Real-World Performance of a Reverse-Horn Vent

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Abstract
The present study compared differences in subjective and objective performance in completely-in-the-canal (CIC) hearing aids with conventional uniform 1.5 mm parallel vents and another with a reverse horn vent where the diameter increased from 1.5 mm on the lateral faceplate to 3 mm on the medial opening of the hearing aid. Nine hearing-impaired persons with a high-frequency hearing loss participated. The test battery included unaided in situ thresholds, amount of available gain before feedback, speech in quiet, speech in noise (HINT), subjective ratings of hollowness and tolerance, objective measures of the occlusion effect, and real-ear aided response. Results showed less available gain before feedback but less occlusion effect for subjective ratings and objective measures with the reverse horn vent. This type of vent design may be useful to increase the effective vent diameter of custom (including CIC) hearing aids.

Key Words: Available gain, occlusion effect, reverse horn vent

Abbreviations: BTE = behind-the-ear hearing aid; CIC = completely in the canal; HINT = Hearing in Noise Test; OE = occlusion effect; REAR voc = real-ear aided response during vocalization; REOR voc = real-ear occluded response during vocalization; REUR voc = real-ear unaided response during vocalization; RHV = reverse horn vent; RV = regular vent

Sumario
El presente estudio compara las diferencia subjetivas y objetivas en el desempeño con auxiliares auditivos completamente dentro del canal (CIC) con orificios de ventilación paralelos, de 1.5 mm, uniformes y convencionales, y con orificio de ventilación de cuerno reverso, donde el diámetro se incrementa de 1.5 mm en la placa lateral a 3 mm en la apertura medial del auxiliar auditivo. Participaron nueve personas con hipoacusia en las altas frecuencias. La batería de pruebas incluyó umbrales en situ no amplificados, cantidad de ganancia disponible antes del inicio de la retroalimentación, lenguaje en silencio, lenguaje en ruido (HINT), apreciación subjetiva de sonido hueco y tolerancia, medidas objetivas del efecto de oclusión, y respuesta amplificada de oído real. Los resultados mostraron una menor ganancia disponible antes de la retroalimentación, pero un menor efecto de oclusión en las apreciaciones subjetivas y en las medidas objetivas con el orificio de ventilación de cuerno reverso. Este tipo de ventilación puede ser útil para incrementar el diámetro efectivo de dicha ventilación en auxiliares auditivos hechos a la medida (incluido el CIC).
One frequent complaint from hearing aid wearers is the “hollowness” of their own voice when talking with their hearing aids in situ. The reported incidence varied from as little as 30% (Dillon et al, 1999) to as much as 60% (Lazenby et al, 1986). This variation in reported incidence is probably affected by several factors, including the experience of the wearers with amplification, styles of hearing aids (and earmolds), and the magnitude of the low-frequency hearing loss of the wearer. In most instances, the hollowness of the wearer’s voice occurs because the occlusion of the ear canal by the hearing aid shell/earmold prevents the leakage of the low-frequency vibration. This results in a buildup of low-frequency SPL in the ear canal and can be as much as 20 dB on average over the unoccluded condition (Revit, 1992). This effect has been called the occlusion effect (OE).

The use of shorter vent lengths and increasing the diameter of the vent has been an accepted approach to alleviating the OE. Many investigators reported that as vent diameter or leakage increases, OE decreases. Revit (1992) reported that a 2 mm vent decreased the OE by 8 dB in the low frequencies. Westermann (1987) reported that a 2 mm vent was sufficient to overcome the majority of the OE. On the other hand, the recent commercial readoption of “open fitting” suggests that some wearers may require a vent diameter much larger than 2 mm to completely resolve the occlusion complaint. The dependence on a relatively large vent diameter to reduce the OE can impose a significant restriction on the successful use of small hearing aids such as the completely-in-the-canal (CIC) style and on people who have a narrow ear canal. Frequently, wearers of CIC style hearing aids also have normal or a mild hearing loss in the low frequencies. The increase in low-frequency energy from the OE will be more noticeable by this group of wearers and can exacerbate the perception of the occlusion effect. Although the recent proliferation of open fittings using a behind-the-ear (BTE) hearing aid have reduced many occlusion complaints, open fittings may compromise audibility and the effectiveness of the signal processing algorithms on the hearing aids. For example, Ricketts (2001) reported a lower directivity index with a vented earmold than a closed earmold. Furthermore, open fittings may not be acceptable to wearers who desire the cosmetics of CIC hearing aids. Therefore, there is a need to increase the effective (or usable) vent diameter on a CIC (or other custom product or earmold) hearing aid in order to ensure wearer satisfaction for CIC (or other custom product) style hearing aids.

An “reverse horn vent” (RHV) has been used to minimize the OE on custom (especially CIC) hearing aids for many years. This vent configuration is characterized by a narrow vent opening (1 to 2 mm, space permitting) on the lateral side (faceplate) of the custom hearing aid, which graduates to a wider vent opening (3 to 4 mm, space permitting) on the medial side of the hearing aid (see Figure 1). The rationale is that for a narrow ear canal or a CIC, the faceplate may not provide sufficient space to allow a vent diameter wider than 1.5 to 2 mm (because of components like battery door, microphone, etc.). Because the medial end of the hearing aid has only the receiver opening, one may install a larger opening on this end. This could increase the “effective” size of the vent and provide more occlusion relief. On the other hand, if the performance of a vent is
determined only by its narrowest diameter (as implied with the use of the Select-A-Vent [SAV] venting system), then the regular vent (RV) and the reverse horn vent (RHV) that have the same lateral diameter should not yield differences in occlusion perception. Interestingly, no systematic studies have been conducted (or reported in archival references) to examine which aspects of hearing aid performance (such as objective and subjective OE, likelihood of feedback, speech recognition, etc.) may be affected by an RHV configuration. Such information would be useful for dispensing professionals in order to have a greater understanding of the realistic expectations for such a vent configuration.

METHOD

Study Participants

Nine adult hearing-impaired listeners participated in the study. Their mean age was 67.9 years (ranged from 55 yr. to 79 yr., SD = 6.8 yr.). All but one had a mild-to-moderately severe bilaterally symmetrical (within 10 dB) high-frequency sensorineural hearing loss. This participant (#9) had otosclerosis and exhibited a mild mixed loss (air-bone gap about 15 dB across frequencies). Because her data (static compliance and performance) were similar to the other participants’ data, they were included in all subsequent reporting. Because of the symmetrical hearing loss, only the audiograms for the right ear of each participant are shown in Figure 2. Six of the participants were experienced hearing aid users (ranged from 1 yr. to 6 yr.), but only one had worn a CIC prior to the study (two subjects wore BTE aids, and three wore ITC aids). All participants had normal middle ear functions as verified with tympanometry and middle ear compliance measurements (ranging from 0.3 ml to 1.3 ml) using the GSI-38 screening tympanometer. All participants signed informed consent prior to their enrollment in the study and were blinded to the purpose of the study. All participants wore the study hearing aids for at least one month prior to data collection.

Hearing Aids

Two sets of binaural Senso Diva CIC hearing aids were manufactured for each participant. One set used a uniform (or conventional) vent diameter (RV) of 1.5 mm throughout the CIC shell, and the other set used a notched reverse horn vent (RHV) that had a 1.5 mm vent diameter on the lateral end of the hearing aid (faceplate side), which gradually increased to a 3–4 mm (space permitting) vent diameter on the medial end of the hearing aid (receiver side). Both sets of hearing aids were identical in length for each individual participant, and all terminated at the second bend of the wearer’s ear canal. The lengths of the hearing aids

![Figure 1. Lateral view of a CIC shell with a reverse horn vent (RHV). The contour of the horn is highlighted.](image)

![Figure 2. Individual audiograms for the right ear of each participant. Subject numbers are indicated.](image)

Frequency (Hz)
among participants ranged from 15 mm to 19 mm with an average of 16.2 mm (sd =1.2 mm). In order to minimize the possibility of unintentional venting from any slit leakage, a feedback test that examined the maximum available gain of the hearing aid was conducted on both sets of hearing aids with the vent openings occluded. Hearing aids that did not yield the full maximum available gain were determined to have a slit leakage. For those hearing aids, a soft, thin rubber sleeve was wrapped around the shells to minimize any potential slit leakage. The sleeve was added to four of the nine participants’ hearing aids during evaluation.

Test Protocol

The evaluation was conducted in a 10’ x 10’ x 6 1/2’ double-wall sound-treated booth (Industrial Acoustics) for the RV and RHV conditions. The battery of evaluative tools included:

- Participants’ in situ unaided thresholds (or sensogram) were first determined using the fitting software (Compass 3.4) via the Noahlink interface. This was followed by a feedback test that initialized the feedback path characteristics and measured the available gain before feedback.
- The recorded W-22 (full-list) monosyllabic word lists were used to evaluate the word-recognition score in quiet. The stimuli were presented via a GSI 61 clinical audiometer with the attenuator set at 35 dB HL and at 50 dB HL via a loudspeaker placed at 0° azimuth one meter away. The participants’ ability to recognize speech in the presence of noise was evaluated with the HINT (Hearing in Noise Test) (Nilsson et al, 1994). Both speech and noise were presented from the same loudspeaker placed directly in front of the participants. The noise was presented continuously at 75 dB SPL one minute prior to the delivery of the first test sentence. The speech level was adaptively varied in 2 dB steps until 50% correct identification was reached. All stimuli were presented from their digital files via a custom MATLAB program that also controlled the presentation levels via a Tucker-Davis digital attenuator.
- Participants were asked to judge the hollowness of their voice (with the hearing aids in situ) when they repeated the phrase “Baby Jeannie is teenie tiny” at a normal vocal effort. A 1–10 point hollowness rating scale, with “1” being the most hollow/ problematic and “10” the most natural/the least hollow or problematic was used. In addition, they also chose from five categories that described their reactions to the hollowness of their voice. These categories were:
  1. It’s very noticeable and very distracting. I cannot adapt to it.
  2. It’s moderately noticeable and distracting, but I can adapt to it.
  3. It’s noticeable but not distracting.
  4. It’s hardly noticeable unless I focus my attention on it.
  5. It’s not there (very natural).
- To measure the objective OE for the two types of vents, participants were instructed to sustain the vowel /i/ for five seconds. The real-ear output (dB SPL) during the vocal production was recorded unaided, aided with the hearing aids turned off (i.e., occluded response), and aided with the hearing aids turned on (i.e., aided response) using the Fonix 6500 real-ear analyzer (that was calibrated prior to the study). A Radio Shack sound level meter (model 33-2050) was used for the participants to monitor and sustain their voice at the same VU reading. Although the noise reduction algorithm remained active during the recording, the short duration of the vocalization (5 sec) would not have activated the noise reduction algorithm during the recording process. The recorded output was frequency-averaged for 3 sec with a custom MATLAB program to improve the response stability.
- The real-ear aided response (REAR) of the hearing aids with the RV and RHV was measured using a speech-shaped noise (ANSI 92) at input levels of 50, 65, and 80 dB SPL. The stimuli were presented for 3 sec to avoid activation of the noise reduction algorithm. Output from only the right ear was measured. The same probe tube insertion depth was used for each participant in all real-
Each subject spent two two-hour sessions for data collection. The order of testing of the vent conditions, the order of tests administration, and the word/passage lists used were counterbalanced.

RESULT

In Situ Unaided Threshold (Sensogram)

Table 1 reports the averaged unaided in situ thresholds (i.e., sensogram) at 500, 1000, 2000, and 4000 Hz for the RV and RHV vents for both ears. Although a change in vent dimensions could theoretically affect the magnitude of the in situ thresholds, the change associated with the reverse horn vent was not significant enough to result in a change of the in situ thresholds.

Figure 3 shows the available gain before feedback for each vent type, along with the maximum available gain during a forced feedback test (finger over the receiver opening to simulate a completely occluded and sealed condition). Two observations were apparent. First, the maximum available gain was 10–15 dB higher in the 800 Hz to 3000 Hz region than the hearing aid gain in situ. Second, the regular vent (RV) provided 3–4 dB greater available gain than the reverse horn vent (RHV) between 500 Hz and 3000 Hz. A two-factor, repeated measures ANOVA was used to study the main within-subject effects of vent (RHV and RV) and frequency (500, 1000, 2000, and 4000 Hz). Results showed that both factors were significant (vent: $F[1,17] = 6.5, p < 0.03$; frequency: $F[3,51] = 11.2, p < 0.01$). This suggests that the RV allowed greater available gain than the RHV at 500–3000 Hz.

Speech Recognition

Figure 4 shows the mean word recognition scores for the W-22 word lists presented at the 35 dB HL (unfilled) and 50 dB HL (shaded) levels. Although the

![Figure 3](image-url) **Figure 3.** Average available gain across frequencies for the RV and RHV conditions. The solid line is the maximum available gain measured during a forced feedback test.

![Figure 4](image-url) **Figure 4.** Average word-recognition score in quiet. The filled bars were scores determined at the 35 dB HL presentation level and the shaded bars at the 50 dB HL level. Error bars indicate the magnitude of one standard deviation.
The difference between the 35 dB HL and the 50 dB HL presentation levels was significant ($F_{[1,8]} = 24.123, p < 0.001$), the mean word scores for the RV and the RHV were similar at both presentation levels (35 dB HL = 88% vs. 87%; 50 dB HL = 96% vs. 93%).

Figure 5 shows the mean absolute signal-to-noise ratios (SNRs) for 50% correct identification on the HINT. The mean SNR was 5.9 dB and 7.1 dB for the RV and the RHV conditions, respectively. This difference was not statistically significant ($t = -0.51, df = 8, p > 0.6$).

**Subjective Occlusion Ratings**

Figure 6 displays the subjective ratings that participants assigned to their voice with the use of the RV (unfilled) and the RHV (shaded) hearing aids using the 1–10 point scale after repeating the phrase “Baby Jeannie is teeny tiny.” One participant (# 2) did not notice any difference in his voice between the RV and RHV. Two participants (#1 and #9) found their voices to be slightly better with the RV than with the RHV. One of these two participants (#9) had the mixed hearing loss. The remaining six participants felt that the reverse horn vent was better than the regular vent when listening to their own voice. This was significant as evaluated on the Wilcoxon signed-ranks test ($Z = -2.108, p < 0.05$).

Figure 7 shows the category each participant assigned to his/her own voice with the RV (unfilled) and the RHV (shaded) using the 1–5 categories. Five participants with the RV and three with the RHV rated their voice as a “2” (i.e., hollowness “moderately noticeable and distracting, but I can adapt to it”). Four participants had a higher category rating with the RHV, and two had a higher category rating with the RV. The RHV had a median rating of “3” while the RV had a median rating of “2.” This difference did not notice any difference in his voice between the RV and RHV. Two participants (#1 and #9) found their voices to be slightly better with the RV than with the RHV. One of these two participants (#9) had the mixed hearing loss. The remaining six participants felt that the reverse horn vent was better than the regular vent when listening to their own voice. This was significant as evaluated on the Wilcoxon signed-ranks test ($Z = -2.108, p < 0.05$).

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was not significant ($Z = -1.186$, $p > 0.2$).

Figure 8 is a scatterplot showing the relationship between these two rating scales while combining the data for both the RV and RHV conditions. Good correlation was seen between the data obtained from the two scales ($R^2 = 0.69$, $p < 0.01$).

**Objective Occlusion Measurement**

Figure 9 shows the average real-ear unaided response (REUR$_{voc}$), real-ear occluded response (REOR$_{voc}$), and real-ear aided response during vocalization /i/ (REAR$_{voc}$) for both vent types (RV and RHV). Because the REUR$_{voc}$ was independent of vent conditions (and because of good reliability), the average REUR$_{voc}$ was identical between the two vent conditions. The REOR$_{voc}$ for the RHV was lower than the REOR$_{voc}$ for the RV by about 3 dB between 200 Hz and 400 Hz. The same was also true for the REAR$_{voc}$ in the same low-frequency region. This difference was statistically significant on a paired t-test ($t = 2.61$, df = 8, $p < 0.05$). There was no difference between the REAR$_{voc}$ and the REOR$_{voc}$ in the low frequency. Furthermore, there was no difference in the REAR$_{voc}$ and the REOR$_{voc}$ in the higher frequencies between the two vent types. The correlation of the occlusion effect at 258 Hz measured with the regular vent and the reverse horn vent was high ($r = 0.84$, $p < 0.01$).

The lower REOR$_{voc}$ seen in the RHV condition was evident on the majority of the participants. Figure 10 is a scatterplot showing the occlusion effect (OE) measured at 258 Hz between the RV and the RHV conditions. A smaller OE was measured in seven of the nine participants with the RHV. The magnitude of the OE measured in the RHV condition was only 1–2 dB higher than the RV condition in the other two participants.

**Figure 9.** Rear-ear measurements made during vocalization of /i/. The REOR$_{voc}$ and REAR$_{voc}$ overlapped below 1000 Hz. For both the REOR$_{voc}$ and the REOR$_{voc}$, the real-ear output measured with the regular vent (RV—solid line) was higher than that of the reverse horn vent (RHV—in dotted line).

**Figure 10.** Scatterplot of occlusion effect measured between the RHV and the RV conditions. Individual participant numbers are displayed in the scatterplot.

**Figure 11.** Average real-ear aided response for the RV and the RHV conditions at 50, 65, and 80 dB SPL input levels. The solid line is the RH condition, and the dotted line is the RV condition.
Real-Ear Aided Output

The average real-ear aided output curves to the ANSI speech-shaped noise presented at overall input levels of 50, 65, and 80 dB SPL for both vent conditions are shown in Figure 11. The in situ unaided thresholds (which were used to determine gain settings) were set to the thresholds of the RV condition. No significant difference was observed in the REAR between these two vent conditions at any of the three input levels.

DISCUSSION

The present study showed that a reverse horn vent, when compared to a regular or conventional vent of the same lateral diameter (in a CIC style), resulted in a significant decrease of objective OE (3 dB) and subjective complaints of the OE. However, such a vent configuration also resulted in 3 dB less available gain before feedback than the RV. The available gain difference was not sufficient to result in any differences in the measurement of in situ thresholds, speech recognition in quiet, speech recognition in noise and real-ear output levels measured at three input levels.

An intuitive explanation for the effect of the reverse horn vent, through the gradual enlargement of the vent diameter toward the medial end, is that the overall diameter of the reverse horn vent across the length of the vent is larger than that of the conventional vent. Because occlusion effect decreases (e.g., Revit, 1992) and available gain before feedback decreases as vent diameter increases (Kuk, 1994), the current observations support the speculation that the action of the reverse horn vent is achieved through an increase of effective vent diameter over the conventional vent. This speculation also explains why a reverse horn vent increases the likelihood of feedback over a conventional vent of the same lateral diameter as seen in this study. On the other hand, the current study does not support a belief that the smallest diameter of a vent governs its performance. If such a belief were valid, the performance of the reverse horn vent would have been identical to that of the conventional vent. These observations suggest that one must consider the characteristics of the entire vent and not just one aspect (i.e., smallest diameter) to estimate its performance.

The reverse horn vent improved the occlusion effect over the conventional vent by about 3 dB. This magnitude of improvement is not sufficient to completely eliminate the occlusion effect. On the other hand, if one realizes that this difference is additional to what is possible from a conventional vent (given the limitation of the size of the wearer's ear canal), this may be a welcome improvement. To this end, the use of the RHV configuration should not be restricted to CIC style hearing aids. All custom products from in-the-canal style to half-shell and full-shell hearing aids may also use this vent configuration to further increase the effective diameter of the vent system. This is especially valuable if the wearer has a narrow ear canal such that the widest conventional vent cannot reduce the occlusion effect sufficiently. It is important to recognize that a reverse horn vent reduces more occlusion effect than a conventional vent that has the same lateral diameter; it would probably be less effective than a conventional vent that has the medial diameter of the reverse horn vent throughout.

A reverse horn vent yielded lower available gain before feedback than a conventional vent. This suggests that some individuals using this vent configuration may not be able to use the full available gain from the hearing aid. This may compromise audibility for those individuals. One reason for the lack of difference in speech scores (in quiet and noise) between the two vent conditions is that the participants in this study had primarily a high-frequency hearing loss who may not need to use all the available gain on the hearing aids. The results may have been different if the participants had greater hearing loss. Fortunately, these people generally do not have amputation complaints that originate from a shell origin (Kuk and Ludvigsen, 2002). Rather, it is those with a mild hearing loss who require a larger vent diameter. Consequently, despite the available gain limitation, the practical applicability of this vent type is not compromised.

The magnitude of the reduction in OE was about 3 dB in the current study. It is possible that this magnitude of improvement represents the improvement specific to the manner in which these RHVs were made. Other ways of configuration, such as the
proportion of the vent that has a wider diameter, how one achieves the wider diameter (e.g., gradually or stepped), the ratio of the medial diameter to the lateral diameter, et cetera, may affect the amount of improvement. A more systematic study is underway to examine how the physical parameters such as length and diameter of the vent segments interact to affect the occlusion effect.

To conclude, it is important to realize that a reverse horn vent can increase the effective diameter of the vent and lead to a reduction of the occlusion effect. Although the results reported in this study suggest that this vent configuration should be used in all custom hearing aids (and possibly earmolds), the concomitant decrease in maximum available gain before feedback with this vent configuration would argue that its use be restricted to those with up to a moderate degree of hearing loss only. Fortunately, individuals who have a high gain requirement typically do not have occlusion complaints that have a shell origin. Often, these individuals are satisfied with hearing aids with only a small vent diameter. The limitation of a reverse horn vent may be inconsequential.

REFERENCES


