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The Occlusion Effect in Unilateral versus Bilateral Hearing Aids

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Abstract

The benefit of bilateral hearing aids is well documented, but many hearing-aid users still wear only one aid. It is plausible that the occlusion effect is part of the reason for some hearing-aid users not wearing both hearing aids. In this study we quantified the subjective occlusion effect by asking ten experienced users of bilateral hearing aids and a reference group of ten normal-hearing individuals to rate the naturalness of their own voice while reading a text sample aloud. The subjective occlusion effect was evaluated in the unilateral versus bilateral condition for a variety of vent designs in earmolds and in a custom hearing aid. The subjective occlusion effect was significantly higher for bilateral hearing aids with all vent designs with the exception of a non-occluding eartip option. The subjective occlusion effect was reduced with the more open vent designs in both the unilateral and bilateral conditions. Assuming that the occlusion effect is a barrier to bilateral hearing aid use, these results indicate that open-hearing-aid fittings can help promote the use of two aids.

Key Words: Bilateral fitting, conventional venting, hearing aids, novel venting, subjective occlusion effect, unilateral fitting

Abbreviations: CIC = completely-in-the-canal

Sumario

El beneficio de los auxiliares auditivos bilaterales está bien documentado, pero muchos usuarios de dichos auxiliares utilizan sólo uno de ellos. Es posible que el efecto de oclusión sea parte de la razón por la que algunos usuarios de auxiliares auditivos no utilicen ambos. En este estudio, cuantificamos el efecto subjetivo de oclusión, preguntándole a diez sujetos con experiencia en amplificación bilateral y a un grupo de referencia de diez individuos con audición normal, que juzgaran la naturalidad de sus propias voces durante la lectura de un texto en voz alta. El efecto subjetivo de oclusión fue evaluado en la condición unilateral versus bilateral, usando una variedad de diseños de moldes y en un auxiliar hecho a la medida. El efecto subjetivo de oclusión fue significativamente mayor para aquellos con auxiliares auditivos bilaterales, incluyendo todos los diseños de ventilación, con la excepción de la opción de molde no oclusivo. El efecto subjetivo de oclusión se redujo con los diseños de ventilación más abierta, tanto en la condición unilateral como en la bilateral. Asumiendo que el efecto de oclusión es una barrera para el uso de auxiliares auditivos bilaterales, estos resultados indican que las adaptaciones con

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auxiliares auditivos abiertos pueden ayudar a promover el uso de dos dispositivos.

Palabras Clave: Adaptación bilateral, ventilación convencional, auxiliares auditivos, ventilación novedosa, efecto subjetivo de oclusión, adaptación unilateral

Abreviaturas: CIC = completamente dentro del canal

Individuals who wear hearing aids often complain that their own voice sounds unnaturally loud and "boomy." The root of this complaint is often the occlusion effect, the buildup of low-frequency sound pressure for self-generated sounds occurring when the ear canal is blocked by the earmold or hearing aid shell. The perceptual correlate of this objectively measurable effect is subjective occlusion and is most problematic for individuals with relatively good low-frequency hearing. Evidence suggests that occlusion-related complaints are significant contributors to dissatisfaction with hearing aids (Dillon et al, 1999; Kochkin, 2000a) as well as reasons for not acquiring hearing aids (Stephens et al, 1990; Davies et al, 1991; Jerram and Purdy, 2001; Davis, 2003). One approach to alleviating the occlusion effect is venting the earmold or hearing aid. In Kiessling et al (2005), we documented that a specific soft silicone eartip was non-occluding in terms of both measured occlusion effect and subjective judgment of occlusion. Also, a novel vent design incorporating a very short length significantly reduced both objective and subjective occlusion effects compared to traditional parallel vents of the same cross-sectional area. Finally, our data indicated that the degree of occlusion was systematically related to the acoustic mass associated with the dimensions of the vent. Although the novel vent design and the specific soft silicone eartip might prove to be useful in encouraging use of amplification among non–hearing aid wearers, an equally interesting question is whether they might promote use of bilateral amplification.

The use of bilateral amplification has become generally accepted as beneficial for most individuals with bilateral hearing impairment (Byrne, 1980; Ross, 1980; Byrne, 1981). For example, the binaural advantages enjoyed by normal-hearing listeners have also been shown to apply to hearing-impaired listeners fit with two hearing aids rather than one. These include better localization in the horizontal plane (Noble et al, 1998; Köbler and Rosenhall, 2002), binaural squelch (Dillon, 2001), binaural redundancy (Kaplan and Pickett, 1981; Browning and Gatehouse, 1988), and binaural summation (Dermody and Byrne, 1975; Hall and Harvey, 1985; Hawkins et al, 1987). Together with head diffraction effects, these factors contribute to better speech intelligibility in background noise and reverberant surroundings (Dillon, 2001). Bilateral hearing aids have additional advantages as compared to unilateral hearing aids, such as better sound quality (Balfour and Hawkins, 1992), avoiding late-onset auditory deprivation (Silman et al, 1984), and better masking of tinnitus (Brooks and Bulmer, 1981).

Despite the documented advantages of bilateral hearing aids, not all individuals with bilateral hearing impairment are fit with two hearing aids. In the United States, 75% of the hearing-impaired population with bilateral hearing loss is reportedly fit bilaterally (Kochkin, 2000b). Unfortunately, the rate of bilateral hearing aids in other developed countries is much smaller, ranging from an estimated 35% in Europe to 10% in Asia (Kochkin, 2000b). There are probably a number of reasons why many hearing-impaired individuals do not obtain two hearing aids, one of these being subjective occlusion, as mentioned above. Another factor that appears to influence who is fit bilaterally is degree of hearing difficulty, as noted by Stephens et al (1991). They found that individuals with bilateral hearing impairment who opted for two hearing aids had a greater hearing disability as measured with the *Social Hearing Handicap Index* (SHHI) and worse hearing threshold levels than those who opted for one hearing aid. Additional barriers to acquiring two hearing aids are the stigma of hearing aid use (Surr and Hawkins, 1988; Stephens et al, 1991), cost, and hearing aid management (Erdman and Sedge, 1981).

These obstacles to obtaining two hearing aids fall short of explaining why many of those who are fit bilaterally choose to wear only one hearing aid. In a survey of 4,421 hearing-impaired individuals, 20% of the 1,920 bilaterally fitted respondents reported that they only used one hearing aid (Dillon et al, 1999). Increased wind noise is a disadvantage of bilateral hearing aids (Dillon, 2001) and thus a probable reason why two hearing aids might not be worn. Difficulties with telephone usage might also contribute. It is not uncommon for hearing-aid users to prefer to use the telephone unaided and therefore leave one ear open for convenience. Another reason for not wearing two hearing aids can be binaural interference, which can result in worse speech recognition performance with two hearing aids than with one. Binaural interference is thought to result from prolonged deprivation or age-related changes in the central auditory system and causes marked differences between ears in sound processing and awareness. Binaural interference is, however, only present in a very small proportion of the hearing-impaired population (Allen et al, 2000; Dillon, 2001) and thus unlikely to be a common reason for not wearing two hearing aids.

Another possible reason for only wearing one hearing aid is that the bilateral advantages are not as obvious in daily use of the hearing aids as indicated by laboratory measures. In fact, Arlinger et al (2003) pointed out a lack of studies proving bilateral advantages in real life situations. If additional benefit due to the second hearing aid is not readily perceived, the incentive to wear both would understandably be diminished, particularly if it were less comfortable to wear two hearing aids. The issue of comfort is also likely to play a role in why so many bilaterally fitted individuals do not wear both of their aids. Stephens et al (1991) found lack of comfort to be a reason given by some bilaterally hearing-impaired individuals for preferring a unilateral hearing aid fitting to a bilateral fitting. The term "comfort" applied to hearing aids can refer to ease and well-being, both in terms of the physical fit of the hearing aids and how they sound. When speaking of occlusion of the ear, physical and sound sensations may even seem intertwined to the user, as feeling "plugged up" can apply to both. It is well-known that the occlusion effect is an important determinant of wearing comfort for hearing-aid users with good low-frequency hearing. As subjective occlusion increases, hearing aids become less pleasant to wear for this group. This has been shown in numerous studies (French-Saint George and Barr-Hamilton, 1978; MacKenzie et al, 1989; Kuk, 1991; Brügel et al, 1992) and is also the common experience of many practitioners.

An effective way of reducing both objective and subjective occlusion is by increasing the effectiveness of the venting in the earmold or hearing aid shell. By "effectiveness," we mean that the vent is efficient in transferring low-frequency energy into and out of the ear canal. An effective vent will allow self-generated low-frequency sound to escape from the ear canal, thereby reducing the sound pressure level of these sounds in the ear and alleviating the perception of them as excessively loud or boomy. The effectiveness of a vent is determined by its acoustic mass. The acoustic mass describes the inertia of the air column in the vent that must be overcome to transmit acoustic energy. The acoustic mass of a vent is inversely proportional to the square of the cross-sectional area of the vent, and directly proportional to its length. Thus, wider, shorter vents will exhibit a lower acoustic mass and be more effective than narrower, longer vents. In Kiessling et al (2005), we found that the calculated acoustic mass was strongly correlated with subjective occlusion ratings. Moreover, the correlation between acoustic mass and subjective occlusion was higher than the correlation between objective and subjective occlusion. This led us to speculate that acoustic mass might be a useful predictor of subjective occlusion. But since the acoustic mass calculations were based on average vent dimensions rather than on individual data, this idea required further investigation.

In the present study, our hypothesis was that subjective occlusion would be consistently worse for bilateral than for unilateral fittings. We further sought to investigate whether subjective occlusion is predictable based on the calculated acoustic mass of the vent in a given individual.

METHODS

Subjects

The study was carried out with a test group of ten experienced bilateral hearing-aid users with mild-to-moderate sloping sensorineural hearing loss and a reference group consisting of ten normal-hearing individuals. The hearing-aid users were accustomed to occlusion of the ear canal by either in-the-ear (ITE) hearing aids or earmolds. They had an average of 5 years of experience (range: 1–12 years) with occlusion of the ear canals. Their own hearing aids all had parallel vents measuring 15 mm or longer and with vent diameters ranging from 1 mm to 2 mm. Figure 1 shows the average pure-tone audiogram of the hearing-aid-user group. The normal-hearing participants all had hearing threshold levels at or better than 15 dB HL and were not accustomed to occlusion of the ear canal.

Earmolds, Eartips, and Completely-in-the-Canal Hearing Aid Shells

The vent configurations tested in this study included conventional earmolds with parallel vents, completely-in-the-canal (CIC) dummy hearing aids, shell type earmolds with a novel vent design (FlexVent™ earmolds), and non-occluding silicone eartips. A complete description of the FlexVent earmolds and rationale for their design can be found in Kiessling et al (2005). Briefly, FlexVent earmolds consist of acrylic shells with a detachable 1 mm vent plate. The thinness of the vent plate has the effect of reducing the acoustic mass associated with the vent without having to increase its diameter, thus requiring less space in the ear canal. The non-occluding silicone eartip, also described by Kiessling et al (2005), is made of a dome-shaped, medical grade silicone that is connected to a very thin sound tube and attached to a behind-the-ear housing. The eartips and tubes come in a variety of standard sizes, which allows fitting of the majority of adult ears.

Deep ear impressions were taken using a two-component silicone material (HEBA-Form A+B) applied with an impression gun. One ear impression per ear was used for all types of custom earmolds and the custom CIC hearing aids needed for this study. Four pairs of bilateral earmolds and one pair of CIC hearing aid dummies were custom made for each subject, and one pair of silicone eartips was selected based on the subject's ear size (see Figure 2). All four pairs of custom earmolds and the CIC hearing aid dummies for each subject were manufactured to terminate at the same insertion depth in the ear canal.

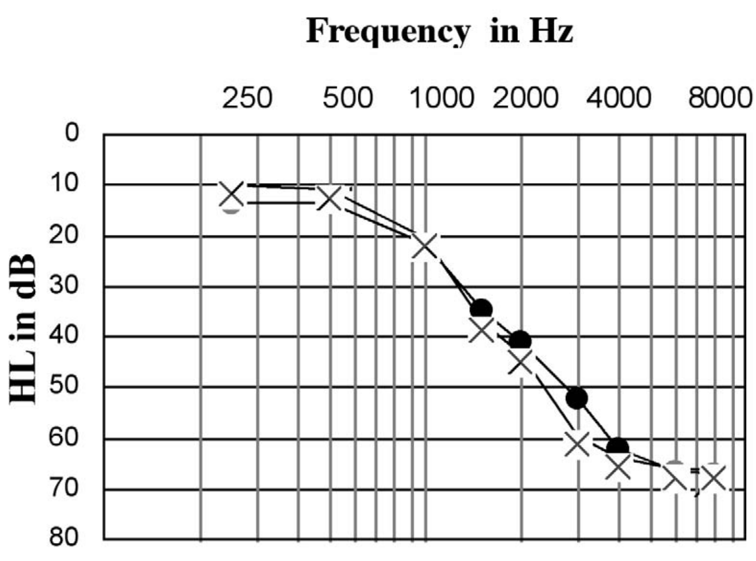

Figure 1. Mean hearing threshold levels for the right and left ears of the ten hearing aid users. ● = right ear, X = left ear.

- Two pairs of conventional earmolds with parallel vents, one pair with a 1.6 mm diameter vent and one pair with a 2.4 mm diameter vent (Figure 2, far left).
- Two pairs of shell-type earmolds with a novel vent design, one pair with a cross-sectional vent area equivalent to a circular vent with a diameter of 1.6 mm and one pair 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, second from left).
- One pair of silicone eartips used with a commercial behind-the-ear hearing aid (ReSoundAIR™, Figure 2, second from right).
- One pair of CIC hearing aid dummies with parallel 3 mm venting (19 mm long, Figure 2, far right).

Procedure

Participants were tested in two sessions. At the first session, a case history was taken; otoscopy, pure-tone audiometry, and tympanometry were performed; and bilateral ear impressions were obtained. Appropriately sized soft silicone eartips were also selected.

At the second session, the subjective occlusion effect was evaluated for each type and size of vent in the earmolds and CIC hearing aids in both the unilateral and bilateral conditions. The evaluations were performed in a sound-treated audiometric test booth. No amplification was provided in order to isolate effects due to the ear canal occlusion only.

Because a boomy or too-loud-sound quality of one's own voice is the most common occlusion-related complaint, it was assumed that the participants' evaluation of their own voices would provide a measure of subjective occlusion. Participants were asked to rate the naturalness of their own voices while reading a text sample aloud at a conversational level. The same ten-point rating scale was employed as by Kiessling et al (2005), where 0 corresponded to the sound of one's own voice being "very natural" and 9 corresponded to "very unnatural." "Very natural" was defined as the way the participants' voices sounded to them with their ear canals unoccluded. Participants read the entire text at least once before assigning a rating but were encouraged to read it as many times as needed to make their judgments. Both hearing-aid users and normal-hearing individuals have previously demonstrated a high degree of reliability on this task (Kiessling et al, 2005). The investigator placed the earmolds in the participants' ears without informing them

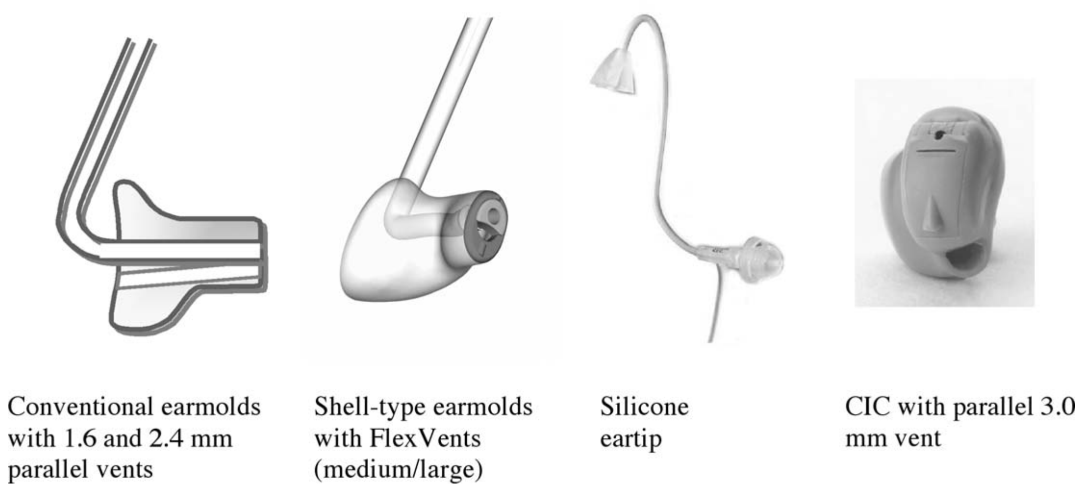

Figure 2. Illustrations, from left to right, of the conventional earmolds with parallel vents, the FlexVents in shell type earmolds, the eartip, and the parallel vents in CIC hearing aids.

which type of vent they were evaluating. The sequence of vent types as well as whether the bilateral or unilateral condition was evaluated first was counterbalanced to avoid order effects. The entire procedure was performed twice so that there were two ratings per participant for each condition.

Control of the level of the participants' voices during this experiment was of concern. While they could have monitored their voice productions with a VU meter, this was judged to be too distracting and difficult since they were also reading a text. To ensure that they were able to consistently speak at the same level in varying test conditions, the examiner monitored each participant's voice with a sound level meter (Bruel & Kjaer, Type 2205) held at a distance of 50 cm from the speaker's mouth for two conditions: with the ear canals unoccluded and with both ear canals occluded with the standard earmolds having 1.6 mm parallel vents. Kiessling et al (2005) showed this to be the most occluding of the conditions tested. The average sound pressure levels of the participants' voices in these two conditions were not significantly different (paired t-test, $p < 0.05$), and individual differences in the sound pressure level of the participants' voices between these two conditions were within 3 dB for all participants.

Calculation of Acoustic Mass

Acoustic mass M_a for each individual vent was calculated according to the following formula:

M_a = Constant • Vent length /(Vent diameter)^2,

with end correction.

STATISTICAL ANALYSIS

The Wilcoxon-Signed-Rank test was employed to test whether the normal-hearing participants' ratings differed from those of the hearing-aid users (significance level $p < 0.05$). Friedman two-way analysis of variance by ranks followed by Dunn's multiple comparisons tests were used to determine any differences among conditions within the group of hearing-aid users and the group of normal-hearing participants (significance level $p < 0.05$).

RESULTS

Figures 3 and 4 show the median subjective occlusion ratings for the normal-hearing individuals and the hearing-aid users. The median subjective occlusion ratings followed

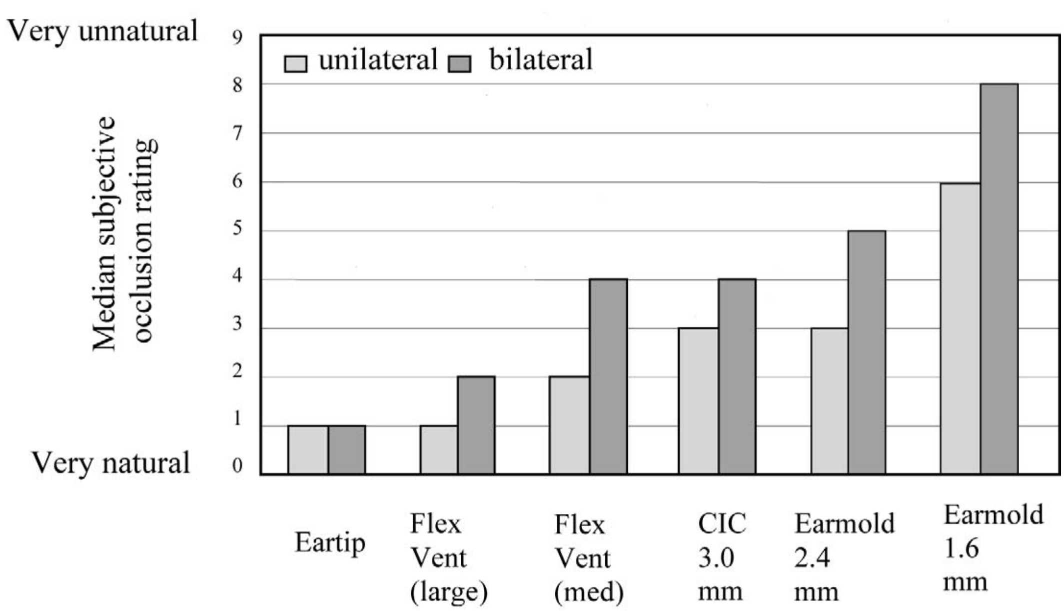

Figure 3. Median subjective occlusion in the unilateral and bilateral conditions for the various vent configurations for the normal-hearing listeners.

the same increasing trend for both the normal-hearing individuals and the hearing-aid users in both the unilateral and bilateral conditions. The lowest ratings were obtained for the silicone eartip, followed by the large FlexVent, the medium FlexVent, the CIC with 3.0 mm parallel vent, the conventional earmold with 2.4 mm parallel vent and the conventional earmold with 1.6 mm parallel vent. For the bilateral condition, the FlexVents resulted in significantly reduced subjective occlusion compared to the conventional earmolds with parallel vents with equivalent cross-sectional vent areas ($p < 0.01$). The silicone eartip yielded comparable results to the non-occluded condition and was rated significantly lower than any of the other configurations tested ($p < 0.01$).

Figures 5 and 6 present the individual subjective occlusion ratings in the bilateral condition as a function of the ratings in the unilateral condition. Ratings for the experienced hearing-aid users ranged from 0 to 7 with the different vent configurations in the unilateral condition and from 0 to 8 in the bilateral condition. The normal-hearing participants' ratings also ranged from 0 to 7 with the different vent configurations in the unilateral condition and from 0 to 9 in the bilateral condition. Both the normal-hearing individuals and the hearing-aid users rated their own voices as significantly ($p < 0.001$) more unnatural sounding for the pooled bilateral conditions than for the pooled unilateral conditions. The normal-hearing participants' median ratings in the bilateral condition were significantly higher ($p < 0.05$) than in the unilateral condition for all vent configurations except the silicone eartip. The hearing-aid users' median ratings in the bilateral condition were significantly higher ($p < 0.05$) than in the unilateral condition for all vent configurations except the silicone eartip and the traditional 2.4 mm vent.

The normal-hearing listeners and the hearing-aid users assigned similar occlusion ratings for the unilateral conditions, with no difference in median ratings. In the bilateral conditions, the median rating was 0.5 scaling units worse for the normal-hearing participants than for the hearing-aid users, which represented a significant difference ($p < 0.05$). Finally, we calculated the acoustic mass for each participant and each venting system used in this study based on the individual vent dimensions. A linear regression analysis of individual acoustic mass data (x) with perceived occlusion (y) results in a correlation according to the equation (Figure 7):

$$y = 1.42 * \mathrm{Ln}(x) - 7.04 \text{ with } r^2 = 0.493.$$

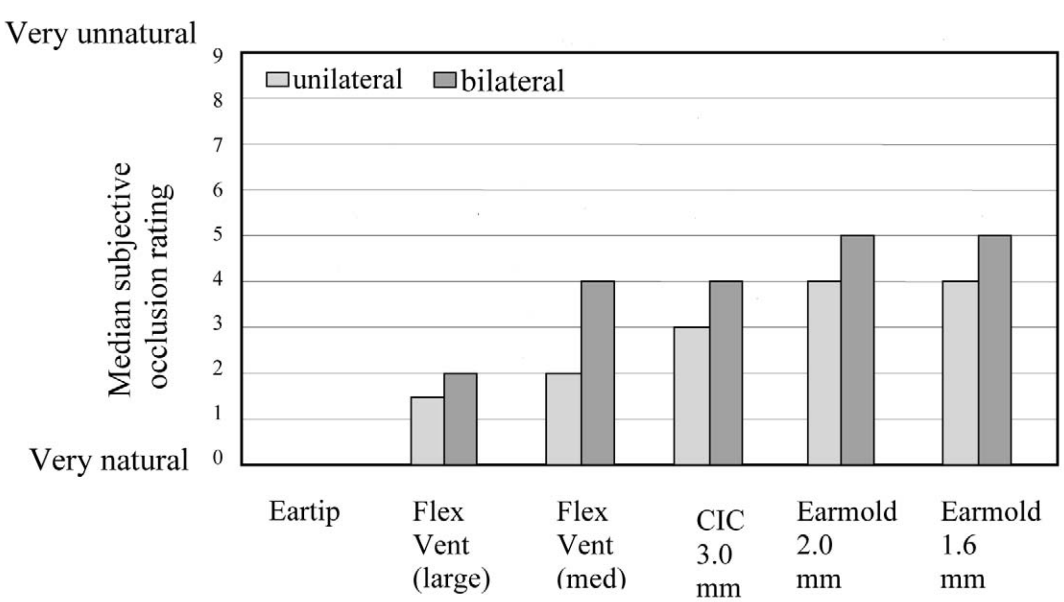

Figure 4. Median subjective occlusion in the unilateral and bilateral conditions for the various vent configurations for the hearing aid users.

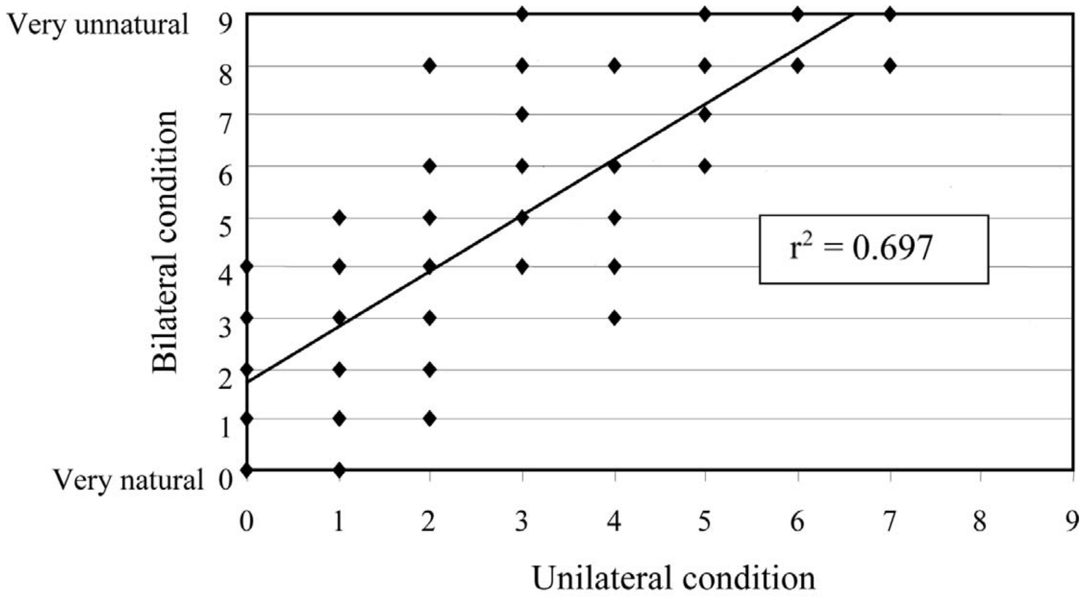

Figure 5. Individual subjective occlusion ratings in the bilateral condition as a function of ratings in the unilateral condition for the normal-hearing listeners.

DISCUSSION

In a previous study (Kiessling et al, 2005), we showed that bilateral open venting solutions resulted in significantly reduced objective occlusion effect as well as reduced subjective perception of occlusion for both hearing-aid users and normally hearing listeners. Both groups assigned similar ratings of subjective occlusion, and the severity of mean rated subjective occlusion was found to be predictable based on the acoustic mass associated with the particular vent. The present study replicated the findings that the vent configurations associated with lower acoustic mass were

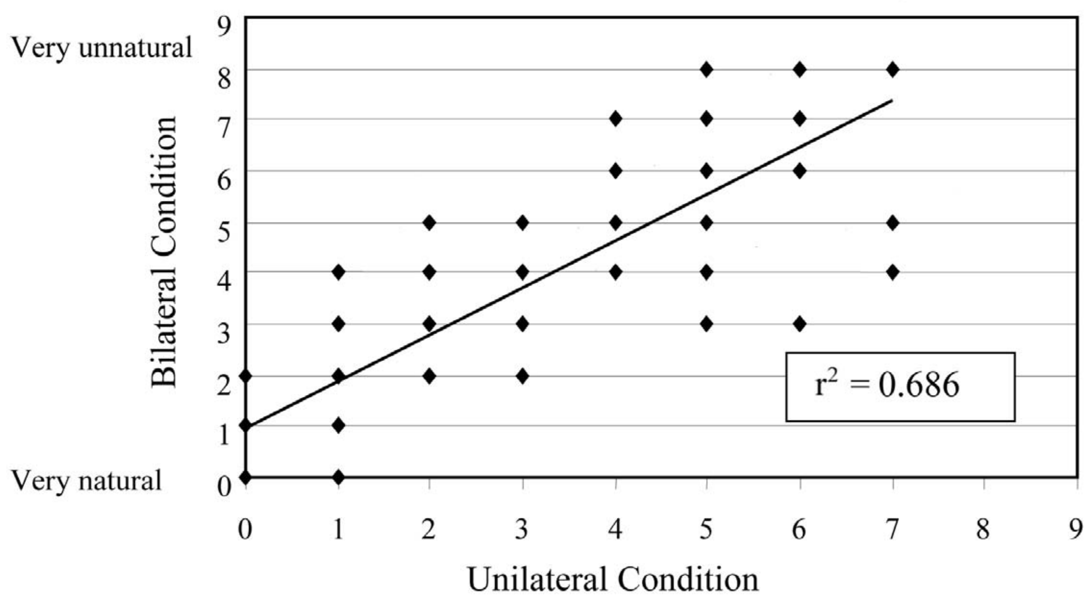

Figure 6. Individual subjective occlusion ratings in the bilateral condition as a function of ratings in the unilateral condition for the hearing aid users.

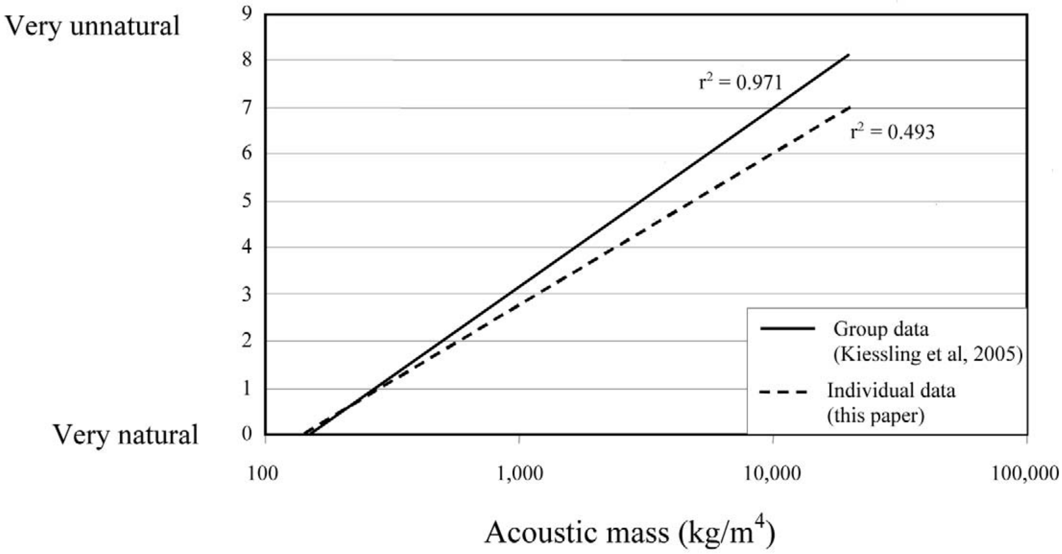

Figure 7. Linear regression analysis of perceived occlusion (y) versus individual acoustic mass data (x).

rated as giving less subjective occlusion. In addition, the significant reduction in subjective occlusion for the open vents holds true for a unilateral fitting, and the ratings for the unilateral condition followed the same pattern as for the bilateral condition.

The main objective of this investigation was to determine whether occluding both ear canals of individuals with good low-frequency hearing would result in worse subjective occlusion than occluding only one ear. The present results strongly support that this is the case. Both normal-hearing listeners and hearing-aid users rated their own voices as sounding significantly more unnatural when fitted with two earmolds or CIC hearing aids than when wearing just one. This held true for all venting configurations except the silicone eartip among the normal-hearing listeners, and for all venting configurations except the silicone eartip and the traditional 2.4 mm vent among the hearing-aid users. Both groups rated their own voice as sounding equivalent to unoccluded (corresponding to "very natural") when wearing either one or two silicone eartips. This is not surprising, as the silicone eartip has previously been shown to be non-occluding.

These findings support the idea that regular use of bilateral amplification could be promoted if hearing-aid users with mild-to-moderate sloping sensorineural hearing loss are provided with as open a fitting as possible. In fact, rated subjective occlusion in the bilateral condition for the most open configurations was actually less than in the unilateral condition for the traditional 1.6 mm vented earmold. From a practical standpoint, this means that hearing-aid users with good low-frequency hearing are likely to be more comfortable wearing two open-fitted hearing aids than only one conventionally fit hearing aid. While acoustic feedback has traditionally limited the application of open fittings, current hearing aids featuring acoustic feedback management based on phase cancellation allow fitting of high-frequency hearing losses up to 60 or 70 dB HL. Hearing aid fittings that maximize vent efficiency or that do not occlude the ear effectively remove a major objection to wearing aids for individuals with relatively good low-frequency hearing.

The normal-hearing listeners and the hearing-aid users were similar in their ratings of subjective occlusion in the unilateral conditions. However, the normal-hearing listeners rated subjective occlusion worse in the bilateral conditions than the hearing-aid users did. This finding is inconsistent with the results of our previous study in which both groups assigned similar ratings in the bilateral condition. One methodological difference that might explain this discrepancy was the fact that the listeners in Kiessling et al (2005) did not rate the unilateral conditions. Having this basis for comparison may have led the normal-hearing listeners to rate the bilateral conditions even worse than they otherwise would have. The hearing-aid-users' experience with occlusion of the ear canal may also have impacted their ratings. Although the variances are large in both groups, the degree of increase in rated occlusion for the bilateral condition was slightly more consistent and smaller for the hearing-aid users. Perhaps this was due to the normal-hearing subjects being less able to differentiate between the occlusion effect and the physical discomfort of having the ear canal occluded. The hearing-aid users may have been less prone to mix the physical sensation of having their ear canals blocked into the rating of their own voices. One way to help clarify the contribution to the subjective rating of occlusion of hearing loss versus experience with occlusion would be to carry out this test with hearing-impaired listeners who do not wear hearing aids and are not experienced with occlusion.

In this paper, we have revisited the correlation of perceived occlusion (y) with the acoustic mass of the vent (x). In our previous study (Kiessling et al, 2005) the strong correlation found between these two parameters led us to propose that subjective occlusion could be predicted by the geometric dimensions of the vent. In fact, the vent's acoustic mass appeared to be a better predictor of subjective occlusion than the measured occlusion effect. The correlation between measured occlusion effect and rating of subjective occlusion was found to be 0.461. In the present investigation, actual vent dimensions rather than group averages have been used to calculate the acoustic mass for each venting system. Interestingly, the resulting regression parameters are very similar for the two independent studies and approaches. For the present set of individual data, we obtained a correlation according to the equation:

$$y = 1.42 * \mathrm{Ln}(x) - 7.04$$

whereas in the previous paper we arrived at the equation

$$y = 1.65 * \mathrm{Ln}(x) - 8.25.$$

Both approaches provide almost the same mathematical basis to predict the amount of occlusion based on the vent dimensions. However, as expected, the coefficient of determination is considerably lower for individual data ($r^2 = 0.493$) compared to group data ($r^2 = 0.971$). While this supports our previous idea that subjective occlusion can be predicted based on the vent dimensions, it is with no more accuracy than measured occlusion effect. The main sources of error in predicting subjective occlusion are probably different for measured occlusion than for acoustic mass. The calculation of acoustic mass does not take into account any acoustic aspects of the fitting other than the vent itself. Thus, acoustic leakage around the earmold, which is likely to have a great effect on occlusion effect, is not reflected by such a calculation. Measured occlusion effect, on the other hand, takes all acoustic aspects of the fitting into account but is sensitive to measurement errors due to such factors as probe-tube placement and consistency of the listener's vocalization.

CONCLUSIONS

The subjective occlusion effect is significantly higher for bilateral hearing aids as compared to the occlusion effect with unilateral hearing aids for both the normal-hearing participants and the hearing-aid users, except for the non-occluding eartip, where no significant difference was found between the unilateral and bilateral condition.

- The FlexVent earmolds are significantly less occluding than parallel vents with equivalent cross-sectional vent area in both the unilateral and bilateral conditions.
- The soft silicone eartip provides a non-occluding hearing aid fitting in both the unilateral and bilateral condition.
- Less occlusion was perceived with bilaterally fitted large FlexVent earmolds and silicone eartips than with unilaterally fitted conventional earmolds with parallel venting for both normal-hearing listeners and hearing-aid users.
- Ratings of subjective occlusion for individuals with good low-frequency hearing can be predicted on the basis of acoustic mass with approximately the same degree of accuracy as predictions based on objective occlusion effect.

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