Vent Configurations on Subjective and Objective Occlusion Effect

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Abstract
The current study reexamined the effect of vent diameters on objective and subjective occlusion effect (OE) while minimizing two possible sources of variability. Nine hearing-impaired participants with primarily a high-frequency hearing loss were evaluated. Laser shell-making technology was used to make ear inserts of completely-in-the-canal (CIC) hearing aids for the study. This was to minimize any potential slit leakage from the inserts. The vent dimensions were systematically altered during the study. Participants sustained /i/ for 5 sec, and the real-ear occluded response was measured with a custom-made program that performed frequency averaging to reduce response variability. Participants also repeated the phrase “Baby Jeannie is teeny tiny” and rated their own voice. The results showed a systematic change in the objective OE and subjective ratings of OE as the vent diameter was modified. Furthermore, a significant correlation was seen between subjective rating and objective occlusion effect.

Key Words: Laser shell-making, occlusion effect, reverse horn vent, subjective occlusion ratings, vent

Abbreviations: AE = occlusion effect; CIC = completely in the canal; OE = occlusion effect; REORvoc = real-ear occluded response during vocalization; REURvoc = real-ear unoccluded response during vocalization; RMS = root mean square

Sumario
El actual estudio re-examinó el efecto de los diferentes diámetros en el orificio de ventilación sobre el efecto de oclusión (OE), objetiva y subjetivamente, minimizando dos posibles fuentes de variabilidad. Se evaluó a nueve participantes hipoacúsicos con pérdidas auditivas primariamente en las altas frecuencias. Se utilizó una tecnología laser de fabricación de conchas para producir, para el estudio, dispositivos de inserción de auxiliares auditivos completamente en el canal (CIC). Esto se hizo para minimizar cualquier fuga de hendidura de los insertos. Las dimensiones de orificio de ventilación fueron sistemáticamente alteradas durante el estudio. Los participantes produjeron una /i/ sostenida por 5 segundos, y se midieron las respuestas occluidas de oído real con un programa hecho a la medida que realizaba promediaciones de la frecuencia para reducir la variabilidad en la respuesta. Los participantes también repitieron la frase “Baby Jeannie is teeny tiny” y califiaron su propia voz. Los resultados mostraron un cambio sistemático en las apreciaciones objetivas y subjetivas del OE conforme se modificó el tamaño del orificio de ventilación. Más aún, se vio una correlación significativa entre la apreciación subjetiva y el efecto objetivo de oclusión.

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Amplification effect (AE; Painton, 1993), or the perception of hollowness in one's own voice during vocalization with hearing aid wear, is a common complaint of hearing aid wearers. The incidence of such a complaint varied among surveys from 30% (Dillon et al, 1999) to 60% (Lazenby et al, 1986). One possible reason for such a complaint is that the low-frequency sound pressure level (SPL) that is produced during vocalization remains trapped within the ear canal when it is occluded, thus giving the complaints of “hollowness,” “talking through a barrel,” “echoic”—descriptors that are frequently associated with excessive low-frequency energy (Jenstead et al, 2003).

The portion of the AE that originates from the hearing aid shell that occludes the ear canal is termed the occlusion effect (OE). Typically, the OE is measured as the difference between the real-ear unaided response during vocalization (REUR voc) and the real-ear occluded response during vocalization (REOR voc) in the low frequencies when the wearer vocalizes (Revit, 1992). One common approach to reducing the OE is to enlarge the vent diameter of the hearing aid shell or earmold. Typically, the performance of a vent is determined by its acoustic mass (Dillon, 2001), which is directly proportional to the length of the vent and indirectly proportional to the square of the vent diameter. The acoustic effect of these dimensional changes on hearing aid output has been reported on coupler or simulated ear measures (Valente et al, 2000) and real ears (Tecca, 1992; Kuk, 1994) where standard signals like sinusoids and speech-shaped complex noises are used as the test signals.

On the other hand, reports on the effect of vent dimensions on the occlusion effect (both subjective and objective) had been mixed. One of the difficulties in studying the occlusion effect was that human vocalization was used as the stimulus. During real-ear occlusion measurements, test subjects were instructed to sustain their vocalization for a fixed duration. They may differ in their vocal efforts as well as how long they can sustain vocalization. Furthermore, individual subjects may show fluctuation in their voice levels. This may have led to conflicting results among studies.

For example, Revit (1992) showed that a 2 mm vent would reduce the occlusion effect at 200 Hz by about 8 dB. Westermann (1987) also showed that a 2 mm vent would reduce the majority of OE. On the other hand, Kampe and Wynne (1996) showed no systematic effect of vent diameter on the objective OE (measured with Frye 6500 real-ear system) although their ten normal-hearing subjects reported less occlusion as the vent diameter increased from 0.79 mm to 2.36 mm. However, no correlation was observed between subjective ratings of own voice quality and objective OE. Similarly, Sweetow and Valla (1997) also reported no correlation between subjective ratings of OE and objective measure of OE.

There are at least two other reasons why observations on the OE may be inconsistent. One is the potential of slit vent, or unintentional leakage around the hearing aid shell or earmold. In the conventional shell-making process, an earmold impression is waxed before it is cast to create the shell. Depending on how long it has been immersed in the wax, the skill of the technicians, et cetera, shells made with the same impression but with different thickness of wax would result in shells or earmolds that have different amounts of slit leakage when worn (Cortez et al, 2004). And if the amount of slit is significantly larger than the leakage created by the vent diameter, any changes in the vent diameter may not be evident (i.e., no effect). For example, consider the effect of a 0.05 mm slit between the shell and the ear canal wall. If one assumes that the faceplate
is circular and the individual’s ear canal has a diameter of 10 mm, the surface area of the ear canal would be $\pi (5)^2$ or 25 $\pi$. A slit vent of 0.05 mm would mean that the surface area of the faceplate becomes $\pi (4.975)^2$ or 24.75 $\pi$. This is a difference of 0.25 $\pi$ in the surface area, or a vent with a radius of about 0.5 mm (0.25)$^{0.5}$ or a diameter of 1.0 mm (two times the radius)! Using the same calculation, a slit of 1 mm would have the equivalent result as a 4.4 mm vent diameter. If the changes in the vent diameter are smaller than that of the slit vent, the effect of those changes would not be easily observable. This may partly explain the between-subject variability in the noted OE. Tecca (1991) and Pirzanski (1998) also indicated manufacturing variability and the presence of uncontrolled slit leakage as one reason for variable OE. Thus, it is critical that all the earmolds/shells used for these types of studies must not only be identical, but also not allow any unintentional leakage. This criterion may not have been easily met until recently where laser technology has been applied in hearing aid shell making (Cortez et al, 2004), in which one of the advantages is that the shells made from ear impressions that are prepared for shell fabrication are exact replica of the ear impressions in all dimensions. This offers an opportunity to reexamine the effect of vent changes.

Measurement error is another possible reason for the observed variability in the measured OE. Typically, during OE measurement with commercial real-ear systems of the REOR$_{voc}$ and REUR$_{voc}$, the loudspeaker is turned off, and wearers are asked to maintain their vocalization (of /i/) until the online, instantaneous spectral display on the computer monitor “is relatively stable.” In some commercial units, the instantaneous overall SPL in the low frequencies is displayed. Regardless of the systems used, the audiologist “freezes” the screen (i.e., stops the sample-and-display process) when a good or reasonable display is shown and reports the difference in the magnitude between the REOR$_{voc}$ and the REUR$_{voc}$ as the OE (e.g., Revit 1992; Sweetow and Valla, 1997).

Despite the best attempts in monitoring the subject's vocal effort through instructions and the use of sound level meters as visual monitors, it is difficult for any human subjects to maintain the same level of vocal output during the course of vocalization. It is possible that minor fluctuation in the wearer's voice occurs to result in a change in the measured spectrum or overall low-frequency energy of the vocal production. This is especially true if the vocalization is sustained over a long period of time. Voice level monitoring may not be sufficient to record a reliable (or repeatable) response if only a sample of the output is measured (such as freezing the screen). Recording of the sample over a period of time and averaging of the responses would be necessary to obtain a reliable measure. For example, Kampe and Wynne (1996) measured the OE with a Frye 6500 real-ear analyzer in ten normal-hearing subjects during their vocalization of /i/ and /u/ while they changed the vent diameter of a lucite skeleton earmold from 0.79 mm to 2.36 mm. The authors froze the screen once the real-ear spectral display was “relatively stable.” Two separate recordings were averaged for the measurement. Their subjects also read the “Rainbow passage” and rated their voice on a 1–5 scale. These authors saw large variability in the measured OE and did not observe any consistent pattern of occlusion reduction with vent diameters. Although their subjects reported less hollowness when the vent diameter was increased, no correlation was found between subjective rating of occlusion and objective occlusion effect. The authors raised the possibility that the lack of a consistent relationship was probably due to their use of commercial real-ear system to “freeze” the response whereas some averaging of the response may improve their observation. Any studies of vent effects on occlusion must ensure good repeatability of the measured responses.

The purpose of the current study was to study the effect of vent dimensions on the objective (such as measured increase in low-frequency SPL in the ear canal) and subjective (such as hollowness ratings) occlusion effect while minimizing some of the limitations encountered in previous studies. Specifically, efforts will be made to minimize the variability due to unintentional leakage and sampling variability. In addition to studying vents with a uniform diameter, vents with multiple sections of varying diameters will also be studied in order to understand how some vent systems (e.g., reverse horn vent which increases its diameter medially) achieve their functions.
Consequently, the objectives of this study were to determine:

1. The relationship between vent dimensions and occlusion effect while the vent diameter of a CIC (completely-in-the-canal) insert that terminated at the second bend was systematically changed from 0 mm to 3 mm throughout, including intermediate configurations approximating reverse horn vents of different dimensions;

2. The relationship between objective occlusion effect and subjective rating of hollowness;

3. The test-retest reliability of objective occlusion measurement.

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.). 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, middle ear compliance of 0.6 ml). Because her data were similar to the other participants’ data, they were included in all subsequent reporting. The individual audiograms for the right ear of each participant are shown in Figure 1. Five were experienced hearing aid users (ranged from 1 to 3 yr.). 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. Although no hearing aids were actually evaluated in this study, all participants wore two vented versions of binaural Senso Diva CIC hearing aids home for at least one month prior to the study. In one version, a uniform 1.5 mm diameter vent was used, while the other version had a 1.5 mm diameter on the lateral surface that belled out to a 3–4 mm diameter on the medial opening. All the participants signed an informed consent prior to their enrollment and were blind to the purpose of the study.

Equipment Setup

The purpose of the study was to measure the occlusion effect (defined as the increase in low-frequency energy between the open-ear and the occluded ear conditions during vocalization, e.g., Revit, 1992) of different vent configurations. The Frye 6500 Real-Ear System was used to transduce the real-ear output during vocalization. Instead of “freezing” the instantaneous display on the Frye monitor and using that spectral display for analysis, the commercial real-ear system was used as a conduit to direct the real-ear output from the remote module of the real-ear system to the “Line In” of a Compaq Evo computer sound card that had a 16-bit resolution (or a dynamic range of 96 dB). This way, we were able to frequency-average the recorded output via a custom MATLAB program for a more stable measure.

The MATLAB program was written so that the recorded output was above the noise floor but did not exceed the upper limit of the sound card so as to create saturation distortion. The maximum and minimum values that could be stored (+/- 32768, or $2^{16}/2$) were first estimated. The gain settings on the Fonix 6500 remote module and the “Line In” of the computer sound card were adjusted (and fixed afterwards) so that the output of the sound card did not reach saturation with input as high as 90 dB SPL. Each day prior to data collection, the gain settings were verified with a calibration.
program written in MATLAB. The probe microphone was placed in the sound booth 50 cm from a loudspeaker (Cerwin-Vega). A 60 dB HL white noise from a clinical audiometer (GSI 61) was presented. The average RMS (root mean square) of the recording was measured and compared to the RMS level of the original calibration. The amplifier setting on the Fonix 6500 remote module was adjusted until the RMS level was within +/- 0.5 dB.

A custom MATLAB program was written to capture and analyze the recording. This program collected the real-ear acoustic waveforms and saved them on the hard drive for off-line analysis. The MATLAB program was written to accept 5 sec of the participant’s vocal production at a sampling rate of 22 kHz and a resolution of 256 bins (and bandwidth of 86 Hz). During the analysis, the program discarded the first sec and used the middle 3 sec for analysis. A Fourier analysis was first performed on each sampled response in order to transform the sample into the frequency domain. The spectra that were formed were then averaged over the course of the 3 sec to result in one averaged spectrum. Monthly calibration of all test equipment was conducted in addition to daily calibration checks during the course of the study.

**Stimuli**

Self-vocalization of /i/ was used as the stimulus to examine the effect of vent configurations. This vowel was chosen because it has the lowest F1 formant frequency, which would make it ideal to study the occlusion effect. For each vent condition, participants vocalized at a normal vocal effort and sustained /i/ for 5 sec. A Radio Shack sound level meter (Model 33-2050) was placed at 12" from the participants' mouths, and they were instructed to maintain their voices around the "0" VU reading. The voice levels of all the participants were at least 70 dB SPL measured at that distance. All participants practiced vocal production until they were able to consistently peak the VU at "0" prior to any data collection. In addition, the test audiologist also monitored the pitch level of the participants’ production. They were alerted to any shifts in their pitch during the production; if so, a new recording was made for that condition. At the end of each vocal production, participants also judged the hollowness of their own voice using a 1–10 point scale with “1” reflecting extremely hollow voice quality and “10” natural voice quality without any hollowness. Participants repeated the phrase “Baby Jeannie is teeny tiny” as many times as they felt necessary at a normal vocal effort for this subjective rating task.

**Ear Inserts**

Custom ear inserts resembling a CIC hearing aid shell were made for each participant. At the initial visit, an impression of the participant’s right ear was taken using silicon impression material. The impression was then sent to our shell lab where the inserts were made using Widex’s proprietary laser shell-making technology (Cortez et al, 2004). Briefly, this was a new shell-making approach whereby a laser scanner was used to scan the impression for a “wire-frame” of the impression with a precision of 1/10 mm. The image was then saved digitally. It was subsequently manipulated by a “modeling” technician who designed the layout of the circuitry within the shell as well as the characteristics of the shell including the vent dimensions. The “modeled” shell was then sent to a “printer” that fabricated the shells using a method called SLA (Stereo Lithographic Apparatuses). The advantage of using laser technology for shell making over conventional shell making is the precision this technology offers. Because of individual technician differences, shells made with conventional approaches were more variable than shells made with laser shell-making technology (see Cortez et al, 2004, for a review). Because the objective of this study was to study the dimensional effect of vents on the occlusion effect, laser shell-making was used in order to minimize the occurrence of slit vent that may compromise the observations of the study. Cortez et al (2004) showed that hearing aid shells made with the laser technology allowed higher available gain before feedback than shells made with conventional technology.

An insert that had the typical length of a CIC hearing aid was made for each participant. The lateral surface terminated at about 8 mm from the tragus, and the medial end terminated at the second bend of the ear canal. The inserts ranged from 13 mm to 18 mm with an average length of 15 mm. A 1 mm probe vent was included near the upper ridge
of the insert to allow probe-tube placement for
greater precision during real-ear
measurements. The probe-tube was marked
at the tragus and was inserted to the same
depth in all measurements (approximately 29
to 32 mm from the tragus marker) for each
participant. A removal line was also installed
in the inserts for ease of removal.

Each insert had a 1 mm vent drilled
through its center. This is the “1 mm (100%)”
vent condition. Other vent conditions were
derived from this vent by either plugging up
the vent on the lateral and medial ends (“0
mm”) or by drilling it from the medial end in
a systematic, proportionate manner using
the appropriate size drill bit. For example,
after testing with the “0 mm” and “1 mm”
condition, the next vent condition was created
by using a 2 mm drill bit and drilling 60%
toward the lateral end of the insert. In this
case, the medial 60% of the length of the
insert had a vent diameter of 2 mm while the
lateral 40% had a 1 mm vent diameter. This
was labeled as the “2/2/1” vent condition. By
drilling from the medial end toward the
lateral surface in a predetermined manner,
we had four more vent conditions. They were
“3/2/1,” “3/2/2,” “3/3/2,” and “3 mm (100%).” This
sequence of modification allowed us to
systematically study the change in objective
OE and subjective rating of occlusion as the
physical dimensions of a vent were gradually
modified from a vent with a uniform diameter
to a vent with a gradually increasing
diameter. This systematic enlargement of the
vent diameter also allowed us to calculate
the effective acoustic mass of the vent system,
as explained later. The sequence of vent
configurations is shown in Figure 2.

![Figure 2. Sequence of vent configurations (from top to bottom).](image-url)
Procedure and Test Conditions

All testing was conducted in a 10' x 10' x 6'6" sound-treated booth. In addition to the first visit for the ear impression and fitting of the hearing aids, each participant was seen for at least two visits (test and retest). During each session, the left ear was occluded with a foam plug while the right ear was evaluated with the insert. The real-ear unaided response during vocalization (REUR\textsubscript{voc}) was first measured by asking the participants to sustain /i/ vocalization for 5 sec.

The real-ear occluded response during vocalization (REOR\textsubscript{voc}) was measured for each vent condition on the insert. The “0 mm” vent condition was created by closing off the 1 mm vent on the insert medially and laterally with putty. After the REOR\textsubscript{voc} was measured, the participants were asked to repeat “Baby Jeannie is teeny tiny” and judge the hollowness of their voice using the 1 (poorest) to 10 (best) scale. Afterwards, the putty from the occluded vent was removed, and participants repeated the testing (i.e., REOR\textsubscript{voc} with /i/ and subjective rating) with the 1 mm vent condition. Modifications to the vent were made using a Red Wing lathe (model 26A) with the appropriate size drill bit in the sequence described earlier. The measurements (REOR\textsubscript{voc} and subjective rating) were again repeated for each vent condition until the final vent condition (3 mm [100%]).

Participants returned after two months for a retest on the 0 mm and 3 mm vent diameter conditions in order to estimate the reliability of the measurement. A retest on the other vent configurations was unavailable because the insert had been drilled out.

RESULTS

Effect of Vent Diameter on Objective Occlusion (REOR\textsubscript{voc})

The real-ear occluded responses during vocalization (REOR\textsubscript{voc}) of /i/ for the different vent configurations were plotted in Figure 3.

As might have been expected, there was a general change in the measured REOR\textsubscript{voc} as the vent dimensions were altered. In general, the occlusion effect, at least for the vowel /i/, was primarily below 800 Hz with the peak frequency at around 300 Hz with an insert that terminated at the second bend of the ear canal. As the vent diameter increased, the REOR\textsubscript{voc} below 800 Hz decreased.

Table 1. Summary Table Comparing the Significance of the Measured REOR\textsubscript{voc} among Vent Configurations

<table>
<thead>
<tr>
<th>Vent Condition</th>
<th>1</th>
<th>2/2/1</th>
<th>3/2/1</th>
<th>3/2/2</th>
<th>3/3/2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-2.54*</td>
<td>-2.66*</td>
<td>-2.54*</td>
<td>-2.66*</td>
<td>-2.66*</td>
<td>-2.66*</td>
</tr>
<tr>
<td>1</td>
<td>-2.66*</td>
<td>-2.07*</td>
<td>-2.66*</td>
<td>-2.66*</td>
<td>-2.66*</td>
<td>-2.66*</td>
</tr>
<tr>
<td>2/2/1</td>
<td>-2.66*</td>
<td>-2.07*</td>
<td>-2.66*</td>
<td>-2.66*</td>
<td>-2.66*</td>
<td>-2.66*</td>
</tr>
<tr>
<td>3/2/1</td>
<td>-1.12</td>
<td>-2.66*</td>
<td>-2.42*</td>
<td>-2.54*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/2/2</td>
<td>-2.66*</td>
<td>-2.54*</td>
<td>-2.54*</td>
<td></td>
<td>-0.05</td>
<td></td>
</tr>
<tr>
<td>3/3/2</td>
<td></td>
<td>-1.36</td>
<td>-0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries with Z-values that were significantly different (p < 0.05) were marked with an asterisk.
example, the peak REOR\textsubscript{voc} at 258 Hz was about 85 dB SPL when the insert was fully occluded. It decreased to about 79 dB SPL with a 1 mm (100%) vent diameter and to about 70 dB SPL for a 3 mm (100%) vent diameter. The significant drop in REOR\textsubscript{voc} when the insert was changed from 0 mm to 1 mm vent diameter suggests that the insert provided a tight seal; otherwise, a smaller change will be observed. For an intermediate vent diameter, such as the “3/2/1” vent configuration, the REOR\textsubscript{voc} was about 77 dB SPL. Thus, the REOR\textsubscript{voc} measured with a 1 mm (100%) vent was higher than the REOR\textsubscript{voc} measured with the “3/2/1” vent and the 3 mm (100%) vent diameter conditions. The REOR\textsubscript{voc} of the “3/2/1” vent condition was between the 1 mm (100%) vent and the 3 mm (100%) vent. This suggests that the amount of objective occlusion effect was not determined by the smallest opening of the vent. Nonparametric Wilcoxon Signed Ranks tests were used to compare the significance of the REOR\textsubscript{voc} differences at 258 Hz observed among vent configurations. This test was used to minimize the effect of the large variability among participants and the small dB change associated with vent changes. The Z-statistics were summarized in Table 1 below, and differences that were significant were marked with an asterisk. Many of the comparisons were significantly different (p < 0.05).

### Occlusion Effect

The occlusion effect shown in each vent configuration was calculated by taking the difference between the REUR\textsubscript{voc} and the REOR\textsubscript{voc} with the particular vent configuration. Because the dominant peak on the REOR\textsubscript{voc} occurred at around 300 Hz (258 Hz was the closest frequency for measurement) for all participants in the 0 mm vent condition, the individual and the averaged OE measured at that frequency for each vent configuration was reported in Figure 4.

There are several observations. First, although the magnitude of the individual OE varied, all participants showed a gradual decrease in OE as the vent dimensions were increased. Second, the average OE was about 17 dB with a fully occluding insert (ranged from 10 to 27 dB). Third, the average OE for the 1 mm (1/1/1 or 100%) vent configuration was about 13 dB. This decreased to about 5 dB for the 3 mm (100% or 3/3/3) vent configuration. Although a 2 mm (100% or 2/2/2) vent configuration was not available in the study, it was estimated to be about 10 dB. Fourth, the average OE for the intermediate vent configurations, such as “2/2/1,” “3/2/1,” and “3/3/2,” were intermediate between the “1 mm (100%)” and “3 mm (100%)” vent configurations. On the other hand, many of the individual OE and the averaged OE for the “3/2/2” vent and the “3/3/2” vent, or between the “2/2/1” vent and the “3/2/1” vent, were similar. The dimensional changes of the vent may not be sufficient to result in a measurable difference in OE. Lastly, the OE for the 1 mm (100% or 1/1/1) vent was higher than that of the “2/2/1” vent and the “3/2/1” vent condition even though all three had a lateral vent diameter of 1 mm. This would suggest that the smallest opening on a vent does not dictate the OE of the vent.

### Relationship between Occlusion Effect and Acoustic Mass

#### Calculation of Acoustic Mass

In order to determine the physical relationship (or lack of it) between OE and
vent dimensions, the acoustic mass of each vent configuration was calculated based on Dillon’s (2001) formula. The result was then transformed logarithmically, that is,

\[
\text{Acoustic Mass (Henry, log scale)} = \log_{10}(1500 \times L / D^2)
\]  

where \(L\) is the length of the vent section (in mm) and \(D\) the diameter (in mm). In other words, a larger vent diameter or a shorter vent length would result in a smaller acoustic mass and vice versa.

For a vent system that has multiple diameters like the inserts used in this study, the acoustic mass of the vent system is the sum of the acoustic mass of each section with a specific diameter. Thus, assuming that the length of the vent system was \(L\), the three sectional lengths would be 0.4\(L\), 0.3\(L\), and 0.3\(L\) (measured from lateral to medial). The vent diameters of these sections would be \(D_1\), \(D_2\), and \(D_3\) (from lateral to medial). The total acoustic mass (in log) of this vent system may be expressed as:

\[
\text{Acoustic Mass (Henry, log scale)} = \log_{10}(1500 \times (0.4L/D_1^2+0.3L/D_2^2+0.3L/D_3^2))
\]  

**OE against Acoustic Mass**

Each of the 7 vent configurations (from 0 mm to 3 mm diameters) was associated with an acoustic mass and with a value of objective OE (measured at 258 Hz, the dominant OE). Figure 5 is a scatterplot showing the relationship between the individual OE and the corresponding acoustic mass of each participant (each participant was identified by a number and a different symbol). In addition, the best-fit linear regression line for each participant was also included to show the strength of the relationship between the OE and acoustic mass. The strength of the relationship (\(R^2\)) for each individual participant was also indicated.

Figure 5 shows that, when acoustic mass was expressed logarithmically, there was a linear relationship between occlusion effect and acoustic mass. The strength of the relationship (\(R^2\)) varied across participants from as low as 0.09 (#8) to as high as 0.94 (#1). The majority of the participants had \(R^2\) around 0.83. These individual correlations were significant at the \(p < 0.05\) level for all but participant #8. The overall \(R^2\) between OE and acoustic mass across all participants was 0.62 (\(p < 0.01\)).

The participant with the poorest correlation (#8) had a mild-to-severe sloping high-frequency hearing loss with middle ear compliance of 0.3 ml in both ears (the lowest of all participants). She also had the least objective OE but the highest (or best) subjective occlusion rating. She had a history of shingles and severe pain in the head that was treated by severing the trigeminal nerve on the left side in 1996. She reported of...
experiencing a “rushing” tinnitus in the left ear that subsided one month afterwards. On the other hand, the subject with the mixed hearing loss (#9) had an R² of 0.85 between OE and acoustic mass. This correlation was very similar to those of the other participants’.

When the data from all the participants and vent configurations were collapsed, one was able to generate the following regression equation that relates OE to the vent dimensions (assuming uniform diameter):

\[ OE_{258Hz} = 8.3489 \log_{10}(1500 L / D^2) - 23.52 \]  

where L is the length of the vent and D is the diameter of the vent, and 1500*L/D² is the acoustic mass of the total vent system.

**Correlation between OE at 258 Hz and Middle Ear Compliance**

In order to examine if the measured occlusion effect at 258 Hz may be related to the middle ear compliance of the participants, we calculated the correlation coefficients between the OE_{258Hz} measured with various vent dimensions and middle ear compliance at 220 Hz. Figure 6 is a scatterplot showing the relationship between the OE measured with the occluded insert (i.e., 0 mm vent diameter) and middle ear compliance. The correlation was calculated to be R = 0.59 (p < 0.05). The correlations measured between middle ear compliance and OE_{258Hz} at the other vent conditions were nonsignificant (p > .05).

**Correlation between Subjective Ratings and Objective Occlusion Effect**

Subjective Occlusion Rating as a Function of Vent Conditions

The individual subjective occlusion ratings (as well as the median rating) as a function of vent dimensions were summarized in Figure 7. All but one participant (#3) showed an expected increase in subjective OE ratings as the vent dimensions increased, although the rate at which the subjective ratings changed varied among participants. For example, participant #2 showed a fairly monotonic increase as the vent dimensions changed from 1 mm (100%) to a 3/2/2 vent condition, whereas participant #8 (participant with the poorest correlation between OE and acoustic mass) reached the ceiling of “10” when the vent was less than 2 mm (i.e., 2/2/1 combination). On the other hand, participant #3’s responses were unpredictable in that no clear pattern between subjective ratings and vent dimensions was discernible. The median rating, however, was relatively unchanged beyond a 2/2/1 vent condition.

Another way to examine the group effect of vent configurations on subjective ratings was to use a cumulative frequency distribution function that reflects the total
number of participants who provided a specific rating. For example, Figure 8 shows the cumulative frequency distribution function for the “0 mm or no vent” condition. One participant had a rating of “3” or less, 3 had a rating of “5” or less, 6 had a rating of “6” or less, and 9 had a rating of “9” or less. The median response, or the rating chosen by half of the participants (as marked by the horizontal line on Figure 8) was 5.5. In other words, half of the participants had a rating lower than 5.5 for the “0 mm” vent diameter condition.

Figure 8 shows that the median rating changed from 5.5 for the 0 mm vent condition to around 6.2 when a 1 mm vent was used. The median subjective rating increased to 7.5 for a 3 mm (100%) vent configuration. The biggest increase in subjective rating was also noted from the 0 mm vent to 1 mm vent condition (from 5 to 6).

In general, subjective ratings tended to improve as the vent configurations moved toward a larger vent diameter (or greater portion of a larger diameter). The most substantial increase was from a 0 mm condition to a 1 mm vent diameter condition. Subsequent increase in vent diameter showed a small, but incremental, increase in subjective rating. This is somewhat similar to the findings reported in Figure 4, which suggests that most of the decrease in OE was from a 0 mm vent to a 1 mm vent. A Friedman related-sample test showed a significant vent effect ($\chi^2 = 21$, df = 6, $p = 0.002$) in subjective ratings. However, post hoc Wilcoxon Signed Rank test showed that only the subjective ratings obtained in the 0 mm vent condition were significantly ($p < 0.05$) different from the ratings obtained in the other vent configurations. Other comparisons were nonsignificant.

**Correlation between Objective Occlusion Effect and Subjective Occlusion Ratings**

Figure 9 is a scatterplot displaying the relationship between the objective OE at 258 Hz and subjective occlusion ratings. Several observations may be made. First, there was a wide scatter of objective OE for each subjective rating. For example, a rating of “2” showed OE from as little as 1 dB to as much as 21 dB, or a 20 dB range. Second, the range of OE was smaller for the higher ratings than for the lower ratings. For example, the rating of “9” or “10” only showed an OE range of 6 to 10 dB. This was significantly smaller than the 20 dB range seen with the ratings of “2” or “3.” Third, despite the wide variability, there was a general tendency for subjective ratings to improve (or rated higher) as OE decreased. The strength of the relation (or $R^2$) was 0.33 ($p < 0.05$). Fourth, an average rating of “9” or “10” was assigned even though there were still 5–7 dB of OE. This last point suggested that good subjective occlusion rating was possible even though some (5–7 dB) OE was measured.

One may argue that the observed correlations between subjective ratings and

| Table 2. Summary of Correlation Coefficients between Subjective Ratings and OE and Acoustic Mass When the Effect of the Other Variable was Controlled |
|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| OE | OE without Acoustic Mass | Acoustic Mass | Acoustic Mass without OE |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Subjective Rating | -0.457** | -0.369** | -0.326** | -0.154 |
Objective OE may reflect the correlation between OE and acoustic mass (or physical dimensions of vents) and not between subjective rating and OE. In order to control for the effect of acoustic mass (i.e., vent dimensions) on the correlation (between subjective and objective OE), correlation analyses among subjective ratings, objective OE (at 258 Hz), and acoustic mass were performed. Partial correlations between subjective ratings and objective OE, and between subjective ratings and acoustic mass, were determined as well. Table 2 summarizes the correlations between subjective ratings and OE and acoustic mass when the effect of the other variable was controlled. Correlations that were significant (p < 0.01) were marked with asterisks.

Table 2 shows that both OE and acoustic mass were significantly correlated with subjective ratings when the effect of the other variable was included. When the effect of acoustic mass was controlled (i.e., effect of vent dimensions were controlled), objective occlusion effect was still negatively correlated with subjective occlusion ratings. However, when the effect of OE was controlled, subjective ratings were not correlated with acoustic mass. This suggests that subjective rating of occlusion was negatively related to the OE measured in the wearer's ear canal. The strength of the relationship, although statistically significant, was mild to moderate, however.

**Test-Retest Reliability of Occlusion Measurements**

Figure 10 shows the measured OE between test and retest sessions for the 0 mm (10a) and 3 mm (10b) vent conditions. The test-retest difference in measured OE for most of the participants was within 2 dB. For both vent conditions, there was always one participant who showed more variability than the other participants. For example, it was participant #9 in the 0 mm vent condition and #5 in the 3 mm vent condition. The standard deviation of the test and retest difference (between sessions) was 2.7 dB and 2.1 dB for the 0 mm and 3 mm vent conditions, respectively, when every participant was included. The standard deviation of the difference was reduced to 2.1 and 1.8 for the 0 mm and 3 mm vent conditions when the worst (most difference) participant was removed. Typically, the average REORvoc curves measured with the 0 mm (100%) and 3 mm (100%) vent diameter conditions differed by less than 1 dB between sessions. This suggests that the OE measurement conducted in this study was relatively reliable for most participants.

**DISCUSSION**

The present study examined the effect of vent dimensions on objective occlusion effect and subjective occlusion ratings while minimizing the potential confounding effect of slit leakage (with laser shell-making technology) and measurement variability (with
frequency or spectral averaging). Assuming that both of these variability were suitably controlled, the results showed that there was a systematic relationship between objective occlusion effect and vent dimensions as predicted by the acoustic mass of the vent. Furthermore, there was a moderate correlation between subjective ratings of occlusion and objective OE, even when the effect of acoustic mass was controlled.

Comparison with Previous Studies

The results of this study disagreed with some studies but agreed with others. For example, Kampe and Wynne (1996) reported no systematic relations between objective OE and vent dimensions (0.79 mm and 2.36 mm) and between subjective occlusion ratings and objective OE. Pirzanski (1998) made 23 inserts from one single ear impression and noted that the effect of vent diameter (0, 0.9, and 1.15 mm) was not predictable. Both of these researchers used a commercial real-ear analyzer to measure the occlusion effect. In contrast, a systematic relation was observed between vent dimensions and objective OE (and subjective occlusion ratings) in this study.

On the other hand, Dillon (2001) reported measuring the vent effect on ten normal-hearing subjects and found a systematic change in OE as the vent diameter in an earmold was changed. In general, they measured 15 dB of OE with a 0 mm vent that decreased to about 7–8 dB when the vent diameter was opened to 2 mm. No reduction of OE was observed with the 1 mm vent diameter (about 4 dB was noted in this study). This may have been the result of a slit leakage in the earmolds used in the Dillon study (2001). Approximately 3–4 dB of OE was observed with a 3 mm vent. The author suggested that a 2 mm vent is a good starting point for fixing the occlusion problem, but warned that a vent will have to be widened to 3 mm to alleviate the problem. A high correlation between subjective rating of occlusion and objective OE was also reported ($r = 0.63$).

In this study, it was noted that a systematic change in objective OE was seen as the vent diameter was changed. The average occlusion effect was measured to be around 17 dB in the 0 mm vent condition that decreased to 13 dB for the 1 mm vent, 10 dB for the 2 mm vent, and 5 dB for the 3 mm vent. Other than the observation seen with the 1 mm vent diameter, the results of this study are similar to those of Dillon's (2001). Any differences noted between Dillon (2001) and this study probably originated from the use of different vent lengths and the possibility of slit leakage that was minimized in this study.

This study also showed a moderate correlation between compliance and OE at the 0 mm vent condition. Carle et al (2002) also showed that compliance correlated moderately with the minimal vent diameter necessary to eliminate the subjective occlusion perception in 82 hearing aid wearers, the rationale being that a larger vent diameter is necessary to remove more objective OE. The same authors also noted a similar relation between OE and compliance in a smaller sample of subjects. Of special interest in this study was the observation that only the 0 mm vent diameter condition correlated significantly with compliance; no other vent conditions correlated significantly. Because shells fabricated using laser shell-making technology are accurate to 1/10 mm (which was extremely form fitting), these observations suggest that the correlation between middle ear compliance and OE can be significantly affected by the vent conditions in which the OE was recorded. Any leakage in the earmold or hearing aid shell would reduce the OE and mask the relationship between middle ear compliance and OE. The correlation between OE and compliance may explain why participant #8 had negligible correlation between OE and acoustic mass. Her low middle ear compliance (0.3 ml) would have suggested low OE regardless of changes in the acoustic mass of the vent.

Despite the precautions used in this study to minimize slit leakage and measurement errors, there are both controllable and uncontrollable variables that may have affected the reliability of the current results. First, the effect of the vent dimensional change is dependent on the relative impedance difference between the residual ear canal and the vent. Despite the known change in the acoustic mass of the vent, the impedance of the residual ear canal is unknown. This could have affected the strength of the relationship seen between OE and vent dimensions. Secondly, the stability of the stimulus may be improved. Despite our use of frequency averaging and our effort to maintain the participants’ vocal production, uncontrollable fluctuations in the vocal levels (albeit minor) would still
occur. Consequently, a signal that is independent of the participant's effort, but would still test the bone-conduction mechanism, may be desirable. Revit (1992) suggested using standard signals delivered through a bone oscillator as an alternative to study the dimensional effect of vents on occlusion. This may be an area worthy of further exploration. Unfortunately, no additional work has been reported on this possibility. Finally, all the vent configurations were hand drilled. Despite the experience of the study audiologist in earmold modifications, imprecision in the drilling (for the sections with different diameters) may occur to affect the actual acoustic mass in both directions. At the time of this study, the laser shell-making technology did not allow the manufacturing of the vent configurations used in this study. Future laser shell-making technology would be able to manufacture inserts with the precise specifications.

Clinical Implications

The correlation seen between OE and acoustic mass in Figure 5 suggests that OE is affected by the acoustic mass of the vent. Because acoustic mass of a vent is affected by its diameter and its length, increasing the vent diameter will decrease its acoustic mass. For a fixed residual ear canal volume, this increases the relative impedance of the ear canal to that of the vent. Consequently, the low frequency in the ear canal “leaks” through the vent; thus, the objective occlusion effect decreases.

Selection of Vent Dimensions to Minimize Occlusion

The information on the systematic change in occlusion effect and vent dimensions would allow the selection of “acceptable” vent diameter. Let us assume that the wearer in question has characteristics similar to the participants used in this study. Let us further assume that she or he has an average ear canal and that a hearing aid shell of the typical length was used (terminates at second bend with a length of 16 mm). One may use the regression equation generated from the present study (Eq. 3) to predict the average occlusion effect as a function of vent diameter. Alternatively, one may use the following figure (Figure 11, generated from Eq. 3) to estimate the optimal vent diameter for an “acceptable” amount of OE. For example, Figure 11 shows that a vent diameter must be at least 2 mm to have less than 8 dB occlusion effect. Furthermore, it also shows that the most significant decrease in OE occurs when the vent diameter is changed from 0 (or 0.5 mm) to 1 mm. Progressive increases in vent diameter leads to a smaller decrease in OE.

What Is an Acceptable Occlusion Effect?

The experience of the participants to amplification and occlusion may be one of the reasons that explains the varying relationship between subjective ratings and objective occlusion effect among studies. Someone who had never listened to their own voice while occluded would probably react more negatively to the occluded sensation the first time, while another person who had worn hearing aids before and was somewhat accustomed to the occluded perception may be more tolerant of the occlusion effect, even if both had the same amount of objective occlusion effect. Getting the participants to acclimatize to wearing the hearing aids (and occlusion effect) at least one month prior to and during the study certainly could have altered the participants’ tolerance to the occlusion effect. This may be one reason why a correlation was seen between subjective ratings and objective
occlusion effects in this study whereas no correlation was seen in previous studies that used normal-hearing subjects. The caveat is that the conclusions drawn in this study may only be applicable to “experienced” or current hearing aid wearers and may not be generalized to first-time hearing aid wearers.

Figure 9 shows the relationship between subjective occlusion ratings and objective OE ($R^2 = 0.33$). As indicated earlier, there were significant variations between subjective ratings and OE. However, there was less variability (in the range of OE) for the higher subjective ratings. If one takes a rating of “9” or “10” to reflect acceptability, one would see that a “9” had OE that ranged from 0 to 10 dB whereas a rating of “10” had OE that ranged from 0 to 6 dB. The best fit linear regression line would suggest an OE of 7 dB for the “9” rating and 5 dB for a “10” rating. And from the companion paper (Kuk et al, 2005) that showed that a rating of “9” or above was viewed as acceptable (“It is hardly noticeable unless I focus my attention to it”) by most wearers, the average experienced wearer would probably find 5–7 dB of OE acceptable. If a vent of 16 mm length is used, one may select a vent with a uniform diameter between 2 and 2.5 mm to meet the criterion OE. Alternatively, one may select a reverse horn vent that has the same acoustic mass as this 2 to 2.5 mm vent. Obviously, this conclusion is based on participants who had been wearing completely-in-the-canal (CIC) hearing aids (with about 1.5 mm uniform-

diameter and reverse horn vents) prior to and during the course of the study. New wearers may tolerate a lower OE. This speculation should be further explored.

Alternate Vent Systems

Because the OE is related to the acoustic mass of the vent, vents that are designed to minimize the acoustic mass may minimize the occlusion effect. One example of an alternate vent system is to gradually increase the diameter of the vent as approximated in this study where the medial diameter of the vent is larger than the lateral diameter (i.e., vent configurations like 3/2/1 or 3/2/2). Such a vent design is seen in the use of the “reverse horn vent” in custom hearing aids. Because of space limitations in CIC hearing aids, the faceplate of these devices typically does not allow a vent opening larger than 1.5 mm. Such a diameter may only reduce the potential occlusion effect by 7–8 dB (see Figure 11). At least 8 to 9 dB of OE may still exist in the wearer’s ear canal. This is higher than the 5–7 dB of OE that was seen as “acceptable” in this study. On the other hand, there could be more space near the medial end of the canal where one may install a larger vent opening and use the space within the cavity of the hearing aid shell to build a hornlike vent with a 3 to 4 mm opening at the medial end. This could effectively increase the diameter (or lower its acoustic mass) of the vent. Kuk et al (2005) in the companion paper showed the results of such a vent system implemented on a CIC style hearing aid. Three decibels less occlusion effect was reported (and subjective preference as well) for the reverse horn vent than the conventional vent option.

Select-A-Vent (SAV) Use

Another implication from the observation of the dependence of OE on acoustic mass is in the use of Select-A-Vent (SAV). These are vent systems where one may select a particular vent diameter by choosing a vent plug with the chosen diameter. The idea is that the smallest opening of a vent governs its performance. On the other hand, in this study it was shown that the performance of a 3/2/1 vent was quite different from a 1 mm vent (or a 2/2/1 vent). Indeed, depending on the dimensions of these SAV plugs, the total acoustic mass of the SAV may be quite
different. For example, Figure 12 shows the acoustic mass of a 3 mm SAV system with a typical length of 16.6 mm. Its acoustic mass would be 24,900 H if it had a uniform diameter of 1 mm. If it were occluded with a 1 mm vent plug that was only 3 mm in length, its acoustic mass would be 6767 H, about 27% of the 1 mm vent. Using Equation 3, one may calculate that the OE of the 3 mm parallel vent is 5.24 dB and that the OE of the 1 mm vent is 13.2 dB. On the other hand, the 1 mm vent plug that is 3 mm in length will have an OE of 8.48 dB, and the 8 mm SAV plug will have an OE of 11 dB. In other words, depending on the length of the SAV plug, the characteristics of the vent system will be intermediate between the diameter of the vent plug used and the diameter of the unplugged SAV. If the purpose of the vent plug is to approximate a vent of the specific vent diameter, then the vent plug should be as long as the SAV system. On the other hand, if it were to approximate the unplug vent, it should be as short as possible.

CONCLUSION

The current study showed that vent dimensions affect the amount of objective occlusion effect in a predictable manner according to its length and diameter. The total amount of occlusion is not dependent on the smallest (or largest) vent diameter but on the acoustic mass of the whole system (and its relationship to the impedance of the residual ear canal). Furthermore, the moderate correlation between subjective occlusion ratings and objective occlusion effect and OE and acoustic mass suggests that methods that decrease the acoustic mass of the vent system would decrease the OE, and could improve subjective ratings. Because subjective ratings higher than “9” (which are considered “natural” voice) are still associated with some degree of OE, it is possible that in managing the occlusion complaint, one may not need to totally eliminate all the occlusion effect for complete wearer satisfaction.

REFERENCES
