Comparison of Vent Effects between a Solid Earmold and a Hollow Earmold

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Background: Hollow earmolds have become a popular type of earmold used in thin-tube, microphone hearing aid fittings. It is desirable for clinicians to be familiar with their characteristics and limitations.

Purpose: This investigation compared the effects of vent diameter between a traditional solid earmold and a hollow earmold that is used in modern thin-tube hearing aid fittings.

Research Design: A single-blind, 2 × 4 factorial design was used.

Study Sample: Eight adults with a high-frequency hearing loss participated.

Intervention: Custom earmolds for use with thin-tube hearing aids were made for each participant. Two types of earmolds were made: a solid earmold with a traditional vent length and a hollow earmold where the thickness of the shell was the length of the vent. Vent diameters were 0, 1, 2, and 3 mm.

Data Collection and Analysis: The vent effect was evaluated on real-ear aided response, real-ear occluded response during vocalization, subjective occlusion rating, insertion loss, and maximum available gain before feedback. Real-ear measurements were made with the Fonix 6500 probe-microphone real-ear system. Vocalizations from the participants were analyzed with a custom MATLAB program, and statistical analysis was conducted with SPSS software.

Results: A systematic vent effect was seen with each earmold type as the nominal vent diameter changed. For the same vent diameter, the vent effect seen with the hollow earmold was greater than that of the solid earmold.

Conclusions: Because of the difference in vent length (and thus acoustic mass) between a solid and a hollow earmold, the effect of vent diameter in a hollow earmold is more pronounced than that seen in a solid earmold of the same nominal vent diameter. Thus, a smaller vent diameter will be needed in a hollow earmold than in a solid earmold to achieve similar vent effects.

Key Words: Acoustic mass, earmold, occlusion effect, thin-tube fitting, vent

Abbreviations: BTE = behind the ear; OE = occlusion effect; REAR = real-ear aided response; REOR = real-ear occluded response; REOR_voc = real-ear occluded response during vocalization; REUR = real-ear unaided response; REUR_voc = real-ear unaided response during vocalization

The perception of hollowness of one’s own voice (or occlusion effect [OE]) has been attributed as one of the main reasons for hearing aid dissatisfaction (Kochkin, 2000). Briefly, such an effect is observed when the sound pressure level (SPL) that is generated during activities such as speaking and eating is significantly higher when the ear canal is occluded than when it is unoccluded. This accumulation of SPL in the ear canal, especially that in the low frequencies, has been cited as the origin of the “hollow” or “echoic” perception reported as the OE.

Two distinct solutions have been advocated to minimize the OE. Deep insertion of the hearing aid/earmold beyond the cartilaginous portion of the ear canal into the bony portion effectively reduces the amount of vibration; thus reducing the OE (Killion et al, 1988). Reportedly, a large portion of the OE can be reduced with this approach leaving only 2–5 dB of the OE. Unfortunately, the discomfort associated with deep earmold insertion has discouraged dispensing audiologists from fully endorsing this approach as a practical solution to reduce the OE.

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Another solution is the use of vents. For example, Kuk et al (2005) showed a systematic decrease in the OE as the vent diameter of an earmold was increased. The amount of reduction was best characterized by a decaying function with the most OE reduction when the vent was first introduced (from 0–1 mm). Less reduction was seen as the vent diameter was further increased. The OE reduction, however, was not complete until the effective vent diameter was greater than 5 mm. This of course is not easily achievable in a conventional earmold. Vent diameters of greater than 5 mm are only possible with a completely open earmold or in an open-ear fitting.

Open-ear fittings were originally attempted for patients with a high-frequency hearing loss who have either normal hearing or a mild hearing loss in the low frequencies. The earlier open-ear fittings include behind-the-ear (BTE) hearing aids coupled to a #13 tube (an internal diameter of 1.9 mm). The more recent open-ear fittings use a smaller BTE coupled to a thinner tube (an internal diameter of 0.8 mm), which is coupled to a nonoccluding silicone tip. These changes enhanced the cosmetic appeal of the fitting and popularized the use of thin-tube, open-ear fittings in the last few years (Nemes, 2008).

This increased enthusiasm for thin-tube open-ear fittings has not only increased the number of first-time wearers trying hearing aids, but it has also prompted more people with a significant amount of hearing loss in the low frequency to try hearing aids using thin-tube, open-ear fittings. This is problematic because the openness of the earmold leads to a significant decrease in the amount of low-frequency amplification at the eardrum and limits the amount of available high-frequency gain before feedback (Dillon, 2001). It is likely that such individuals may not be fit optimally.

A solution to overcome the loss of low-frequency amplification and limited high-frequency gain is to increase the amount of occlusion of the ear canal. Instead of the open ear tip that is connected to the thin tube, many earmold manufacturers make occluding or partially occluding earmolds that can be connected to the thin tube. The thin-tube, occluded-ear fittings significantly increase the fitting range of thin-tube fittings to more people with a severe degree of hearing loss. It is not uncommon to see a recommended fitting range of up to 80 dB HL for a thin-tube, occluded-ear fitting. On the other hand, the use of thin-tube, occluded-ear fitting may increase the likelihood of a significant and potentially detrimental OE.

In recent years, digital laser technology has been applied in the manufacturing of earmolds and custom hearing-aid shells (Cortez et al, 2004). One characteristic of such an earmold/shell is that it is hollow on the inside (versus solid in traditional earmolds). Because the vent length of a vented hollow earmold is the thickness of the shell (which is typically less than 1 mm thick), and the vent length of the solid earmold is typically the length of the earmold/shell (20 mm), the acoustic mass associated with a hollow earmold will be lower than that of a solid earmold of the same vent diameter. This is because the acoustic mass is directly proportional to the vent length and indirectly proportional to the vent diameter (acoustic mass = (1500 × L / D²) where L is the length of the vent in mm and D is the diameter of the vent in mm (Dillon, 2001). And if acoustic mass is directly proportional to the OE, one would expect a hollow earmold to yield a lower OE than a solid earmold with the same vent diameter. Indeed, Kiessling et al (2005) demonstrated that the OE reported (and measured objectively) by users of a hollow earmold was significantly lower than that reported from users of a solid earmold with the same nominal vent diameter when a #13 tube was used. Currently, hollow earmold is the default type provided by many hearing aid manufacturers who use laser-shell technology to fabricate the earmolds.

While the use of hollow earmolds may minimize the OE, its acceptance has the potential to create confusion for dispensing audiologists on the choice of earmold vent dimensions. This is because our current view of vent effects (defined as the amount of low-frequency reduction and gain limitations of vent diameters) is largely based on the work of Lybarger (1980), who studied the vent effect using solid earmolds. Indeed, the literature on vent effects (e.g., Valente et al, 1996) only describes the systematic effects of vent diameters and vent lengths using a standard solid earmold. The systematic effects of a vent in a hollow earmold are not available. Furthermore, while it is gratifying to know that a hollow earmold could reduce the OE, it is unclear if this OE reduction comes at a “cost” to the wearers. At least in a solid earmold, Kiuk et al (2005) showed that while an increase in vent diameter led to a decrease in OE, it also decreased the amount of maximum available gain and increased the contribution of direct sounds at the eardrum. These changes could affect the performance of the hearing aids. Thus, a comprehensive examination of the vent effect of a hollow earmold should include measurements of the loss in low-frequency output, the attenuation of direct sound at the eardrum, the OE, and the maximum available gain before feedback as the vent diameter of a hollow earmold is changed. These systematic effects are important to know so that a proper decision on the optimal vent diameter of a hollow earmold can be made.

Because many hollow earmolds are also shorter than the standard solid earmolds (or custom shells), a comparison of vent effects between the current shorter hollow earmold and the standard length solid earmold/
shell would be beneficial in transferring what we have learned from the solid earmold/shell to the current hollow earmold. Thus, the objective of the current study was to compare the vent effects of a hollow earmold and a solid earmold/shell with vent diameters of 0, 1, 2, and 3 mm. Specifically, the effects on the aided output of the hearing aid, the attenuative effect on the directly transmitted sounds at the eardrum, the OE, and the maximum available gain before feedback were studied.

**METHOD**

**Participants**

A pilot study was conducted based on three normal hearing participants in order to estimate the required sample size for the study. Normal hearing participants were used as pilot subjects because hearing sensitivity of the participants should not affect the outcome or the interpretation of the outcome. Using the G*Power calculator (Faul et al, 2007) and depending on the performance measure, we estimated that a sample size of three to seven participants was needed to properly test the hypothesis with a power of greater than 0.8. Thus, eight adults with a high-frequency hearing loss were recruited into the study. All were experienced hearing aid wearers. All participants had normal middle ear compliance as evaluated by a GSI-38 screening tympanometer. Participants signed an informed consent form prior to the study. Each took part in one two-hour evaluation and was compensated at $25/hr for his or her participation.

**Equipment Setup**

The present study measured the following: (1) real-ear unaided and aided responses (REUR and REAR) to a 60 dB SPL composite speech signal generated from the Frye 6500, (2) real-ear unaided and occluded responses during vocalization (REUR\textsubscript{voc} and REOR\textsubscript{voc}), (3) real-ear unaided and occluded responses (REUR and REOR) to an external 85 dB SPL speech-shaped noise generated from an audiometer, (4) subjective occlusion rating, and (5) maximum available gain before feedback. The composite speech signal was a synthetic stimulus that has the same long-term spectral characteristics as the speech-shaped noise available from the audiometer. These measures were made for each vent diameter (0 mm, 1 mm, 2 mm, 3 mm, and open) and earmold type (hollow versus solid) conditions.

A Fonix 6500 real-ear system was used for all real-ear measurements. However, the output from the Frye was stored in a Compaq Evo computer using the WinChap software program that enabled data transfer for offline analysis. When performing the REOR\textsubscript{voc}, the instantaneous output was taken from the remote module of the Fonix system and fed through the “line-in” of a Compaq Evo computer. The output was averaged with a custom MATLAB program (time window of 185.8 msec with a 50% overlap) to reduce the moment-by-moment fluctuation of the output and to ensure a more consistent result. The custom MATLAB program recorded five seconds of the participant’s vocalization once it stabilized. A sampling rate of 22 kHZ and a 256 bin resolution (and a bandwidth of 86 Hz) were used. The middle 3 sec of the saved waveform were averaged and analyzed offline. The same method of recording and analysis of vocalization was reported in Kuk et al (2005).

**Earmolds**

Two types of earmolds/shells were compared in this study—a shorter, hollow earmold that is typically made by hearing aid manufacturers for coupling to microsize BTEs, and a longer, solid earmold where the lateral surface sits at the entrance of the ear canal. An earmold impression that extended 2–3 mm beyond the second bend was taken at the research site. The same impression was used to make both earmolds at the manufacturing site using laser shell-making technology (Cortez et al, 2004) to ensure an accurate and identical fit. Both earmolds were coupled to a Widex Inteo (IN-9) BTE hearing aid via a thin tube of 0.8 mm internal diameter. The tubing length varied from 55–61 mm (median of 58 mm) among individuals because of differences in pinna sizes. Earmold lengths varied slightly across participants, but they were fabricated for the typical lengths appropriate for that style of earmold.

**Hollow Earmold**

The hollow earmold had an average length of 13 mm and a shell thickness of 0.7 mm. Thus, the default vent length was 0.7 mm. Vents were made by drilling through the medial end of the earmold beginning with no vent (0 mm) followed by vents of 1, 2, and 3 mm. All measurements were made for each vent condition.

**Solid Earmold**

The solid earmold had an average length of 22 mm. Because the vent went through the length of the earmold, the averaged vent length of the solid earmold was 22 mm. Separate (but identical) earmolds were made for each vent diameter for each participant using the same ear impression. It should be noted that because of space limitations, only half of the participants could have a 3 mm vent diameter. The remaining participants
had a 3 mm vent diameter on the lateral surface of the earmold that tapered to a 2.5 mm diameter on the medial end. The vent diameters were verified using a caliper. Figure 1 shows the different views (lateral, side, and medial) of the hollow and solid earmolds.

Open-Fit Earset

Additional measurement using an open earset was included in order to compare the vent effect to an open-ear fitting. The open earset used a nonoccluding soft silicone tip (four sizes) on the end of a thin tube. The tip size was chosen based on the size of the individual’s earcanal. The average REUR and the REOR with this earset to an 85 dB SPL speech-shaped noise were identical, confirming the openness of this earset.

Procedure

Participants sat in the center of a 3.3 × 3.3 × 2 m sound-treated test booth. Only one ear was tested. The nontest ear remained unoccluded. All real-ear measurements were completed for the unaided condition first. An otoscopic inspection was performed prior to real-ear measurements to ensure proper probe-tube placement. Once the correct insertion depth was ensured, a mark was made on the probe tube to mark the position of the tragus. The insertion depth of the probe tube in all subsequent measures used that mark as a guide.

Earmold types were counterbalanced across participants. However, earmold vent diameters were used in sequential order (i.e., started at 0 mm and followed by 1, 2, and 3 mm). For the solid earmold, separate earmolds were available for each vent diameter. For the hollow earmolds, vents at the desired diameter were drilled by using a Red Wing lathe (model 26A) with the intended drill bit in a sequential order. The order of the evaluative measures was counterbalanced. After all the measures were made with one earmold-vent diameter type, they were repeated with the remaining earmold-vent types and the open-fit earset.

The hearing aid was in the off position during measurements of REORvoc and REOR. For the REORvoc measurements, participants were asked to produce the vowel /i/ and sustain their vocalization for as long as they could. A Radio Shack sound level meter (Model 33-2050) was placed 12 in from the participant’s mouth. They were asked to monitor their vocal effort so the sound level meter measured at least 70 dB SPL. The participants practiced their production prior to each measurement. In addition, the tester also monitored the pitch of the participants’ production. Participants were asked to repeat their productions should any alteration of the pitch be noted. The output difference between the REURvoc during vocalization and the REORvoc represented the amount of objective OE.

Subjective OE rating was measured by asking participants to judge the “hollowness” of their voice as they repeated the phrase “Baby Jeannie is teeny tiny” at a conversational level. This phrase was used by the first author in several studies to examine the occlusion effect (Kuk, 1990; Kuk et al, 1992). It was constructed with an abundance of /i/ in a conversational context. The /i/ vowel has the lowest first formant, which makes it desirable to use when studying low-frequency phenomena such as the OE. A 1–10 rating scale was used with 1 being the hollowest and 10 being the most natural sounding. Participants were allowed to repeat the phrase as many times as they needed before making a decision.

To measure the effect of venting on the output of a hearing aid (i.e., REAR), a composite speech signal at 60 dB SPL from the Fonix 6500 was used as the stimulus. The loudspeaker was 12 in from the participant and was adjusted to the level of the participant’s ear. The study hearing aid was set to the maximum gain setting, and all the adaptive features were deactivated (omnidirectional, no noise reduction, feedback cancellation off). The maximum gain before feedback for each earmold-vent condition was measured during a feedback test with the hearing-aid-earmold combination in situ.

The insertion loss characteristics (or transmission loss) of each earmold-vent condition were measured.

Figure 1. Lateral view (top row), side view (middle row), and medial view (bottom row) of hollow earmold (left) and solid earmold (right).
using an 85 dB SPL speech-shaped noise (generated from a GSI clinical audiometer) presented 1 m directly in front of the participants. The REOR to this stimulus was measured while the hearing aid remained off.

**RESULTS**

**Vent Effect on Real-Ear Aided Response**

The effect of vent diameter on the average REAR with the solid earmold and the hollow earmold is displayed in Figures 2a and 2b respectively. For this illustration, the difference in real-ear output between the 0 mm vent condition, and a specific vent diameter (including the open-ear) was calculated for the solid and hollow earmolds separately. Thus, a display at zero (0) would suggest identical output as the 0 mm vent condition of the specific earmold type. A negative value would indicate that the vented condition yielded a lower output than the 0 mm vent condition. The "open-ear" curves were different between the solid earmold (Figure 2a) and the hollow earmold (Figure 2b) because of the difference in REAR at the 0 mm vent diameter condition.

Figure 2a shows minimal output difference between the 1 and 0 mm vent diameters for the solid earmold. As the vent diameter increased beyond 1 mm, the decrease in low-frequency output increased. At 200 Hz, there was a 10 dB decrease at the 2 mm vent diameter and a 15 dB decrease at the 3 mm vent. Negligible low-frequency reduction was seen above 600 Hz for the solid earmold.

The hollow earmold reduced more low frequencies than the solid earmold of the same vent diameter (Figure 2b). A 1 mm vent decreased the output at 200 Hz by as much as 15 dB, and a 2 mm vent reduced the output by 25 dB. The 3 mm vent diameter reduced the output by an additional 1–2 dB. In contrast to the solid earmold, a 5–8 dB output reduction was observed above 1000 Hz for the 2 and 3 mm vent diameter conditions. A hollow earmold with a 2–3 mm vent diameter showed a similar low-frequency effect as an open-ear fitting.

The difference in real-ear output reduction measured between the solid earmold and the hollow earmold of the same vent diameter was determined. A positive number shows a higher output from the solid earmold than from the hollow earmold. Figure 3 shows that the solid earmold yielded a higher low-frequency output (or less reduction in low-frequency output) than the hollow earmold. Indeed, as much as 20 dB was noted at 200 Hz. The differences decreased with increasing frequency. A repeated-measures GLM revealed that the effects of earmold type (F(1,7) = 152.33, p < 0.001, power = 1.0), vent diameter (F(3,21) = 129.28, p < 0.001, power = 1.0), and frequency (F(4,28) = 85.9, p < 0.001, power = 1.0) were statistically significant.

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Vent Effect on Objective Occlusion

The average objective OE for each earmold-vent condition was calculated by taking the difference between the REOR voc and real-ear unaided response during vocalization (REUR voc). The results are shown in Figure 4a for the solid earmold and in 4b for the hollow earmold. With the solid earmold, there was an average of 15 dB of OE in the 0 mm vent condition. As expected, OE decreased as the vent diameter increased. However, as much as 10 dB of OE remained with a 3 mm vent diameter. The peak of the OE also shifted higher as the vent diameter increased. The “negative OE” seen around 2500 Hz is the artifact of the subtraction method to estimate the OE and should be ignored in interpreting the OE. This is because with the hearing aid in the “off” position, no amplification was available to compensate for the loss of the ear-canal resonance during the REOR voc measurement. This dip disappeared when the hearing aid was turned on because the gain on the hearing aid compensated for the loss in ear-canal resonance. However, the gain of the hearing aid in the low frequency would have confounded the interpretation of the magnitude of the shell-induced OE.

Figure 4b shows that the maximum OE measured in the hollow earmold was only 12 dB in the 0 mm vent condition measured at around 400 Hz. As the vent diameter increased from 0–1 mm, the OE at 400 Hz decreased dramatically to less than 6 dB, and the frequency of the peak OE shifted to 1000 Hz, where it stayed relatively constant with increases in vent diameter. With a 3 mm vent diameter, there was less than 3 dB of OE across a broad frequency range below 1000 Hz. There was less OE with a 1 mm vent in a hollow earmold than a 3 mm vent in a solid earmold.

Figure 5 shows the difference in objective OE between the solid and the hollow earmolds. When vented, the solid and hollow earmolds showed a peak difference of 7–9 dB in OE for each vent diameter (1, 2, and 3 mm). In addition, the peak frequency also shifted higher for the hollow earmold. For example, the frequency where OE showed the peak difference was 300 Hz when the vent diameter was 1 mm. It became 500 Hz when the vent diameter was 2 mm, and around 700 Hz when the vent diameter was 3 mm. The difference in OE between a solid earmold and a hollow earmold was statistically significant at the dominant frequency (of 344 Hz) \( F(1,7) = 18.17, p < 0.005, power = 0.95 \). A dip was still present at around 2500 Hz because the insertion loss of a solid vented earmold is different from a hollow vented earmold. This point was demonstrated in the section on “Vent Effect on Insertion Loss.”

Vent Effect on Subjective Occlusion Rating

Figure 6 shows the individual (and median) hollowness ratings for each earmold-vent combination. As
expected, subjective ratings improved as the vent diameter increased for both earmold types. Similar to the observations in objective OE, the median ratings for the hollow earmold were consistently higher (better) than those of the solid earmold. This is true even for the 0 mm vent condition where the hollow earmold was rated approximately 4 intervals higher than the solid earmold. A related-sample Wilcoxon test revealed that the difference in subjective OE ratings between the solid earmold and the hollow earmold was statistically significant for all three vent diameters ($p < 0.05$). Thus, the hollow earmold provided more occlusion relief than the solid earmold with the same nominal vent diameter.

**Vent Effect on Insertion Loss (or transmission loss)**

The attenuation characteristics (or insertion loss) of each earmold-vent type were measured by subtracting the REUR to an 85 dB SPL speech-shaped noise from the REOR for each earmold-vent condition. Figures 7a and 7b show the averaged insertion loss for the solid earmold and hollow earmold respectively. As expected, the completely occluding earmold yielded the greatest amount of insertion loss (or attenuation) especially in the high frequencies. As the vent diameter increased, the amount of insertion loss decreased in a systematic manner. For the solid earmold, almost 30 dB of insertion loss was noted with the 0 mm vent diameter at 3000 Hz. About 20 dB of insertion loss was noted with a 3 mm vent at 3000 Hz.

Figure 7b shows that the amount of insertion loss seen with the hollow earmold was substantially less than that of the solid earmold. For example, the amount of attenuation was about 25 dB at 3000 Hz, which decreased to only 15 dB with a 1 mm vent diameter. In addition, no loss in low-frequency transmission below 1500 Hz was noted even with the 1 mm vent diameter. The amount of insertion loss with a 1 mm hollow earmold was less than that of a 3 mm solid earmold. There was only about 10 dB of attenuation for a 3 mm vent at 3000 Hz.

The difference in insertion loss between the two earmold types is shown in Figure 8. Approximately 5 dB more attenuation was noted with the solid earmold than with the hollow earmold in the 0 mm vent condition. This may be attributed to the difference in insertion depth between the earmolds. The difference was around 15 dB at 2000–3000 Hz for all three nominal vent diameters. The difference between the solid and hollow earmolds was statistically significant [$F(1,7) = 113.79$, $p < 0.001$, power $= 1.0$]. This suggests that a vented hollow earmold allows more direct sound transmission than a solid earmold of the same vent diameter. The magnitude of that difference varied with frequencies.
Vent Effect on Maximum Available Gain

The maximum available gain before feedback for each earmold-vent condition was measured with the feedback cancellation mechanism deactivated. Figure 9a shows the maximum available gain in the solid earmold for different vent diameters. The maximum available gain in the high frequencies decreased slightly (2–4 dB) when the solid earmold was vented (i.e., from 0–1 mm). With a 3 mm vent diameter, one still retained about 35 dB of maximum available gain around 2500 Hz. In contrast, the maximum available gain provided by the hollow earmold reflected a more dramatic decrease as the vent diameter changed (Figure 9b). There was a 6–9 dB decrease in maximum available gain above 1500 Hz when the vent diameter increased from 0–1 mm. It decreased another 4–7 dB when the vent diameter increased from 1–2 mm. There was little or no difference in maximum available gain between vent diameters of 2 mm and 3 mm. There was less than 25 dB of maximum available gain around 2500 Hz with a 3 mm vent diameter.

The difference in maximum available gain between the two earmold types is shown in Figure 10. There was no difference in maximum available gain below 1000 Hz since feedback was not prevalent in the lower frequencies. However, there was up to 14 dB of gain difference between the two earmold types at 2000 Hz with a 2 mm vent and 13 dB gain difference at 2500 Hz with a 3 mm vent. The frequency region between 2000 and 3000 Hz appears to be the most sensitive to differences between a solid earmold and a hollow earmold. The noted differences were statistically significant in favor of a solid earmold [F(1,7) = 454.91, p < 0.001, power = 1.0].

Discussion

The present study evaluated the differences in vent effects on real-ear output, occlusion, insertion loss, and maximum available gain before feedback between a solid earmold and a hollow earmold of typical lengths. The results showed systematic changes in the vent effects of both earmolds as the vent diameter
increased. Furthermore, for the same nominal vent diameter, the hollow earmold yielded a greater reduction of low-frequency output, less subjective and objective occlusion effect, less insertion loss, and less maximum available gain before feedback than a solid earmold. These observations are in line with the speculation that the shorter vent length of a hollow earmold results in a lower acoustic mass, which may have mediated the observed differences.

**What Do These Observations Mean?**

The observation that a hollow earmold exhibited a stronger vent effect than a solid earmold of the same nominal vent diameter has important implications. If one simply examines the effectiveness of the hollow vented earmold at reducing the OE, one may be tempted to use a vented hollow earmold exclusively. Indeed, Figure 5 shows that a hollow vented earmold reduced the objective OE much more than a solid vented earmold. The 2–5 dB of OE in a 2–3 mm (vent diameter) hollow earmold could be acceptable to a large number of hearing-aid wearers (Kuk et al., 2005).

Unfortunately, Figure 3 shows that the low-frequency output of the hearing aid is substantially reduced in the hollow earmold. Furthermore, the hollow earmold reduces the output in the mid to high frequencies by an additional 5–7 dB more than a solid earmold when the vent diameter is 2 mm or larger. This suggests that hearing-aid wearers who have a substantial degree of hearing loss in the low frequencies may likely not receive adequate low-frequency output in a vented hollow earmold, especially when the vent diameter is greater than 1 mm.

Figure 8 reveals that a hollow earmold attenuates less of the direct sound than a solid earmold of the same nominal vent diameter. A corollary is that a hollow earmold of a specific nominal vent diameter allows more direct transmission of sounds than a solid earmold of the same vent diameter. In other words, the resultant SPL at the eardrum of a hearing aid wearer may have a higher contribution of direct sounds (through vents) between 1000 and 4000 Hz with a hollow earmold than with a solid earmold of the same nominal vent diameter. This suggests a greater potential of interaction (phase and magnitude) between the direct sounds and the processed sounds. Depending on the relative magnitude of the processed sounds and the direct sounds, the efficacy of specific signal processing algorithms (such as noise reduction and directional microphone) may be affected differently between a hollow and a solid earmold (vented). This possibility should be investigated in the future.

Figure 10 shows that the maximum available gain of a hollow earmold is substantially less than that of a solid earmold of the same nominal vent diameter. This means that the OE advantage of a vented hollow earmold occurs at the expense of reduced maximum available gain. Audibility of mid to high frequency sounds may be sacrificed. This, along with the reduced output in the low frequencies, would suggest that the overall output of a vented hollow earmold could be substantially less than that of a solid earmold of the same nominal vent diameter. This has several implications. First, clinicians must not expect the same vent effect from a solid earmold and a hollow earmold of the same nominal vent diameter. In general, clinicians should use a much narrower vent diameter in a hollow earmold than in a solid earmold. Second, clinicians should be cognizant of the trade-offs between the OE and available gain and be conservative in choosing an optimal vent diameter when using a hollow earmold. Third, a modestly vented hollow earmold may be restricted only to those with a mild-to-moderate hearing loss in order to ensure sufficient gain/audibility. When a more severe loss is encountered, it may be more appropriate to use a solid earmold to achieve the desired gain and output. If a hollow earmold has to be used, the choice of the vent diameter must be conservative. However, an issue with using a very small vent diameter (e.g., less than 1 mm) is the possibility of accumulation of cerumen or other debris at the vent opening. Thus, the wearer has to be instructed on the proper care of the earmold. Last, to ensure adequate gain in the high frequencies, an effective active feedback cancellation algorithm may be more desirable in a vented hollow earmold than in a vented solid earmold.

**Equivalence of Vent Effect between Solid and Hollow Earmolds**

The differences in vent effects between a hollow earmold and a solid earmold suggest that the choice of an optimal vent diameter in a hollow earmold must be different from that of a solid earmold. Thus, guidelines that show the equivalence in vent diameters between a solid earmold and a hollow earmold that yields the same vent effect would be of interest to dispensing audiologists. If the observation that the acoustic mass of the vent correlates with the OE (Kuk et al., 2005; Kiessling et al., 2005) can be generalized to all performance measures reported in this study, one may estimate such equivalence by calculating the acoustic mass of the vents used in the solid earmold and the hollow earmold using Dillon’s acoustic mass equation (2001). The data measured in the current study offer an approximate validation.

Assuming that the solid earmold is 22 mm long (thus a vent length of 22 mm) and that the hollow earmold is 13 mm in length with a shell thickness of 0.7 mm (thus a vent length of 0.7 mm), Dillon’s equation (2001)
would suggest that a 1 mm vent hollow earmold would have the same acoustic mass as a 5.6 mm vent solid earmold. Thus, a 1 mm vent in a hollow earmold has a much lower acoustic mass than the largest possible vent diameter (i.e., less than 4 mm) in a solid earmold! A 2 and 3 mm vent diameter in a hollow earmold would have the same acoustic mass as a solid earmold with an 11 and 16.8 mm vent diameter respectively.

The data obtained in the current study may be used to empirically validate the equivalence. To do that, we first identified the frequency showing the greatest vent effect for each performance measure (such as REAR, Objective Occlusion Effect, Maximum Available Gain).

### Table 1. Equivalence in Vent Diameter between a Hollow Earmold and a Solid Earmold

<table>
<thead>
<tr>
<th>A Frequency (Hz)</th>
<th>B Equivalent Vent Diameter of Hollow Mold on Insertion Loss</th>
<th>C Equivalent Vent Diameter of Hollow Mold on Objective Occlusion Effect</th>
<th>D Equivalent Vent Diameter of Hollow Mold on Maximum Available Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid mold 0 mm</td>
<td>Solid mold 1000 1500 2000 3000 4000</td>
<td>Solid mold 172 258 344 430 516</td>
<td>Solid mold 2000 2500 3200 4000 6000</td>
</tr>
<tr>
<td>0.5 mm 1 mm 1.5 mm</td>
<td>0.5 mm 1 mm 1.5 mm</td>
<td>0.5 mm 1 mm 1.5 mm</td>
<td>0.5 mm 1 mm 1.5 mm</td>
</tr>
<tr>
<td>2 mm 2.5 mm 3 mm</td>
<td>2 mm 2.5 mm 3 mm</td>
<td>2 mm 2.5 mm 3 mm</td>
<td>2 mm 2.5 mm 3 mm</td>
</tr>
<tr>
<td>Solid mold 200 500</td>
<td>0 mm 0.072 0.217</td>
<td>0 mm 0.023</td>
<td>0 mm 0.045 0.266</td>
</tr>
<tr>
<td>0 mm 0.5 mm 1 mm</td>
<td>0 mm 0.5 mm 1 mm</td>
<td>0 mm 0.043 0.060 0.014 0.209 0.570</td>
<td>0 mm 0.045 0.266</td>
</tr>
<tr>
<td>1.5 mm 2 mm 2.5 mm</td>
<td>1.5 mm 2 mm 2.5 mm</td>
<td>1.5 mm 2 mm 2.5 mm</td>
<td>1.5 mm 2 mm 2.5 mm</td>
</tr>
<tr>
<td>3 mm</td>
<td>3 mm</td>
<td>3 mm</td>
<td>3 mm</td>
</tr>
</tbody>
</table>
We then compared the measured performance for each vent diameter and identified the diameters that yielded the same performance between the two earmold types. For example, the panel on the left of Figure 11 shows the REAR of the hearing aid as a function of vent diameter for the two earmold types. If one draws a horizontal line that intersects the REAR curves for the hollow earmold and the solid earmold, the point of intersection would reflect the vent diameter that yielded the same performance. For example, a horizontal line drawn at 65 dB SPL intersects the curve generated by the solid earmold at 2.2 mm and the curve by the hollow earmold at 0.4 mm vent diameter. This means a hollow earmold with a 0.4 mm vent diameter has the same output (i.e., is equivalent to) as a solid earmold with a 2.2 mm vent diameter. Similar horizontal lines at different output levels may be drawn to yield the panel on the right of Figure 11. In this case, a solid earmold that has a 2.2 mm vent diameter has the same vent effect (low-frequency output reduction) as a hollow earmold with a 0.4 mm vent diameter; and a 3 mm solid earmold is similar to a 0.7 mm hollow earmold. The same analysis can be repeated for the other frequencies as well as for other vent effect measures (such as available gain or occlusion effect).

Table 1 shows the equivalence in vent diameter between the hollow earmold and the solid earmold used in this study on low-frequency output reduction, insertion loss, objective OE, and maximum available gain at frequencies that can be extrapolated. No entries were available at some frequencies because the vent effect curves generated by the hollow and solid earmolds were parallel to each other—thus, no intersection points can be estimated. This difficulty limits the estimation of the equivalence at some frequencies and at some vent diameters. For example, in section A (on REAR), one can see that a hollow earmold of 0.72 mm diameter reduces as much low-frequency output at 200 Hz as a solid earmold of 3 mm vent diameter. When one examines the equivalence in insertion loss at 1000 Hz, one sees that a 0.99 mm hollow earmold resulted in the same amount of insertion loss as a 3 mm solid earmold. By the same token, the amount of OE reduction at the strongest OE peak (344 Hz, section C) offered by a 0.7 mm hollow earmold is similar to that offered by a 3 mm solid earmold. The maximum gain permitted by a 3 mm solid earmold is similar to that permitted by a hollow earmold of 0.6–1.5 mm in vent diameter across frequencies. In view of these observations, one may conclude that the vent effect associated with a 0.7–1 mm hollow earmold is similar to that of a 3 mm solid earmold.

**Should There Have Been a Difference in Vent Effect When the Vent Diameter Was 0 mm?**

The readers will notice that the vent effects of the hollow earmold were different than the solid earmold.
even when there was no vent in the earmolds. One explanation is that even with a 0 mm nominal vent diameter, there was leakage between the earmold and the ear canal wall. Consequently, the effective vent diameter was not zero. This resulted in differences in vent effect between the solid and the hollow earmolds.

There is also another possible reason for the difference in vent effect noted in the 0 mm vent condition. Because this study was designed to examine the difference in vent effect between a solid earmold and a hollow earmold of their respective typical lengths, the effects observed will not only demonstrate the effect of vent length but also the potential difference in insertion depth between the hollow and the solid earmolds. In order to examine such a hypothesis, we repeated the measurements in three of the participants using a solid earmold (also made with laser-shell technology) that was identical in length and shape to the hollow earmold. The vent length of the solid earmold was 13 mm instead of 0.7 mm in the hollow earmold.

Figure 12 (a: aided output, b: objective OE, and c: insertion loss) shows the difference in vent effect for the three participants between the new solid earmold and the hollow earmold when the nominal vent diameters were 0, 1, 2, and 3 mm. In contrast to previous figures where there was a difference between the two earmold types in the 0 mm vent condition, there was virtually no difference in any of the measured results for the 0 mm vent condition. This means one should not expect an unvented solid earmold and an unvented hollow earmold of the same length and depth of insertion to yield any difference in aided output, occlusion effect, attenuation (or insertion loss), or maximum available gain.

**CONCLUSIONS**

The current study confirmed that a hollow earmold yielded more OE reduction than a solid earmold of the same nominal vent diameter; however, other performance measures such as maximum available gain in the mid to high frequencies were negatively affected. In using a vented hollow earmold, one must remember the trade-offs between OE and the additional loss in available gain and low-frequency output in a hollow earmold and be conservative in choosing the optimal vent diameter.

**REFERENCES**


