Earmold Acoustics

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ABSTRACT

Several fitting disappointments can be traced directly to improper earmold acoustics introduced by the earmold impression, or the instructions to the earmold laboratory, or to the earmold laboratory itself. To understand these disappointments requires some understanding of why earmolds do what they do to the sound passing through them. The reader possessing a certain eagerness to learn may find the present description (labeled theory) novel and useful. Following that theoretical description, an argument is made that many of the problems of occlusion effect and feedback can be alleviated by the proper use of a comfortable deeply-sealed earmold (requiring good impressions beyond the second bend, of course). The performance of actual earmolds is used throughout to illustrate the points made here.

KEYWORDS: Horns, resonance, damping, choked, sound channels, earmolds

Learning Outcomes: As a result of this activity, the reader will: (1) define occlusion effect and propose an earmold solution to this problem, (2) explain the influence of earmold fit on feedback production, and (3) list two advantages of a deeply-seated earmold.

A superb lecturer, Hans Bergenstoff of the old Danavox Company gave a 1980 lecture on the importance of good earmold acoustics—in particular, the importance of using horn construction for good high-frequency response.[1] During the question and answer period someone asked: "Why do I have to do all that work with the earmold; why doesn't the hearing aid manufacturer use an electrical circuit to give the high-frequency boost?" His answer: "We could,

but that would be like driving your car with one foot on the brake and one foot on the gas!"

In the same time period, I examined the earmolds of a number of children. Each had been made with too small a bore (a common practice to keep the tubing from pulling out). Those choked-off earmolds produced some 15 dB less high-frequency output than a proper horn earmold (Fig. 1). In the case of a profound hearing loss, it is impossible for the hearing aid
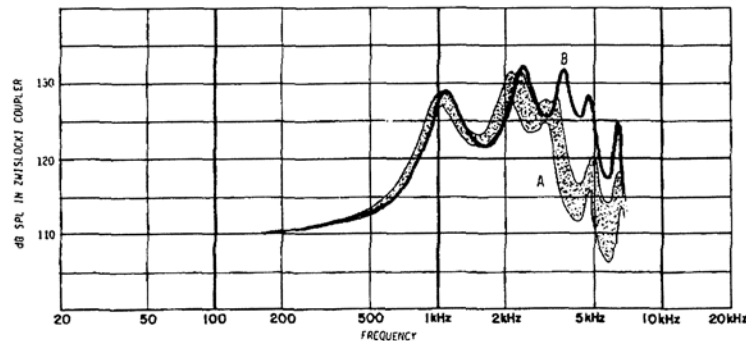
Figure 1 6LF versus standard children's construction.

(modern digital or older analog) to make up the difference; there is not enough power available. Probably more damage to hearing aid response is done inadvertently than any other way.

Recently, I was shown a canal aid that could not be equalized to 16 kHz because of the length and diameter of the tubing within the case. Even with the sophistication of seven digital "biquad" equalization circuits, the unfortunate response shaping introduced by the earmold construction could not be overcome.

These examples illustrate the importance of earmold acoustics, which are just as important today as decades ago.[2] Even though the average digital hearing aid of today has only a 5.8 kHz bandwidth, the earmold can still help make the *most* of the signals in that limited bandwidth.

THEORY: HORNS FOR HIGH FREQUENCY CONTROL

We'll break the rules and start with the theory. The reader for whom this prospect is unattractive may skip to the section titled "Practical Horns."

Three things control the response of a hearing aid/earmold combination: (1) horn action, (2) air-column resonances, and (3) damping. Much misunderstanding about horn action stems from inattention to the basic physics: a horn produces its full gain only above its cutoff frequency. Below the cutoff frequency, the falling gain provides the rising part of the high-

frequency response. The formulae needed to determine the responses are:

(1) Gain = Dm/Dt (Gain in dB = 20*LOG (Dm/Dt))
(2) Cutoff Frequency = 120/DDD in kHz
(3) DDD = Diameter Doubling Distance in mm

Dm is the diameter of the mouth of the horn and *Dt* is the diameter at the beginning or throat of the horn. The *Diameter Doubling Distance* is the distance required for the diameter to double (see example below).

These terms are taken by analogy from the human vocal tract (Fig. 2), which provides a nice illustration of the use of these formulae.

The vocal tract starts at the throat with a diameter of roughly 10 mm at the larynx, and ends at the mouth with ~40 mm diameter when it is fully opened. (For the latter, imagine an opera singer singing an Ah vowel on a high A = 523 Hz.) The vocal tract is ~160 mm long and the diameter increases by a factor of four; doubling once in the *first 80 mm* and *again in the next* 80 mm. The distance for each doubling of diameter is thus ~80 mm, so we say the DDD is 80 mm.

Now we can use the formulae. Because the ratio Dm/Dt of the mouth to throat diameter is 4:1, there should be some 12 dB of horn-action gain, giving the singer sixteen times the radiated acoustic power. But will the horn action do any good? The fundamental frequency of high A is 523 Hz, well below the horn cutoff frequency of the vocal tract, which we calculate as f_C = 120/80 = 1.5 kHz, but the harmonics at

Figure 2 Professionally trained opera singers learn to move their larynx down rather than up as they sing high notes. Moving the larynx down increases the length of the vocal tract from perhaps 160 mm to 180 mm, moving the effective horn cutoff frequency from 1.5 kHz to 1.3 kHz, and giving a richer tone.

$\geq$ 1.5 kHz give the singer's voice the power. The "singer's formant" that allows opera singers to sing out over the full orchestra falls at ~3 kHz, which is above the cutoff frequency. Without vocal tract horn action and vocal tract resonances, it would be nearly impossible for human voices to be heard at a distance.

PRACTICAL USE OF HORNS

Horns that *Do* Work

Probably the simplest method of obtaining earmolds with more high-frequency horn action is to use an elbow such as the continuous flow adapter (CFA) #2 horn or the CFA #3 stepped bore. Dillon[3] reports that both earmolds provide the same gain at 4 kHz as the HA-2 horn and nearly as much gain at 3 and 6 kHz. The HA-2 horn is built into the standard 2cc coupler used with test boxes. Alternately, the Baake horn (an elbow plus earmold bore) popular in Europe will provide even more high-frequency

gain.[4] There are three advantages to the use of an elbow: (1) it makes proper replacement of tubing easier, (2) it avoids the risk of accidental tubing restrictions, and (3) it often simplifies the construction of horn and resonant-cavity earmolds.

Another approach to improved high-frequency response is the use of special molded tubing that incorporates the desired horn shape. Three such horns are the Libby 3 mm horn,[5] the Libby 4 mm horn,[5] and the Lybarger high-pass tube.[2] The advantages of molded horns are somewhat higher performance (especially the 4 mm horn), pre-determined horn dimensions, and—according to some users—better appearance.

Figure 3 shows two constructions for the Libby 4 mm horn earmold, illustrating that any earmold tip large enough to accommodate the 3 mm horn (which has a 4 mm *outside* diameter) can accommodate the 4 mm horn, using the construction shown in Figure 3B. Similarly, any earmold that can accommodate #13 tubing to the tip can accommodate the 3 mm horn using the same style of construction. Indeed, all of the children's earmolds in Figure 1 could be fitted with the 6LS Lybarger style earmold using the construction shown in Figure 3A. Earmolds for infants may require the use of the Lybarger high-pass tube with such a construction.[5]

Table 1 shows the amount of gain (relative to #13 tubing) that can be provided with various well-designed BTE earmolds. In these earmolds, the diameter doubling distances have been chosen so that the cutoff frequency is approximately 2 to 4 kHz. Note that three of the earmolds in Table 1 (6C5, 6C10, and 1.5 LP tube) reduce the high-frequency response. These are primarily useful when the hearing aid does not have adequate high-frequency roll off capability. In these cases, the earmolds can quickly eliminate feedback that "everyone but the hearing aid wearer can hear."

The 6 dB of gain provided by a typical horn is accompanied by a 6 dB increase in undistorted output. To accomplish such an increase using a conventional earmold (without horn tubing), the hearing aid would have to deliver four times the power, which would mean four times the
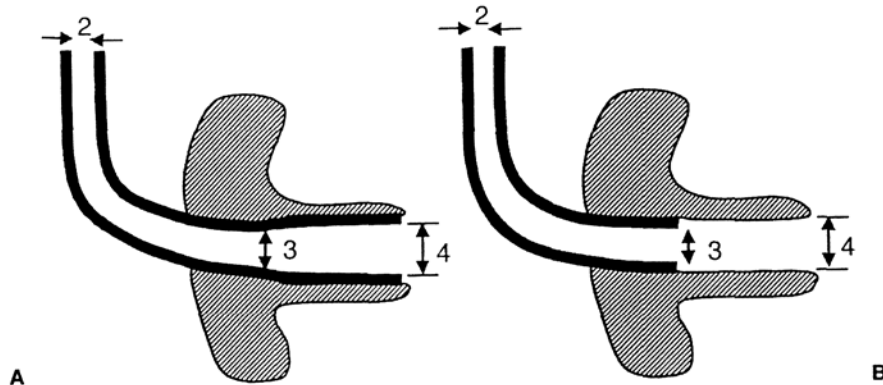
Figure 3 Constructions for Libby 4 mm horn (Dillon[3], used with permission).

battery drain. A battery drain of 12 mA in a power aid is probably practical; a drain of 48 mA is probably not. This was Hans Bergenstoff's conclusion in 1980.[1] More to the point, obtaining adequate undistorted high-frequency output at any power level has been the Achilles heel of most hearing aids for patients with severe high-frequency hearing loss.

While a digital BTE hearing aid cannot produce any more undistorted sound through a choked-off earmold than a good conventional aid, the digital aid can flexibly shape the frequency response at conversational levels. This leads to the suggestion that all digital BTE hearing aids be ordered with some form of horn earmold, allowing the electronics to reduce the highs in the unlikely case that they are excessive, but preserving the maximum undistorted output capability of the hearing aid. Ironically, this is exactly the suggestion Bergenstoff[1] made in 1980 regarding *all* BTE hearing aids. The fact that the majority of earmolds are ordered with constant-diameter, sometimes choked-off #13 tubing, indicates that such suggestions have been mostly ignored.

Horns that *Don't* Work

In hearing aids, attempts to obtain high gain in a short horn can produce disappointing results. An ITE "horn" construction made up of three successive tubes of inner diameter 1 mm, 2 mm, and 4 mm, each 4 mm long, has a theoretical gain of 12 dB (the mouth diameter is four times the throat diameter). Unfortunately, the DDD is only ~6 mm, so the cutoff frequency is 20 kHz. The gain is there, but only for ultrasonic sounds; no one can hear it. On the other hand, if we try for a gain of only 3 dB in that same 12 mm total length, we can pull the cutoff down to ~5 kHz where it might do some good.

What if we bore out just the last 8 mm of a BTE earmold? It will certainly give horn action above its cutoff frequency of 10 kHz or so (depending on the size of the bore), but that is well above the cutoff frequency of most digital hearing aids.

A horn that works against the audiologist is the horn built into the standard 2cc coupler used with test boxes. For years, all BTE hearing aids have been measured with this "HA-2" coupler, whose internal sound channel is 18 mm long, 3 mm in diameter. This provides the larger-diameter section of the horn and the horn action shown in the upper curve of Figure 4. The middle curve in Figure 4 shows what the patient typically hears when a conventional earmold is used (constant-diameter #13 tubing leading from the earhook to the tip of the mold). The patient receives an average of 6 dB less output than the data-sheet response indicates. The advertised response is *not* what is delivered to the patient.

The careful audiologist, of course, tests the aid in a test box using the actual earmold, and/or obtains probe measurements of the actual response. The HA-2 horn is not really a secret, but its continued use in standards is justified only by tradition, and perhaps the fact that the typical BTE response would not look good

Table 1 Effect on Gain and OSPL90 (in dB) of Various Sound Bore Profiles Relative to a #13 (2mm) Tube of Constant Diameter

Sound Bore	Frequency (Hz)								
	250	500	750	1000	1500	2000	3000	4000	6000
Libby 4 mm	-1	-2	-3	-3	-1	-2	6	10	6
Libby 3 mm	-1	-1	-2	-2	1	1	5	5	2
CFA #2 horn	0	0	-1	-1	0	-1	4	6	4
CFA #3 stepped bore	0	0	-1	-1	0	-1	4	6	2
Lybarger high-pass tube	2	4	0	-11	-13	-12	-10	-1	-1
#13 glued-tube	0	0	0	0	0	0	0	-1	-5
6C5	0	1	0	0	0	0	-4	-6	-11
6C10	0	2	0	-2	-1	-5	-10	-12	-17
1.5 LP tube	1	3	0	-9	-10	-9	-10	-10	-12

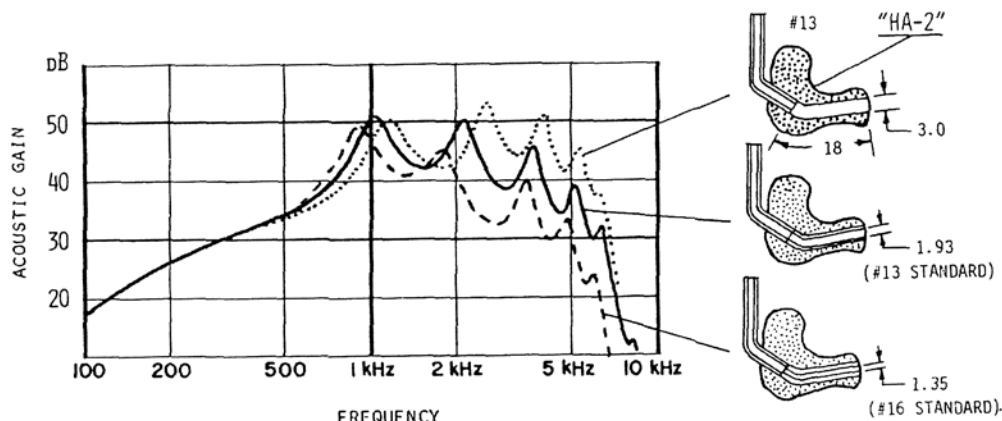From Dillon,[3] used with permission.

Figure 4 HA-2 horn action and constriction action.

without it. The HA-2 coupler is appropriate for a BTE aid that uses horn tubing that matches the coupler horn.

Fortunately, the proportion of BTE earmolds ordered with straight tubing has dropped to less than half (and as low as 11%, according to one laboratory, if tubes going half way are included). This is a welcome change, as indicated by the fact that even a few years ago Dillon, in his already-classic book *Hearing Aids*, based all his BTE CORFIG (coupler response for flat insertion gain) curves on the assumption that the hearing aid would be *measured* with the HA-2 horn but *worn* with a constant-diameter #13 tubing earmold.[3] Ideally, of course, the type of tubing to be used—horn or constant-diameter—should be taken into account in evaluating the 2 cc curve.

Worse than the straight-tube earmold are the few BTE earmolds that still arrive with a reverse horn built in by a drilling and gluing process. More often, perhaps, this reverse horn is created when the original tubing is replaced in the field with heavier tubing. The outside diameter of different grades of #13 tubing varies from 2.95 mm (Standard, which is seldom used now) to 3.1 mm (Medium) to 3.3 mm (Heavy) (R. Morgan, National Association of Earmold Labs, verbal communication, 2002). The inside diameter of all grades is held constant at 1.93 mm in free space, but pulling a Heavy tube through a hole made as a tight fit for a Medium or Standard tube will squeeze it down and choke off the sound channel. The effect of severely

restricting the #13 tubing is shown by the bottom curve in Figure 2. This is almost exactly the amount of restriction that was found in the earmolds illustrated in Figure 1. When this restriction occurs, the delivered response (and undistorted output) at high frequencies is approximately 12 dB less than predicted by the HA-2 coupler response.

A loss of 5-10 dB in high-frequency gain arising from a restriction in the earmold channel can be readily compensated for with programmable hearing aids. The accompanying 5-10 dB loss in maximum undistorted output (just before clipping), however, cannot be corrected by programming.

THEORY: RESONANCES

Some of the horn cutoff frequency estimates above were arrived at by using a shortcut. Instead of estimating the Diameter Doubling Distance and using the horn cutoff formula, a simpler calculation—the frequency of the quarter-wave resonance boost introduced by a stepped-bore tubing construction—was used. The effective horn cutoff frequency of the tubing often coincides reasonably well with the quarter-wave resonance of the large-bore section(s), and the latter is easier to calculate. The formula is:

$f_{1/4 \text{ wave}}$ = 86/L, where L is the length of the large-bore section in mm and the frequency (f) is given in kHz.
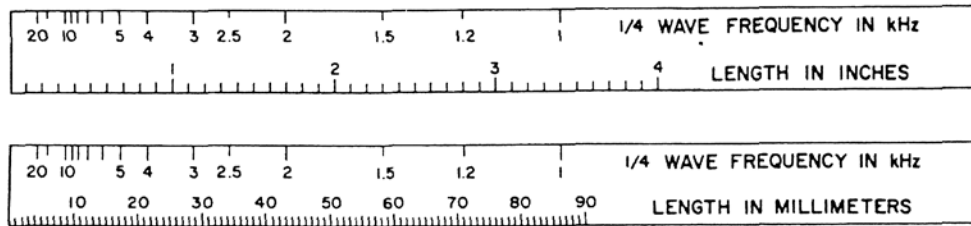
Figure 5 Quarter-wave resonance ruler.

Figure 5 shows a ruler that solves the equation $f = 86/L$. More usefully, a copy magnified 117% can be held up to a section of tubing or the large-bore section in a transparent earmold to estimate the quarter-wave resonance.

THE HOW OF RESONANCE PEAKS

The typical resonance in a hearing aid is a quarter-wave resonance that forms when one end of a tube is blocked and the other is relatively open. The blocked end is at the receiver diaphragm, whose movement is not significantly affected by reflected sound. Acoustically, it is a high impedance source, meaning the volume velocity depends very little on the load. This is the same as saying the receiver diaphragm acts like a rigid wall for reflections. The ear canal, on the other hand, appears as a large bucket to the air velocity coming in, and thus appears as a low impedance load. It reflects a positive pressure pulse as a rarefaction pulse, and we have the conditions for a one quarter-wave resonance that inserts a large peak in the frequency response. It also inserts peaks in the response at frequencies where the tube length is 3/4, 5/4, 7/4, etc. wavelengths.

The resonance peaks come from the fact that sound is reflected back to the receiver from the open end. Assume a push of sound goes down the tube from the receiver. It takes a certain time to go down and come back. At the frequency at which the reflected sound is in phase with the next push from the receiver, the two pushes add and a push of sound twice as big is sent down the tube. This process continues to build up the SPL until the losses equal the energy fed in by the receiver. If the receiver delivers 1 push unit, for example, and the SPL at the resonance frequency builds up to a 20-dB peak (10 times the receiver SPL), a steady-state condition is reached when 10 push units go out, 9 are returned, the receiver adds 1, and 10 push units go out again.

The suspicious reader might wonder how a quarter-wave tube length provides a resonance peak because the returning reflection, having gone a quarter wavelength down and a quarter wave back, should arrive exactly out of phase and cause a cancellation rather than a reinforcement of the receiver output at the quarter-wavelength frequency. The explanation for the quarter-wave resonance is that for a tube open at the far end, the reflection comes back in opposite phase. While down and back gives only a half-wave (interfering) time delay, the inverted reflection puts the returning sound in phase. For example, if you stand at least 25 feet back from the edge of a sharp cliff and clap your hands, you will hear a reflection just as if you were approaching a wall. You would need an oscilloscope, however, to confirm that the returning reflection was inverted in phase. Although not related to earmold response, it is interesting to note that if you stand closer than 25 feet from the edge of the cliff, the echo will occur within the 50 milliseconds time window for the auditory fusion phenomenon studied by psychoacoustians, so you won't hear the echo. Without the ability of the auditory system to fuse early reflections into a single perceptive event, we would hear dozens of echos from our living room walls. A 75 mm quarter-wave tube open at one end and a 150 mm half-wave tube closed at both ends have the same resonance; the tube closed at both ends must be twice as long because its reflections are in phase.

Why do most BTE hearing aids have a response peak at ~1.1 kHz? Some 30 years ago it was popular to blame the Knowles Electronics
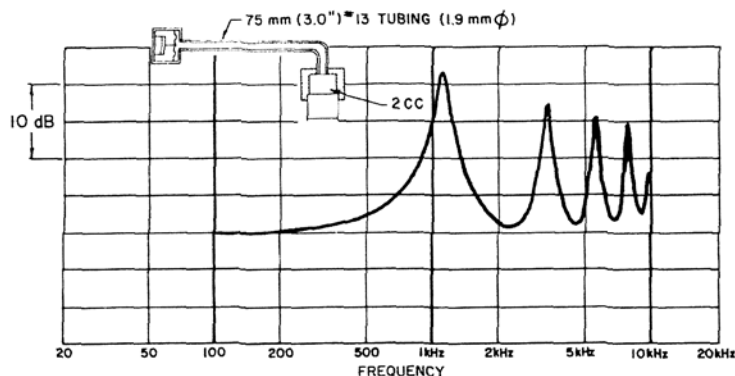
Figure 6 Resonances in constant-diameter tubing.

receivers (Itasca, IL) for the peaks in the BTE response. Most peaks, however, are simply the result of tubing resonances. The typical BTE has a total of 75 mm of tubing from the receiver to the eartip, which—unavoidably— introduces a peak at 86/75 = 1.14 kHz, using the formula given previously. Peaks also occur at ~3.4 kHz, 5.7 kHz, etc. These peaks are illustrated in the simple case of a constant-diameter coupling (Fig. 6).

A milder one quarter-wave resonance occurs when the sound channel changes diameter. The resonance occurs because of reflections from the partial wall formed at the point (looking toward the smaller-diameter tube) where the tubing sound channel suddenly gets larger. The length from there to the open end of the tube forms the one quarter-wave resonance length.

If the 18 mm length in the HA-2 coupler is increased to 22 mm, then the quarter-wave resonance boost moves down from 4.8 kHz (which is a little high) to a more favorable 3.9 kHz.

While a smooth-tapered horn (the trombone, for example) is not needed for horn action, the smooth taper gives a more uniform high-frequency response. Because musical instruments need to play a continuous range of notes with equal energy, stepped-bore tapers are not generally found in brass instruments.

PRACTICAL USE OF RESONANCES

In hearing-aid design, quarter-wave resonances can come in handy. An earmold designed to produce its maximum boost at a particular frequency (such as the 2.8 kHz frequency of the open-ear resonance) could use a quarter-wave resonance boost to help out. In Figure 7, the use of horn and two quarter-wave boosts are shown to provide a resonance boost at 2.8 kHz (the total 30 mm section) plus a boost at 8 kHz (the 11 mm section), even in the presence of heavy smoothing with two dampers.[6]

The 8CR earmold provided an early high-fidelity hearing aid design,[7] something that can now be created with electronic (analog or digital) equalization.[8-10] With today's technology, the same thing can be done with one of the Horn earmolds (Table 1) and electronic adjustments without fear of clogged dampers.

Even so, there are still times when the response shaping of the Etymotic Research series of special earhooks provides the simplest solution to a difficult reverse-slope or cookie-bite audiogram.

DAMPING

The two responses shown in Figure 7 illustrate an undamped and a damped response. The smoother response results from the presence of acoustic dampers, which absorb acoustic energy (by turning it into heat!). The action is not unlike the energy that is absorbed by the tightly woven cloth of your shirtsleeve as air blows through it. The careful reader will recall that a 20 dB resonance peak occurs when only 10% of the pressure is lost on each round trip of the reflected energy. A damper that absorbs enough so that only 30% of the pressure is returned will drop the peak to 3 dB.

It should be self evident that a damper using a weave that is too open will present little
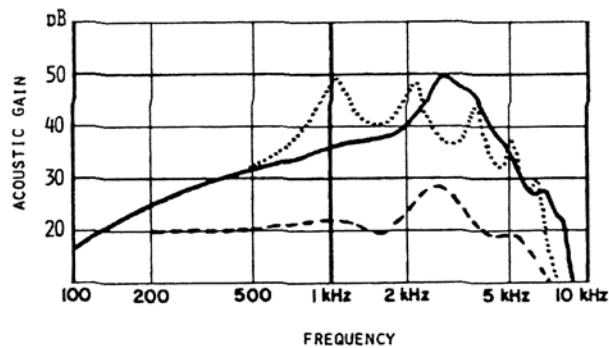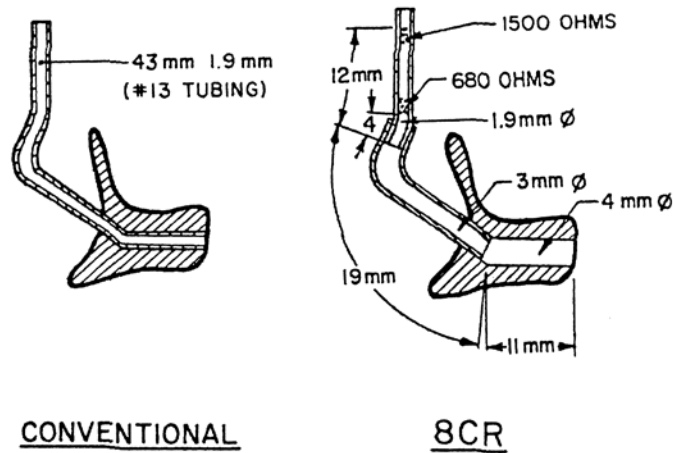
Figure 7 The 8CR earmold: intentional use of one-quarter-wave resonances.

resistance to the flow of air and have very little effect on the response. A damper having too tight a weave, on the other hand, may present so much resistance that very little sound gets through, much like a tube clogged with wax. A cantankerous engineer named Heaviside[11] got kicked out of Britain's Royal Philosophical Society for proving that its members were either stupid or ignorant of the laws of nature. The members of the Society stoutly held that a telephone conversation could not go great distances before the distributed resistance and capacitance of the telephone lines would kill the high-frequency response. Heaviside realized that not only was that incorrect, but that it was possible to obtain a completely high-fidelity transmission if the *correct* value of resistance was placed at the end of the line; it would completely damp the peaks without *affecting the response between the peaks.* This response is illustrated in Figure 8.

This apparent magic can be partly explained by observing that the damper absorbs more energy as more volume velocity of sound passes through it, so that it automatically acts to damp the tubing resonances and leave the rest of the response more or less untouched.

Although Heaviside calculations were for telephone transmission lines, exactly the same response to the question of "how much resistance do I need" applies to earmold tubing— the resistance should equal the characteristic impedance of the acoustic transmission line formed by the tube. In the case of acoustic tubes, the formula is:

$$R_0 = /Z_0/ = 41/\text{Area}, \text{ where the answer is in}$$
cgs (*centimeter-gram-second*) acoustic ohms for Area in cm^2.

For example, a #13 tubing has a sound channel (inside diameter) of 1.93 mm (0.193
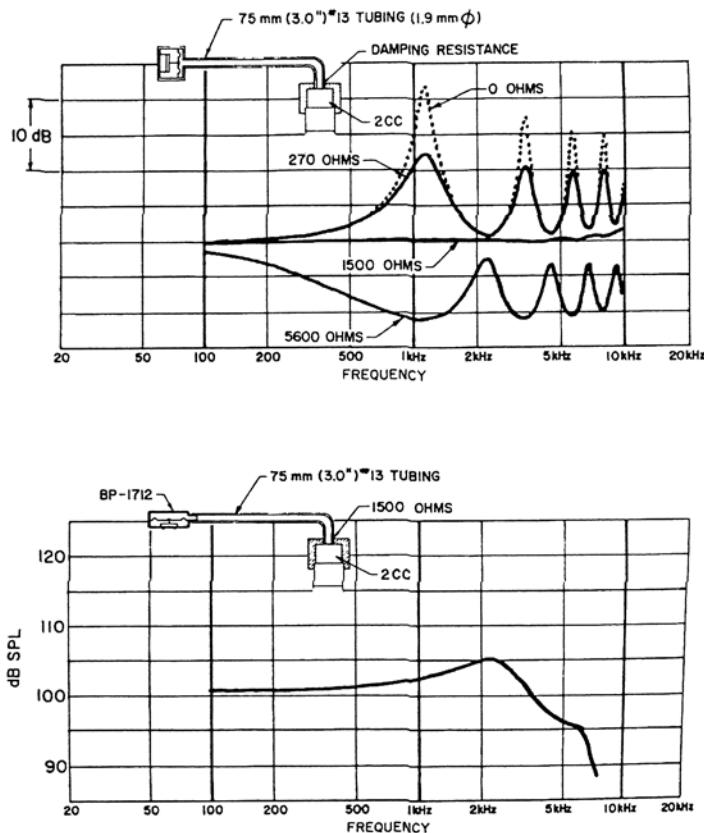
Figure 8 Heaviside's solution: The right value damper gives perfectly flat tubing transmission.

cm), and an area of 0.029 cm², making R_0 = 1400 ohms. A 1500-ohm resistor will damp the tubing resonances in #13 tubing (Fig. 8). With the damper located in the earhook, somewhat different values may, in practice, give a better response.

The world of BTE acoustics would be simple if dampers could be placed near the tip of the earmold. In many ears, unfortunately, such dampers become quickly clogged with earwax or moisture. This is true for both BTE and ITE aids. Because of the earwax problem, dampers located at the earmold tip or in the earmold tubing are less common today. Most BTE dampers are now located in the tip of the earhook of the hearing aid. That location does *not* provide damping at frequencies near the frequency where the roughly 40 mm between the tip of the earhook and the damper is one-quarter wavelength, or at the frequency f = 86/40 = 2.2 kHz. That is not so bad because we usually prefer a bit of

peaking at 2.8 kHz, the resonance of the external ear. At other frequencies, the ear tip location provides good damping. That explains why the desired 2.8 kHz and 8 kHz peaks in the 8CR earmold (Fig. 7) were not suppressed, while the other peaks were.

VENTING AND DEEP SEALS

In the author's view, there are only four *acoustic* reasons to vent beyond a tiny moisture vent[12]:

(1) to reduce the mid-low-frequency response of a hearing aid because it has no real highs,

(2) to allow undistorted low-frequency sounds in through the vent because the low-frequency output of the hearing aid is distorted,

(3) to reduce low-frequency noise from the hearing aid (especially in the case of patients with normal low-frequency hearing), and

(4) to reduce the annoyance of the patient's own voice because of the occlusion effect.

The first two are readily dispensed with because they have little validity today for most hearing aids. Indeed, the effect of a large amount of venting is often to put a 5–12 dB *boost* in the response in the 300–800 Hz region. One of the reasons for sealing the vent when making test box measurements is because the vented response looks so bad. However, the response in the ear will not appear as bad because slit-leakage damping and eardrum-resistance damping usually tame the vent resonance peak somewhat. Real-ear response measurements often show that the slit leak is more important than the vent.

VENT EFFECT

At this point, it is worth reviewing the topic of overall vent effect, which is the sum of the vent-reduced sound from the hearing aid and the natural sound coming into the open ear through the vent.

At first glance, the effect of a vent seems to be to roll off the lows (Fig. 9); however, at sufficiently low frequencies the sound coming in through the open vent can dominate and the hearing aid output does not matter.
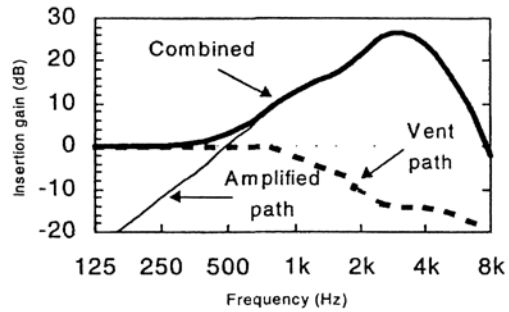

Figure 9 Insertion gain of the vent path and the amplified path, and the way these might combine to form the insertion gain of the complete hearing aid (Dillon[3], used with permission).

Two Problems with Venting

The first problem accompanying a large amount of venting is that it can reduce the effectiveness of directional-microphone hearing aids. The combination of venting and low-frequency rolloff in a directional-microphone hearing aid (sometimes done intentionally to invoke the "WOW" effect on how much the hearing aid decreases the noise) may reduce or eliminate the low-frequency directivity of the microphone. Figure 10 illustrates a case where the AI-DI (effective noise reduction estimated from the articulation-index weighted directivity index of the aid) has been reduced an estimated 1 dB
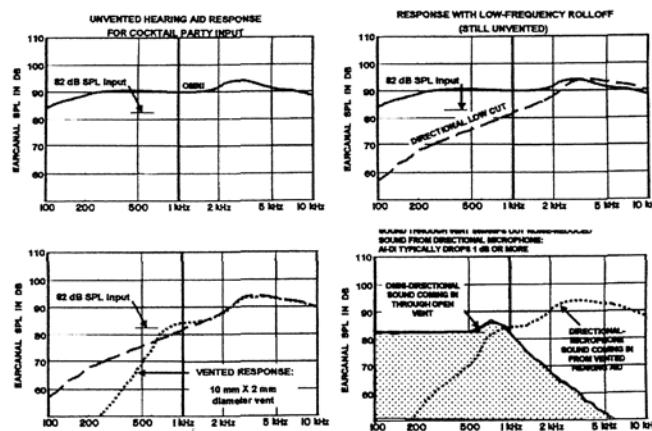

Figure 10 In this example, the effective noise reduction estimated from the articulation-index weighted directivity index of the aid has been reduced an estimated 1 dB by the combination of venting and low frequency rolloff.

by the combination of venting and low-frequency rolloff. This example assumed a typical 82 dB SPL cocktail party noise and the 8 dB gain prescribed by Figure 6 at that level to achieve a flat loss of a little over 50 dB HL. Caution should be exercised in venting if the maximum directivity is desired.

The other problem is the well-know problem of feedback from venting. The greater the amount of venting, the greater the likelihood of feedback whistling from sound leaking out of the vent. The only point needed here is the reminder that "Y" vents cause even greater problems.

THE OCCLUSION EFFECT

The need for venting is real and acute in a typical earmold with a shallow seal in the ear canal. Anyone who has worn such hearing aids for prolonged periods of time has almost certainly experienced the annoyance of the occlusion effect. The annoyance is pervasive. At breakfast, for example, the crunch of cereal can virtually preclude conversation because of the 80–100 dB SPL that the noise can produce.

The effect of different size vents on occlusion in a male subject is illustrated in Figure 11. The SPL in the subject's ear canal behind an unvented earmold exceeded 105 dB. Even with the vent he was using, his own voice created over 90 dB SPL in his ear canal. Several recordings of the occlusion effect are available.[13]

Venting reduces the occlusion effect, as illustrated in Figure 11. Indeed, venting acts on the occlusion effect sound exactly as it acts on the direct output of the hearing aid.

A BETTER SOLUTION: DEEPLY SEALED EARTIPS

Several years ago, in response to the request of members of the Chicago Symphony Orchestra who sat directly in front of the "world's most powerful brass section," the author's company (Etymotic Research, Inc., Elk Grove Village, MI) introduced what are called high-fidelity Musicians Earplugs.[14] These had actually been developed by Elmer Carlson[15]; Etymotic Research makes and sells the earplugs under license from Knowles Electronics.) We quickly determined that anyone playing an instrument that vibrated the lips or jaw could find that the occlusion effect almost defeated the purpose of the earplugs. In fact, one jazz trombone player reported that he had roaring tinnitus after playing with the plugs in place!

The solution was and still is to obtain deep impressions, well beyond the second bend, and to have the earmold laboratory make vinyl or silicone earmolds that sealed at or near the bony portion of the ear canal. In the case of the trombone player, once new impressions were taken and new earmolds were made, his occlusion effect disappeared and he obtained the desired protection from the trumpet players behind him.
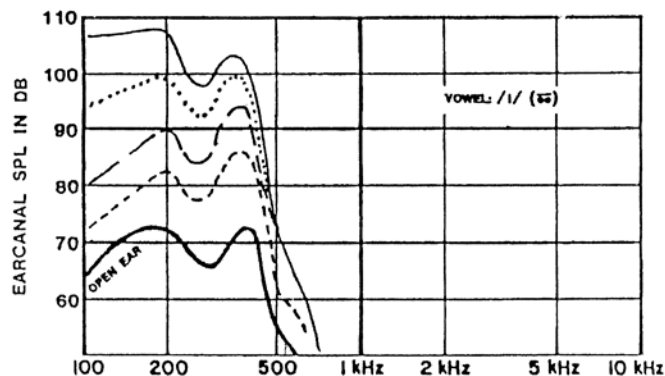

Figure 11 The amount of ear canal SPL produced by one person vocalizing /i/(ee) in a closed earmold, an open ear, and with various amounts of venting.

Although we had previously demonstrated to our satisfaction that deeply sealed earmolds could eliminate the occlusion effect,[16] just as Zwislocki had indicated, the question for the first few years was whether or not such deeply sealed earmolds would be comfortable. While it is probable that not all the Musicians Earplugs made over the past 14 years have been deeply sealed, many of them have been, including several pairs made for the author. The deeply sealed earmolds can be entirely comfortable.

Another great advantage of deeply sealed earmolds is that they can reduce feedback. Once an earmold is well sealed in the ear canal, there remains an important feedback path. The sound behind the earmold causes the earmold to pump in and out of the ear canal, causing a newly radiated sound just as if the surface of the earmold or hearing aid were a miniature loudspeaker. Nothing much can be done about this pumping as long as the earmold is sealed in the fleshy cartilaginous portion of the ear canal, where there is little to restrict the movement of the ear tip. Once in the bony portion, however, the extremely thin layer of skin over the bone provides high mechanical shear impedance. An earmold sealed in the bony portion will exhibit less feedback.

So a deeply sealed soft eartip attacks two problems simultaneously: feedback and the occlusion effect. The lack of adequate ear impressions probably has been the major limitation to its use.

SUMMARY

Many of the most vexing problems with hearing aids can be alleviated or cured by careful attention to earmold construction: (1) Avoid squeezing down the sound channel inside the earmold. This can be done by use of one of the constant-diameter elbows, such as the CFA. (2) The undistorted high frequency output of a hearing aid is critically dependent on earmold construction. An additional 5–7 dB of clean sound can be obtained with one of the horn or CFA constructions. (3) Venting should be done carefully if maximum directional performance is expected. (4) The writer's experience teaches

him that a deeply sealed soft shell that seals at or near the bony part of the ear canal can completely eliminate the occlusion effect.

ABBREVIATIONS

AI –DI	articulation-index weighted directivity index
BTE	behind-the-ear
CFA	continuous flow adapter
CORFIG	coupler response for flat insertion gain
DDD	diameter doubling distance
Dm	diameter of the mouth of the horn
Dt	diameter at the beginning or throat of the horn
ER	Etymotic Research
HL	hearing level
ITE	in-the-ear
OSPL	output sound pressure level
SPL	sound pressure level

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