EARMOLD OPTIONS FOR WIDEBAND HEARING AIDS

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A summary of recent developments in earmold constructions for wideband hearing aids is presented. Earmold modification techniques, special earmolds, and temporary earmolds are discussed. The appendix contains the results from transmission line theory as applied to earmold acoustics and some sources for useful earmold supplies.

With the recent advances in transducer design and earmold acoustics, wideband hearing aids with high-fidelity sound quality, extended frequency response, and reduced battery drain become possible. Since many of these techniques are still evolving, this paper presents a "state-of-the art" summary of recent earmold developments.

Just how many of the special earmolds described below will have enduring value is uncertain. There are several ways to improve hearing aids; some involve earmold designs, some amplifier designs, and some internal acoustic damping in the earhook or the hearing aid itself (Carlson, 1974). The earmold options described in this report may prove useful until the final answers are in.

EARMOLD MODIFICATIONS

Several approaches to earmold modifications are possible. Two can be accomplished with tools no more complicated than a #50 (1.8-mm diameter) drill bit or a section of 1.9-mm diameter tight-coil spring for inserting damping elements and a knife or scissors for cutting tubing sections to appropriate lengths. Before discussing specific modifications, however, a word about measuring the acoustic effect of such modifications is in order. Each of the frequency responses shown in Figures 1–6 were obtained by sealing the designated earmold directly into the "HA-1" configuration of the standard 2-cm^3 coupler, as illustrated in Figure 13 of ANSI S3.7-1973. In this configuration, the earmold outlet is made flush with the top surface of the coupler cavity. By way of contrast, the frequency response curves shown on a manufacturer's data sheet are typically obtained with what is properly called an HA-2 earphone coupler with entrance through a rigid tube (Figure 14 of ANSI S3.7-1973), usually a 25-mm length of 2-mm diameter tubing followed by the HA-2 configuration, which is an 18-mm length of 3-mm diameter sound channel leading into the 2-cm^3 coupler cavity.

Some commercial hearing-aid test instruments are supplied only with the HA-2 coupler. Needless to say, sealing a custom earmold into such a coupler, an occasional practice of the unwary, will provide only marginally useful information because of the 18-mm long sound channel interposed between the custom earmold tip and the coupler cavity proper.

Even when custom earmold modifications are measured with the proper HA-1 configuration of the 2-cm^3 coupler, the 2-cm^3 coupler still is not a good simulation of the average real ear. The greater sound pressure level (SPL) developed by a hearing aid earphone-earmold combination in real ears was compared with the 2-cm^3 coupler by Sachs and Burkhard (1972). As a rough rule of thumb, the higher level in real ears amounts to 3.5 dB at low frequencies, 5 dB at 1 kHz, 10 dB at 3 kHz, and 15 dB at 6 kHz.

Although the use of a realistic occluded ear-simulator such as the Zwislocki (four-branch) coupler will provide a more direct estimate of the average real-ear SPL that will be produced by a (subminiature) earphone-earmold combination, a large number of experiments conducted by the author and others have confirmed that, up to 8 kHz or so, the differences between 2-cm^3 coupler and Zwislocki-coupler measurements are nearly independent of the earphone-earmold combination and are equal to the differences given by Sachs and Burkhard (1972). The only important exceptions occur when "open canal" earmolds or those with extreme venting are measured. For such measurements, a realistic ear simulator, including concha and pinna simulation, is required (Lybarger, 1980) for greatest accuracy.

Thus, an earmold modification that produces a 10 dB change in 2-cm^3 coupler response can be expected to produce approximately a 10 dB change in the SPL delivered to a real ear. The greater availability of the 2-cm^3 coupler was the deciding factor in the choice of coupler used to obtain response curves for this paper.

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Damping

For decades, damping has been successfully used to smooth the frequency response of headworn hearing aids (Knowles, 1955). Until recently, however, a stable and predictable damping element that provided a nearly pure acoustic resistance (without also adding unwanted acoustic mass) was not readily available. Such a resistance can be obtained by the use of cotton or lambs wool inserted into the earmold tubing, but obtaining a predetermined resistance value using lambs wool involves a fair amount of "cut and try" technique.

A new series of damping elements (Carlson and Mostardo, 1976) has become available recently. These dampers contain a color-coded fused-mesh damping cup that is trapped inside a metal ferrule, 2.5 mm long and 2 mm in diameter, that was designed to fit snugly into the 1.93-mm diameter of the #13 plastic tubing commonly used in earmold construction. These dampers are presently available in nominal resistance values of 680, 1500, 2200, 3300, and 4700 cgs acoustical ohms (Knowles Electronics, 1979a).

Dual Damping. The first problem encountered in attempting to damp the peaks introduced into the frequency response by tubing resonances is that no one location may be adequate to damp all peaks completely. Placing a damper at one location might smooth a peak at 1000 Hz, for example, but would leave a peak at 4000 Hz relatively unaffected. Such a lack of damper effectiveness occurs when the damper is located at a velocity minimum in the standing wave corresponding to the resonance peak. Since an acoustic damper can absorb energy only by resisting the flow of air, it will have little effect at any frequency corresponding to a velocity minimum in the tube. (Velocity minima occur at locations at which the distance to the open end of the tube is an odd multiple of a quarter wave length. See Appendix A and Figure 12.)

One solution to this problem is to use two dampers spaced so that one or the other will be effective at each frequency of interest. (A single damper placed at the tip of the earmold would also do the job at all frequencies, but such a location is generally ruled out because the damper may become clogged with earwax fairly promptly.) Another solution is to use a single damper, located at a best-compromise position in the tubing, and simply accept a somewhat less smooth frequency-response curve. In accordance with the first solution, nearly all the damped earmolds described in this paper use a pair of dampers. Single-damper earmolds may be entirely satisfactory in many cases, however.

Effect of Damping Resistance. As is well known, the higher the value of damping resistance, the greater the reduction in sound transmitted down the damped tube. As shown by the top two curves in Figure 1, however, the proper choice of resistance will damp undesired resonance peaks effectively without appreciably reducing the output at other frequencies. Further increases in resistance tend to reduce output at all frequencies, as illustrated in the lower curves in Figure 1.

It follows from this example that two distinct uses can be made of acoustic dampers: (a) Reduction of sharp response peaks, especially the generally undesirable peak near 1 kHz; and (b) attenuation of the hearing aid's output. In both cases the gain and the maximum output (for example, the SSPL-90) are equally affected, and the result is usually a relative increase in the high frequency response.

An attenuation of output as drastic as that shown in Figure 1 for the 4700 Ohm dampers would be better accomplished by choosing a hearing aid with a gain and saturation SPL output more suited to the task. With 1500 Ohm dampers and the proper hearing aid, for example, approximately the same gain and maximum output can be obtained with 10 times the battery life. Where the maximum output of an existing hearing aid selection must be modified to reduce frequency complaints of loudness discomfort, however, the careful use of damping elements may produce the desired result.

One commonly overlooked effect of damping is a reduction in the tendency towards feedback in high-gain hearing aids. Since whistling due to acoustic feedback normally occurs at the frequency of a response peak, the use of earmold damping can often increase the usable broadband gain.

Tubing Inserts

The National Association of Earmold Laboratories (NAEL) has standardized the dimensions of several common earmold tubings. These dimensions are given in Table 1, taken from Blue (1979). Most "conventional" earmolds use approximately 45 mm of #13 tubing to conduct the sound from the earhook to the tip of the earmold. The sound channel in such an earmold has a constant 1.93-mm nominal diameter, as shown in Table 1.

TABLE 1. NAEL standardized tubing sizes (Blue, 1979).

Size	*Dimensions (ID × OD)* (mm)	(in.)
#9	3.00 × 4.01	0.118 × 0.158
#12 Standard	2.16 × 3.18	0.085 × 0.125
#13 Standard	1.93 × 2.95	0.076 × 0.116
#13 Medium	1.93 × 3.10	0.076 × 0.122
#13 Thick	1.93 × 3.30	0.076 × 0.130
#14 Standard	1.68 × 2.95	0.066 × 0.116
#15 Standard	1.50 × 2.95	0.059 × 0.116
#16 Standard	1.35 × 2.95	0.053 × 0.116
#16 Thin	1.35 × 2.16	0.053 × 0.085

Although seldom produced in the United States, a custom earmold having about the same dimensions as on the HA-2 coupler, that is, 25-mm of #13 tubing followed by a 3-mm diameter sound channel for the last 18-mm of its length, will provide a 5-7 dB greater high-frequency output than a conventional earmold when used with most wideband hearing aids. (A hearing aid will exhibit almost exactly the same frequency response whether it is

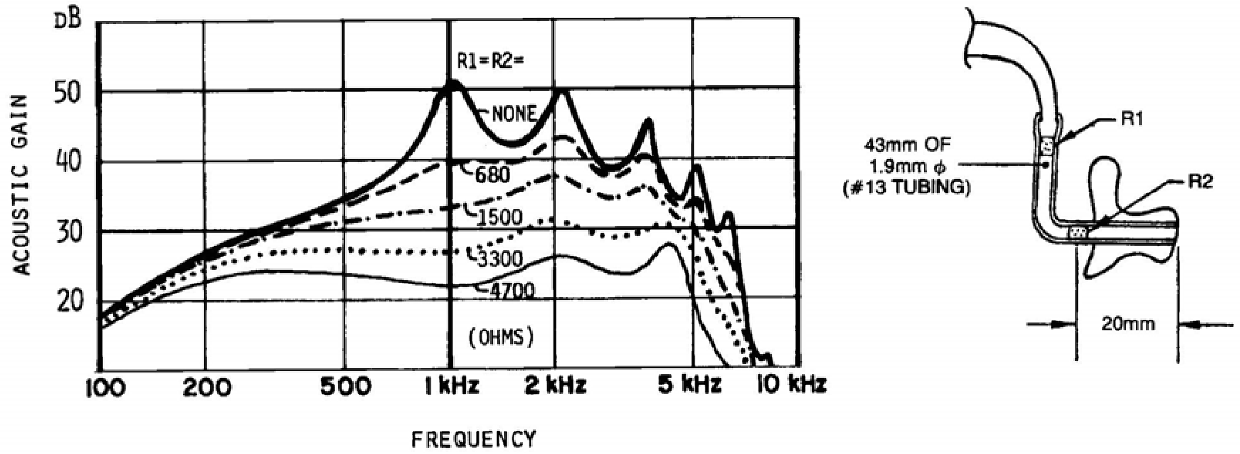

FIGURE 1. Frequency response of wideband aid with earmold damping as shown, measured with a 2-cm^3 coupler (HA-1 configuration).

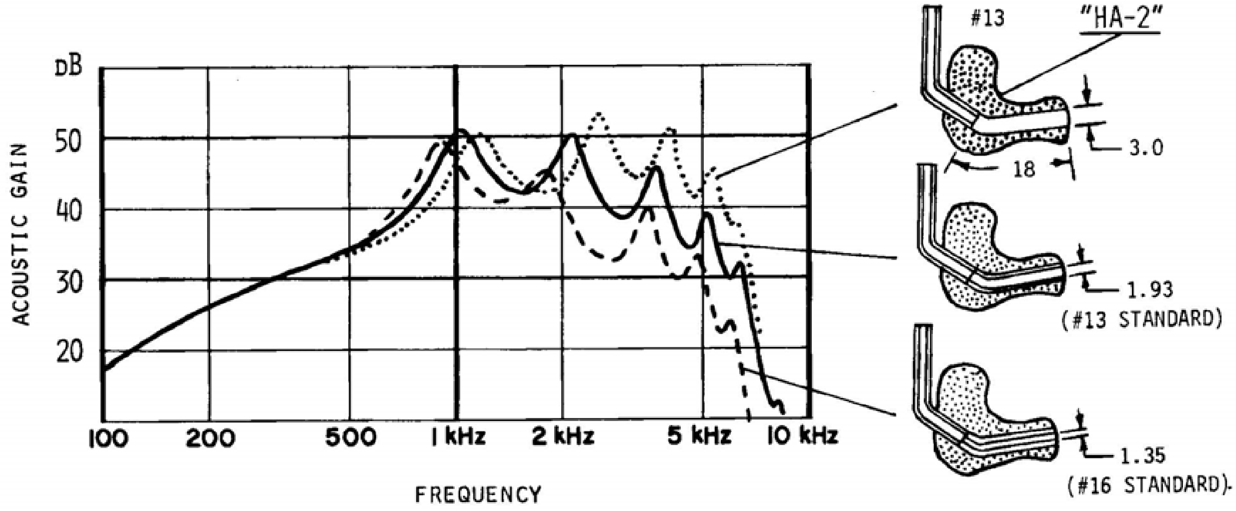

FIGURE 2. High-frequency response control obtained with 18-mm long tubing sections cemented into "HA-2" style earmold, measured with a 2-cm^3 coupler (HA-1 configuration).

coupled through a custom HA-2 earmold into an HA-1 coupler or coupled through 25-mm of 2-mm rigid tubing into an HA-2 coupler. The sound channel between the hearing aid and the coupler cavity is nearly the same in both cases.)

Of particular interest is that the 2.95-mm outer diameter of #16 standard and #13 standard tubings (see Table 1) fits nicely inside the 3-mm inside diameter of the sound channel of an earmold made to the HA-2 configuration. If an 18-mm length of #13 standard tubing is inserted into the 3-mm diameter portion of such an HA-2 earmold, exactly the same frequency response will be produced as would have been produced if a conventional earmold had been used in the first place. This is shown in Figure 2.

One possible HA-2 earmold construction uses a full-sized (concha filling) conventional earmold with the #13 tubing cemented in place 18 mm from the tip. Alternately, a "shell" or "skeleton" HA-2 earmold could be made with #9 tubing used to form the 3-mm diameter portion of the sound channel. In either case, inserting an 18-mm length of #13 tubing restores the constant-diameter sound channel of a conventional earmold.

If, instead of a section of #13 tubing, a section of #16 standard tubing is used, a 5-7 dB reduction in high-frequency response is produced. Figure 2 shows the response of one wideband hearing aid measured under the three conditions described above: HA-2 earmold, HA-2 with a #13 insert, and HA-2 with a #16 insert. If a hearing aid is tried with an HA-2 mold with a #13 insert as the starting condition, therefore, a 5-7 dB increase or decrease in high-frequency response can be obtained as needed by removing the #13 insert or substituting a #16 insert.

The HA-2 earmold shown in Figure 2 is an undamped earmold, as is evident from the response curves. Essentially similar high-frequency response control can be obtained with damping in the tubing, which smooths the response peaks. Two 680 ohm dampers, one located 20 mm and the other about 35 mm from the tip of the earmold, will produce good response smoothing.

Limitations

Earmold damping will smooth response peaks with both conventional and wideband hearing aids, but changes in high frequency response as great as those shown in Figure 2 will only be seen with a wide-band hearing aid containing a high-acoustic-impedance receiver. Similarly, *many hearing aids contain internal damping to smooth the tubing resonance peaks. The use of earmold damping with such aids is generally unnecessary and may result in undesirable loss in output.*

There have been occasional reports of water droplets in the earmold tubing under high-humidity, cold-weather conditions, droplets presumably caused by water vapor from the moist ear canal diffusing into the chilled earmold tubing and condensing out. Under some conditions, these droplets may temporarily fill the openings in an acoustic damper, causing a reduction in the sound delivered to the ear.[1] While this moisture will generally evaporate if the earmold is left in a warm, dry place for a few hours, the use of a forced-air earmold cleaner syringe (for example, Hal Hen #731) will rapidly dissipate the moisture. The problem of condensed moisture is an old one, as is the forced-air solution. Less moisture is required to close off the small pores in an acoustic damper than is required to close off the entire earmold tubing.

A somewhat different problem can occur if the damper is located too close (a few millimeters, for example) to the tip of the earmold, and that problem is the "wicking" of moist earwax into the pores of the damper. To the writer's knowledge, this has not been a problem with stepped-diameter earmolds in which the closest damper is 10-20 mm from the tip of the earmold. If the problem does occur, however, cleaning of the dampers can be readily accomplished without removing them from the earmold tubing by soaking the entire earmold in a mild detergent solution for a few minutes, rinsing thoroughly, and removing the moisture with a forced-air earmold cleaner as mentioned above. Obviously, this procedure should not be tried with in-the-ear hearing aids!

SPECIAL EARMOLDS

Several special earmolds have been described. They have been given somewhat arbitrary designations (6R12, 8CR, etc.) by the writer. Each was designed to produce a specific result or solve a particular problem. A brief overview of these earmolds may be helpful before each is described in detail.

The 6R12 earmold (Knowles and Killion, 1978) was designed to provide a 6 kHz cutoff frequency with a maximum high-frequency boost below that frequency and a well-damped response throughout. The "R" stands for "Rising response."

The 8CR earmold (Killion, 1979) provides a high-frequency response extension to 8 kHz and a response maximum at about 2.7 kHz to compensate for the loss of external ear resonance caused by blocking the earcanal with an earmold; it also provides a smooth response throughout. The "8" stands for the 8 kHz cutoff, and the "CR" stands for "Canal Resonance compensation."

The 6AM earmold is a well-damped dual-tube variation on the Acoustic Modifier® type of high-frequency earmold. The 6AM earmold was described (but not named as such) by Knowles and Killion (1978).

The 6BC-series of earmolds was designed to illustrate that the use of horn coupling and reverse horn coupling could provide a series of earmolds that produced up to a 10 dB high-frequency boost or a 10 dB high-frequency cut. The "B" stands for high-frequency Boost and the "C" for high-frequency Cut.

Finally, the 16KLT earmold was designed to allow a smooth response out to 16 kHz with a super-wideband over-the-ear hearing aid construction. Although to the writer's knowledge not currently available, such an aid is technically feasible with today's transducers. The 16K stands for 16 kHz cutoff frequency, and the LT indicates that this earmold is the Long Tube version of a similar in-the-ear hearing aid earmold construction, which has been used with a built-in receiver and a body-aid electronics package to provide a frequency up-shifting hearing aid for subjects with profound loss below 8 kHZ but with good hearing above 10 kHz (Halperin, Cullen, Berlin, and Killion, 1977).

This section describes the physical construction and acoustical performance of these earmolds in the hope that some readers may find one or more of these special earmolds useful. A more detailed explanation of the theory underlying the acoustical design of special earmolds can be found in Knowles and Killion (1978), Cox (1979), and Killion (1980).

The 6R12 Earmold

The construction of the 6R12 earmold is shown in Figure 3 along with the frequency response obtained with it and a conventional mold used with a wideband hearing aid. (The greater volume of air enclosed in a large-bore earmold causes a reduction, typically of 1 or 2 dB, in the low-frequency output of a wideband hearing aid. This reduction is not seen in Figures 3–11 because all response curves have been normalized to the same levels at low frequencies, illustrating the effect of various earmold constructions on the shape of the frequency response curves.) As a general rule, the change from a conventional earmold (#13 tubing to the tip of the ear-

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[1] S. Ewans, personal communication (1979).

mold and no damping) to a 6R12 earmold will produce a 10–15 dB reduction in the height of the typical response peak near 1 kHz and about a 5 dB increase in output in the 4–6 kHz region.

The 6R12 construction shown in Figure 3 is what Knowles and Killion (1978) labeled the dual-tube "shell" version of the 6R12, a construction that uses a section of #9 tubing to provide the 3-mm diameter portion of the sound channel. This dual-tube version appears somewhat more popular than the original single-tube version, which required a "regular" (concha-filling) earmold construction to provide sufficient length to accommodate both the 3-mm and 4-mm diameter portions of the sound channel.

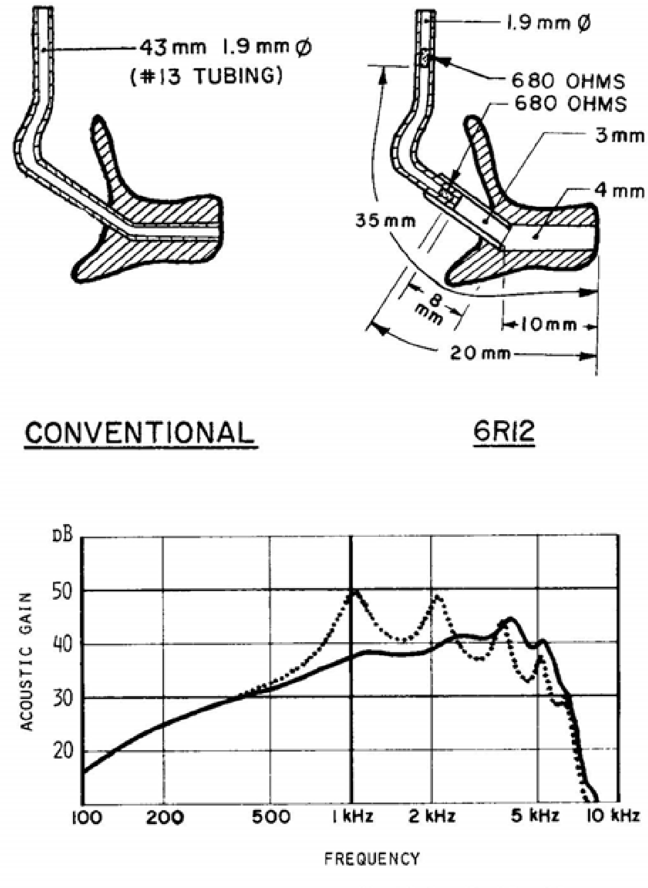

FIGURE 3. Frequency response of wideband aid with conventional (·····) and 6R12 (———) earmolds, measured with a 2-cm³ coupler (HA-1 configuration).

That users can hear the difference between damped and undamped frequency responses was confirmed recently by Lawton and Cafarelli (1978). They compared speech discrimination and sound-quality judgments obtained from a group of 28 hearing-impaired subjects listening to speech through hearing aids coupled through conventional and 6R12 earmolds. Not only did the average speech discrimination score improve slightly with the use of a 6R12 earmold, but 24 of their 28 subjects preferred the sound quality with the 6R12 earmold. Moreover, most (21) of their subjects preferred the sound quality of a wideband aid over a conventional (narrowband) aid. The frequency response of their wideband aid with the two earmold types is shown in Figure 4. (Note the use of a different scale in Figure 4.)

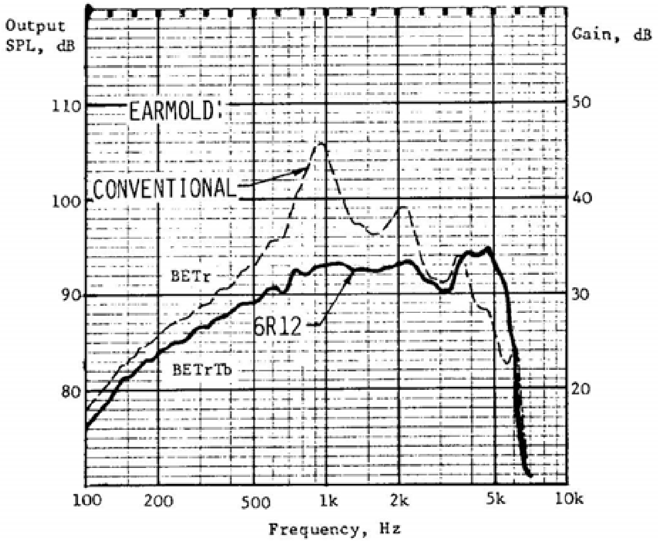

FIGURE 4. Comprehensive frequency response of each experimental aid, measured using 2-cm³ acoustic coupler (60 dB input, maximum gain setting) (from Lawton and Cafarelli, 1978).

The #13 and #16 insert options can readily be used with the 6R12 earmold. The 6R12 has a 4-mm instead of a 3-mm diameter for the last 10 mm of its sound channel, but if one of the tubing inserts is selected as the desired option, permanently filling in the surrounding space with one of the "instant" earmold compounds is possible. The frequency response curves produced with and without tubing inserts in a 6R12 earmold are shown in Figure 5. Note that a 6R12 earmold with a #13 tubing insert becomes, for all practical purposes, a damped conventional earmold.

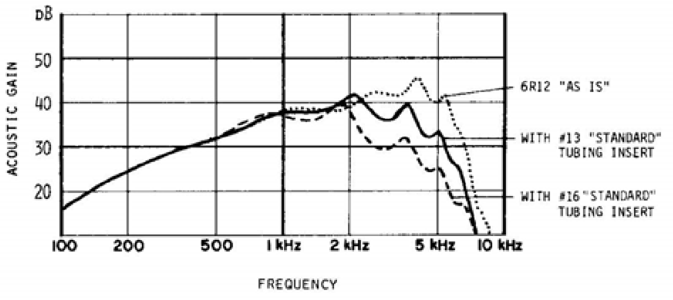

FIGURE 5. High-frequency response control obtained with 18-mm tubing sections cemented into "6R12" earmold, measured with a 2-cm³ coupler (HA-1 configuration).

The 8CR Earmold

The construction of the 8CR earmold is shown in Figure 6, along with the frequency response obtained with it and with a conventional earmold used with a wideband hearing aid. With that aid coupled through a conventional earmold, there are two peaks below 2.7 kHz, but there is a trough in the frequency response near the 2.7 kHz frequency where the unoccluded-ear resonances normally produce a peak. For many users, the result is an unnatural sound quality.

A better sound quality judgment is often obtained with the 8CR earmold in these cases. This comes about because the 8CR earmold produces a peak in the hearing aid output at 2.7 kHz, a peak which, when the earcanal is occluded with an earmold, tends to compensate for the loss of "nature's own peak" at 2.7 kHz.

A detailed discussion of the "real ear" or insertion-gain response of a hearing aid is beyond the scope of this paper. Killion and Monser (1980), however, report an estimate of the coupler response required of an over-the-ear hearing aid if it is to provide the average user with a subjectively flat frequency response, that is, with an insertion gain independent of frequency (dashed curve in Figure 6). (The dashed curve is plotted at 20 dB gain solely for visual convenience; the shape of the curve is all that is important to the present discussion.) With the 8CR earmold, the shape of the coupler response curve of the hearing aid comes closer to that required for a "transparent" sound quality.

If there is a problem of user intolerance to intense sounds in the region around 2.7 kHz, the 6R12 earmold would be a better choice than the 8CR. It also eliminates the two peaks below 2.7 kHz, but it does not reintroduce "nature's own peak" at 2.7 kHz.

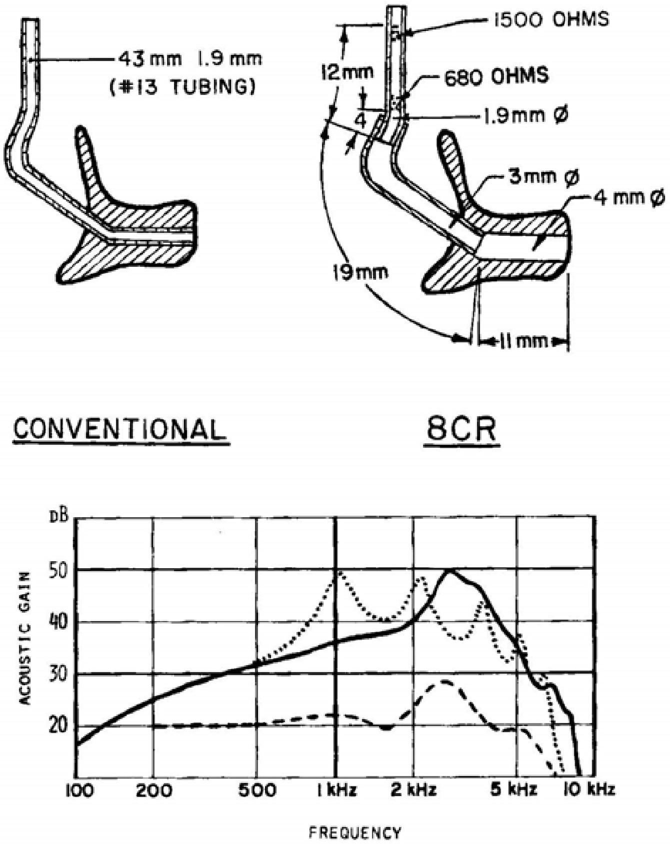

FIGURE 6. Frequency response of wideband aid with conventional (·····) and 8CR (——) earmolds, measured with a 2-cm^3 (HA-1) coupler. Note: Shape of 2-cm^3 coupler response for Over-The-Ear aid required to provide typical user with flat insertion gain (-----) is shown, plotted arbitrarily at 20 dB gain level for ease of visual comparison.

The 6AM Earmold

The construction and increased high-frequency response of a dual-tube variation on the original Acoustic Modifier® earmold (McGee, 1964) is shown in Figure 7. For reasons discussed earlier, it is measured on a complete ear simulator instead of on the 2-cm^3 coupler. This variation has been labeled the "6AM" earmold because of its 6 kHz cutoff frequency and its general similarity to the Acoustic Modifier construction. The "vent" in the 6AM earmold consists of a single 5mm long hole of 4mm diameter. Two 3mm diameter holes side by side would provide nearly the same low-frequency rolloff.

The 6BC-series of Earmolds

The construction of the undamped 6BC-series earmolds, along with the frequency response curves obtained with a wideband hearing aid, are shown in Figure 8. The undamped "6B10" (Boost 10 dB) earmold has a large-diameter 4mm hole for a full 18mm. In practice, such an earmold would probably be constructed by cementing a section of #13 tubing inside a section of #7 tubing (with a few millimeters of #9 tubing as adapter) and cementing the composite into a "shell" or "skeleton" mold.

The undamped "6C10" (Cut 10 dB) earmold uses a 13-mm long section of #18 tubing (1 mm inside diameter) cemented inside a 13-mm long section of #13 tubing (whose inside diameter matches the outside diameter of #18 tubing), which is in turn cemented in an earmold. The undamped 6C5 uses only a 14-mm section of #16 standard tubing cemented into an HA-2 type of earmold, but it is otherwise similar to the HA-2 earmold with #16 tubing insert described above.

The undamped 6B0 earmold is nothing more than a conventional earmold. It is the "zero boost" base member of the undamped 6BC-series of earmolds.

The curves of Figure 8 were included to illustrate again that the use of damping and the use of stepped-diameter "horn coupling" produce relatively independent effects. That is, the increased or decreased high-frequency response obtainable with stepped-diameter constructions is obtained whether damping is employed or not. Similarly, the resonance peaks of a tubing system can be damped whether a constant-diameter or stepped-diameter construction is employed. The basic 6BC-series is well damped, as illustrated in Figure 9. Indeed, any of the 6BC-series earmolds is assumed to be damped unless it is specifically labeled as an "undamped 6C10," "undamped 6B10," and so on.

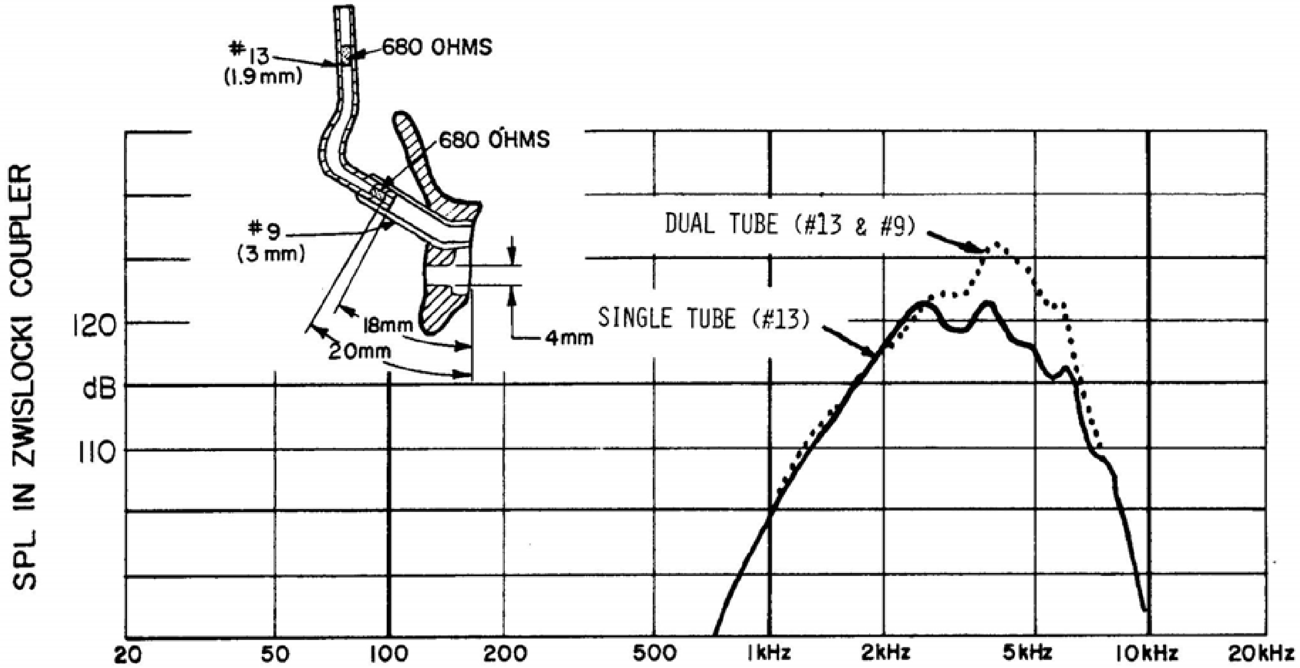

FIGURE 7. Wideband receiver response with 6AM earmold.

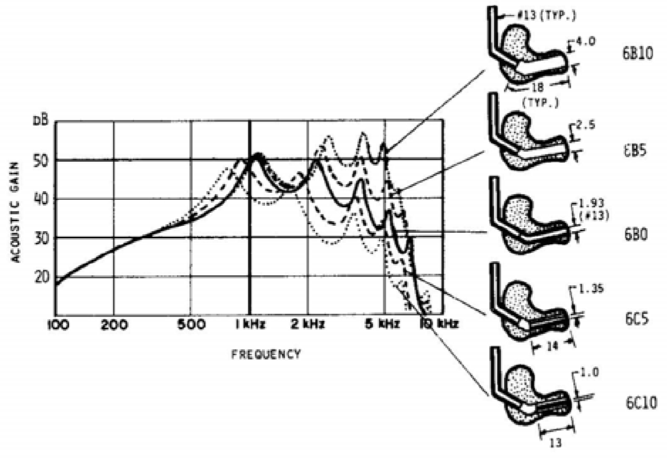

FIGURE 8. Graduated high-frequency response control using undamped 6BC earmolds with wideband aid.

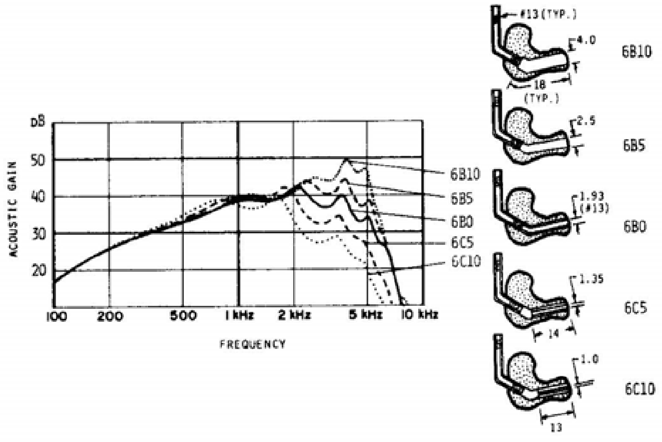

FIGURE 9. Graduated high-frequency response control using damped 6BC earmolds with wideband aid. Note: One 680 ohm damper at earhook; one 20-mm from tip of mold.

The 16KLT Earmold

The construction of the 16KLT earmold is shown in Figure 10. The frequency response shown in Figure 10 was obtained with a simulated super-wideband hearing aid having a flat microphone and amplifier response and a wideband receiver mounted in an OTE hearing aid case with a 10 mm of 1-mm receiver tubing and 25 mm of 1.3-mm diameter sound channel in the earhook (Knowles, 1979b).

Vented Earmolds

None of the earmolds except the 6AM earmold fall in what might be called the "vented earmold" class. However, just as the use of damping and stepped-diameter sound channels produce relatively independent effects, the use of "parallel" earmold venting will produce essentially the same changes in low-frequency response whether or not damping or stepped-diameter constructions are used. Similarly, the venting will have essentially no effect on the high-frequency response of vented or stepped-diameter earmolds.

The last statement is not necessarily true of "diagonal" vents that may influence high-frequency response, but these vents also tend to introduce feedback problems and thus should generally be avoided. The reader interested in further information on earmold venting is

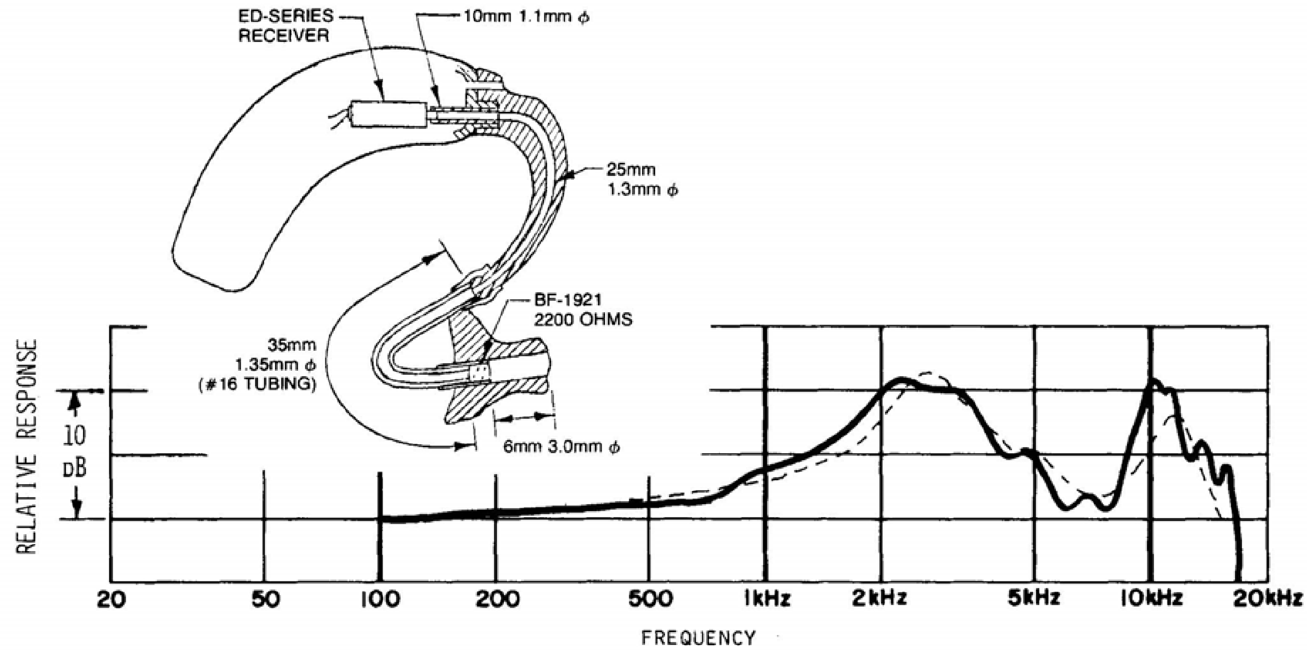

FIGURE 10. Zwislocki coupler response of typical ED-series earphone in OTE aid with 16 KLT earmold (——). Note: Shape of estimated Zwislocki coupler response required to provide typical user with flat insertion gain in diffuse sound field shown (-----) for comparison.

urged to consult the excellent articles on the subject by Lybarger (1975, 1978, 1980), Grover (1976), and Studebaker and Cox (1977). Goldberg (1977) provides a convenient table of approximate length-diameter combinations required to produce nominal cutoff frequencies of 250, 500, 750, and 1000 Hz.

TEMPORARY FOAM-PLUG EARMOLDS

In some cases, trying several different earmold types within a short period of time is useful. Under those circumstances, ordering a custom earmold in each of the constructions to be tried is generally impractical. One solution to this problem is the use of temporary earmolds assembled from pre-bent tubing and pre-punched closed-cell foam earplugs such as the E.A.R.® or DECIDAMP® earplugs (Gardner, 1974). These readily available earplugs can be compressed to a flat pancake between the thumb and forefinger, after which they will easily fit within the jaws of an inexpensive hand paper punch so that a hole may be punched along their axis. A ⅛ in. paper punch is ideal for use with #13 tubing. Pre-bent sections of #13 tubing are available from several earmold supply houses and can be used to construct "conventional" or damped conventional earmolds. To avoid tube slippage during insertion of the earplug, a small drop of alpha cyanoacrylate "instant" cement may be used to cement the tubing into the hole in the foam plug.

Stepped-Diameter Temporary Earmolds

Stepped-diameter temporary earmolds are readily assembled from telescoping sections of plastic tubing. The #9 and #7 sizes of PVC or "vinyl" clear plastic insulation tubing available from most electronic supply houses provide, along with #13 standard pre-bent tubing, a telescoping set of tubings; the #13 tubing fits inside the #9 tubing, and the #9 tubing fits inside the #7 tubing. A 3/16 in. paper punch will produce a hole, in a pre-flattened foam plug, suitable for either #9 or #7 tubing.

In constructing any of the special earmolds described using telescoping tubing sections, it is important to keep in mind that the only thing that affects the sound is the sound channel itself. Thus all section lengths given in the Figures should be applied to the inside dimensions of the sound passageway. For example, an HA-2 type of earmold is readily assembled from a section of #13 tubing approximately 28 mm long and a section of #9 tubing approximately 22 mm long, with the #9 tubing slipped over the #13 tubing a distance of 4 mm. This leaves an active length of 18 mm of 4 mm internal diameter sound channel (22 mm minus the 4 mm of #13 tubing) at the ear canal end of the earmold. Similarly, when the #13 tubing is slipped over the earhook of the OTE hearing aid, the active length of #13 tubing will be about 25 mm (allowing 3 mm overlap of the tubing over the end of the earhook).

Damping elements can be inserted in the #13 tubing portion of telescoping-tube style earmolds by using the back end of a #50 drill bit or a short length of 1.9 mm diameter tight-coiled spring as a push rod. In either case, stopping at the proper location is made easier if the push rod is first inserted into a clamp or "pin vise" and locked into position so that exactly the proper amount of push rod protrudes. Fortunately, the individual location of two damping elements is less critical than the location of a single element. An error of 1 mm either way in the location of either of two dampers will have minimal effect on the frequency response. Large location errors should be avoided, however, if consistent results are expected.

Venting Temporary Foam-Plug Earmolds

Earmold venting is often useful to relieve the pressure buildup caused by inserting the mold into the ear canal (minimal-diameter vent hole) or to reduce the low-frequency output of the hearing aid. Venting is readily accomplished with temporary foam-plug earmolds by simply punching an additional hole parallel to the main hole and inserting a vent tube with the desired internal diameter. With a vent tube equal to the typical 20-mm length of the foam plugs, a #13 tubing section will give roughly a 550 Hz cutoff, a #16 standard tubing section will give roughly a 400 Hz cutoff, and a #18 tubing (cemented inside a section of #13 tubing to provide the proper outside diameter) section will give roughly a 300 Hz cutoff. Shortening the foam plug and the vent tube to a 10-mm length (by cutting them in half with scissors) will produce about a 40% increase in each of the cutoff frequencies given above.

For pressure-relief purposes, a 20-mm section of #24 tubing (cemented inside a section of #16 standard tubing to provide the proper outside diamter) will provide a cutoff frequency of roughly 150 Hz. When cementing tubing sections together, care should be taken not to block the sound channel with cement. With the smaller tubings such as #18 and #24 cemented into the larger tubing, blocking can be avoided if an excess length of the smaller tubing is cemented into the larger tubing and the two ends are trimmed flush after the cement has cured.

Additional Observations

While temporary foam-plug earmolds are comfortable enough to allow extended trial periods, they are not nearly as comfortable for long-term use as a well-fit acrylic or "soft" permanent earmold (which are also much easier to clean). Several earmold laboratories will now provide permanent earmolds in one or more of the special constructions described.

Another problem can arise with ear canals that bend sharply; full insertion of the foam plug can cause the sound outlet to become partially obstructed by the canal wall. A similar problem can occur if the plug goes around the bend but the sound tube is pinched or kinked in the process. The solution in either case is to use a half-length plug inserted only so far as a visual examination indicates will preserve an unrestricted sound passageway.

DISCUSSION

With the availability of stable and predictable acoustic damping elements and the recent advances in our knowledge of earmold acoustics, it is now possible to provide a dispenser-level control of the frequency response and maximum output of wideband hearing aids at the mid and higher frequencies. This control is a tool that can be used, much as earmold venting has been used for several decades, to provide response modification at the lower frequencies. In combination, these tools—earmold venting below 1 kHz, damping in the 1–3 kHz region, and stepped-diameter sound channels above 3 kHz—provide a means for systematic control of the hearing aid output.

The selective response emphasis that can be achieved by the choice of earmold construction is illustrated in Figure 11, which compares three special earmolds to a conventional earmold.

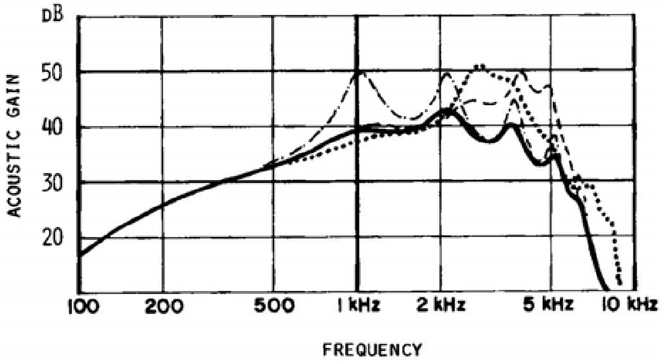

FIGURE 11. Selective response emphasis by choice of earmold construction: (-·-·-) conventional; (———) same, damped (6BO); (-----) 6B10; (·····) 8CR.

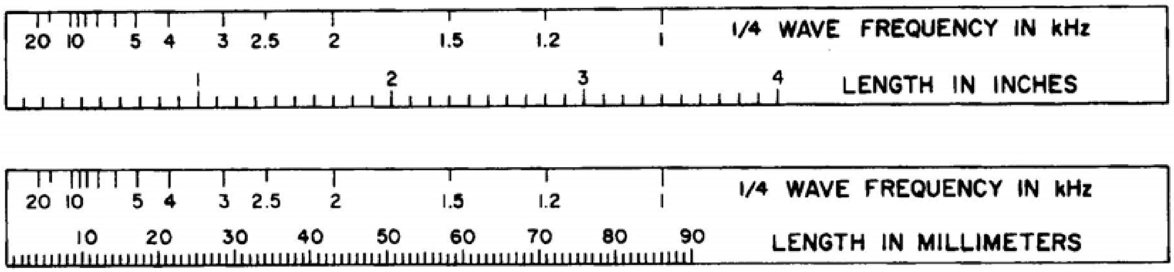

FIGURE 12. Quarter-wave resonance rulers.

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APPENDICES

A. Observations Guiding Earmold Design

Useful Results from Transmission Line Theory Applied to Earmold Acoustics

1. Tapered Line ("Horn Effect"). A progressive increase in the diameter of the coupling tube between the receiver and the earmold tip will provide increased high frequency output. (A progressive decrease will produce a decreased high frequency output.)

Notes: a) Little increase in output will be seen at frequencies below the effective "flare cutoff frequency," determined by the rate at which the diameter of the coupling tube increases with length ("rate of flare"). Doubling the diameter every 39 mm, using either a continuously-tapered or a stepped-bore coupling, will give a cutoff frequency of about 3 kHz; doubling every 13 mm (3 × the flare rate) will provide a cutoff frequency of about 9 kHz, etc.

b) The increase in output above the effective cutoff frequency will be approximately proportional to the ratio of the diameters of the outlet and inlet ends of the coupling tube.

Example: A 6R12 earmold used with a wideband OTE hearing aid will provide a coupling system of about 43 mm that starts with a roughly 2 mm diameter inlet and ends with a 4 mm diameter outlet at the earmold tip. This 2:1 ratio corresponds to an expected pressure gain of 6 dB above a 2.7 kHz cutoff frequency.

2. Quarter-wave Resonance. An abrupt increase in the diameter of the coupling tube will provide increased output at the frequency at which the distance between the abrupt increase and the tip of the earmold is equal to ¼ wavelength (also ¾, 5/4, etc.).

3. Velocity Minima. An acoustic damping resistance will have little effect at the frequency at which the distance between the damper and the tip of the earmold is equal to ¼ wavelength (also ¾, 5/4, etc.).

4. Terminated Line. An acoustic damping resistance with a value equal to the Characteristic Impedance (see Formulae) of a constant-diameter coupling tube will provide a transmission that is nearly independent of the length of the tube between the source and the damper.

5. Shortened Lines. A progressive increase in the diameter of the sound channel shortens the apparent "acoustic length" of

the line as inferred from the first (quarter-wave) resonance frequency (Olson, 1957; Benade, 1976). This phenomenon can be manipulated to present a stiffness load to a wideband earphone in the 2500 Hz region, which may be useful in moving its main resonance nearer to the 2700 Hz frequency of the normal external-ear resonance.

Useful Formulae

¼ wavelength
$$\lambda/4 = \frac{c}{4f} = \frac{8.6}{f(\text{kHz})}\ \text{cm} = \frac{3.38}{f(\text{kHz})}\ \text{in.}$$

Characteristic impedance of a coupling tube in cgs acoustical ohms
$$Z_c = \frac{\rho c}{A} = \frac{41}{A(\text{cm}^2)}\ \text{ohms} = \frac{6.4}{A(\text{in}^2)}\ \text{ohms}$$

c = velocity of sound = 34,400 cm/sec
ρ = density of air = 0.0012 gm/cm^3
f = frequency
A = cross-sectional area of coupling tube
λ = wavelength of sound in air

Quarter-wave Resonance Ruler

Figure 12 provides a simple scale for estimating the frequency at which quarter-wave resonance boosts and velocity minima may occur in the earmold system (see A.2 and A.3).

B. Sources for Materials

Some of the materials useful in making temporary earmolds or modifying custom earmolds are not normally stocked by hearing aid dispensers, but are readily available. The foam earplugs can be obtained from local safety-equipment distributors in most areas. The NAEL standardized earmold tubings can be obtained from most earmold laboratories. The PVC insulation tubings are available from most industrial electronics distributors. Other items can be obtained from suppliers of hearing-aid accessories.