Occlusion Effect of Earmolds with Different Venting Systems

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Abstract

In this study the occlusion effect was quantified for five types of earmolds with different venting. Nine normal-hearing listeners and ten experienced hearing aid users were provided with conventional earmolds with 1.6 and 2.4 mm circular venting, shell type earmolds with a novel vent design with equivalent cross-sectional vent areas, and nonoccluding soft silicone eartips of a commercial hearing instrument. For all venting systems, the occlusion effect was measured using a probe microphone system and subjectively rated in test and retest sessions. The results for both normal-hearing subjects and hearing aid users showed that the novel vents caused significantly less occlusion than the traditional vents. Occlusion effect associated with the soft silicone eartip was comparable to the nonoccluded ear. Test-retest reproducibility was higher for the subjective occlusion rating than for the objectively measured occlusion. Perceived occlusion revealed a closer relationship to measured occlusion in the ear in which the measured occlusion effect was higher ("high OE" ear) than in the "low OE" ear. As our results suggest that subjective judgment of occlusion is directly related to the acoustic mass of the air column in the vent, the amount of perceived occlusion may be predicted by the vent dimensions.

Key Words: Acoustic mass, earmold, hearing instruments, measured occlusion, novel venting system, occlusion effect, perceived occlusion, prediction of occlusion effect

Sumario

En este estudio se cuantificó el efecto de oclusión de cinco tipos de moldes con diferentes sistemas de ventilación. A nueve sujetos normo-oyentes y a diez usuarios con experiencia en auxiliares auditivos, se les proporcionaron moldes convencionales con ventilaciones circulares de 1.6 y 2.4 mm, moldes de tipo concha con un novedoso diseño de ventilación con áreas transversales equivalentes de ventilación, y puntas no oclusivas de silicón suave de un instrumento auditivo comercial. En todos los sistemas de ventilación, se midió el efecto de oclusión utilizando un sistema de sonda con micrófono, clasificándolos subjetivamente en sesiones de evaluación y re-evaluación. Los resultados, tanto para los sujetos normo-oyentes como para los usuarios de auxiliares auditivos, mostraron que las ventilaciones novedosas causaron un efecto de oclusión significativamente menor que los sistemas tradicionales. El efecto de oclusión asociado a las puntas de silicón suave fue comparable
It is widely known that only a small proportion of candidates for amplification actually own and wear hearing aids. The extremely low penetration for hearing aids is observed worldwide and can be ascribed to a number of factors, including stigma of hearing aid use, availability of services, and economic aspects. In addition to these factors, wearing comfort and poor sound quality are common reasons for not acquiring hearing instruments (Stephens et al, 1990; Davies et al, 1991; Wilson et al, 1993; Saunders and Cienkowski, 1996; van den Brink et al, 1996; Cienkowski and Pimentel, 2001; Jerram and Purdy, 2001; Davis, 2003).

Sound quality is one of the major complaints of individuals who do wear hearing aids, specifically the unnaturalness of one's own voice and the disturbance of other self-generated sounds. Such complaints are due to the blocking of the ear canal by an earmold or hearing aid shell, creating the so-called occlusion effect (French-Saint George and Barr-Hamilton, 1978; Dempsey, 1990; Warland and Tonning, 1993; Brooks, 1994). The occlusion effect is the buildup of low-frequency sound pressure in the residual ear canal that occurs when body-conducted sound is trapped (Studebaker and Zachman, 1979; Grover and Martin, 1979; Dillon, 1991; Carle et al, 2002). Hearing aid users often describe the subjective effect of occlusion as sounding like they are talking in a barrel. In addition, sounds like chewing, swallowing, throat clearing, and even breathing can be perceived as being so loud that they interfere with the user hearing external sounds.

The degree of perceived occlusion is related to the amount of sound pressure buildup in the ear canal but also to the hearing loss. While wearers with low-frequency hearing threshold levels greater than 40 dB are unlikely to be bothered by the occlusion effect (May and Dillon, 1992; Dillon, 2001), most hearing aid fitting practices will still see a great many patients who may experience difficulties with occlusion. Analysis of audiometric data from a dispensing practice's database of 700 patients revealed that 59% of the patients demonstrated hearing losses ≤45 dB below 500 Hz (Laureyns, unpublished study), indicating a considerable potential for problems with occlusion. Analysis of audiometric data from a dispensing practice's database of 700 patients revealed that 59% of the patients demonstrated hearing losses ≤45 dB below 500 Hz (Laureyns, unpublished study), indicating a considerable potential for problems with occlusion. There is also evidence to suggest that having to deal with occlusion-related complaints is daily fare for hearing instrument fitters. For example, a survey of 4421 hearing aid wearers conducted by Dillon and his colleagues (Dillon et al, 1999) showed that 27% of the respondents found occlusion to be problematic. Similar findings were reported by Kochkin (2000). Other investigations (French-Saint George and Barr-Hamilton, 1978; MacKenzie et al, 1989;
The availability of this processing has sparked renewed interest in venting solutions designed to reduce occlusion.

As widening of the vent diameter is limited by the dimensions of the ear canal, a novel venting system with an extremely short vent length has been developed under the working hypothesis that the occlusion effect is mainly determined by the acoustic mass and therefore proportional to the effective vent length. The purpose of this study was to investigate the occlusion effect and perceived occlusion associated with this novel vent design and compared to a conventional vent design. Specifically, we sought to address the following questions:

- Does this novel venting system give a reduced sense of occlusion and/or a reduced objectively measured occlusion effect for normal-hearing and hearing-impaired individuals compared to traditional earmolds with the same cross-sectional vent diameter area?
- What is the measured occlusion effect and perception of occlusion with a commercially available soft silicone eartip for open fittings?
- How reproducible and reliable are objective measurements and subjective judgments of occlusion?
- Is there a relationship between objective and subjective occlusion?
- Can the amount of perceived occlusion be predicted?

**METHOD**

**Subjects**

The study was carried out with a test group of ten hearing-impaired listeners with mild to moderate sloping sensorineural loss and a reference group consisting of nine normal-hearing individuals. The hearing-impaired subjects were experienced hearing aid users who were accustomed to occlusion of the ear canal by either in-the-ear hearing instruments or earmolds for at least three years. The type of venting they were used to was ranging from traditional 2 mm vents to almost open fittings. The inclusion criteria for the test group were hearing threshold levels better than 30 dB at frequencies up to 1 kHz, and between 50 and 90 dB from 4 to 8 kHz.
Participants in the reference group were not accustomed to ear occlusion. Figure 1 shows the average pure-tone hearing loss of both the test and the reference groups. In this figure the data for right and left ears were pooled, as hearing losses were highly symmetrical.

**Earmolds**

Ear impressions were taken past the second bend using a two-component silicone material (Heba-Form) applied by a double-cartridge impression gun. One ear impression per ear was used for all types of custom earmolds needed for this study. All subjects were provided with bilateral earmolds as described below and depicted in Figure 2. All four types of custom earmolds for each subject were manufactured to terminate at the same depth in the ear canal.

- Two pairs of conventional earmolds with parallel vents, one with 1.6 mm and one with 2.4 mm diameter (Figure 2, left)
- Two pairs of shell type earmolds with a novel vent design, one with a cross-sectional vent area equivalent to a circular vent with a diameter of 2.4 mm (medium and large sized FlexVent™, Figure 2, center)
- One pair of soft silicone eartips used with a commercial behind-the-ear hearing instrument (ReSoundAIR™, Figure 2, right).

**Rationale for Novel Vent Design**

An effective vent allows low-frequency sound to escape from the ear canal, thereby reducing the occlusion effect. Vent effectiveness is determined by the inertia of the air column in the vent. The inertia can be described in terms of acoustic mass, which is proportional to the effective vent length (geometric length plus end correction) and inversely proportional to the cross-sectional area of the vent. Therefore, a vent should be as short and as wide as possible to achieve minimum occlusion effect. In the extreme case it becomes an open fitting. These considerations led to the novel design (Figure 2, center). The FlexVent is used in an earshell produced in the same manner as shells for in-the-ear hearing instruments. A 1 mm vent plate (available in red for right ears and blue for left ears), with a hole in the middle, is attached to the canal part of the shell.
earmold. The FlexVent system consists of a changeable vent insert (also 1 mm thick) carrying the sound tube. The vent insert is available in two sizes: medium (with a cross-sectional vent area equivalent to a circular vent with a diameter of 1.6 mm) and large (with a cross-sectional vent area equivalent to a circular vent with a diameter of 2.4 mm). The sound tube is attached to the vent insert and is placed in the vent plate; that is, the part of the hole in the plate not filled out by the insert constitutes the vent. The size of the insert can be chosen according to the needed gain. This solution results in a constant vent diameter along with a full vent length of 1 mm. A previous investigation with this type of earmold revealed significant improvements in perceived and measured occlusion compared to traditional earmolds with equivalent cross-sectional vent area and termination of ear mold length in the ear canal (Jespersen and Asgaard, 2003). The FlexVent was tested to verify this finding.

Soft Silicone Eartip

The soft silicone eartip was included to corroborate previous findings suggesting that occlusion effect was almost eliminated with this coupling to the ear canal (Kiessling et al, 2003; Groth and Søndergaard, 2004). This eartip system consists of a dome-shaped, medical grade silicone earplug with multiple vents like a sieve and is connected to an extremely thin sound tube. It is snapped onto a behind-the-ear (BTE) housing as a single unit. The earplugs and tubes come in a variety of standard sizes, which allows fitting of the majority of adult ears. The retention of the soft silicone eartip has been proven to be sufficient in a previous study (Kiessling et al, 2003).

Procedure

Subjects were invited to the clinic for three appointments. At the first session, a case history was recorded and otoscopy, pure-tone audiometry, tympanometry, and bilateral ear impressions were performed. Then, a set of traditionally vented earmolds and FlexVent earmolds were manufactured, and appropriate soft silicone eartips were selected.

In the second session, the occlusion effect was measured objectively, and subjective ratings of naturalness of own voice were determined for each type of earmold. All measurements and subjective evaluations were performed in a sound-treated audiometric test booth. Objective occlusion

Figure 2. Types of earmolds used: traditional earmold with venting (left), shell type earmold with flexible vent (center), nonoccluding soft silicone eartip of a commercial hearing aid (right).
measurements were performed with the GN Otometrics VisibleSpeech probe microphone system. After the probe tube was placed in the ear canal, a reference response of the subject's own voice was recorded for the nonoccluded ear. For this purpose, the subject was asked to vocalize the vowel /ee/ at about 75 dB SPL for a couple of seconds until the measurement system had averaged a stable frequency response. The stability of the sound pressure level produced by the subjects was monitored by the VisibleSpeech unit. Then, the same procedure was repeated for each type of earmold connected to a BTE hearing instrument in the turned-off position. The result of this measurement shows the difference in frequency response compared to the nonoccluded condition. Finally, the nonoccluded condition was measured again to verify that the position of the probe tube was unchanged; that is, the frequency response of the open ear canal was 0 ± 3 dB. The procedure was repeated on the other ear. In this study, we quantified the occlusion effect in the following way: the three-frequency average (250, 500, and 750 Hz) of the real ear sound pressure level for the test condition minus the three-frequency average of the real ear sound pressure level for the nonoccluded condition.

To obtain a subjective measure of the perceived occlusion, the participants were asked to rate the naturalness of their own voice while reading a text sample aloud. They were encouraged to read the text as many times as needed to make their judgments. For this experiment, the participants were blinded as far as possible concerning the conditions, which were absolutely rated on a 10-point scale (0: very natural sound of own voice … 9: very unnatural sound of own voice). For the rating procedure, earmold configurations were paired to achieve a certain contrast between related conditions as true pair comparisons were impossible due to the objective of the study: 1.6 mm traditional vent/medium FlexVent, 2.4 mm traditional vent/large FlexVent, and open soft silicone eartip/nonoccluded ear canal. The sequence of the paired conditions as well as the sequence within each pair was randomized to avoid order effects.

The third visit took place about two weeks after the second appointment. At this session, both the objective occlusion measurements and the subjective occlusion ratings were repeated to check test-retest reliability of the data.

### STATISTICS

The Wilcoxon-Signed-Rank test was employed to test for significance between relevant pairs of conditions for both measured and rated occlusion, and two-sided p-values were calculated. Pearson correlation coefficients and coefficients of determination r² were calculated to describe, respectively, test-retest reliability and relationships between measured and related occlusion.

### RESULTS

#### Measured Occlusion

The objective occlusion measure varied from -8 to 25 dB over all subjects and conditions. Mean values and standard deviations for test and retest are shown in Figure 3. Because this objectively measured data was not dependent on the presence or degree of hearing loss, data for hearing-impaired and normal-hearing listeners were pooled. The average measured occlusion for traditional earmolds with 1.6 mm circular venting was approximately 12 dB whereas FlexVents with an equivalent cross-sectional vent area resulted in only about 5 dB average measured occlusion. A similar relationship was found for larger vents with 2.4 mm cross-sectional vent areas, with a measured occlusion effect of about 10 dB for traditional earmolds and 3 dB for the FlexVent. The soft silicone eartip produced an occlusion effect comparable to the nonoccluded ear. The Wilcoxon test revealed a significant difference (p < 0.01) between the following pairs of test conditions: medium FlexVent versus traditional circular 1.6 mm vent, large FlexVent versus 2.4 mm circular traditional vent, and soft silicone eartip versus large FlexVent. There was no significant difference in measured occlusion between the soft silicone eartip and nonoccluded conditions.

#### Rated Occlusion

Figure 4 shows average results and standard deviations for naturalness of own voice ratings (rated occlusion plotted upwards) for both the reference (normal hearing [NH]; upper panel) and the test group (hearing impaired [HI]; lower panel). For both populations, the FlexVents resulted in
significantly (p < 0.01) reduced perceived occlusion compared to traditionally vented earmolds with equivalent cross-sectional vent areas. Also for both groups, perceived occlusion effect associated with the soft silicone eartip was significantly (p < 0.01) lower than for any other venting system tested here and yielded comparable results to the nonoccluded condition.

Test-Retest Reliability

Average test (Figure 3, white columns) and retest (Figure 3, gray columns)

![Figure 3](image1.png)

**Figure 3.** Mean measured occlusion (three-frequency average at 250, 500, and 750 Hz) with standard deviations for different types of earmolds for all subjects pooled (n = 19). Test-retest results are given by white columns and retest results by gray columns.

![Figure 4](image2.png)

**Figure 4.** Mean rated occlusion (on a scale 0 … 9) with standard deviations for different types of earmolds for the normal-hearing (NH) listeners (upper panel) and the hearing-impaired (HI) subjects (lower panel). Test results are given by white and retest results by gray columns.
measurements showed similar results. However, individual test-retest reliability for the measured occlusion was fairly poor as evidenced by the scattergram in Figure 5 containing all data for hearing-impaired and normal-hearing test persons over all conditions. The test-retest reliability is described by a coefficient of determination of 0.429 for a linear relation.

As was the case for the objectively measured occlusion, the average results for the subjective ratings were replicated at the retest session, as can be seen in Figure 4 by comparing the white columns (test) with the gray columns (retest) for each condition. For the hearing-impaired participants, the test-retest reliability was given by a coefficient of determination of 0.823 for a linear relation. For the normal-hearing group, the coefficient of determination for a linear relation was determined to be 0.782.

Relation between Measured and Rated Occlusion

The issue of how rated occlusion is related to the measured effect raises the question of whether the rated occlusion is predominantly determined by the ear in which the measured occlusion effect is higher ("high OE" ear) or by the other ("low OE") ear. One might assume that the "high OE" ear determines the perceived occlusion effect. To check this hypothesis, we plotted rated occlusion as a function of measured occlusion in the "high OE" ear and as a function of measured occlusion in the "low OE" ear. Figure 6 shows this relationship for the ear where the measured occlusion was greatest ("high OE" ear) in the test session. All data from hearing-impaired and normal-hearing listeners are pooled. The coefficient of determination for the relationship between the "high OE" ear and rated occlusion was 0.461, while it was 0.331 for the "low OE" ear. Coefficients of determination for a linear relationship between both variables indicate that the correlation of rated occlusion with measured occlusion in the "high OE" ear is slightly higher than the one for the "low OE" ear for both test and retest measurements.

DISCUSSION

We wanted to confirm previous findings showing that the FlexVents provide a reduced sense of occlusion and reduced measured occlusion effect compared to traditional earmolds with equal cross-sectional vent area (Jespersen and Asgaard, 2003). Our results clearly support that this is the case. Average measures of occlusion were 7 dB lower for the FlexVents than for the traditional vents. These results were
reflected in the subjective ratings in that both the normal-hearing and hearing-impaired groups rated the FlexVents as providing a more natural sounding quality of own voice. None of the participants made use of the entire rating scale when rating their own voice with the FlexVents, while there were maximum ratings for unnaturalness with the traditional earmolds.

A reason for including normal-hearing participants in this study was to represent a “worse case” scenario. It was hypothesized that the normal-hearing participants would be more sensitive to the effects of occlusion by virtue of their hearing acuity. However, the subjective ratings of the hearing-impaired and normal-hearing groups turned out to be remarkably similar. The present data support that normal-hearing persons perceive and rate occlusion effects in the same way as experienced hearing aid users do. This suggests that the perceptual effects of occlusion are not affected by being accustomed to occlusion. This is in agreement with Hansen (1997), who found that hearing aid users do not adapt to the occlusion effect.

Another reason for including normal-hearing participants was to ensure that reliable, reproducible judgments were made. Grover and Martin (1979) performed semantic differential tests for different types of venting and reported that hearing-impaired subjects were less able to make systematic judgments on sound quality than a control group consisting of normal-hearing individuals. In contrast to their findings, our data show that the test-retest reliability for the hearing impaired is marginally higher than for normal-hearing listeners. The discrepancy with Grover and Martin (1979) may be explained by the fact that our hearing-impaired test persons had near normal hearing up to 1 kHz, whereas their subjects had flat losses ranging from 30–70 dB over the speech frequency range. Thus our subjects would have been better able to discriminate low-frequency vent-related effects because of their better hearing. Our results do not indicate that the hearing impaired are less reliable in their judgments of occlusion than normal-hearing individuals.

One of the research questions was related to the measured and perceived occlusion associated with a commercially available soft silicone eartip for open fittings. This was motivated by earlier findings that patients fit with this device had no occlusion-related complaints (Kiessling et al, 2003) and that real ear occluded gain for this ear tip was nearly identical to real ear unaided gain (Groth and Søndergaard, 2004). The present results revealed no significant differences in measured occlusion between the eartip and nonoccluded conditions, nor were there any

![Figure 6](image_url)

**Figure 6.** Scattergram for rated occlusion versus measured occlusion in the “high OE” ear for all subjects pooled (n = 19). Measured occlusion in the “high OE” ear explains about 46% of the variation of perceived occlusion.
differences between these conditions for the subjective ratings. This supports that the soft silicone eartip is indeed nonoccluding.

Although previous studies have not demonstrated a clear relation between sensed and objective occlusion (May and Dillon, 1992; Biering-Sørensen et al., 1994), it has been put forth that objective measures of occlusion effect are a useful clinical tool for troubleshooting occlusion-related complaints (Mueller, 1992). For this to be true requires the ability to perform reliable measurements. We attempted to shed light on this issue by replicating our measurements at a later session. Since the same examiner performed all measurements, we expected the test-retest reliability to be high. Surprisingly, it turned out to be only around 0.4. In contrast, the test-retest reliability of the subjective ratings of naturalness of own voice were much higher, which suggests that what patients report about their experience of occlusion may be a better indication of vent effectiveness than a single measurement of occlusion effect. Measurements of occlusion are subject to the same sorts of procedural errors as other real ear measurements, with shifting of the probe tube arguably being the greatest source of error. It is also the case that the sound pressure level in the ear canal for self-generated sounds is affected by other factors than vent effectiveness alone. For example, Carle and colleagues (2002) demonstrated that increased middle ear impedance can produce a greater occlusion effect. Although this would be measurable, it probably would not lead to increased occlusion-related complaints.

An interesting observation regarding the objective measurements of occlusion was the rather large individual variation in values for the same condition. In some cases, negative values compared to the nonoccluded condition were attained. An obvious explanation for this could be a shift in probe tube position between measurements despite efforts to control for this. However, this could also be accounted for by individual resonances and the fact that the net effect of low-frequency sound transmission into and out of the vent can be either negative or positive (Dillon, 1991).

Discussion of the reliability of objective measurement of occlusion and subjective judgments leads to the question of whether there is a relationship between the two. Our data indicated that objective and subjective occlusion are positively correlated. It was also the case that the average rating of naturalness of own voice was more closely related to the measured occlusion effect in the ear where the occlusion effect was highest. The measured occlusion in the ear with the higher occlusion effect explains about 46% of the variation of perceived occlusion. This finding supports the assumption that the experienced occlusion is mainly determined by the degree of occlusion in the more occluded ear. However, there is still a large degree of variation not explained by the

**Figure 7.** Rated occlusion averaged over all subjects (taken from Figure 4) as a function of the acoustic mass of the air column in the vent. Perceived occlusion can be predicted from the acoustic mass of the vent according to the equation given in the lower right corner.
measured occlusion effect. This would appear to be accounted for by the lower reliability of the objective measurements compared to the subjective judgments.

A final question to be addressed in this study was whether or not perceived occlusion could be predicted for individuals with good low-frequency hearing. In light of the discussion on reliability of objective occlusion measurements and subjective judgments, it is clear that the measured occlusion effect is not a strong predictor of perceived occlusion in individual cases. However, as there are no data points in the lower right corner of the scattergram in Figure 6, a single-edged estimation is possible. For example, if the measured occlusion effect is 15 dB or higher, perceived occlusion is expected to be three scaling units or above, indicating that perception of own voice as “natural” sounding is highly unlikely to occur.

We propose that an alternative way to predict perceived occlusion is to base it on geometric vent dimensions. As mentioned previously in this paper, the effectiveness of a vent in allowing free passage of low-frequency sound is determined by the acoustic mass of the air column in the vent. The increase in ear canal sound pressure level for self-generated sound is also mainly determined by this acoustic mass \((M_a)\), which is given by:

\[
M_a = \text{Constant} \times \frac{\text{Vent length}}{(\text{Vent diameter})^2}
\]

where the constant contains the density of the air. To prove this assumption, we have plotted the rated occlusion taken as the averages from Figure 4 as a function of the acoustic mass of the vent types used in this study. The acoustic mass is calculated from the equation above utilizing the average vent dimensions and taking end corrections for the vent length into account (Dillon 2001). For a semi-logarithmic plot (Figure 7), we find a close linear relation between both variables: the acoustic mass explains about 97% of the variance of the perceived occlusion. Other factors, such as middle ear compliance as studied by Carle et al (2002), seem to play a minor role for this group of subjects with normal middle ear function.

Given this relation, the perceived occlusion can be predicted by the geometric dimensions of the vent. This relation is illustrated in Figure 8. Plotting the calculated occlusion as function of vent length and vent diameter results in a three-dimensional surface. This diagram can be used to assess the expected occlusion from the vent dimensions when the earmold is manufactured; for example, with a long narrow vent (rear corner of Figure 8), one will never get an acceptable result in terms of experienced occlusion. We have marked the position of the types of earmolds used in this study on this surface as black squares to illustrate how the vent dimensions affect the occlusion.

![Figure 8](image_url)

**Figure 8.** Three-dimensional plot of rated occlusion as a function of vent length and diameter calculated according to the equation given in Figure 7. The positions of the types of earmolds used in this study are marked on this surface as black squares.
CONCLUSIONS

- The FlexVent earmolds are significantly \( (p < 0.01) \) less occluding than traditional earmolds with equivalent cross-sectional vent area.
- The soft silicone eartip provides a nonoccluding hearing aid fitting.
- For individuals, subjective evaluation appears to be a more reliable indicator of occlusion than objective measurement of the occlusion effect.
- Perception of occlusion appears to be well predicted by the acoustic mass associated with the vent in the otoplastic.

Acknowledgment. The authors thank two anonymous reviewers for helpful comments on an earlier version of this manuscript. This study was supported by GN Resound.

REFERENCES


