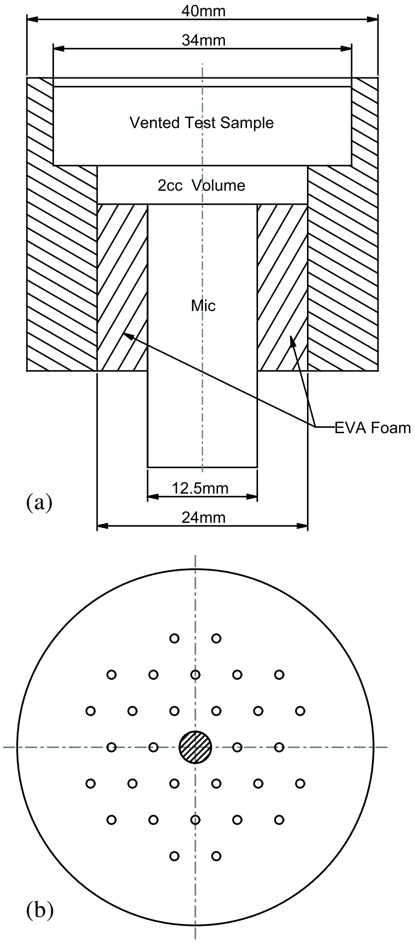

Figure 1. (a) Cross-sectional diagram of test coupler with vented test sample and ½ inch microphone in place (b) Vent layout of Perspex test samples.

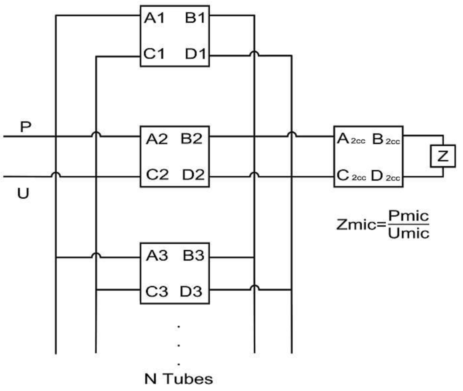

Figure 2. Transfer block system diagram describing acoustic system of sample and coupler.

ReSound Azure hearing aid was attached to the #13 tubing extending above the sample. The BTE device remained off during testing but was included to mimic standard coupler and real ear testing configuration. Samples were tested with 12 different vent numbers ranging from 30 to 0 vents open on all samples with both 75 and 90 dB SPL incident sound. Incident sounds where chosen to avoid the noise floor of the testing equipment as well as test the effect of incident sound level.

The simulated coupler insertion gain was determined as the difference in the sound level measured in the test box compared to that within the coupler. For the purpose of this paper this measure will be referred to as just insertion gain but is not to be confused with the real ear measure of insertion gain. This measure provided the ease of transmission of direct sound through the vent configuration as a function of frequency. Insertion gain of incident sound entering the coupler gives an indication of system resonances as well as the ease of transmission across the multi-vented sample material. Peak occlusion has been reported to occur primarily between 200 and 500 Hz but may occur up to 1000 Hz [24, 25]. Understanding the system resonances of venting systems is important in predicting frequency bands where occlusion may occur.

The acoustic system was modelled to see if the behaviour of the system may be described by basic acoustic principles. The model developed is analogous to an electrical 4 pole network and has been adapted from work by Egolf on acoustic modelling of sound in acoustic paths of hearing aids, human ears and probe tube microphones [26, 27, 28, 29, 30, 31, 32]. The method uses transfer block elements derived from the low reduced frequency analytical solution for viscothermal wave propagation in circular tube to find the transmission characteristics of a system terminating in a microphone of known impedance [33, 34]. These low reduced frequency solutions are found to be adequate to describe sound transmission across the audio frequency range through capillary tubes where both acoustic resistance and reactance are important elements. As such it is ideal for describing the acoustic transmission through the thin venting paths. In order to describe the insertion gain system being tested with multiple vent paths, the following system was established with parallel transfer blocks for the N vent paths (Figure 2). Lampton [35] has described simplifying transfer matrices for branched systems such as the parallel input parallel output system modelled here, into a single transfer block. Combining this with a transfer element representing the 2 cc cavity by matrix multiplication, we can determine the gain through the system.

2.3. Vent effect and feedback path gain

To determine the effect of sound vented out of the coupler an insert earphone (E.A.R-Tone 2A) has been used. Sounds enter the coupler via an insert earphone attached to the central #13 tubing and sound pressure inside and outside the coupler has been measured using a B&K 2250 sound level meter and B&K 4189 ½ inch microphone. Sound level meter measurements were taken as an audiospectrum averaged across a 10 to 20 sec time period. The samples were tested inside a sound treated room and care was made to reduce reflections. Measurements outside the coupler were taken 20 mm away from the coupler in front of the sample. A dummy microphone (diameter 13 mm, length 2.5 mm) was used in the coupler when measuring the level outside the coupler and the measurement microphone shifted to measure level inside the coupler as in Figure 1. This ensured that the same equipment with the same sensitivity was used in all measurements. The 1 mm vent sample was tested with 30, 22, 14, 8, 4, 1, 0 vents open to determine effects of vent number. Vent size effects were tested with both 30 and 8 vents across all vents sizes. All samples were tested at 100 and 90 dB SPL to observe any non-linear sound attenuation effects. Noise levels inside and outside the coupler were measured on 14 different occasions and recorded measurements within 2 standard deviations of average noise were discounted. Vent effect has been determined as the difference between vented and occluded response measured inside the coupler. This measure is useful for determining the effect of venting and the system vent resonances on the sound pressure inside the coupler.

The Feedback Path Gain was defined as the difference in the sound level measurements inside and outside the coupler. This provided information on how effective the venting configurations were to attenuating sound and particularly important higher frequency feedback sounds leaving the coupler.

3. Results

3.1. Simulated insertion gain

Below 2000 Hz insertion gain measurements tested at both 75 and 90 dB SPL exhibit vent associated Helmholtz resonances. Figures 3 and 4 show examples of the typical insertion gain frequency response curves. There is no significant difference in frequency and magnitude of resonance observed between insertion gain data measured at 75 and 90 dB. Increasing vent resonance frequency is seen with increasing vent size and number (Figures 5 and 6). Decreasing vent size is also seen to dampen vent resonance decreasing the magnitude of the observed resonance peak see Figure 7.

3.2. Modelling of insertion gain

The proposed insertion gain system model for the acoustic system shows agreement with the overall profile of the insertion gain curves obtained and trends seen in vent number and size observed (for an example plot see Figure 17). However, the model tends to shift the curves towards higher frequencies compared to the curves of measured data. Peak resonance is shifted up 170 ± 100 Hz and is found to have a level 3.0 ± 1.5 dB greater than that measured in the test box. At low vent numbers attenuation is considerably greater than measured particularly at high frequencies presumably due to sound transmission through the sample and coupler material unaccounted for in the model.

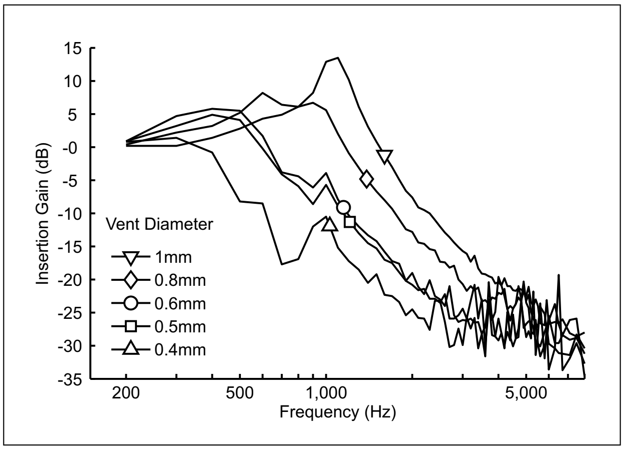

Figure 3. Example plot of the effect of varying vent diameter on the insertion gain of 75 dB SPL incident sound through a sample with 14 parallel vents.

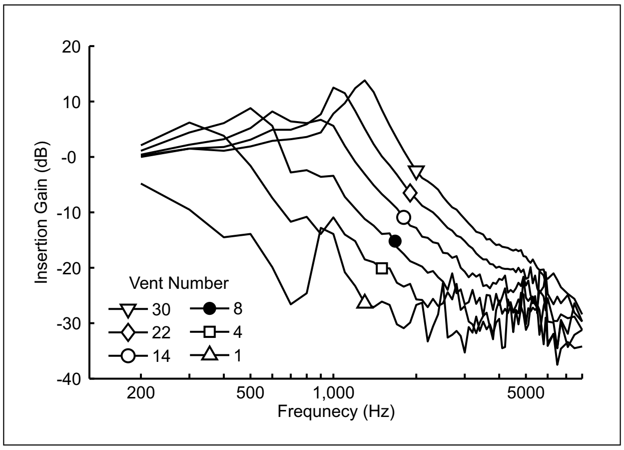

Figure 4. Example plot of the effect of varying vent number on the insertion gain of 75 dB SPL incident sound through a 0.8 mm vented sample.

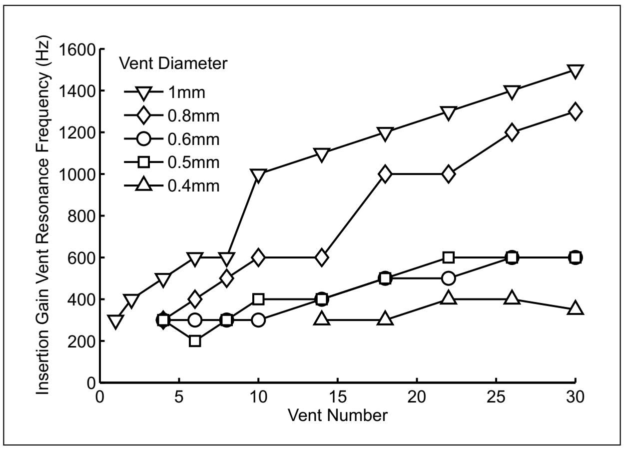

Figure 5. Plot showing effect of vent number on insertion gain vent resonance frequency for all samples tested that exhibited a vent resonance peak.

While this model is not intended to create a complete description of the acoustics of the system it shows that the resonant behaviour of the systems to variable changes is at

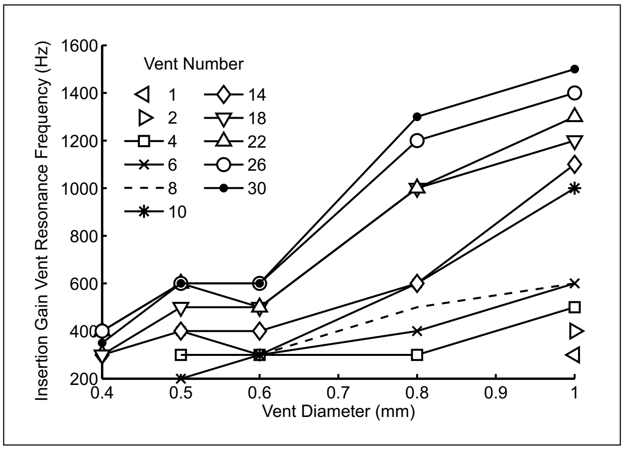

Figure 6. Plot showing effect of vent size on insertion gain vent resonance frequency for all samples tested that exhibited a vent resonance peak.

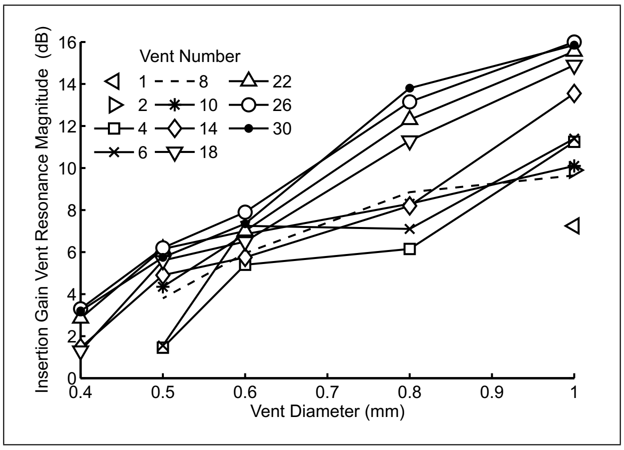

Figure 7. Plot showing effect of vent size on insertion gain vent resonance magnitude for all samples tested that exhibited a vent resonance peak.

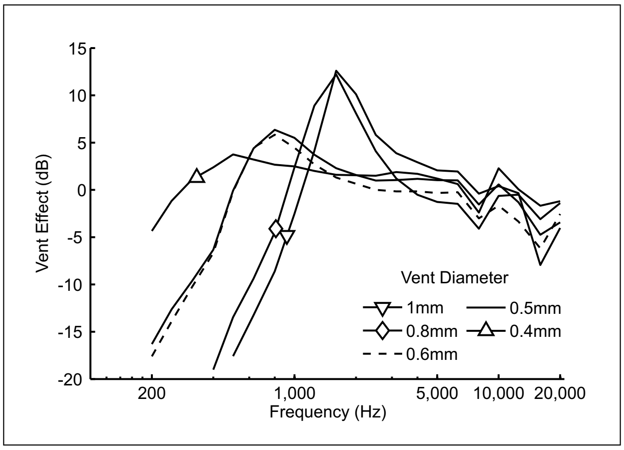

Figure 8. Example plot of the effect of varying vent diameter on the vent effect of 100 dB SPL incident sound through a sample with 30 parallel vents.

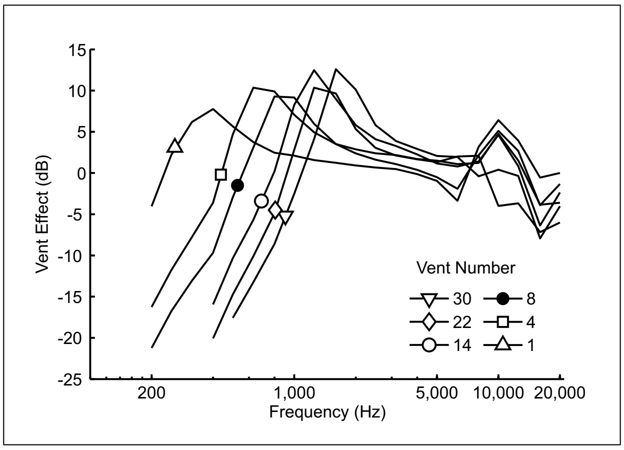

Figure 9. Example plot of the effect of varying vent number on the vent effect of 100 dB SPL incident sound through a 1 mm vented sample.

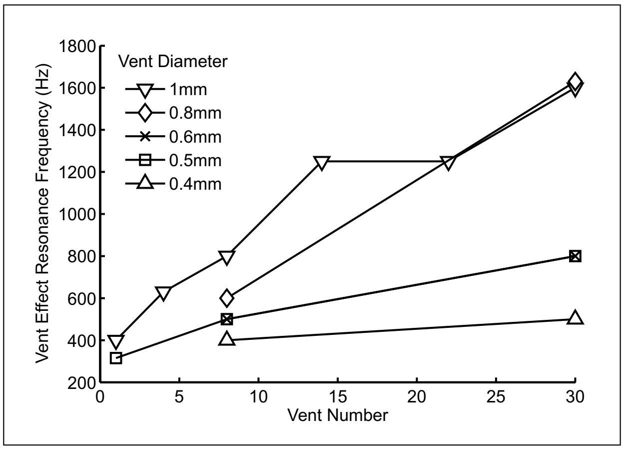

Figure 10. Plot showing effect of vent number on vent effect resonance frequency for all samples tested that exhibited a vent resonance peak.

least predictable according to acoustic principles. Further expansion of the model to include complex sound interference interactions and radiation impedance of sound as well as modelling sound leaking through the coupler may improve model compliance but only for the specific system in question.

3.3. Vent effect

Vent effect measurements also exhibited vent associated Helmholtz resonances. Below the vent resonance frequency attenuation of low frequency sounds is very minimal leading to negative vent effect in the low frequencies. No significant difference in frequency and magnitude of resonance was observed between test at 100 dB and 90 dB SPL. Similar to measurements of insertion gain increasing vent resonance frequency is seen with increasing vent size and vent number (Figures 10 and 11). This shows good agreement with published studies on vent size effects of traditional parallel venting and IROS vents using real ear measures [16, 36, 37]. A decrease in the magnitude of vent resonance is observed with a decrease in vent size (Figure 12).

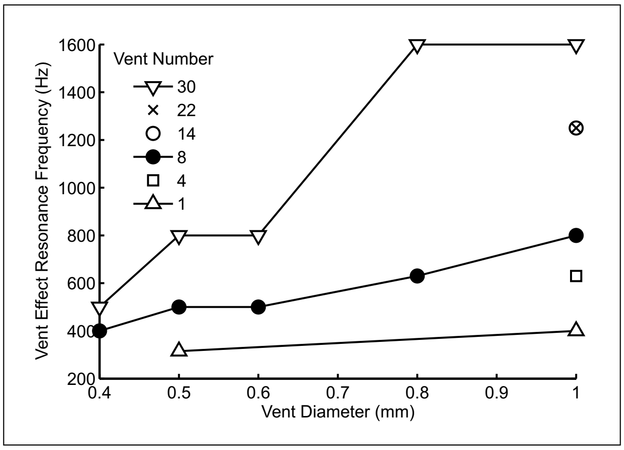

Figure 11. Plot showing effect of vent size on insertion gain vent resonance frequency for all samples tested that exhibited a vent resonance peak.

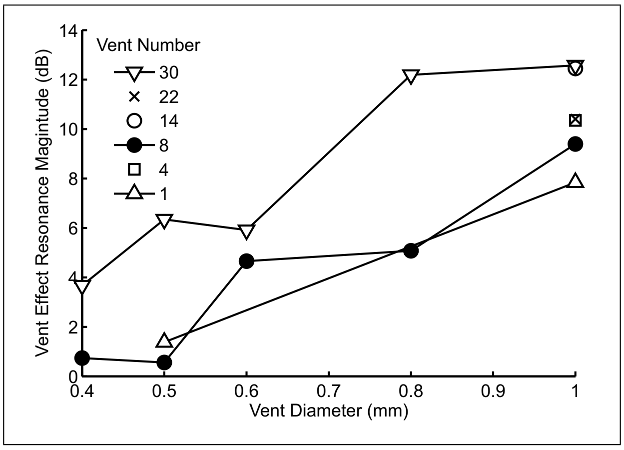

Figure 12. Plot showing effect of vent size on insertion gain vent resonance magnitude for all samples tested that exhibited a vent resonance peak.

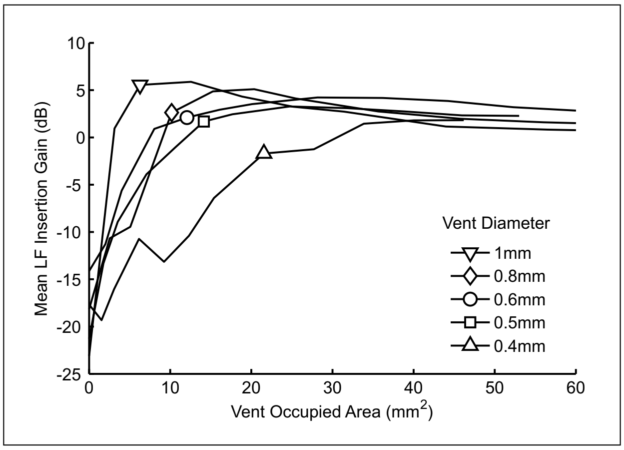

Figure 13. Mean low frequency insertion gain against vent occupied area (VOA) for all the tested venting configurations at 75 dB SPL.

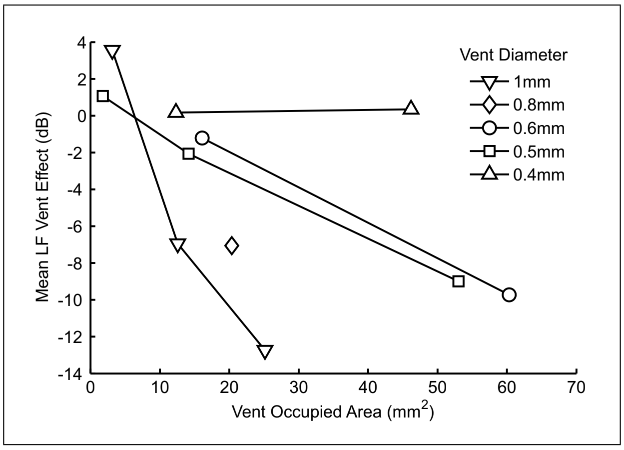

Figure 14. Mean low frequency vent effect against vent occupied area (VOA) for the tested venting configurations at 100 dB SPL.

3.4. Occlusion performance

Results suggest that larger vents provide improved occlusion performance as these larger vents have higher frequency vent resonances that are less likely to effect low frequency occlusion. However significant damping of vent resonances is obtained through the use of smaller vent paths.

In order to compare the occlusion performance of the different venting configurations tested average measures across 200–500 Hz have been used. Vent sizes have been compared according to the combined vent occupied area (VOA) of vents rather than the number of vents as this is a more appropriate comparison metric. As multi-venting requires some spacing between vents, vent diameter is considered an additional 1 mm of diameter wider when calculating the VOA to account for this. This is an important consideration when looking at multiple venting as space constraints on hearing aid faceplate or endplate may limit effective venting and occlusion performance.

We see that larger vents are more efficient at transmitting low frequency occlusion sounds (Figure 13), and reduce the sound level within the coupler the most (Figure 14). However increased systems Helmholtz resonances may greatly affect the occlusion performance of these larger vents at low numbers. Smaller vents show little or no vent associated resonance but require a much greater vent area to achieve comparable occlusion performance. This increased resonance damping may have potential benefits for fitting of real ears with unpredictable acoustic properties. Dillon suggested that Helmholtz resonances observed in coupler measurements show little effect in real ear situations due to damping caused by increased resistances of the ear canal [38]. However these resonance effects have been shown to increase low frequency gain output of hearing aid compared to occluded earmoulds using real ear measures [37, 39].

3.5. Feedback performance

To assess the venting configuration in terms of acoustic feedback performance, mean high frequency (HF) gain across all frequencies from 1–8 kHz were obtained. Venting configurations exhibiting a greater attenuation of these

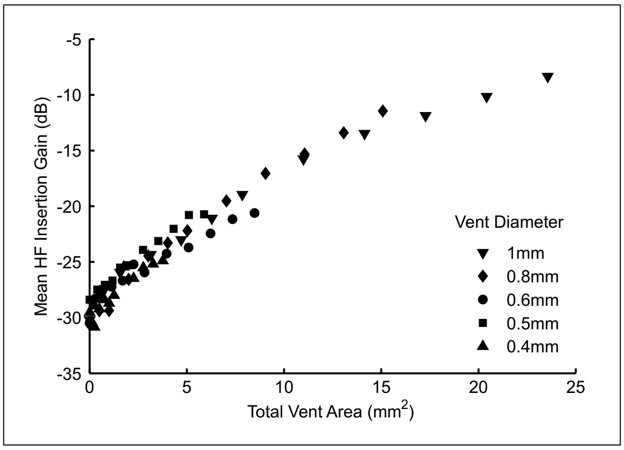

Figure 15. Effect of changing total vent area on mean HF insertion gain measured with 75 dB input sound.

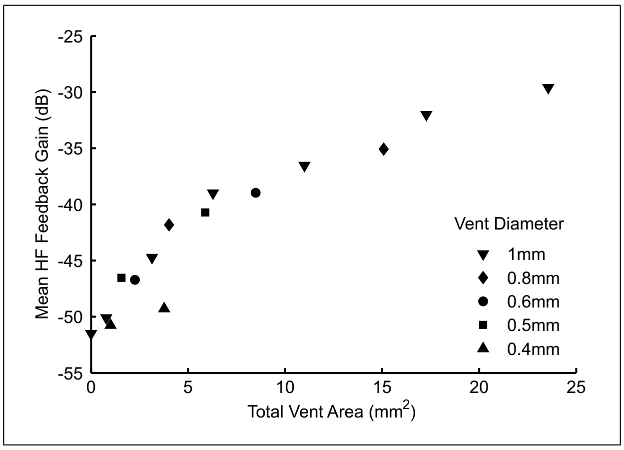

Figure 16. Effect of changing total vent area on mean HF feedback path gain measured with 100 dB input sound.

HF sounds are assumed to have better feedback performance.

Figures 15 and 16 show the effect of vent area on mean HF insertion gain and feedback path gain across the samples. We see from these that the HF attenuation provided by different venting configurations of the same vent channel area are roughly equal falling within 2 or 3 dB of each other (Figures 15 and 16) . That is, for venting configurations of equal length, the transmission of sound in the high frequencies is dependent on the total vent channel area.

3.6. Non linear effects

Measurements taken at different sound levels show some divergence in attenuation characteristics beyond a particular frequency. For the purpose of this discussion we will call this frequency the non-linear cut-off frequency. It is important to note that in all cases this non-linear cut off frequency occurs above 1 kHz and thus no effect on occlusion performance is expected. At frequencies above the cut-off of frequency we see higher intensity sound experiences more attenuation than lower frequency sound. For insertion gain attenuation of 90 dB SPL sounds follow more closely that model curve with a 75 dB SPL sound attenuating less (see example in Figure 17). The two curves are seen to continue diverging with increasing nonlinear effects to higher frequencies.

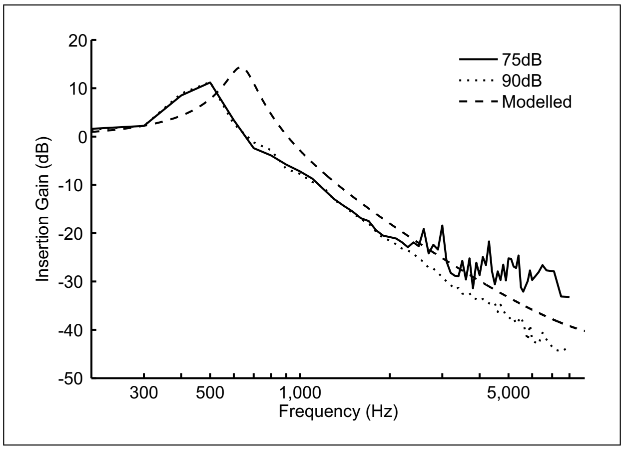

Figure 17. Example insertion gain curves showing increased attenuation of higher level 90 dB SPL sound entering coupler with four 1 mm vents.

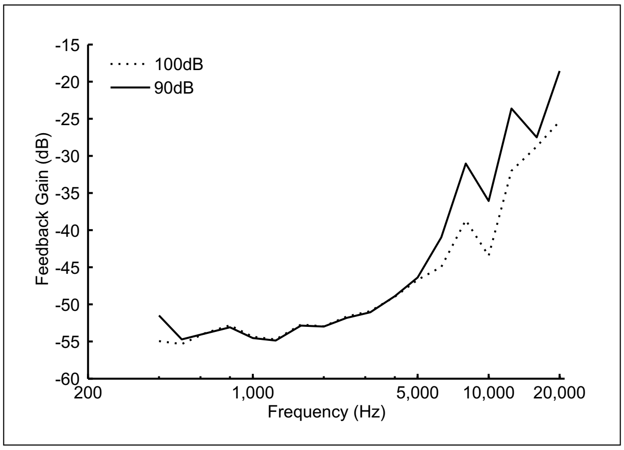

Figure 18. Example feedback gain curves showing increased attenuation of higher level 100 dB SPL feedback sounds leaving coupler via four 1 mm vents.

Feedback gain measurements at 100 and 90 dB SPL show a similar nonlinear effect with 100 dB SPL sound consistently attenuated more above a certain cut-off frequency (see example in Figure 18). Feedback shows no increasing non-linear effects with frequency possibly due to leakage of sound from insert earphone tubing to microphone.

Figures 19 and 20 show the cut-off frequency of insertion gain and feedback gain respectively plotted against vent channel area. Cut-off frequency has been defined as the lowest frequency at which the difference in the spectrum is consistently 1 dB or greater to higher frequencies Cut-off frequency of nonlinear effects is however seen to decrease with both vent number and vent size. Furthermore, we see that cut-off frequency is roughly linear with vent channel area (Figures 19 and 20). Non-linear effects adding to the attenuation in the high frequencies are poten-

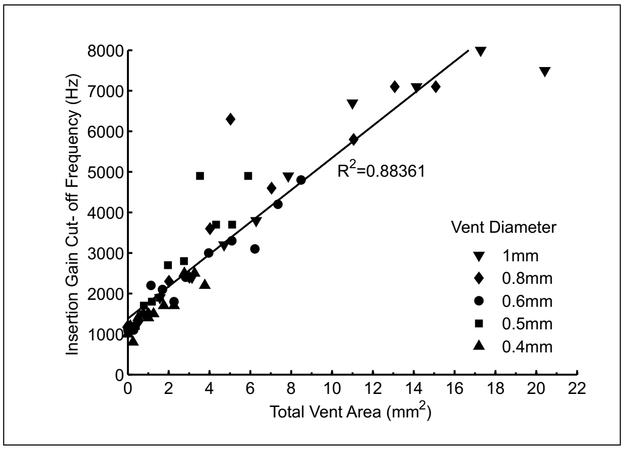

Figure 19. Insertion gain cut-off frequency against vent channel area.

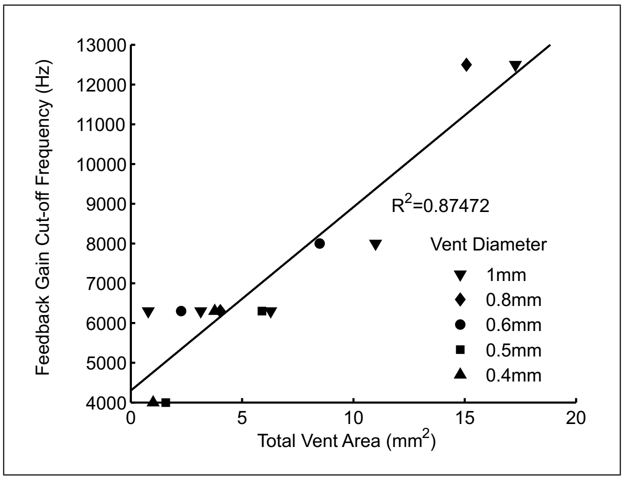

Figure 20. Feedback gain cut-off frequency against vent channel area.

tially advantageous for reducing feedback, as high intensity feedback sounds will be attenuated more through the vent path. These nonlinear effects will provide greater protection down to lower frequencies for vent configurations with less total vent channel area.

4. Conclusions

Coupler tests on multiple small vents for hearing aid applications indicate that small vents can provide similar low frequency transmission characteristics as single larger vents but require a larger area to accommodate them. Larger vents provide easier transmission of low frequency sound but display greater magnitude low frequency vent associated Helmholtz resonance. How these resonances would affect bone conducted occlusion sounds in real ear situations is uncertain and needs to be further investigated. The ear canal resonance varies between people and so smaller multiple vents with less observable vent resonance may be easier to fit. The proposed acoustic model is useful in describing the trends and effects of varying venting parameters but does not yet provide a complete representation of the sound transfer occurring within the system. The attenuation of high frequencies important for limiting feedback has been seen to be dependent on overall vent channel area in sound entering and leaving the coupler, and it shows no difference between vent sizes and numbers with configurations of comparable area. As attenuation in the feedback loop is largely the main determinate of feedback performance, these configurations would likely exhibit very similar acoustic feedback performance.

Overall multiple vented acoustic samples tested indicate that multiple vented samples provide similar feedback performance and reduced occlusion performance to traditional single vents given the same area. However multiple acoustic venting may be a feasible alternative venting method provided the space is available. Despite the increase in the area required for effective multiple venting a benefit in terms of flexibility of design may come from venting through multiple smaller channels. That is, careful vent planning may open up more useable space within the hearing aid for an alternative design approach. This area of the spatial constraints on venting, its variability and the effect of multiple venting on design flexibility requires further investigation in order to determine the benefits and feasibility of multiple acoustic venting in real ear situations.

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