

Coupling of FM Systems to Individuals With Unilateral Hearing Loss

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This study examined the attenuation characteristics of five FM system sound delivery options for a group of 10 adults and 15 children (5-13 years). Sound delivery options included a tube-fitting, lightweight headphones, a CROS earmold with tubing, a CROS earmold with a snap-ring, and a standard snap-ring earmold with a vent. Attenuation was defined as the difference between probe-tube microphone measures of the ear canal resonance and the SPL in the ear canal with each sound delivery option in place. A statistically significant but clinically inconsequential difference in attenuation for the CROS earmold with tubing was noted between adults and children. No significant differences in attenuation for any of the other sound delivery options were noted between adults and children. An investigation of the relationship between magnitude of attenuation and percentage of the ear canal occluded suggests that degree of occlusion is a major factor in determining degree of attenuation provided by a particular sound delivery option. Results also indicate that significant attenuation of high-frequency signals can occur with earmolds commonly considered nonoccluding. Caution should be used in fitting hearing aids or FM systems to individuals with normal high-frequency hearing sensitivity to prevent attenuation of unamplified high-frequency speech information.

KEY WORDS: unilateral hearing loss, FM systems, amplification

Until recently it was assumed that unilateral hearing loss did not have a detrimental effect on the academic performance of school-age children. Consequently, audiological management of unilaterally hearing-impaired children consisted of preferential seating and annual monitoring of hearing and middle-ear status. However, some investigations have indicated that 24-35% of children with unilateral hearing impairment fail at least one grade in their elementary school years (Bess & Tharpe, 1986; Oyler, Oyler, & Matkin, 1988).

The audiological management of children with unilateral hearing loss is often complicated by the fact that the impaired ear is unaidable because of degree of hearing loss, poor speech perception ability, or a limited dynamic range. In an attempt to prevent academic difficulties that may be related to the hearing loss, some investigators have suggested the use of FM systems with this population (Bess, Klee, & Culbertson, 1986; Kenworthy, Klee, & Tharpe, 1990). An FM system is a wireless amplification system that uses an FM radio signal to broadcast the speech signal directly from the teacher's transmitter to the student's receiver. For the unilaterally hearing-impaired child, the FM system is intended to improve the signal-to-noise ratio for the normally hearing ear. However, the manner in which an FM system is coupled to the ear is critical because the child needs to hear other students to follow classroom discussions, question/answer sessions, and other group interactions. In the case of a child with a unilateral hearing loss, a nonoccluding sound delivery option is desirable because partial or complete occlusion of the ear canal will affect the audibility of unamplified signals.

Several sound delivery options are available for fitting an FM system to a normally hearing ear. Two commonly used options are standard snap-ring earmolds with large vents and lightweight headphones. Because the standard earmold presumably occludes the entire ear canal, it attenuates unamplified signals and thus is acoustically undesirable. The lightweight headphones are assumed to be nonoccluding and thus may be more desirable from an acoustic standpoint. However, headphones may be distracting for young children and uncomfortable when worn for long periods, and they are an unstable coupling method for an active child. Other sound delivery options that may be considered are a tube-fitting or a CROS earmold that can be fit with either a snap-ring or tubing. Because children have smaller ear canals than adults, it is possible that sound delivery options that would be considered nonoccluding in adults might be occluding in children.

This investigation was designed to examine the attenuation characteristics of sound delivery options that provided different degrees of ear canal occlusion in a group of adults and school-age children. In addition, we attempted to quantify the degree of occlusion of certain earmolds and correlated those estimates with their respective attenuation characteristics.

Methods

Subjects

Ten adults (ages 20–50 years) and 15 children (ages 5–13 years) served as subjects in this investigation. The children were divided equally among three age groups as follows: 5–7 years ($M = 5.6$), 8–10 years ($M = 9.0$) and 11–13 years ($M = 11.4$). All subjects demonstrated normal middle-ear function by acoustic immittance measures and had ear canals free of cerumen.

Earmolds

Two ear impressions of the same ear were obtained for each subject. One was used to calculate a cross-sectional area of the ear canal and the other to fabricate the earmolds illustrated in Figure 1 as sound delivery Options 3–5. Sound delivery Options 1–4 were used for the adults, and Options 1–5 were used for the children. All earmolds were constructed of a soft, polyvinylchloride material. For the tube-fitting, standard #13 (outer diameter = 2.95 mm) tubing was used. No specific instructions regarding earmold dimensions were conveyed to the manufacturer. As a result, the earmolds represent variations typically encountered in clinical practice.

Procedure

Immediately prior to testing, acoustic immittance measures using a 226-Hz probe tone were obtained to rule out abnormal middle-ear function. Testing was postponed if the middle-ear pressure was less than -150 da Pa or the static

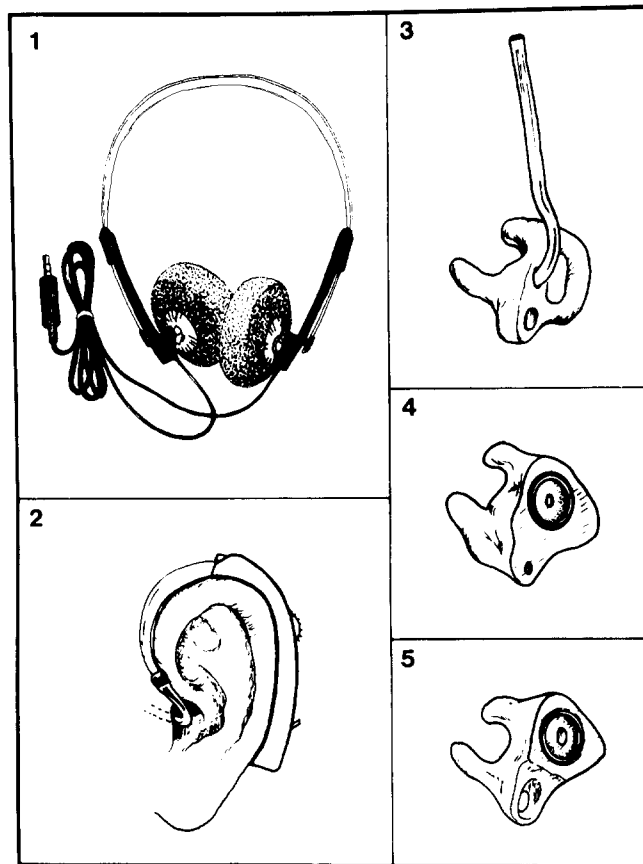


FIGURE 1. Attenuation characteristics were measured for the following sound delivery options: 1—lightweight headphones; 2—tube-fitting; 3—CROS earmold with tubing; 4—snap-ring earmold with a vent; and 5—CROS earmold with a snap-ring. Options 1–4 were used for the adults, and Options 1–5 were used for the children.

(compensated) acoustic immittance measures fell outside the range of normative values suggested by Margolis and Heller (1987). These normative values for the children were developed on a slightly younger age group than the children participating in this study. To investigate the potential relationship between acoustic immittance measures of ear canal volume and the magnitude of attenuation for each earmold, a measure of equivalent ear canal volume was obtained at -200 da Pa.

A clinical probe-tube microphone system (Fonix 6500) was used to calculate the attenuation characteristics of each sound delivery option. The loudspeaker was positioned 45° both horizontally and vertically relative to the test ear. The probe tube was inserted a minimum depth of 10 mm from the entrance to the ear canal for the children and 15 mm for the adults and was always at least 4 mm beyond the end of the earmold. To provide an adequate measurement range above the noise floor of the system, a 90-dB SPL swept pure-tone input (100–8000 Hz) was used for all measures.

During testing, the snap-ring earmolds were coupled to a dummy receiver, and the tubing in all other earmolds was plugged with a putty-like material. Prior to occluded measures, an ear canal resonance was obtained. For each of the

sound delivery options, the ear canal SPL was recorded for a 90-dB SPL swept pure-tone input. After each sound delivery option was evaluated, the ear canal resonance was repeated to ensure that the probe tube had not shifted during placement and removal of the earmold or headphones. The difference between the ear canal resonance and the ear canal SPL in each occluded condition was taken as a measure of attenuation. The following frequencies (in Hz) were used in the subsequent data analysis:

200	1800	2700	3900
500	2000	3000	4000
700	2100	3300	4200
1000	2400	3600	6000
1500			

Cross-Sectional Area Computation

The cross-sectional area of each subject's ear canal was calculated using one of the ear impressions. The ear impression was sectioned 5 mm medial to a point corresponding to the entrance to the ear canal. A print of the cross-section of the ear impression was made by covering it with ink and applying it to paper. A hand-held scanner was used to digitize the print with a scan resolution of 200 dots/in. (dpi). The digitized image was displayed on a computer screen, and the magnified version was edited to smooth irregularities along the edges of the print. The cross-sectional area was computed by counting the number of dots in the digitized image,

dividing by the dpi^2 and converting to cm^2 . The same procedure was followed to obtain the cross-sectional area of the CROS earmold with tubing. The cross-sectional area of the #13 tubing used for the tube-fitting was computed arithmetically on the basis of the outer diameter.

Results and Discussion

Effects of Sound Delivery Options

For the adults, the relationship between attenuation and frequency for the four sound delivery options is shown in Figure 2. The ordinate represents the difference in dB between the ear canal resonance and the ear canal SPL with each sound delivery option in place. Negative values represent attenuation relative to the open-ear response. The error bars represent one standard deviation above and below the mean. For all sound delivery options except the tube-fitting, the magnitude of attenuation increases with frequency. In all cases, the intersubject variability increases as a function of frequency. Also, greater attenuation is noted as the sound delivery option becomes more occluding. The least occluding option (tube-fitting) causes almost no attenuation across frequencies. For the lightweight headphones, less than 5 dB is attenuated through 4 kHz. The attenuation seen at the higher frequencies for this sound delivery option may be due to a loss of the concha resonance, which provides approxi-

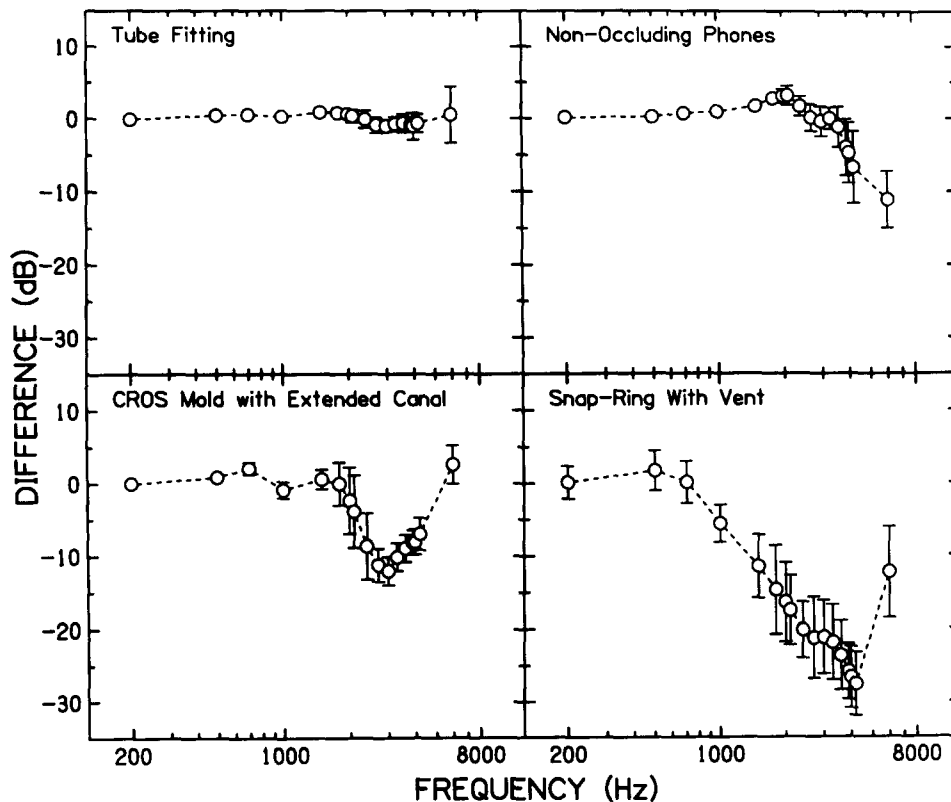


FIGURE 2. Relationship between attenuation and frequency for four sound delivery options for 10 adults. Attenuation is represented by the dB difference between the ear canal resonance with and without the sound delivery option in place. Negative values indicate greater attenuation. The error bars represent one standard deviation above and below the mean.

mately 10 dB of gain in the 4–6 kHz range (Shaw, 1980). For the CROS earmold, which is commonly considered to be nonoccluding, the mean attenuation increases to a maximum of 12 dB (range 9–19 dB) at 3 kHz and then decreases. As we expected, the snap-ring earmold with vent produces the greatest mean attenuation, increasing to a maximum of 27 dB at 4.2 kHz. A previous investigation reported similar results for occluding earmolds (Nielsen, Nielsen, & Nielsen, 1986). The difference in magnitude of attenuation between the latter two earmolds is notable. On average, only a portion of the ear canal resonance was lost with the CROS earmold. For many subjects, the attenuation from the snap-ring earmold was actually greater than the ear canal resonance and as much as 35 dB for some individuals.

In Figure 3, the relationship between attenuation and frequency for the same four sound delivery options is shown for the children. The parameter in each panel is age group. Although standard deviations are not shown, they were comparable to adult values. The patterns observed for the children are similar to those seen in the previous figure. That is, mean attenuation increases with frequency and with the degree of sound delivery option occlusion. Furthermore, the patterns observed for all three age groups are similar.

The attenuation characteristics of a CROS earmold with tubing compared to a CROS earmold with a snap-ring for the children are shown in Figure 4. Each panel represents a different age group. Only small differences are noted be-

tween the two types of CROS earmolds except at 6 kHz in the two younger age groups.

For the children's data, a three-way ANOVA revealed no significant main effect for age [$F(2, 12) = .79, p > .47$] but, as we expected, significant main effects for sound delivery option [$F(4, 48) = 70.84, p < .00005$] and frequency [$F(16, 192) = 90.43, p < .00005$]. In addition, there was a significant coupling by frequency interaction [$F(64, 768) = 31.86, p < .00005$] but a nonsignificant coupling by age interaction [$F(8, 48) = 1.37, p > .25$], a nonsignificant frequency by age interaction [$F(32, 192) = 1.60, p > .11$], and a nonsignificant three-way interaction [$F(128, 768) = 1.21, p > .19$].

Adults Versus Children

The mean data from both children and adults are reported in Figure 5 for comparative purposes. The children's data were collapsed across age because no significant differences were noted between groups. Only small differences are noted between adults and children for all sound delivery options. The results of a three-way ANOVA revealed a nonsignificant main effect for group [$F(1, 23) = 2.09, p > .16$] but, as we expected, significant main effects for frequency ($F(16, 368) = 146.92, p < .00005$) and sound delivery option [$F(3, 69) = 194.07, p < .00005$]. There was a significant coupling by frequency interaction [$F(48, 1104) = 71.29, p < .00005$], and a significant coupling by group interaction [$F(3,$

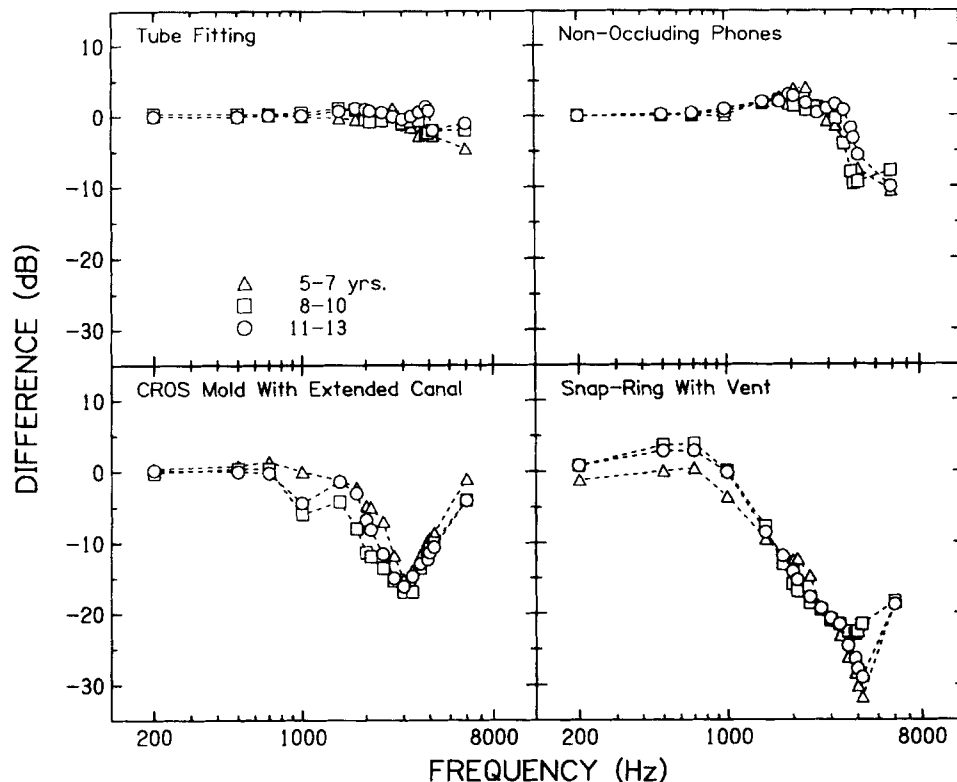


FIGURE 3. Relationship between attenuation and frequency for four sound delivery options for 15 children. The open triangles represent data for 5 children ages 5–7 years, open squares data for 5 children ages 8–10 years, and open circles data for 5 children ages 11–13 years. Attenuation was calculated as for Figure 1.

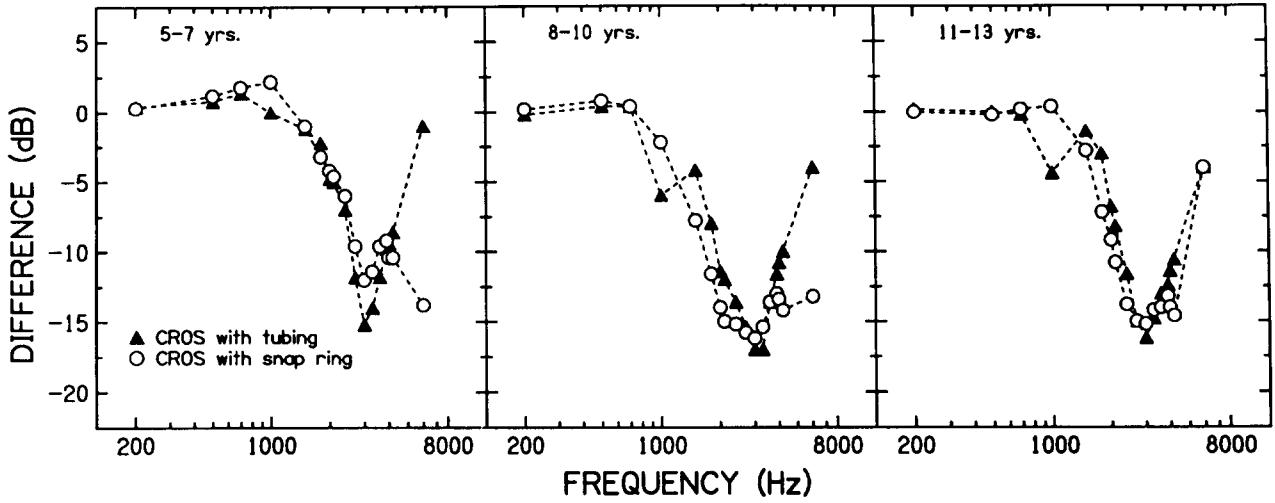


FIGURE 4. Relationship between attenuation and frequency for two sound delivery options for children only. Each panel represents a different age group. The filled triangles represent data for the CROS earmold with tubing, and open circles represent data for the CROS earmold with a snap ring.

69) = 3.09, $p < .0480$]. In addition, there was a nonsignificant frequency by group interaction [$F(16, 368) = 1.92, p > .09$] and a nonsignificant three-way interaction [$F(48, 1104) = 1.60, p > .08$]. For the significant coupling by group interaction, each of the sound delivery options was examined separately. Only the CROS earmold had a statistically significant difference between adults and children. This differ-

ence was 3 dB collapsed across frequency, a clinically nonsignificant difference.

Degree of Ear Canal Occlusion

Because the method used to estimate degree of occlusion in this experiment has not been reported previously, the

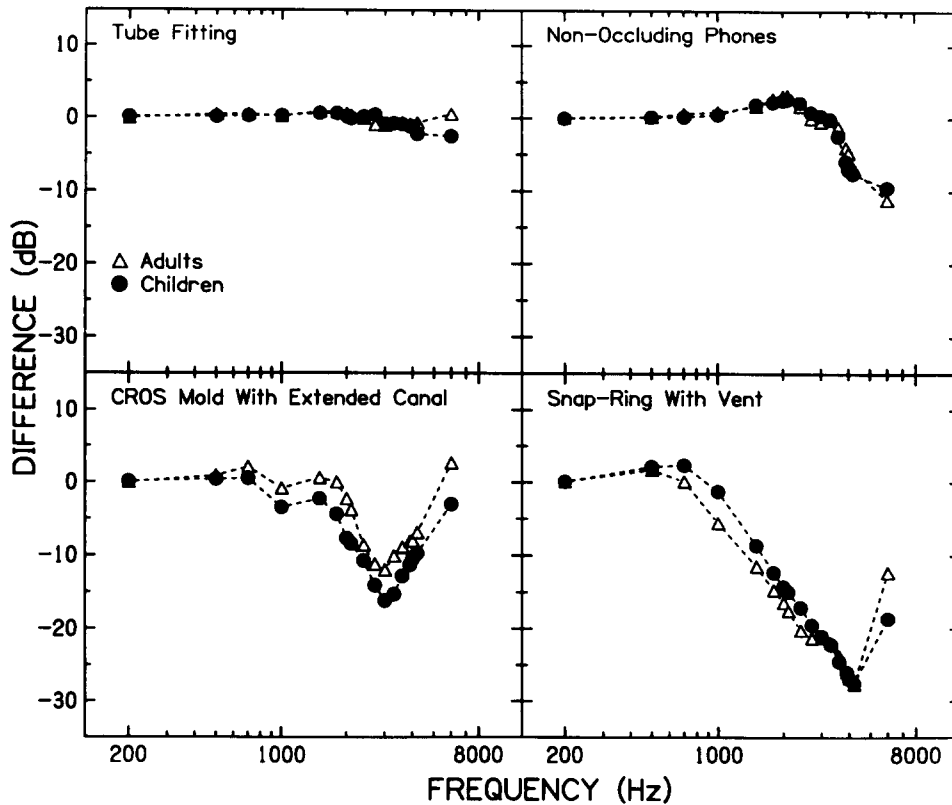


FIGURE 5. Relationship between attenuation and frequency for four sound delivery options for all subjects. Open triangles represent data for the adults, and filled circles represent data for the children.

measurement error associated with each phase of the procedure was estimated and is shown in Table 1. The error between impressions was derived by obtaining five impressions from 1 subject. Each impression was cut, and a print was made of the cross-section. The print was scanned and edited, and the area was computed. Thus, this estimate of variability included all sources of within-subject measurement error. The mean area across the five trials was .4805 cm² with a standard deviation of .019 cm², suggesting excellent repeatability. The error between prints was derived from obtaining five prints from one impression. Each print was scanned and edited and the area computed. This standard deviation was slightly lower ($SD = .016$ cm²), presumably because two sources of variance (impression and cutting) were eliminated. Finally, the scanning error was estimated by obtaining five scans from one print. In this case, the standard deviation was extremely small ($SD = .001$ cm²). These results suggest that the method used to estimate the cross-sectional area of the ear canal and the CROS earmold was reliable.

It is more difficult to address the issue of validity with respect to the goal of estimating degree of occlusion because alternative methods of estimation have not been developed. Because the shape and diameter of the ear canal are not uniform along its entire length, the *estimated* cross-sectional area will vary depending on where the measurement is made. The decision to measure the cross-sectional area 5 mm medial to the position of the entrance to the ear canal was made arbitrarily to provide uniformity across individuals. It is possible that another location may have provided more valid results.

With this limitation in mind, the percentage of occlusion was calculated from the ratio of the earmold cross-sectional area to the ear canal impression cross-sectional area. To determine whether the magnitude of attenuation could be predicted from the degree of ear canal occlusion, the adults' and children's data were combined, and for each subject, degree of occlusion was computed for both the CROS earmold and the tube-fitting. The mean attenuation was computed across the frequency range 2.4-4.2 kHz, the frequencies that were affected most by the occlusion of the ear canal. The results are shown in Figure 6, where the mean difference between the ear canal resonance and the occluded response is plotted as a function of the percentage of the ear canal occlusion. The solid line represents a line of best fit to the data. In general, as the percentage of occlusion increases, the magnitude of attenuation also increases. In addition, if less than 30% of the ear canal is occluded, attenuation is less than 3 dB. A correlation coefficient was computed for the relationship between degree of occlusion

TABLE 1. Variability associated with the earmold area measurements.

Phase	M (cm ²)	SD (cm ²)
Phase 1—ear impression, print, and scan	.4805	.019
Phase 2—print and scan	.4717	.016
Phase 3—scan	.4704	.001

Note. This table shows test-retest reliability associated with each phase of the procedure used to calculate the area of the ear canal.

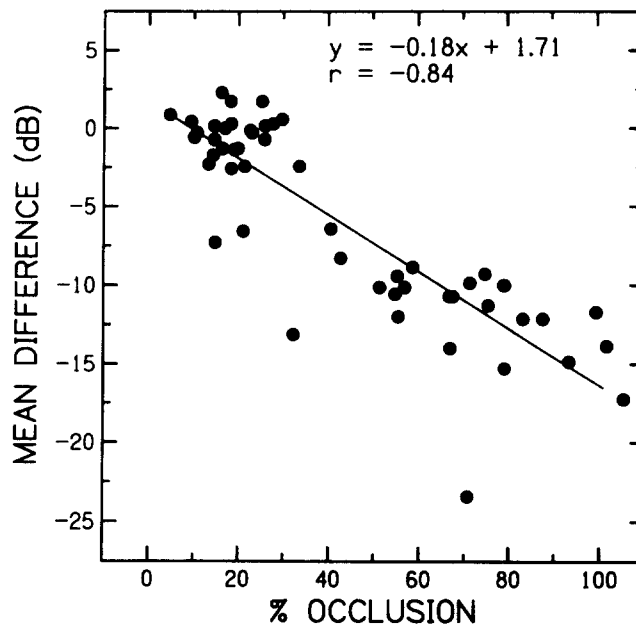


FIGURE 6. Relationship between attenuation and percentage of ear canal occlusion for 10 adults and 15 children. Attenuation is represented by the mean difference averaged across the frequencies 2.4-4.2 kHz. The solid line represents a line of best fit to the data.

and attenuation. The resulting correlation of $-.84$ suggests that degree of occlusion is a major factor in determining the degree of attenuation provided by a particular sound delivery option.

We were concerned that smaller ear canal size in children might yield higher degrees of occlusion than for adults. To investigate this possibility, a correlation coefficient was computed between attenuation with the CROS earmold with tubing and cross-sectional area of the ear canal. The correlation was .75, suggesting that cross-sectional area does play a major role in determining the magnitude of attenuation. Similarly, a correlation coefficient was computed for the relationship between attenuation with the CROS earmold with tubing and acoustic immittance measures of the ear canal volume. The correlation was low ($r = .29$), indicating that ear canal volume as measured by acoustic immittance did not account for a large portion of the variance. On the basis of these data, we can say that absolute ear canal size does play a major role in determining attenuation provided by a CROS earmold with tubing, whereas acoustic immittance measures of ear canal volume do not. These findings suggest that cross-sectional area and immittance measures of ear canal volume are not closely related, a fact further supported by the low correlation between cross-sectional area and immittance ear canal volume measures ($r = .41$) for our sample.

Clinical Implications

For a child with unilateral hearing impairment, the most *acoustically* appropriate sound delivery option for an FM system is the tube-fitting. Although it is possible to couple an

FM system with a behind-the-ear (BTE) receiver to a tube-fitting, some individuals report that this arrangement is uncomfortable. In addition, the FM systems available in many schools may not be compatible with BTE receivers. In these cases, the next most favorable option is the lightweight headphones. For those children who cannot wear headphones for practical reasons, the CROS-style earmold would provide the best practical and acoustic compromise. Because a CROS earmold with tubing and a CROS earmold with a snap-ring appear to produce similar attenuation characteristics below 6 kHz, either option may be used, depending on the specific FM system available. This option will provide the least attenuation of unamplified signals for children who cannot wear lightweight headphones, but it is important to remember that unamplified speech will be attenuated by approximately 12 dB in the high frequencies. This may not be a problem for the child with very good hearing in the better ear, but it may pose considerable difficulties for a child with borderline normal or very mild hearing loss for the high frequencies. For these children, it is essential to consider the most nonoccluding option first. For children who must be fit with a CROS earmold, real-ear measurements of attenuation should be made. If the FM system has an environmental microphone, it may be used to compensate for this attenuation. If the FM system does not have an environmental microphone, classroom performance should be closely monitored to determine whether these children are having difficulty following classroom interactions.

The results of this investigation also may have significant implications for hearing-aid fittings for individuals with low-frequency hearing loss and normal hearing sensitivity in the high frequencies. Many of these individuals are fit with low-pass hearing aids with no amplification in the high frequencies. If a standard earmold is used, incoming signals may be attenuated an average of 27 dB in the region of normal hearing. Even with a CROS earmold, high-frequency signals may be attenuated by 12 dB or more. When fitting hearing aids for these individuals, real-ear measurements of the amount of attenuation with the chosen sound delivery option should be performed. If necessary, adjustments in the earmold or gain of the instrument can be made to compensate for this attenuation.

Summary

In summary, the results of this study reveal that the tube-fitting is the only option that is truly nonoccluding. The lightweight headphones used in this study did not produce more than 5 dB of attenuation through 4000 Hz. The CROS earmolds and the vented snap-ring earmold produced substantial amounts of attenuation in the high frequencies. No

clinically significant differences in attenuation between adults and children were observed, although there was a statistically significant difference for the CROS earmold between adults and children.

There appears to be a clear relation between degree of ear canal occlusion and attenuation of the ear canal resonance. Ideally, 30% or less of the ear canal should be occluded to achieve a truly open fitting. However, there is no way to predict the degree of ear canal occlusion with a particular sound delivery option. Thus, when an open fitting is desired, probe-tube microphone measurements of the effect of the earmold on the ear canal resonance should be obtained prior to fitting a hearing aid or FM system. The gain of the instrument then can be adjusted to compensate for this loss, or an alternative, less occluding, earmold may be fabricated.

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