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Maximum Usable Real-Ear Insertion Gain with Ten Earmold Designs

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Abstract

The present study compared the maximum usable real-ear insertion gain (REIG) permitted by 10 earmold designs that varied in the amount of occlusion. These earmolds were coupled to a high-gain hearing aid (Phonak Super-Front PPCL). In addition, the specificity of a nonoccluding earmold for the Oticon E43 hearing aid was examined. Maximum usable REIG, defined as the insertion gain obtained with the hearing aid set to just below the point of acoustic feedback after jaw movement, was determined in 10 hearing-impaired subjects. The results showed that earmold style had a significant effect on the magnitude of maximum REIG. Among the occluding earmolds, no difference in REIG was noted among the shell, canal, and skeleton earmolds, while the standard earmold permitted the least amount of maximum REIG. For the nonoccluding earmolds, those that were more occluding permitted greater REIG than those that were less occluding. The amount of occlusion on a nonoccluding earmold affected the maximum REIG provided by the Oticon E43 hearing aid.

Key Words: Contralateral routing of signal (CROS), earmold, maximum usable real-ear insertion gain (REIG), nonoccluding earmold

Although the majority of hearing aids dispensed today are in-the-ear (ITE) hearing aids (Cranmer-Briskey, 1992), behind-the-ear (BTE) hearing aids are still the hearing aid of choice for many hearing-impaired individuals. These include children, individuals with severe-to-profound hearing loss, those with atypical ear canal geometry (e.g., tortuous ear canal, slit canal) or medical conditions of the ear canal (e.g., otitis externa, "wetness" of the ear canal, and enlarged ear cavity following a total mastoidectomy), and those who cannot tolerate the bulk of an ITE hearing aid. In addition, the complexity of signal-processing techniques utilized in some digital (not digitally programmable) hearing aids limits their use to a BTE style.

The successful use of a BTE hearing aid, in addition to its appropriate electroacoustic characteristics, is dependent largely on the choice of an appropriate earmold. Occluding earmolds that are too bulky may be more conspicuous, may increase the chance of physical discomfort, and may lead to rejection of the hearing aid. Earmolds with insufficient venting may increase the perception of hollowness of one's voice (Wimmer, 1986), increase insertion loss, and, in cases with recurrent otorrhea, increase the risk of infection of the ear canal. Kuk (1991) compared subject perception in listening and vocalization tasks between vented and unvented earmolds. The results showed that eight of nine subjects preferred the vented earmolds while vocalizing and when listening to passages of connected discourse. MacKenzie et al (1989) showed that hearing-impaired subjects reported significantly less sensation of being "blocked" with vented earmolds than with unvented earmolds, regardless of hearing loss.

The results of Kuk's (1991) and MacKenzie et al's (1989) studies suggest that vented and nonoccluding earmolds should be used whenever possible. In practice, this may not always be feasible. The maximum amount of usable gain is limited by the openness of the earmold. The greater the openness of an earmold, the greater the probability of acoustic feedback. An earmold should allow the user to achieve the desired insertion gain without experiencing a sensation of bulkiness or discomfort.

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Assuming that individuals with greater hearing loss require more gain than individuals with milder hearing loss, it is reasonable to conclude that the choice of the optimal earmold (i.e., style, bulk, and/or venting) depends on the individual hearing loss. Unfortunately, a systematic approach to choosing the optimal earmold is not available. The result is that audiologists may unknowingly fit individuals with earmolds that are more occluding than are necessary. This is seen in the preference for the more bulky shell or standard earmolds in comparison to the less bulky skeleton or canal earmolds for fitting moderately severe-to-profound hearing loss. Another observation is the use of the "helix lock" available on many earmold designs. So far, no evidence is available to support or refute these clinical decisions. Although these decisions may not affect the appropriateness of the selected frequency/gain response, it may result in unnecessary discomfort and prolong the adjustment period for a hearing aid. For example, the extra bulk in a standard earmold may result in an increased sensation of the ear being blocked. The presence of the helix lock may make it more difficult to correctly insert the earmold. It is important that these potential problems be resolved in order to achieve optimal hearing aid use. Wearer comfort, good sound quality, and the ease of insertion/removal of the earmold must be considered when choosing a specific earmold design.

This is a preliminary investigation to examine the effects of variations in earmold design on usable real-ear insertion gain (REIG). Specifically, the following questions are addressed. First, how would earmold design affect the magnitude of maximum usable REIG? Second, how would venting affect the magnitude of maximum REIG? Third, how would the additional features on an earmold, i.e., helix lock and crus, affect the magnitude of maximum REIG? Last, how would different nonoccluding earmolds compare to a specially designed nonoccluding earmold (Oticon E43) in permitting maximum usable REIG from a special-purpose high-frequency hearing aid (i.e., Oticon E43)?

METHOD

Subjects

Ten adult subjects (seven male and three female) participated in the study. Five had a moderate-to-severe sloping hearing loss, two had a moderately flat hearing loss, and three had no measurable hearing in one ear. All hearing losses were sensorineural in nature. All subjects had normal middle ear function as revealed by normal immittance measures (Grason-Stadler GSI-33). The ear was chosen for REIG measurement. The test ear was chosen arbitrarily in cases of symmetrical hearing loss.

Hearing Aids

Two hearing aids were used in this study. They were the Phonak Super-Front PPCL and the Oticon E43. The Phonak hearing aid was chosen because of its wide bandwidth and high gain (70-dB peak coupler gain), which made it ideal for studying the range of maximum usable REIG permissible by different earmold designs. Clinically, this hearing aid may be appropriate for individuals with a severe-to-profound hearing loss. The Oticon E43 was chosen in order to evaluate whether various nonoccluding earmolds can achieve the same insertion gain as its manufacturer's special-design earmold. This hearing aid has a peak coupler gain of 36 dB at 4000 Hz and is designed for individuals with normal hearing up to 2000 Hz and a precipitous hearing loss at 4000 Hz. The 2-cc coupler full-on gain curves of these hearing aids are shown in Figure 1.

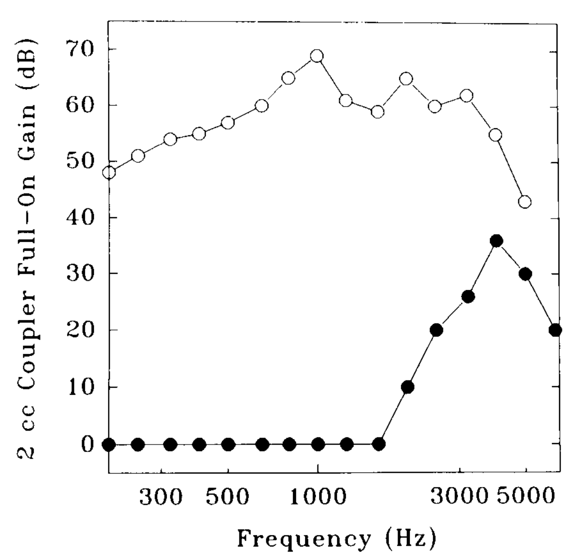

Figure 1 Two-cc coupler full-on gain curves for the Phonak Super-Front PPCL (open circle) and Oticon E43 (closed circle) hearing aids used in the study.

Earmolds

Ten different earmolds were made for each subject from the same silicon ear impression. While taking the earmold impression, subjects were asked to open and close their jaws twice while the impression material was setting up in the ear canal. This procedure may yield earmolds that can better accommodate changes in jaw position during daily activities such as chewing, yawning, and talking (Morgan, 1987). For a standard earmold at least, pilot data on three subjects showed that earmold impressions taken in this manner permitted the same (two of three subjects) if not more (one subject) maximum usable REIG than earmold impressions taken when the subject did not produce any jaw movement.

For all subjects, the length of the sound bore of the occluding earmolds from the tip to the lateral surface of earmold was approximately 23 mm for the standard earmold and 20 mm for the shell and skeleton earmolds. The length from the tip of the earmold to the first bend of the earmold was about 9 mm for all earmold designs. The manufacturer was instructed to fabricate the earmolds in its typical manner. Standard-size #13 tubing was used for coupling in all earmolds. A 3-mm sound bore opening, however, was used in all earmolds except for the tube earmold, where the sound-bore opening had the dimension of the #13 tubing (i.e., 1.93 mm diameter). All earmolds were lucite and were ordered with a secondary 2-mm vent for insertion of a probe tube during real-ear measurements. The different earmolds that were evaluated included:

1. *Standard* mold with helix lock (Westone #6 thick). The standard earmold is typically used with a snap ring for coupling to the receiver of a body aid or power BTEs via an adapter. In a pilot study with three subjects, it was found that the standard earmold with the snap ring permitted significantly less usable maximum REIG than the shell, canal, and skeleton earmolds. Because one of the purposes of the study was to evaluate the effect of bulk on maximum usable REIG, the use of a snap ring may introduce additional variables that could confound results. Consequently, standard #13 tubing was used in lieu of the snap ring in the evaluation. The entire concha region is filled in this earmold design.
2. *Shell* mold with helix lock (Westone #6). The concha bowl is filled, but with less bulk than the standard earmold.
3. *Canal* mold (Westone #4). Only the canal segment is filled. The entire concha remains open.
4. *Skeleton* mold with helix lock (Westone #2). The canal region is filled in addition to a concha rim to the helix region.
5. *Skeleton* mold without helix lock and with a parallel Select-A-Vent (SAV, Westone #2). Used with the SAV closed, as well as with pressure, 1-, 2-, and 3-mm diameter vent plugs.
6. *Skeleton* mold without helix lock and without crus. Used with the parallel SAV closed and with a 3-mm diameter vent plug.
7. *CROS* mold with extended canal (Westone #12). This mold is modified from a skeleton earmold with most of the lower half of the canal portion removed and an opening installed for venting. For all subjects, a 4-mm vent was used. This is also called "2HF" (Earmold Design), "#4 High Frequency" (Mid-States), and "Nonoccluding" (Emtech) mold by other earmold manufacturers.
8. *CROS* mold with a partial IROS vent (Westone #13). Similar to #7, except the canal region is shorter and the vent opening is enlarged by removing half the canal wall that forms the vent. This is also called "2HF," "#4 High Frequency," and "Nonoccluding #1."
9. *Tube* mold. The most nonoccluding earmold. A #13 tubing is used to couple the hearing aid on one end while the other end extends 10 mm medially into the ear canal.
10. *Oticon E43* earmold. Similar to the Westone #12 earmold except that it is made with stringent dimensions required by Oticon. For all subjects, the length of the sound bore was 18 mm and the diameter was 3 mm. In addition, a vent 10 mm long by 3 mm wide was included in this design.

The Oticon E43 earmold and the Westone #12 and #13 earmolds were modified from the skeleton earmold (SAV, no helix lock) after it has been evaluated. The earmold was modified to an E43 earmold first, then to a #12 earmold and finally to a #13 earmold. The Phonak Super-Front PPCL hearing aid was coupled to all but the Oticon E43 earmold. The Oticon E43 hearing aid was coupled to the nonoccluding earmolds and the E43 earmold. Subjects reported that all earmolds fit well and were comfortable.

Procedure

Maximum usable REIG for each earmold design was measured in an Industrial Acoustics Company (IAC) sound-treated booth. A Frye 6500 Real-Ear Analyzer was used to determine REIG. The stimulus was 65 dB SPL of speech-weighted noise presented from a loudspeaker placed at 45 degrees azimuth 18 inches from the side of the aided ear and at an elevation of approximately 45 degrees. This loudspeaker arrangement was reported to yield the most reliable measurements (Killion and Revit, 1987). Because maximum output from the Phonak hearing aid reaches 140 dB SPL, the real-ear analyzer was configured to allow measures up to 140 dB SPL. The default output limit of 120 dB SPL was used when the Oticon hearing aid was tested.

The depth of probe-tube insertion was held constant for all measures. This was ensured by estimating the length necessary for the tip of the probe tube to be 5 mm beyond the sound bore of the standard mold. The position of the probe tube at the lateral surface of the earmold was marked. The part of the pinna to which this mark corresponded was noted. In all subsequent measures, the probe tube was inserted so that the marker on the probe tube aligned with the pinna landmark. None of the subjects reported any physical discomfort with this depth of probe-tube insertion.

Subjects were instructed to avoid any movements during probe-tube measures. For each subject, the real-ear unaided response (REUR) was determined first. When measuring the real-ear aided response (REAR), the probe tube was inserted through the probe vent of the test earmold until the position of the marker aligned with the pinna landmark. The probe vent opening was then sealed with adhesive putty (Fun Tak™).

REAR was measured after jaw movements. In this condition, subjects were instructed to make facial grimaces and lower their jaws as much as they could. The volume control on the hearing aid was adjusted until feedback was heard by the tester and was then lowered slightly to eliminate the feedback. In addition, the experimenter moved the palm of his hand abut 3 inches from the microphone of the hearing aid. The volume control remained at this setting if no audible feedback occurred. The volume, however, was lowered to just below the point of any audible feedback if feedback was heard. The REAR was then obtained at this volume-control setting. The difference between REAR and REUR responses defined the maximum usable REIG permitted by the specific earmold.

The rationale for instructing subjects to move their jaws and make facial grimaces was to approximate real-life use of the earmolds. Typically, a hearing aid is most prone to feedback when any facial (or oral) movements dislodge the earmold from its resting position. Feedback paths may develop and the maximum usable gain will be limited.

The REUR was determined each time the REAR was measured for each earmold design. This was to avoid any artifacts due to inadvertent subject movement. Insertion gain was measured twice for each earmold design in order to obtain a stable measure. Only averaged data, however, are recorded. With the exception of nonoccluding earmolds, the order of earmold testing was counterbalanced across subjects. With the nonoccluding earmolds, the Oticon E43 earmold was tested first, followed by the Westone #12, Westone #13, and tube earmolds. The Phonak hearing aid was tested first.

RESULTS

The effects of earmold designs on the averaged maximum usable REIG are summarized in the following figures. Intersubject variations in REIG (i.e., standard deviations σ_{n-1}) measured at 250, 500, 1000, 2000, and 4000 Hz are shown at the bottom of each figure. The magnitude of the standard deviation measured at interoctave intervals is similar to those measured at octave intervals. The large intersubject variability probably resulted from differences in residual ear canal volume and resonance. Examination of individual data revealed that subjects with whom one measured large maximum REIG with one earmold design also showed large maximum REIG with another earmold design.

Effect of Concha Bulk

The maximum usable REIG permissible by the standard, shell, canal, and skeleton (with helix lock, crus, and no venting) earmolds when they were coupled to the Phonak Super-Front PPCL hearing aid is reported in Figure 2. The skeleton and shell earmolds permitted the greatest maximum usable REIG, followed by the canal and then the standard earmolds. The high-frequency average gain (average of 1, 1.6, and 2.5 kHz) was 44 dB for the skeleton and

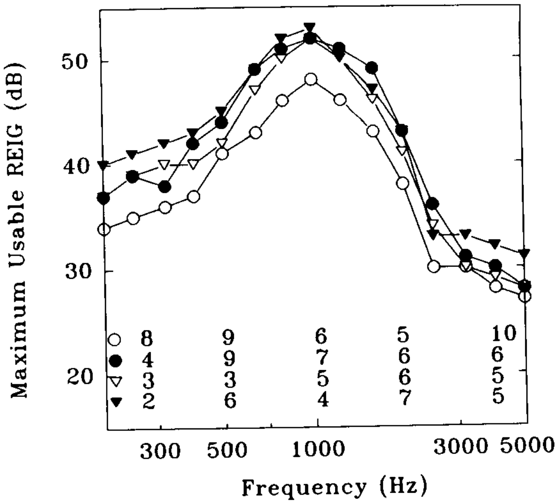

Figure 2 Maximum usable REIG permitted by the standard (open circle), shell (closed circle), canal (inverted open triangle), and skeleton (closed inverted triangle) earmolds (no vent). The magnitudes of the standard deviation (σ_{n-1}) for each earmold at 250, 500, 1000, 2000, and 4000 Hz are shown at the bottom of the figure.

canal earmolds, 46 dB for the shell earmold, and 40 dB for the standard earmold. An analysis of variance (ANOVA) test comparing the average gain at 250, 500, 1000, 2000, and 4000 Hz showed a significant difference in maximum usable REIG among the four earmold designs ($F[3, 39] = 6.3$, $p < .01$). A post-hoc Tukey test showed no significant difference in maximum usable REIG among the shell, canal, and skeleton earmolds. All three earmolds, however, permitted significantly higher usable REIG than the standard earmold ($p < .01$).

Although the mean maximum usable REIG for the skeleton, canal, and shell earmolds is similar, the intersubject variability in maximum REIG permitted by each earmold design is different. Figure 2 shows that the standard deviation associated with the shell and standard earmolds are higher than that associated with the canal and skeleton earmolds. This is especially seen in the lower-frequency region (below 500 Hz). This suggests that the maximum usable REIG provided by the standard and shell earmolds is less predictable than that permitted by the skeleton and canal earmolds. In addition, it suggests that the upper limit of usable REIG (i.e., +2 SD above the mean usable REIG) permitted by the standard earmold can be as high as, if not higher than, that permitted by the average skeleton, shell, or canal earmolds.

Effect of Venting

The maximum usable REIG from the Phonak Super-Front PPCL hearing aid when coupled to a skeleton earmold (without helix lock) with different SAV diameters is reported in Figure 3. Decrease in REIG is noted across all frequencies as vent size increases. The decrease, however, is more dominant for the lower frequencies than for the higher frequencies. The pressure vent, which is believed to produce negligible effect on maximum REIG (Skinner, 1988), resulted in a 1- to 6-dB decrease in maximum usable REIG in the lower frequencies. An ANOVA revealed a significant difference in REIG across the various vent sizes ($F [4,49] = 10.8$, $p < .01$).

Effect of Helix-Lock

Figure 4 shows the maximum usable REIG obtained with the Phonak hearing aid coupled to a skeleton earmold with and without the helix lock. A slight REIG advantage favoring the skeleton earmold with the helix lock is noted. The difference is not statistically significant, however ($t [df = 9] = 1.2$, $p > .01$).

This observation suggests that retaining the helix lock may not provide sufficient usable REIG advantage over the no-lock version to warrant its use. This observation, along with the complaint from some hearing-aid users that the presence of the helix lock makes it more

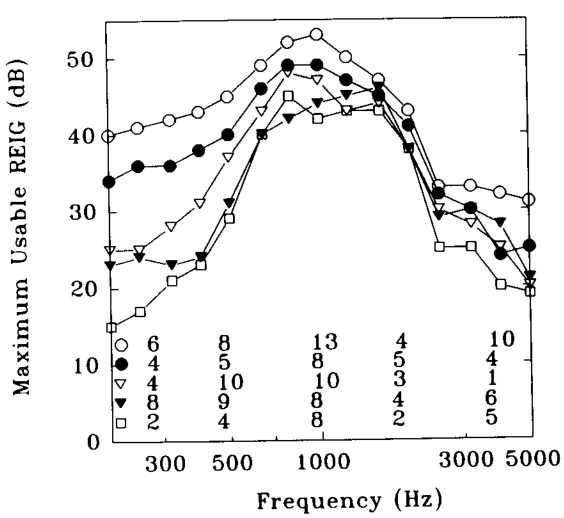

Figure 3 Maximum usable REIG permitted by the skeleton earmold with closed SAV (open circle), pressure vent (closed circle), 1-mm (open inverted triangle), 2-mm (closed inverted triangle), and 3-mm (open square) vents. The magnitudes of the standard deviation are shown at the bottom of the figure.

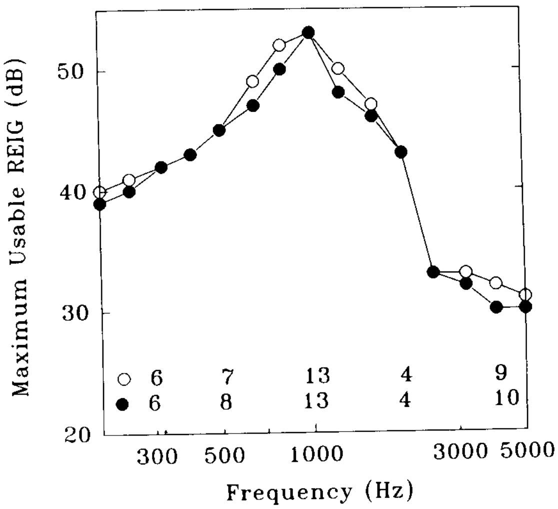

Figure 4 Maximum usable REIG permitted by the skeleton earmold with (open circle) and without (closed circle) the helix lock. The magnitudes of the standard deviation are shown at the bottom of the figure.

difficult to correctly insert the earmold, suggests that its retention may not be an effective approach to ensure maximum REIG.

Effect of Crus (Without Helix Lock)

Figure 5 shows the maximum usable REIG obtained with the Phonak hearing aid coupled to a skeleton earmold with and without the material in the crus region (between the helix and tragus). This comparison was performed because of potential irritations to some wearers.

A significant decrease (up to 10 dB) in maximum usable REIG was noted when the crus region was removed from a closed skeleton earmold (t [df = 9] = 7.3, $p < .01$). On the other hand, the effect of the crus was negligible (1–3 dB) when a vented skeleton earmold (3 mm) was compared. This suggests that the crus region on unvented earmold is important.

Maximum REIG with CROS Earmolds

Figure 6 shows the maximum usable REIG available from the Phonak Super-Front PPCL hearing aid when it was coupled to three nonoccluding earmolds. In general, maximum usable REIG decreases as the earmold becomes more nonoccluding. Despite the openness of these earmolds, as much as 40 dB of insertion gain was observed at 1600 Hz when this aid was coupled to the #12 earmold and 30 dB of insertion gain was observed at 2000 Hz for the #13 earmold. High-frequency average REIGs for the #12, #13, and tube earmolds were 33 dB, 27 dB, and 19 dB, respectively. An ANOVA also revealed statistically significant differences (F [2,29] = 39.5, $p < .01$).

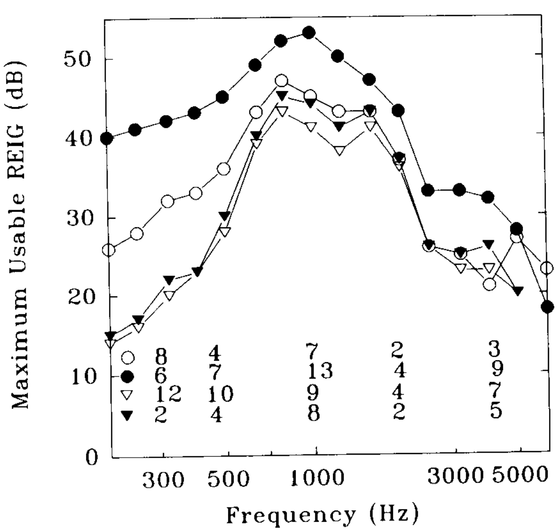

Figure 5 Maximum usable REIG permitted by the skeleton earmold modified in four manners: with crus and SAV closed (closed circle), with crus and 3-mm vent (closed inverted triangle), without crus and SAV closed (open circle), and without crus and 3-mm vent (open inverted triangle). The magnitudes of the standard deviation are shown.

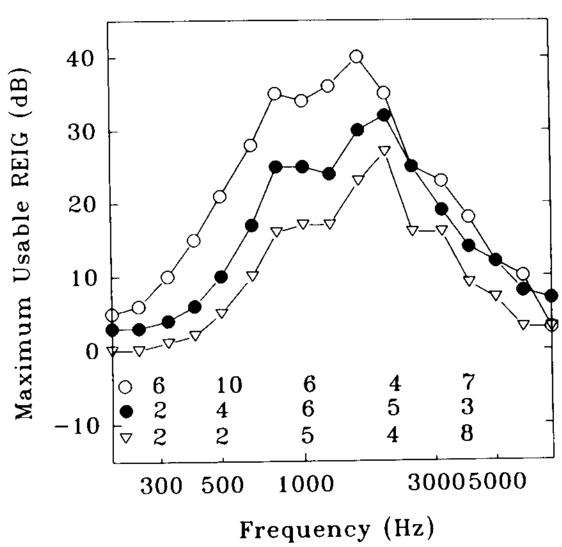

Figure 6 Maximum usable REIG permitted by three nonoccluding earmolds (Westone #12: open circle, Westone #13: closed circle, and Tube earmold: open inverted triangle) coupled to a Phonak Super-Front PPCL hearing aid. The magnitudes of the standard deviation are shown.

Specificity of CROS Earmold for the Oticon E43

Figure 7 summarizes the maximum usable REIG for all three nonoccluding and the Oticon earmolds when they were coupled to the Oticon E43 hearing aid. None of them revealed any appreciable REIG below 2000 Hz. The Oticon earmold, as well as all three CROS earmolds, revealed peak REIG at 5000 Hz. Mean peak REIG was 32 dB for the Oticon and the Westone #12 earmolds. The maximum usable REIG, however, was only 24 dB for the Westone #13 earmold and 17 dB for the tube earmold. Clearly, earmold designs could significantly affect the outcome of the fitting.

DISCUSSION

The present study compared maximum usable REIG permitted by 10 earmold designs. The results suggest that earmold style could limit the amount of maximum usable REIG available from a hearing aid. The optimal earmold must be chosen based on consideration of the wearer's hearing loss and how the earmold would provide optimal physical fit, comfort, and sound quality.

One outcome of the study is that bulkier earmolds do not guarantee greater REIG than earmolds that are less bulky. It is shown in this study that the less bulky canal and skeleton earmolds permitted as much REIG as the shell earmold, and that the shell, skeleton, and canal earmolds permitted more REIG than the standard earmold. This is also true in the case of the helix lock, where no REIG advantage was noted with the lock. Perhaps the increased earmold surface in the standard earmold and in the earmold with the helix lock also increased its likelihood of being dislodged during jaw movements.

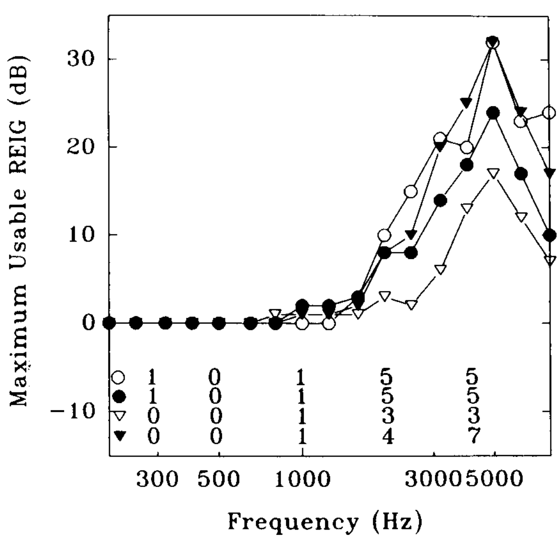

Figure 7 Maximum usable REIG permitted by four nonoccluding earmolds (Westone #12: open circle, Westone #13: closed circle, Tube: open inverted triangle, and Oticon E43: closed inverted triangle) coupled to the Oticon E43 hearing aid. The magnitudes of the standard deviation are shown.

These findings point to the importance of optimal bulk in an earmold. In addition, they illustrate the contribution that the canal portion in an earmold makes to maximum usable REIG and further reinforce the importance of an accurate earmold impression. Inaccuracy in the impression will limit the amount of usable REIG from a hearing aid and such deficiency may not be compensated fully by ordering a bulkier earmold (e.g., standard).

The comparison on the three nonoccluding earmolds showed that the Westone #12 earmold allowed more REIG than the other two earmolds. Using the NAL-R formula (Byrne and Dillon, 1986), the use of this earmold (#12) can be extended to individuals with up to a moderate degree of hearing loss (up to 50 dB) in the mid-frequency region. This may be helpful for individuals with existing medical condition of the external ear canal (e.g., external otitis, itchy ears), those who cannot tolerate a "plugged" ear sensation, or those who exhibit a strong occlusion effect with hearing-aid use.

Although all three nonoccluding earmolds used in this study are used in a CROS fitting, they differ in their effectiveness in achieving their goal. Two considerations are necessary in such fittings. One is that the earmold must not result in large insertion loss to affect hearing sensitivity of the normal ear. The other is that the earmold should permit only minimal gain because of the normal hearing in the ear receiving amplification. Examination of Figure 6 shows that the tube earmold would be the best choice for a CROS fitting. In addition to minimal occlusion, this earmold permits the least amount of usable gain from a hearing aid, thus minimizing the chance of overamplification. The Westone #12 earmold may be the poorest choice for a CROS (but not necessarily BiCROS) fitting.

Most clinicians can agree that the best earmold is one that delivers the target amount of amplification while allowing for comfort and freedom from the sensation of the ear being occluded. Indeed, if a tube fitting can accommodate the target gain for all magnitudes of hearing loss, it may be the earmold of choice for every hearing-aid wearer. Unfortunately, the limited usable gain permitted by this earmold design forces one to seek earmolds that represent a compromise between openness and maximum usable REIG.

The information revealed in this study may provide some guidelines in the selection of optimal earmold option. Several caveats, however, are necessary in using such information. First, these results were determined with an accurate earmold impression and by a manufacturer that has faithfully fabricated the desired earmold. Similar assumptions must be met when making individual predictions based on these results. Second, the data are based on 10 subjects and may not account for every individual variation that one may encounter. Differences in canal geometry, residual volume between the tympanum and the canal tip of the earmold, seal of the earmold, and immittance characteristics of the tympanum and middle ear could affect the maximum usable insertion gain. Such considerations must be taken, especially in view of the large intersubject variability seen in this study. Third, the present data are derived from a wide bandwidth, single-channel, high-gain hearing aid. Maximum usable REIG at one frequency region is dependent on maximum usable REIG at other frequency regions. Its values would likely change as a different hearing aid, a different frequency response, or even a different earmold tubing is used. This is evidenced by the change in maximum usable REIG values with the #12 earmold as the Oticon hearing aid replaced the Phonak hearing aid (Figs. 6 and 7).

In summary, the following conclusions can be drawn from this study. First, contrary to conventional beliefs, bulk in an earmold beyond that occupied in the canal region may not increase the maximum usable REIG permitted by the earmold. Second, modifications to an earmold have specific effects on maximum usable REIG. Venting, even as small as a pressure vent, reduces maximum usable REIG. Removal of the helix lock, or of the crus region on a skeleton earmold that has a 3-mm parallel vent, results in minimal change in maximum usable REIG. On the other hand, removing the crus region from a closed skeleton earmold may result in significant usable REIG reduction. Third, different designs of nonoccluding (or CROS) earmolds permit different amounts of maximum usable REIG. This information is important in the choice of nonoccluding earmolds for fitting specialized hearing aids (e.g., Oticon E43), for specialized fitting (e.g., CROS fitting), and for medically complicated ears (e.g., draining ears). Proper choice of earmold design is important.

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