Earmold Acoustics and Modification for Mild and Moderate Hearing Losses

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INTRODUCTION

Earmold acoustics is perhaps one of the least understood topics by the traditional audiologist. In the past, the earmold has been the domain of the hearing aid dealer. Today, as more and more audiologists are dispensing hearing aids and becoming involved in the direct case management of the hearing-impaired individual, it becomes imperative that audiologists gain knowledge about 1) acoustic principles underlying earmold acoustics, 2) practical changes that can be made to an earmold and the acoustic effects of these changes, and 3) how to accomplish these changes mechanically in the field. Much of our knowledge about these important areas has been brought forth in the last several years. We have found that earmold acoustics does not consist simply of "adding a vent and reducing the lows". The purpose of this paper is to review some of this recent knowledge and try to make it practically applicable by emphasizing real changes that can be made to the earmold and the resultant acoustic effects.

THE ACOUSTICAL DELIVERY SYSTEM

A simple schematic of the acoustical delivery system involved with an ear-level hearing aid is shown in Figure 1 (Studebaker, 1974). The system consists of four main parts: 1) receiver diaphragm and association volume of air. This volume of air is of course inside the hearing aid and is fixed by manufacturer and thus is unavailable for modification. 2) output tube. This consists of any tubing inside the hearing aid connected to the receiver, the earhook, tubing connecting the earhook to the earmold, and the bore through the earmold. This portion of the system offers the greatest opportunity for change. The tubing diameter can be altered, as can the bore diameter. The length of the output tube can be reduced by shortening the canal portion of the earmold or increased by making the canal portion longer. 3) the volume of air between the tip of the earmold and the tympanic

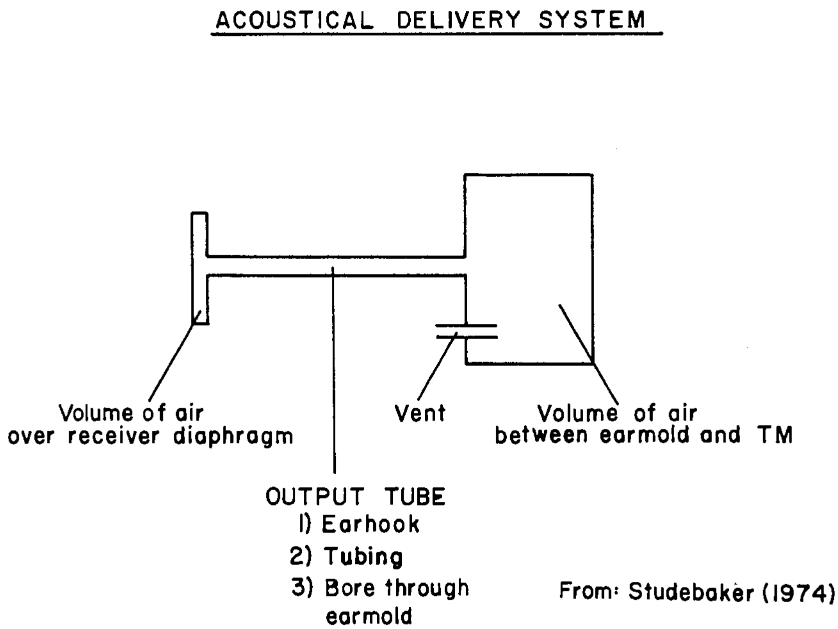


Figure 1. A simplified schematic of the acoustical delivery system of an ear-level hearing aid as described by Studebaker (1974).

membrane. This also can be changed by shortening or lengthening the canal portion of the earmold. 4) vent. The vent is simply an opening to the outside. The vent can be changed by altering the placement (sidebranch or parallel), diameter, and length. With the acoustical delivery system now defined, changes in the system and the resulting effects can be discussed.

MOVING THE PEAKS IN THE HEARING AID RESPONSE

All hearing aids have frequency response curves that are characterized by a series of resonant peaks. One peak is typically located in the 300-1500 Hz region and is called the primary peak. Several other peaks are found in the frequency region above 1500 Hz, and are called secondary peaks. In an excellent study, Studebaker (1974) has clarified the source of these various peaks and demonstrated the underlying acoustic principles.

A tube is in resonance when exposed to input signals of a frequency whose wavelength is related to the length of the tube. If a tube is open at both ends, resonance occurs when the tube is exposed to frequencies whose wavelengths are equal to twice the length of the tube. Resonance peaks also occur at integer multiples of the fundamental. Following these simple rules, if the length of the tube is shortened, the wavelength is less, and the resonant peak moves upward in frequency. Conversely, a lengthened tube means a lower resonant frequency. Studebaker (1974) has identified the output tube as the source of wavelength resonances and the secondary peaks in the hearing aid response as the resonances themselves (Figure 2). The resonances were shown to be independent of the diameter of the output tube.

The only practical way to change the length of the output tube and thus shift the secondary peaks is by changing the length of the canal portion of the earmold. Shortening the canal portion will cause the secondary peaks to shift upward in frequency and lengthening the canal portion will cause a slight downward shift.

The second important principle related to peaks in the hear-

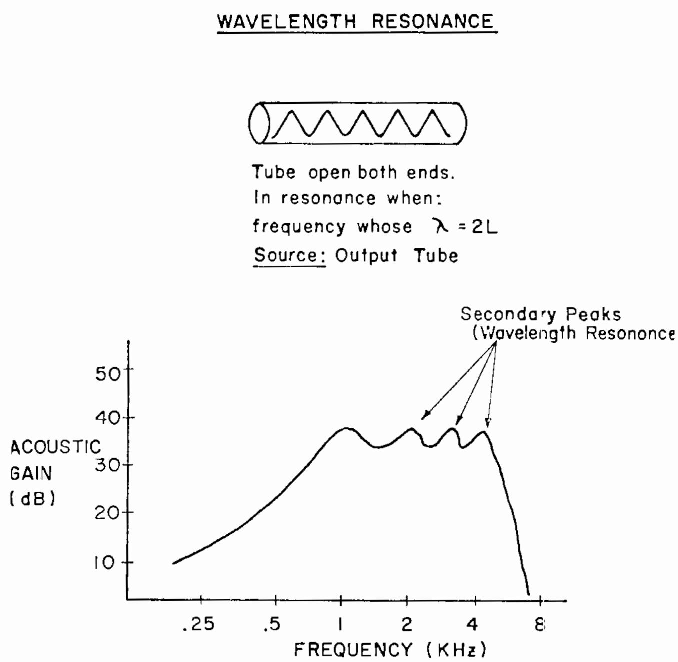


Figure 2. Wavelength resonances, the source and position in the hearing aid response.

ing aid response is ractance resonance. A reactance resonance is produced by a volume of air in a tube connected to a volume of air in an enclosed space. A more familiar term for this type of system is the Helmholtz resonator. The top portion of Figure 3 shows such a resonator and its important charateristics: 1) the volume of air in the enclosed space, 2) the length of the tube, and 3) the diameter of the tube. The reactance resonance is determined by the length (L) and diameter (D) of the tube, and C is the capacitive reactance and is determined by the volume of air (V). If the length of the tube increases or the diameter of the tube decreases, M increases and thus the resonant frequency

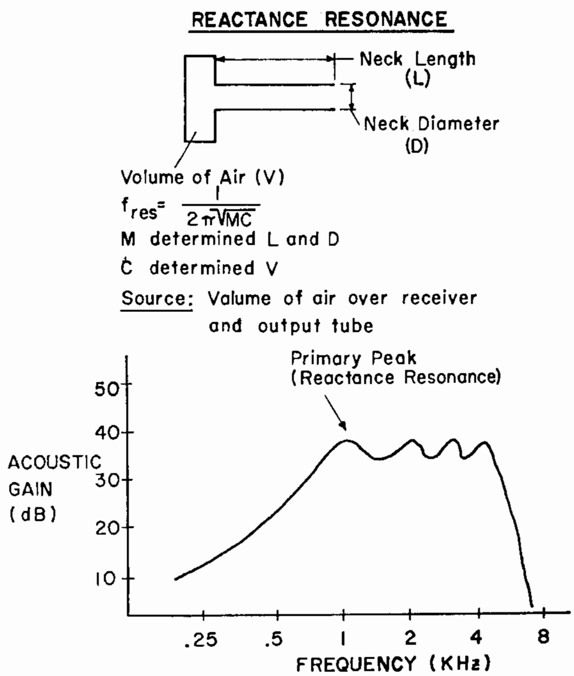


Figure 3. Reactance resonance, the source and position in the hearing aid response .

decreases. Conversely, if the tube is shortened or diameter increased, the point of resonance goes upward in frequency. Studebaker (1974) has shown that the volume of air over the receiver diaphragm and the output tube produce a reactance resonance which is visible in the hearing aid response as the primary peak (bottom, Figure 3).

Practically then, the primary peak can be shifted upward by increasing the tubing diameter and shortening the canal portion of the earmold. Conversely, the primary peak can be moved downward in frequency by decreasing tubing diameter and/or narrowing the bore and lengthening the canal portion of the earmold.

Summarizing, the primary peak (located between 300-1500 Hz) of the hearing aid response is due to a reactance resonance produced by the volume of air over the receiver diaphragm and output tube. It can be shifted upward in frequency by increasing the diameter of the output tube and/or shortening the output tube. The upper secondary peaks are due to wavelength resonances produced by the output tube and are determined by the length (and not diameter) of the tube. The secondary peaks can be shifted upward in frequency by shortening the output tube, thus the canal portion of the earmold.

EFFECTS OTHER THAN MOVING PEAKS

Tubing Diameter. It has been mentioned that decreasing the tubing diameter causes the primary peak to move downward in frequency due to an increase in the mass reactance. A further effect of narrowing the diameter needs to be mentioned. The increased mass reactance also causes a decrease in the mid- and high-frequency region. Figure 4 shows the effect of changing from #12 to #16 tubing. Notice that the primary peak shifts downward, a reduction in intensity occurs for the mid and high frequencies and the secondary peaks do not move, as wavelength resonances are independent of the diameter of the tubing. Because of these effects, narrowing the tubing and bore diameter can be useful in altering the hearing aid response for low-frequency hearing loss clients. An interesting case in this regard will be discussed at a later point in this paper.

Cavity Volume. As the length of the canal portion of the earmold is changed, the volume of air between the tip of the earmold and the tympanic membrane is altered. It is a well-known fact that changes in this air volume produce changes in the sound pressure level (SPL) delivered to the cochlea. McDonald and Studebaker (1970) have shown that the SPL varies inversely with cavity size and the effect is constant across frequency, with a maximum effect of approximately 5 dB. The practical result then is that with a shortened canal portion less SPL will be developed at the tympanic membrane than with a regular or lengthened canal portion. Similarly, with children having small ear canals, more SPL will be present due to the reduced volume.

Opening the Bore. It has often been assumed that changes in the earmold delivery system affect only the low-frequency spectrum delivered to the tympanic membrane. Recent evidence has

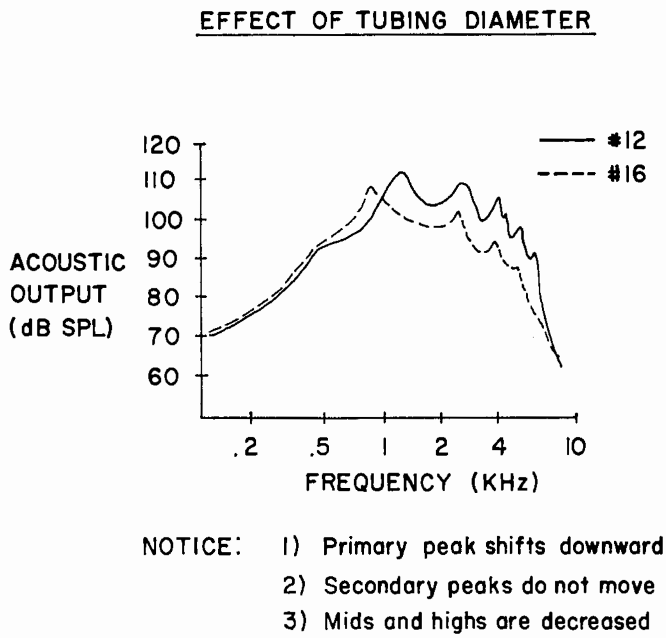


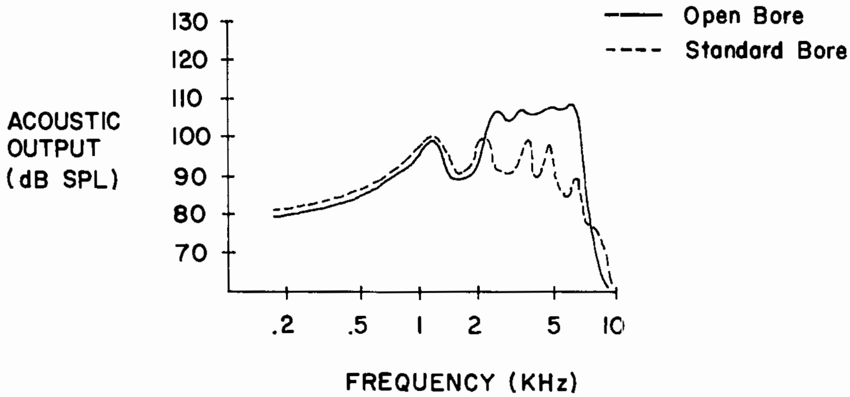
Figure 4. The effect of tubing diameter changes on the hearing aid response.

shown that changes in the output tube can dramatically affect the amplitude of the hearing aid response in the frequency region above 2000 Hz. The change which causes these effects is commonly called "opening the bore." Killion (1976) has shown that if the diameter of the bore is gradually increased (or in stepped portions), producing what he calls the "horn effect," the amplitude of the high frequencies is increased. This increase is due to the more efficient impedance matching between the receiver and the volume of air between the earmold and the tympanic membrane that occurs when the bore is opened. the magnitude of the effect will depend on the specific receiver and the lengths of the various stepped portions. Figure 5 from Killion (1976) shows the magnitude of the effect that can be obtained by simply changing the bore diameter in the appropriate way.

This same principle has important applications for tubing and bore diameter decisions. Figure 6, from Killion (1979), shows the effect of different constrictions of the bore on the high-frequency response. The middle curve shows the response with #13 tubing extending throughout the bore, thus restricting the bore diameter to 1.96 mm (from the standard 3 mm). The top curve shows the increase in the high frequencies when the tubing is inserted just into the edge of the earmold and the bore diameter is enlarged. In the

EFFECT OF OPENING THE BORE

"HORN EFFECT"



Adapted From: Killion (1976)

Figure 5. The effect of opening bore (horn effect) on the hearing aid response. Adapted from Killion (1976).

bottom curve, the bore diameter has been narrowed to 1.3 mm, resulting in a large decrease in the frequencies above 2000 Hz. The importance and practical application should be obvious. If increased gain in the high frequencies is desirable, as it often is, modification of the bore diameter can be a powerful tool. Conversely, the use of tubing throughout the bore or a very restricted bore diameter can drastically decrease the high frequency response of a hearing aid. For a more thorough treatment of output tube changes and the use of sintered filters to damp peaks and extend the high-frequency end of the response curve, the reader is referred to Killion (1977, 1979) and Knowles and Killion (1978).

It should be evident at this point that the earmold is more than a simple coupling device or a means of altering the low-frequency response.

VENTING

Much of our knowledge about the effect of venting has been determined in the last several years by Studebaker (1974), Studebaker and Cox (1977), Studebaker, Cox and Wark (1978), Lybarger (1975) and Lybarger (1978). Knowledge of venting ef-

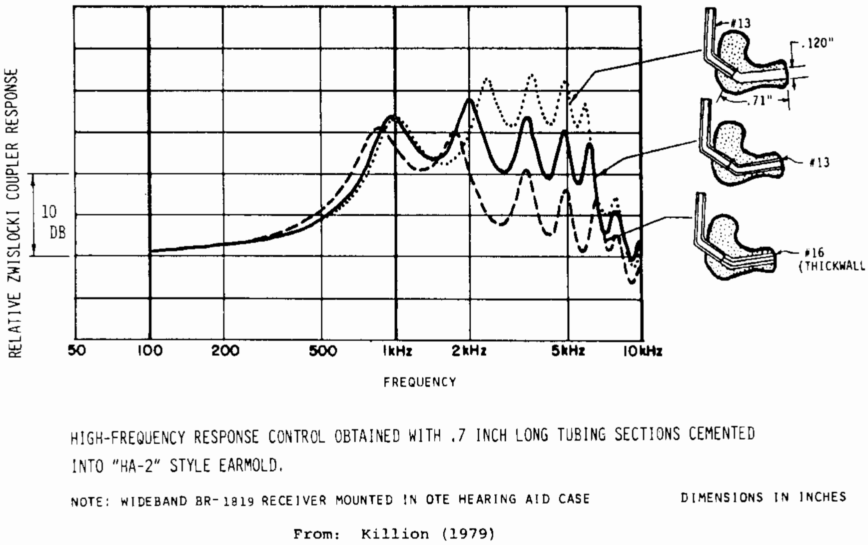


Figure 6. The effect of various bore diameters on the high-frequency response of a hearing aid. From Killion (1979).

fects becomes an important aspect of earmold acoustics when dealing with persons having mild and moderate hearing losses.

A vent can be described in several ways. The placement of the vent can be an important variable. The two means of drilling a vent are shown in the top portion of Figure 7. With a side-branch or diagonal vent, the connection is made between the outside atmosphere and the canal bore, the angle of which can be varied. A parallel vent courses the entire length of the canal portion and terminates at the tip of the earmold, never intersecting the canal bore.

A second aspect of the vent that can be changed is the diameter. Practically it can be varied from less than 1 mm (limited by drill size) to approximately 4 mm (limited by canal portion size). The length of the vent can also be manipulated. With a parallel vent, the length is changed by shortening the canal portion. Changing the angle of the vent alters its length with a side-branch vent.

One of the major effects of a vent is to decrease the low-frequency amplification provided by the hearing aid. The amount of low-frequency attenuation is dependent upon three things: 1) diameter of the vent — the wider the vent, the more low-frequency loss, 2) length of the vent — the shorter the vent, the more low frequencies are attenuated, and 3) placement of the vent — side-branch vent attenuates low frequencies more than a parallel vent (see bottom, Figure 7).

Another effect of a vent is the creation of a reactance

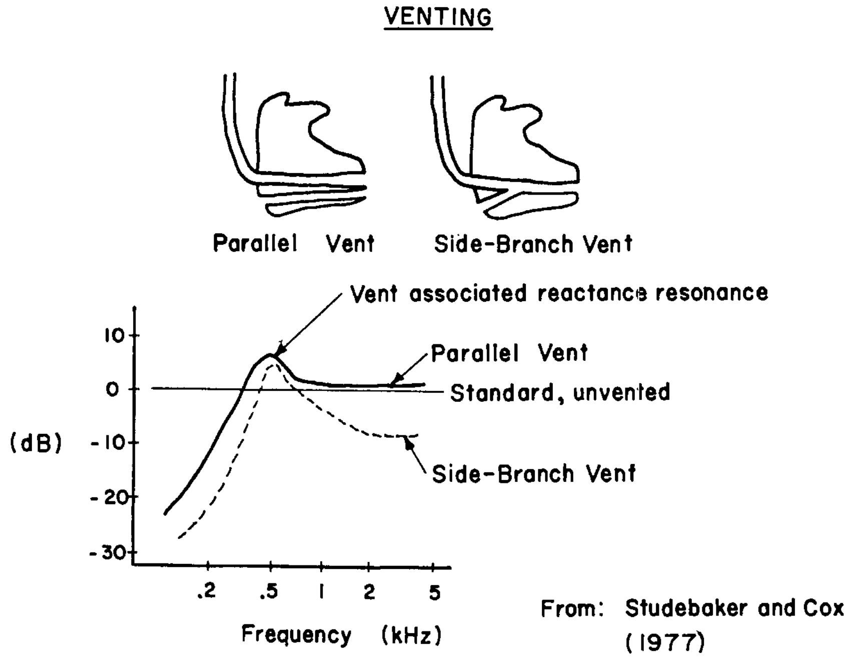


Figure 7. Placement of side-branch and parallel vents (top) and their acoustical effects as compared to a standard, occulded earmold. From Studebaker and Cox (1977).

resonance. The vent channel, in conjunction with the volume of air in the external auditory meatus, causes a resonance which typically occurs in the 300-750 Hz region. This increase in low-frequency amplification as a result of the vent shifts upward in frequency and intensity as the diameter of the vent increases. This effect is larger in the coupler than real ear (Studebaker, 1974) and there is some vidence that it is less pronounced with a loose-fitting earmold (Curran, 1978). The important point is that if a vent of indiscriminate diameter is drilled, it may well be possible to attenuate some low frequencies and amplify others that were also thought to be reduced.

A vent may also have an effect on the gain of a hearing aid in the high frequencies. Studebaker and Cox (1977) have shown that with a side-branch vent, substantial attenuation above 1000 Hz can occur. A parallel vent does not decrease the high frequencies (see bottom, Figure 7). Although a side-branch vent attenuates more low frequencies than a parallel vent, it is at the expense of the higher frequencies.

Feedback is a final and undesirable aspect of venting. It is a well-known fact that the larger the diameter of the vent, the lower the gain at which feedback occurs. Recently, Johansen (1975) and Cox (1978) have shown that feedback is also dependent upon the placement of the vent. Both studies indicate that feedback occurs with a side-branch vent at a gain setting 12-17 dB lower than with a

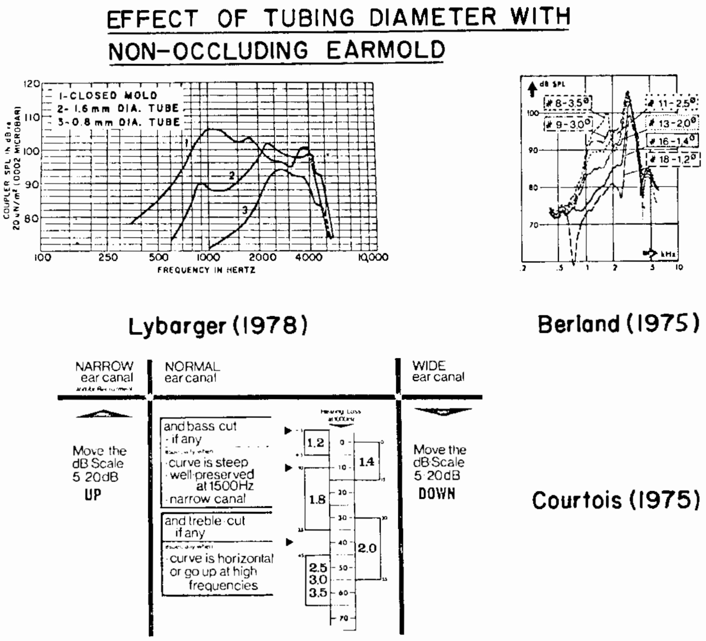


Figure 8. The effect of tubing diameter on the hearing aid response when a non-occluding earmold is employed. Data from Lybarger (1978), Berland (1975) and Courtois (1975).

parallel vent. In summary, while a side-branch vent attenuates low frequencies more efficiently than a parallel vent, the loss of high-frequency gain and the presence of feedback at a lolwer gain setting make side-branch vents undesirable. If a parallel vent cannot be drilled due to a narrow canal portion, it is best to open the bore and have the vent intersect at the base of the open bore (Studebaker, 1979)[1].

A final type of vent is the comfort vent or pressure-relieving

[1] Personal Communication

vent. The diameter is typically less than 1 mm and has little effect on the frequency response except below 200 Hz. It relieves pressure sensations and aerates the ear canal. Its use may eliminate complaints of "hollow" sounds and a "stuffed up feeling." The presence of this vent contributes to feedback only in severe gain cases. In our clinic, some type of vent, either for acoustic or comfort purposes, is used on nearly all mild and moderate hearing loss cases.

The most extreme in large diameter vents is of course the non-occluding earmold, often called a "CROS" or "open" earmold. A non-occluding earmold eliminates virtually all gain below 500 Hz. Above 500 Hz, gain slowly increases as frequency increases. The amount of gain is usually equivalent to closed earmold gain by 1500-2000 Hz. The amount of gain in the 750-2000 Hz region can be altered dramatically by changing the tubing diameter. The two top graphs in Figure 8 (from Lybarger, 1978, and Berland, 1975) show these effects. Notice that as tubing diameter is decreased, the response decreases between 750-2000 Hz, while the higher frequency response is maintained rather well. This knowledge is very useful in cases where normal hearing extends to 1000-1500 Hz. With the narrow tubing, losses restricted only to the higher frequencies can be dealt with more effectively. The bottom portion of the figure shows how Courtois (1975) has utilized this type of information in dealing with specific audiograms with various slopes.

A final effect of earmold modifications is their influence on the loudness discomfort level (LDL) and thus SSPL90 decisions. Figure 9 shows LDLs obtained on a hearing-impaired person with an occluding and non-occluding earmold. Pulsed pure tones were delivered to a hearing aid receiver attached to the earmold tubing. Notice that LDLs are much higher for the lower frequencies with the non-occluding earmold due to the attenuation provided by this configuration. Tolerable coupler SSPL90 values may be quite different under various earmold types.

SUMMARY

A summary of most of the effects mentioned up to this point is shown in Figure 10. At this point, a case study illustrating some of these principles plus a recent theory of low-frequency hearing loss may be interesting. Figure 11 shows the audiogram of a 5½ year old child who was referred to our clinic because he disliked his hearing aid and parents and teachers believed it made him "hyper." Aided sound-field results (▲—▲) indicated excessive high-frequency gain, with thresholds of better than -10 dB HL at

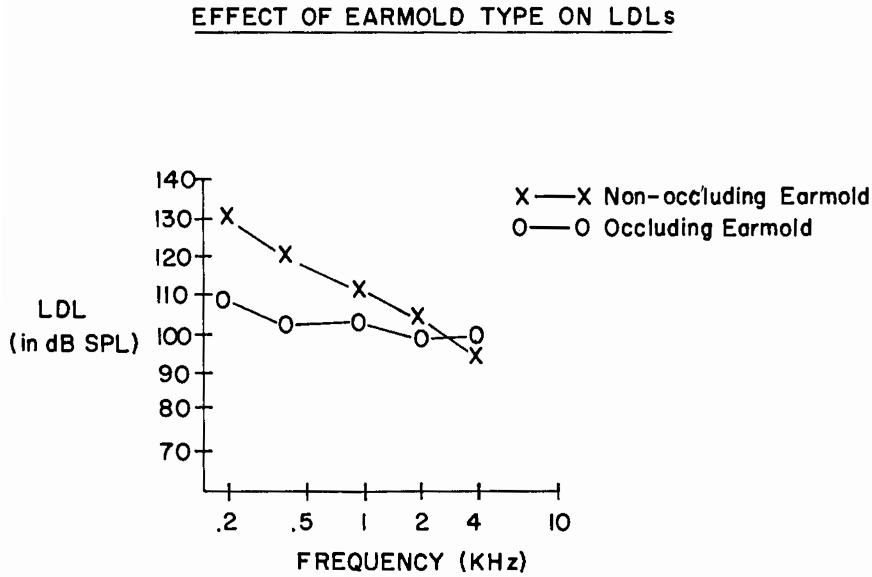


Figure 9. Loudness discomfort levels (LDLs) obtained on occluding and nonoccluding earmold. Pure tones were delivered to an external hearing aid receiver coupled to the tubing of the earmold.

4000 and 6000 Hz. In order to reduce the high-frequency gain, yet maintain the gain between 750-1000 Hz, narrow tubing (#16) was substituted for the original tubing (#13) and was continued through the entire canal bore. Recall that this should move the primary peak lower in frequency and reduce the gain in the higher frequencies. Aided sound-field responses after this modification (●——●) indicated the desired result was accomplished. Now notice the speech audiometry results in the lower portion of Figure 11. In quiet and particularly in noise, aided performance was poorer than unaided performance. An explanation may lie in a theory currently being investigated by Thornton and Abbas (1977). They hypothesize that on some low-frequency hearing losses, the apical end of the cochlea may be nonfunctional. That is, allresponses to low-frequency signals may be originating from basal end fibers, as these fibers respond to moderately intense low-frequency signals due to the biomechanics of the travelling wave. Amplified low- and mid-frequency energy may be masking the high-frequency information travelling on basal fibers. Masking patterns, tuning curves, and filtered speech discrimination scores obtained by thornton and Abbas lend preliminary support to their hypothesis. This case should serve to remind audiologists that the pure-tone audiogram is not a complete description of the functioning of the auditory system and that hearing aid fitting can not be done by rigidly adhered to criteria.

SUMMARY OF EFFECTS OF VARIOUS MODIFICATIONS

1. Increase tubing diameter – Primary peak moves up in frequency.
2. Increase bore diameter – Primary peak moves up in frequency.
3. Shorten canal portion – Whole response curve drops slightly.
   Primary peak moves up in frequency.
   Secondary peaks move up in frequency.
4. Opening the bore – Primary peak moves up in frequency.
   High frequencies increased in amplitude.
5. Vents – Side-branch: lose lows and highs, feedback at low level
   parallel: lose lows but not highs, less feedback.

FOR MAX. H-F-E	FOR MAX. L-F-E
Increase tubing and bore diameter	Decrease tubing and bore diameter
Shorten canal portion	Lengthen canal portion
Open the bore	
Short, wide parallel vent	

Figure 10. A summary list of various earmold modification effects.

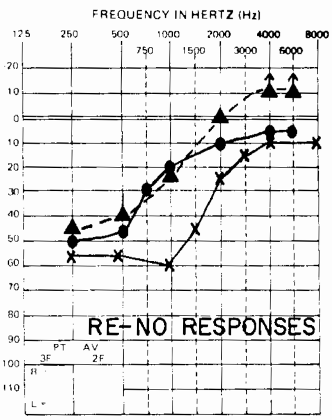
DAMPING

In cases where there are no frequency response and output controls on the hearing aid, it may still be desirable to alter the response in a way so as to reduce the peaks. Adding a resistance to the system will damp the peaks and reduce the output. The two main types of damping material used are sintered filters and Lamb's wool. Proper placement and type can be very useful. With sintered filters, the position of the filter in the system can be crucial. Figure 12 shows a response curve without a filter and with the same filter at three locations. Notice the large differences that can occur as a result of placement locations. Any placement should be analyzed electroacoustically, as predictable outcomes can not be made with an individual hearing aid.

Figure 13 shows a case where the use of Lamb's wool was

AGE: 5 1/2

COMPLAINT: Dislikes Hearing Aid, makes him "Hyper"



X——X Hearing Thresholds

▲- - -▲ Aided Responses, Before Modification

●——● Aided Responses, After Modification

Speech Audiometry Results
(Post-Modification)

	Unaided	Aided
Quiet (50 dBHL)	92 %	84 %
Noise (S/N=0 dB)	80 %	48 %

Figure 11. A case study illustrating earmold modification effects and a theory of processing in low-frequency hearing loss. See text for further information.

EFFECT OF SINTERED FILTER PLACEMENT ON HEARING AID RESPONSE

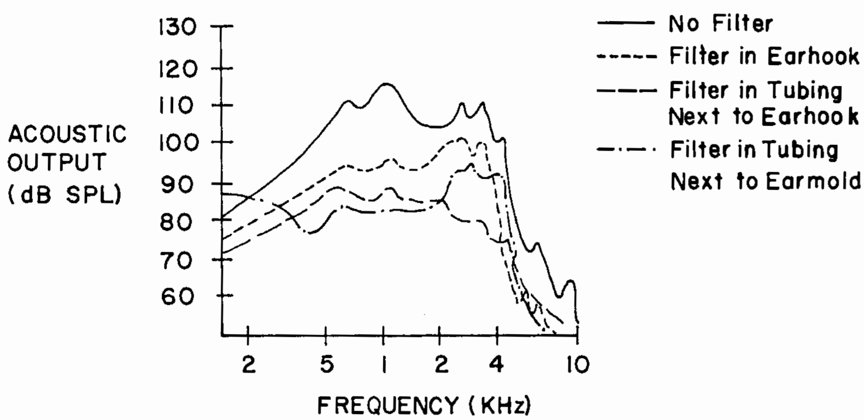


Figure 12. The effect of sintered filter placement location on the hearing aid response.

beneficial. A new hearing aid user complained that certain specific sounds were uncomfortable loud. As the hearing aid had no SSPL90 adjustment, a small amount of Lamb's wool was placed in the earhook. The result is shown in the figure by the dotted line. The peak at 1000 Hz was reduced approximately 10 dB, and eliminated the complaints. Another case where damping elements may be useful is when a child is referred whose hearing aid has an excessive SSPL90 with no external adjustment. Output can be reduced as a permanent solution or until a new hearing aid can be purchased with appropriate output levels.

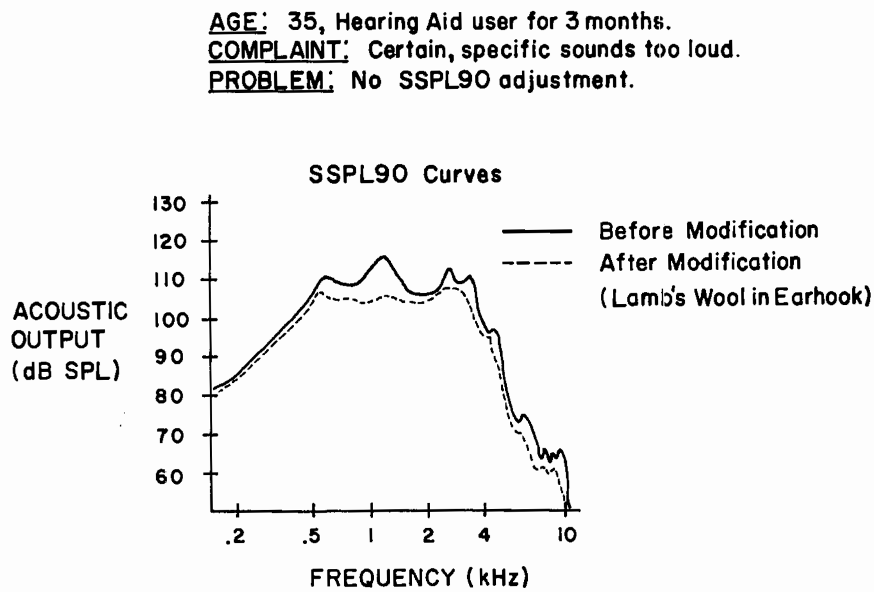


Figure 13. A case study illustrating the use of a damping material (Lamb's wool) to attenuate peaks and eliminate loudness discomfort complaints. See text for further explanation.

MODIFICATION OF EARMOLDS

As audiologists become more involved in delivery of hearing aid services, the ability to make the mechanical changes to the earmold that produce the acoustic results discussed above must be developed. The expertise involved in shortening the canal, widening the bore, opening the bore, drilling a vent, and modifying for comfort can be acquired with only several hours of practice. The necessary tools for office or clinic earmold modification can be purchased for under $100.00. A basic set should include a variable speed drill, grinders, burrs, drill bits, sanding discs, polishing wheel, and polishing compound. Students in audiology programs should be training in the modification of earmolds, perform these modifications for clients, and be aware of the purposes and acoustic results of their changes. For such knowledge to be gained appropriately, the student must follow the client throughout the evaluation and post-fitting adjustment period. This is yet another point in favor of university training programs engaging in some type of dispensing arrangement.

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