

Hearing Aids

Second Edition

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CHAPTER 5

HEARING AID EARMOLDS, EARSHELLS AND COUPLING SYSTEMS

Synopsis

An earmold or earshell is molded to fit an individual's ear and retains the hearing aid in the ear. Pre-molded canal fittings, available in a range of standard sizes and shapes, are an alternative way to connect the hearing aid to the ear canal. Whether custom molded or pre-formed the ear fitting retains the sound bore, which is a sound path from the receiver to the ear canal. In many cases the fitting provides a second sound path, referred to as a vent, between the air outside the head and inside the ear canal. Where no vent exists, as in high-gain hearing aids, the fitting is said to be occluding. Where the cross-section of the ear canal remains largely unfilled for its entire length, the hearing aid is said to be an open fitting, or an open-canal fitting. The three functions of an ear fitting are thus physical retention, transmission of amplified sound to the ear canal, and control of the direct sound path between the ear canal and the air outside the head.

There is a wide variety of physical styles of both earmolds and earshells. These styles vary in the extent of the concha and canal that they fill. These variations affect the appearance, acoustic performance, comfort, and security of retention of the hearing aid.

One unwanted consequence of a hearing aid can be an occlusion effect, in which the aid wearer's own voice is excessively amplified by bone-conducted sound. For many hearing aid fittings, vent selection is a careful juggle between choosing a vent that is big enough to avoid an unacceptable occlusion effect, but not so big that it causes feedback oscillations, or limits the ability to achieve sufficient low-frequency gain and maximum output. For patients with mild or moderate hearing loss, the choice will often be an extremely open fitting comprising a BTE connected to thin tubing, or a wire connection for a RITE style, terminating in a pre-formed, flexible, perforated, dome-shaped canal fitting.

For any ear fitting with a vent or other direct path to the outside air, the speech range of frequencies can

be subdivided into the vent-transmitted frequency range, the amplified frequency range, and the mixed frequency range that is intermediate to these. Hearing aids perform very differently in each of these ranges.

The shape of the sound bore that connects the receiver to the ear canal affects the high-frequency gain and output of hearing aids. Sound bores that widen as they progress inwards (horns) increase the high-frequency output. Conversely, those that narrow (constrictions), whether by design or as a consequence of poor construction technique, decrease the high-frequency output. Horns have to exceed a certain length if they are to be effective within the frequency range of the hearing aid.

Dampers are used within the sound bore to smooth peaks in the gain-frequency response. Careful choice of the placement and resistance of the damper can also control the mid-frequency slope of the response.

The key to a well-fitting earmold is an accurate ear impression. This requires an appropriate material (medium viscosity silicone is good for most purposes), a canal block positioned sufficiently deeply in the canal, and smooth injection of the impression material. Tighter earmolds or shells that reduce leakage of sound from the ear canal can be achieved by a variety of techniques. These techniques include taking an impression with the patient's jaw open, patting down the impression material before it sets, using viscous impression material, and building up the impression in the patient's ear.

Earmolds are made from a variety of materials. The most important difference between materials is hardness. Soft materials provide a better seal to the ear, but they deteriorate more rapidly, can be more difficult to insert, and are more difficult to modify and repair. Earmolds and earshells are routinely constructed by computer-aided manufacture in which lasers guide the "printing" of plastic based on a scanned image of the ear impression.

The earmold (for a BTE), the earshell (for an ITE, ITC, or CIC), and the pre-molded canal fitting (for a thin-tube or RITE BTE) will collectively be referred to as ear fittings. An ear fitting performs three essential functions:

- it couples sound from the hearing aid receiver to the aid wearer's ear canal via the **sound bore** (a tube), and consequently affects the gain-frequency response of the hearing aid;
- it controls the extent to which the inner part of the ear canal is open to the air outside the head (the **venting**), and consequently affects the gain-frequency response, and electroacoustic comfort of the hearing aid; and
- it retains the hearing aid in the ear in a comfortable way.

There is an initially bewildering array of ear fitting styles and materials, some of them proprietary to particular manufacturers of earmold or hearing aids, and some with multiple names. This chapter will help the clinician select an ear fitting that achieves a required combination of sound bore acoustic characteristics, venting characteristics, and retention characteristics.

Consider, for instance, the two earmolds shown in cross-section in Figure 5.1. These two earmolds look completely different. Earmold (a) is a very bulky earmold that completely fills the concha, but it has a vent drilled through the mold. Earmold (b) contains very little material in the concha and in the canal, and may be referred to as a **CROS mold** or **Janssen**

mold. Provided, however, the cross-sectional area of the drilled vent in earmold (a) equals the cross-sectional area of the open space between the sound bore and the canal walls in earmold (b), and provided the two sound bores have the same length and internal diameter, the two molds will have extremely similar acoustic effects on the gain-frequency response and OSPL90 of the hearing aid. Earmold (a) will, of course, be retained much more tightly in the ear than earmold (b).

In this book, *any opening between the inner part of the ear canal and the free air outside the ear will be called a vent*, irrespective of whether it has been formed by drilling a hole (Figure 5.1a) or by forming the canal portion of the ear fitting so that it does not completely fill the cross-sectional area of the ear canal (Figure 5.1b). These methods can be combined to provide a vent path comprised of a hole drilled through the concha part of the mold or shell leading to an open area within the canal portion. Conversely a canal dome fitting can have several openings in the dome within the canal, and no obstruction in the rest of the canal or in the concha. Yet another way to make a vent is to grind a groove along the outer surface of the mold or shell, all the way from the canal tip to the faceplate. This is called a **trench vent** or an **external vent**.

Ear fittings can be **occluding**, **open**, or anywhere in-between. Occluded fittings are those that have no intentional air path between the inner part of the ear canal (the **residual canal volume**) and the outside air. Occluded fittings therefore have no vent: the ear fit-

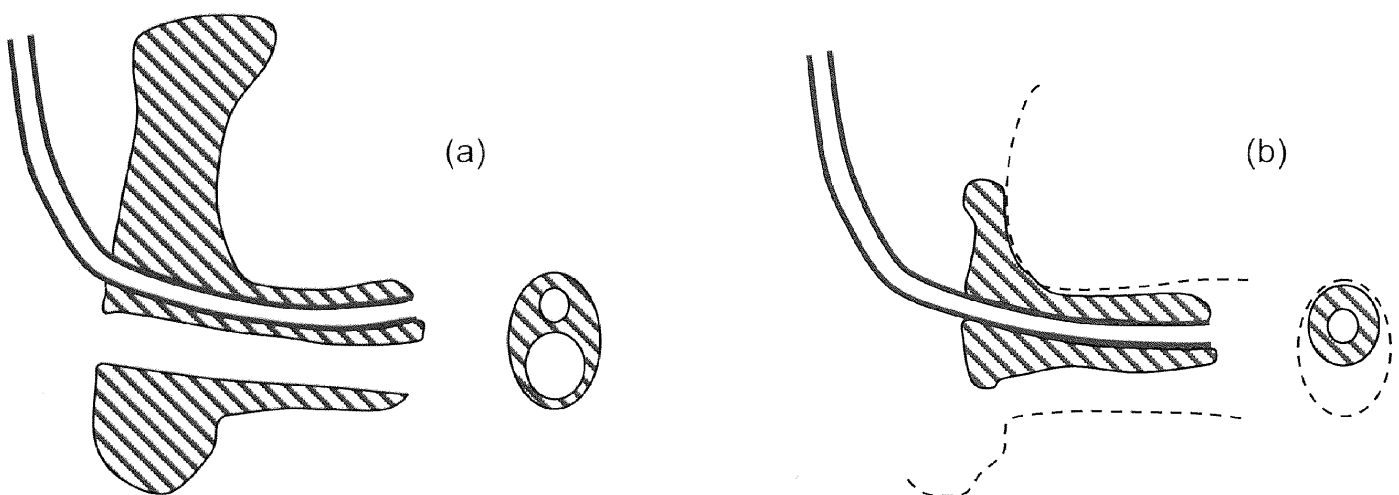


Figure 5.1 Cross sections of (a) a full concha earmold with a wide vent and (b) a Janssen mold that would have extremely similar acoustical properties, but different retention properties. See also Figure 5.4 for perspective views of these molds.

ting completely fills the cross-section of the canal, for at least part of its length. Occluded ear fittings may, and usually do, have a *leakage path* around them as a consequence of: imprecision in the impression of the ear; imprecision of the mold or shell made from the impression; incorrect size or shape of a pre-molded fitting; or flexibility of the ear canal. This leakage path has properties similar to those of a vent, and is sometimes referred to as a *slit-leak vent*.

Open canal (OC) fittings are those that leave the canal almost completely open for its entire length, most commonly achieved with an open dome fitting as shown in Figures 1.7 and 5.4. The term *non-occluding* is more general; in fact, so general that it is practically meaningless. By non-occluding, some people mean that there is some vent path, no matter how small. Other people would describe an ear fitting as non-occluding only if most of the canal cross-section

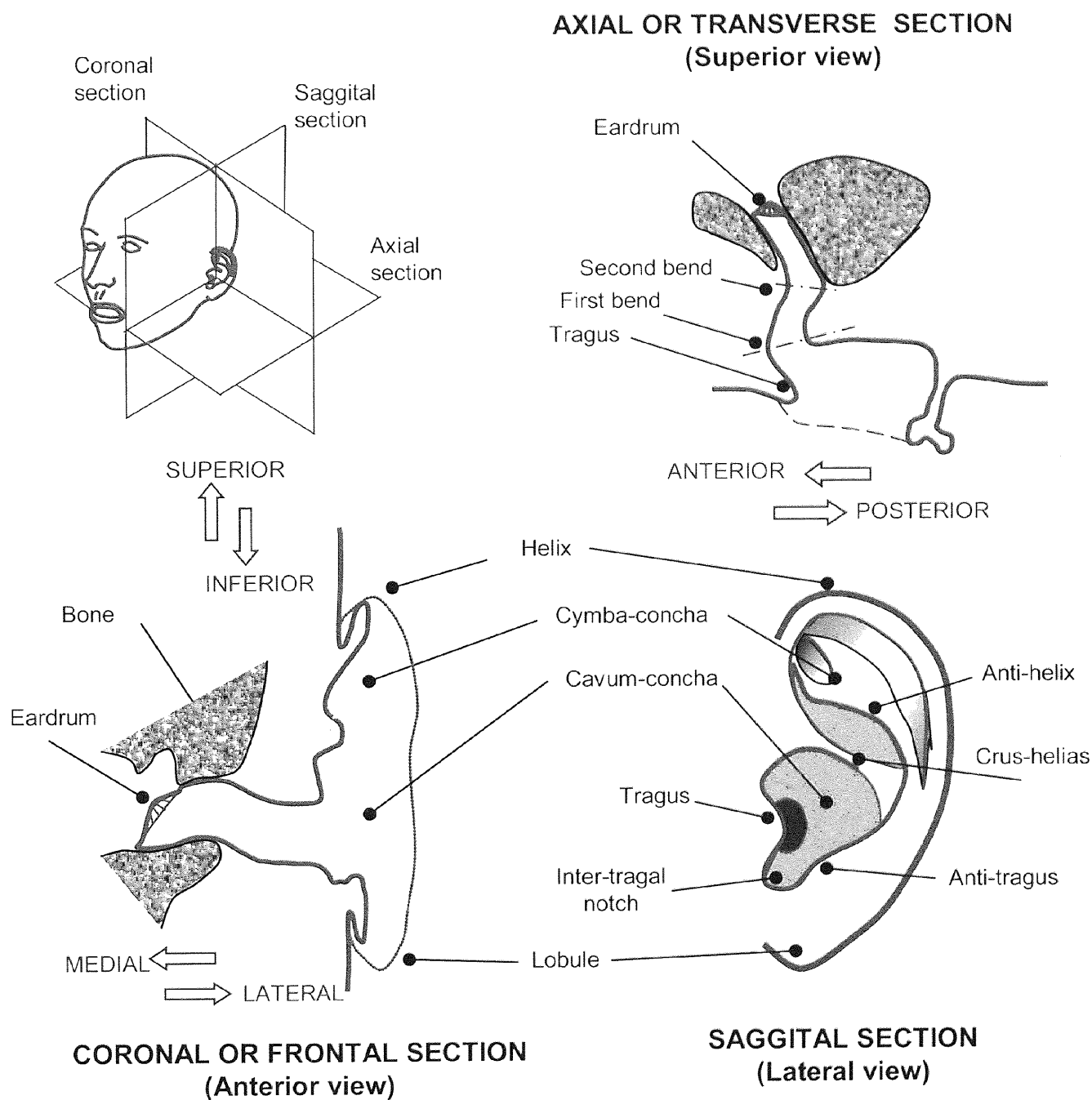


Figure 5.2 Side view and cross section of the external ear, drawn to average full-size dimensions and typical shape,^{1542, 1684} and the names given to various parts of the ear.¹⁶¹⁷

tion were left open for its entire length. Some people may define *non-occluding* in terms of the hearing aid wearer's subjective impression of the earmold, as discussed in Section 5.3.2. There is, of course, a continuum of openness from being completely occluded to being completely open, and the term *non-occluding*, if used at all, should be used in a way that makes its intent clear. All "non-occluding" ear fittings are, in fact, partly occluding, even if the occlusion is minimal.

5.1 Earmold, Earshell and Canal Fitting Physical Styles

Earmolds and shells of different styles fill different portions of the concha and the canal. The parts of the molds and shells can be described by the corresponding parts of the ear in which they fit. Let us therefore review some names for parts of the ear, and for an earmold or earshell³⁷ as shown in Figures 5.2 and 5.3. Some features of the ear have particular significance for hearing aid fitting. The inner half of the ear canal, the **bony canal**, is bounded by smooth skin only 0.2 mm thick overlaying bone³⁶ and is very sensitive to applied force. In the outer half of the canal, the

cartilaginous canal, the skin is much thicker, overlies cartilage, and is less sensitive. Cerumen is produced by glands and these are located only in the cartilaginous part of the canal. Earmold manufacturers refer to the section of the canal just inside the ear canal opening as the *aperture*, and the corresponding part on the earmold can be called the *aperturic seal* (because the earmold most readily seals to the ear canal in this region).

The earmold has two easily recognizable bends. The *first bend* (the most lateral bend) although a pronounced feature on a mold or impression, is less evidently a bend when looking at the ear. The posterior surface of the tragus is continuous with the posterior wall of the canal. The first bend is in fact coincident with the ear canal entrance or a few mm inside the canal, depending on where one considers the entrance to be. The *second bend* marks the start of the transition from the cartilaginous canal to the bony canal, first on the posterior wall, and further in on the anterior wall. The first and second bends are much more acute for some people than for others. When people have a sharp first bend, however, they also tend to have a sharp second bend, so that the most inner and most outer segments of the canal tend to be parallel to each other when viewed as a transverse section.¹⁴²⁰

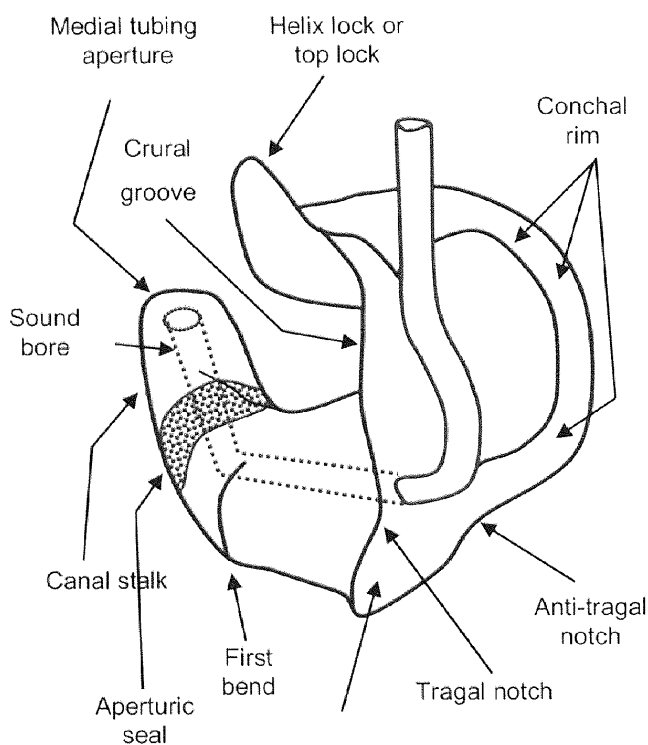


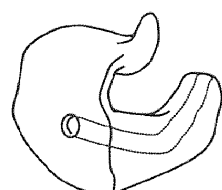
Figure 5.3 Names given to various parts of an earmold or ear shell, based in part on Alvord, Morgan & Cartright (1997).

5.1.1 BTE earmold styles

One of the difficulties in describing different styles of earmolds is the lack of standardization of names. Although the American National Association of Earmold Laboratories (NAEL) agreed on some standard names in 1976,³¹⁹ many new styles have been invented and re-invented since then. Some earmolds are usefully given a descriptive name (e.g. *skeleton*), some are named after their inventor (e.g. *Janssen*) and some are confusingly named after the application in which they were originally used (e.g. *CROS*), even though they are used more frequently in other applications.

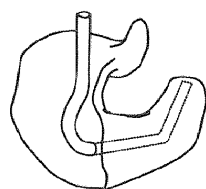
Figure 5.4 shows a number of earmold styles that are available from different earmold manufacturers. The names may vary from manufacturer to manufacturer. The diagram does *not* include styles that differ only in the diameter of the sound bore. Every one of the styles shown could include a sound bore that widens or constricts along its length, so it is unnecessarily confusing to give a new name to an earmold on the basis of its sound bore internal diameter(s). The effects of sound bore variation, and names for several

commonly used sound bore shapes, will be covered in Section 5.4. Those in the bottom row are pre-molded canal fittings supplied by hearing aid manufacturers, and are typically used with thin tubing. These have become the most commonly used method of holding the tube of a BTE in the ear canal.

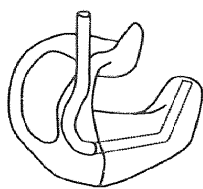


"Standard" mold

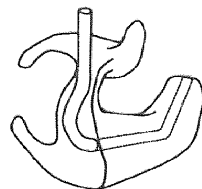
Figure 5.4 Earmold styles for BTE hearing aids.



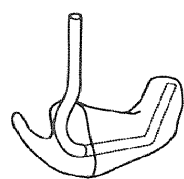
Carved shell



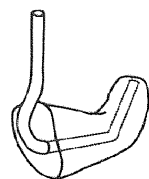
Skeleton



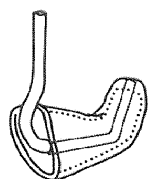
Semi-skeleton



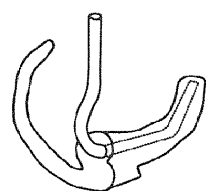
Canal lock



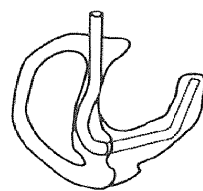
Canal



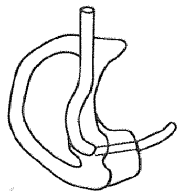
Hollow Canal



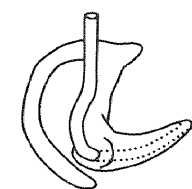
CROS - A



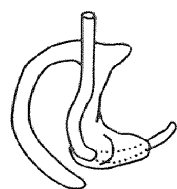
CROS - B



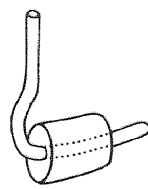
CROS - C



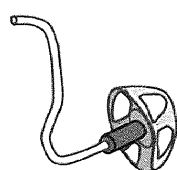
Janssen



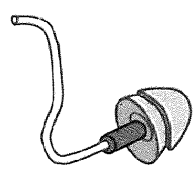
Free Field



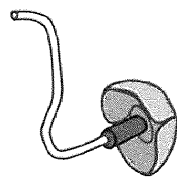
Sleeve



Open dome



Closed dome



Tulip

The **receiver mold** (confusingly called a **standard** or **regular** mold, despite being rarely used these days) is the only one that can be used for a body aid: a button receiver clips firmly into the ring on the surface of the mold. It can also be used for a BTE aid by clipping a plastic angle piece into the ring. A length of tubing connects the angle piece to the hearing aid earhook. For BTE use, however, its disadvantages (leakage of sound, appearance, potentially decreased high-frequency response) outweigh its advantage (easy replacement of tubing).

A better way to enable tubing to be easily replaced is to have an elbow mounted in the earmold, to which the tubing is connected, as shown in Figure 5.5a. The sound bore inside the mold consists of a drilled hole rather than a tube. To avoid decreasing the high-frequency response of the hearing aid, the internal diameter of the elbow should be the same as that of the tubing. One particular brand of elbow that achieves this is known as a **Continuous Flow Adapter (CFA)**TM, as shown in Figure 5.5b.

The top seven earmolds shown in Figure 5.4 can be ordered as occluding earmolds, or they can be ordered with vents drilled through them. The remaining six molds and the open dome can never be completely occluding, because the canal portion of the mold does not fill the entire cross-section of the ear canal at any point along its length.

The most commonly used fittings are the pre-molded, **dome-shaped** canal fittings and thin sound-bore tubing shown in the bottom row of Figure 5.4. These

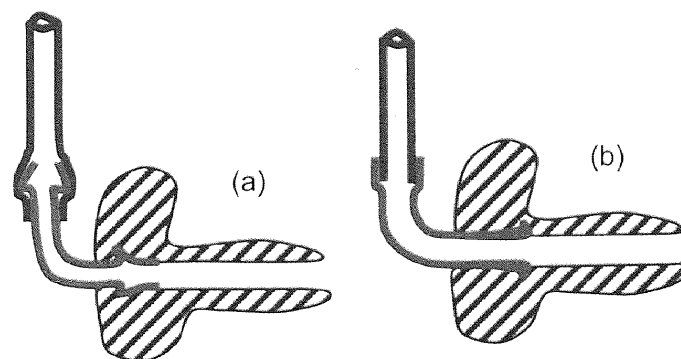


Figure 5.5 Two types of elbows used in BTE earmolds. In (a) the tubing fits around the elbow, which creates some constriction. In (b) the tubing fits inside the elbow.

have a soft flexible flange or flanges and come in a range of diameters, and tubing lengths. There are essentially two styles, the *open dome* with holes in the flange which is designed to leave the canal as open as possible, and the *closed dome* with no holes which is designed to seal the canal as completely as possible. Because the fitting is completely enclosed within the ear canal, and because it is mostly combined with thin tubing and very small BTE hearing aids, the open and closed dome styles, and the very similar tulip style, enable a very inconspicuous overall appearance. The same designs are used for RITE hearing aids, except that the central portion of the dome contains the receiver, encased in plastic, so the sound bore is only 1 or 2 mm long. For RITE hearing aids, the thin tube from the hearing aid is replaced by an equally thin electrical connection to the receiver, so the result is just as inconspicuous.

The dome and tulip fittings also have the advantage of not requiring an ear-impression to be made, and so facilitate same-day fitting. Selection of the correct dome size and tubing length is important: if the dome is too large it will be uncomfortable; if too small it will fall out, or itch as it moves around. If the tubing is too long or short then either the hearing aid will not sit comfortably behind the ear or the dome will not sit comfortably within the ear canal. The open dome fittings fulfill the same function acoustically as the *sleeve mold*²³⁵ and *vented hollow canal mold*,⁹⁹⁸ and have largely superseded them. The latter two designs may, however, be better retained in the ear.

The top four molds in Figure 5.4 are shown with the *helix lock* segment intact. Each of these molds can be ordered with the helix lock removed, or the helix lock can be cut or ground away by the clinician. Retaining the helix lock helps the mold stay in place, and thus maximizes security of the aid, provided the user can fully insert the mold with the helix lock properly tucked in under the helix and anti-helix. By helping retain the earmold in its correct position, the helix lock can also slightly decrease the likelihood of feedback.^{1012, 1189} Unfortunately, many people cannot tuck in the helix lock properly, in which case its presence pushes the mold out of position, thus increasing feedback. The helix lock area of the mold can also create pressure discomfort. Some patients find it easier to insert the mold if the helix lock is removed.¹¹⁸⁸ Consequently, some clinicians order molds without a helix lock for all patients, whereas others start with it in, and remove it if it creates problems.

There are systematic procedures that can be followed for determining how open (i.e. non-occluding) an earmold should be for a particular aid wearer, as outlined in Sections 5.3 and 5.7. It is not so clear how to systematically choose between molds that differ only in appearance, fragility, and degree of retention properties (e.g. shell versus skeleton versus semi-skeleton, or CROS-A versus CROS-B). There is no difference in the retention properties or occlusion properties of a shell versus a skeleton, because the material removed to turn a shell into a skeleton comes from the center of the concha region. As a general rule, the mold becomes less firmly anchored in the ear as more and more segments are removed from around the rim of the concha, and as the diameter of the canal stalk is decreased below the diameter of the ear canal itself. For people who have pinnae that move excessively during talking, chewing and head turning, however, the mold or shell may be best retained if it makes minimal contact with the concha, in which case a canal-sized ear fitting may be optimal.⁸⁴¹

No matter what style of earmold or earshell is selected, there must be a *retention region* somewhere on it. A retention region is an area where the earmold or shell pushes against the skin if it were to start moving out of the ear canal. The part of the ear against which the retention region pushes might be the canal wall, the tragus, anti-tragus, or the helix. If the retention region is too small or not sufficiently angled against the exit motion, the earmold will work its way out of the ear. If the retention region is too large or excessively angled against the exit motion, it will be hard to insert the earmold.¹⁴¹⁷

5.1.2 ITE, ITC, and CIC earshell styles

Because the electronics of the hearing aid are inside the shell for an ITE, ITC or CIC hearing aid, there are fewer possibilities for alternative shell styles within each of these classes of hearing aids. ITE hearing aids that extend above the crus-helias are classified as *full-concha ITEs*, those that are fully contained below the crus-helias are referred to as *half-concha ITEs*, and those that fit entirely above the crus-helias could be called *cymba-concha ITEs*, although they are too new to have developed a terminology. These differences are best seen from a lateral view, as shown in Figure 5.6.

If the full-concha or half-concha ITEs do not extend laterally sufficiently far to fill the concha, they are referred to as *low-profile ITEs*. ITC hearing aids

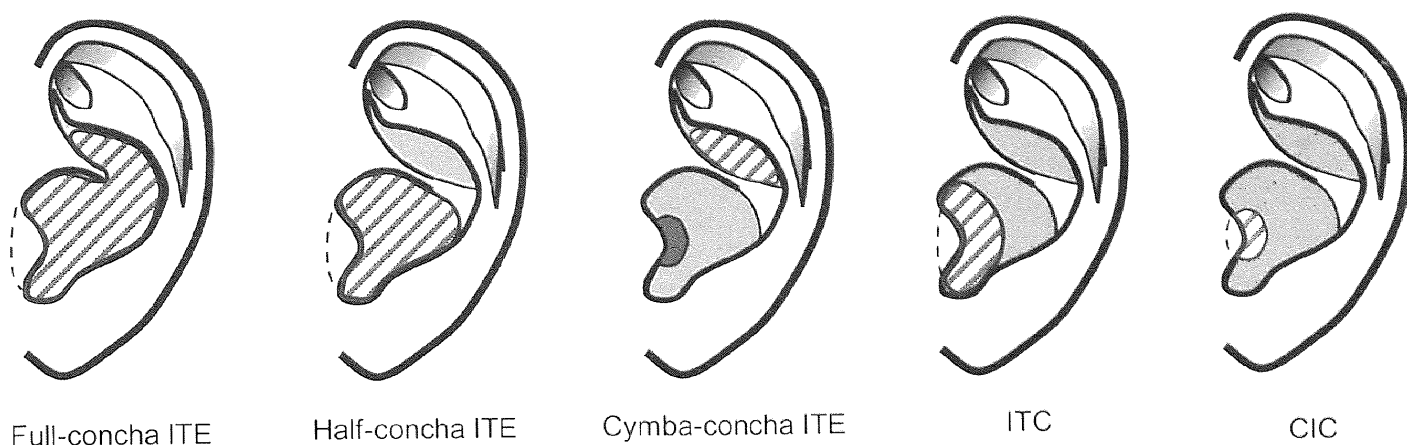


Figure 5.6 Lateral view of different ITE, ITC, and CIC hearing aid styles, with the visible part of faceplate shown hatched.

that extend only part of the way along the posterior-medial wall of the tragus are sometimes referred to as *mini-canal* hearing aids. Mini-canal hearing aids can be thought of as low-profile ITCs.

The distinction between ITEs, low-profile ITEs, ITCs, CICs, and deeply seated (long-wear) CICs can best be seen in an axial section through the ear, as shown in Figure 5.7. The faceplate of an ITE (whether low- or high-profile) is approximately parallel to the plane containing the lateral surfaces of the tragus and helix. The faceplate of an ITC, by contrast, is approximately at right angles to the posterior-medial surface of the tragus. The faceplate of CIC hearing aids may be at the ear canal entrance or medial to the entrance. Any hearing aid that extends to within a few mm of the eardrum is referred to as *peri-tympanic*, or as *deeply-seated*, but it is rare for any hearing aid other than a CIC to extend this far. One such device on the market is inserted by a clinician and is then worn continuously for several months until the battery is depleted,

when the whole hearing aid is disposed of and a new one inserted by the clinician. As the hearing aid itself is out of reach of the patient's fingers, a remote control of some type is needed to turn the hearing aid on or off or change the volume control.

Many of the comments made about BTE molds are also true of earshells. In particular, earshells can be occluding or partly occluding and, in general, the hearing aid becomes less securely anchored in the ear as more of the concha material is removed. Despite this generality, ITC and CIC hearing aids, with little or no material in the concha, can usually be retained in the ear provided that an appropriate impression technique is used (see Section 5.8).

When the vent path in an ITE or ITC hearing aid is opened out by removing some of the shell at the medial and lateral ends of the vent, leaving only a short, wide vent path, as shown in Figure 5.29b, the style is called an IROS vent.^a

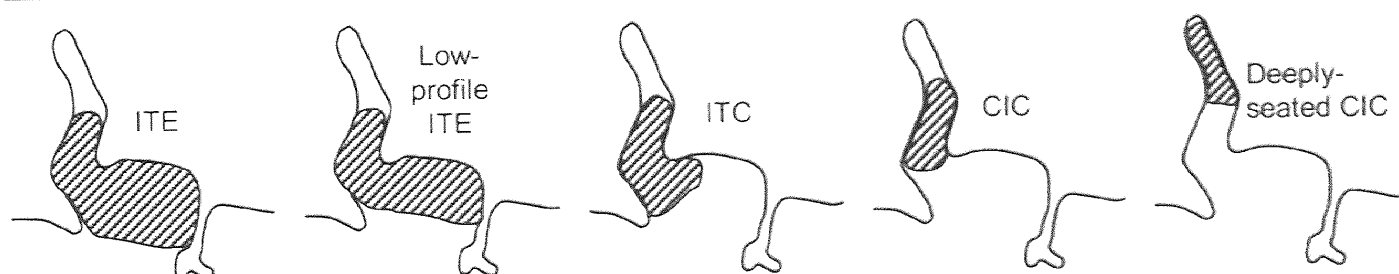


Figure 5.7 Axial view of typical placements for ITE, low-profile ITE, ITC, CIC, and low-profile CIC hearing aids.

^a The term IROS stands for *Ipsilateral Routing of Signals*, and was named to contrast with *Contralateral Routing of Signals* (see Section 17.1) which was the context in which such open earmold styles were first used.

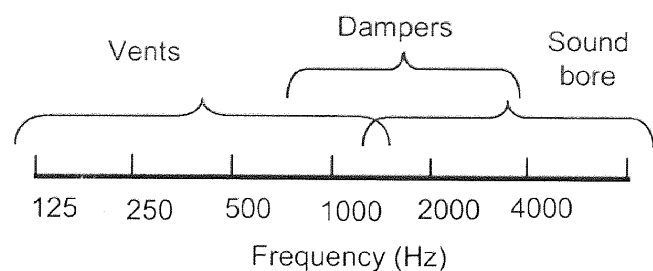


Figure 5.8 Frequency regions affected by each of the components of the hearing aid coupling system.

5.2 Overview of Earmold, Earshell and Canal Fitting Acoustics

The ear fitting affects three broad acoustic characteristics of the hearing aid: the shape of the gain-frequency response of the aid when it is mounted in the ear, the self-perceived quality of the patient's voice, and the likelihood of feedback oscillation.

There are also three acoustic aspects of the coupling system: the *sound bore*, the *damping*, and the *venting*. These primarily affect the frequency response in different frequency regions, as shown in Figure 5.8. Sound bore dimensions affect only the mid and high-frequency response (above 1 kHz for BTE aids and above 5 kHz for ITE/ITC/CIC aids). Damping mainly affects the response shape in the mid-frequency region (from 800 Hz to 2500 Hz for BTE aids, and from 1500 Hz to 3500 Hz for ITE/ITC/CIC aids) although it has some effects outside this range. Venting mainly affects the low-frequency response, from 0 Hz up to approximately 1 kHz, although if the vent is large enough, such as with an open-canal fitting, it affects the entire frequency range because it leaves the open-ear resonance largely intact.

5.3 Venting

Although this section on venting may seem to be excessively comprehensive, it is the author's experience that the effects of vents and leakage paths lie behind much of the seemingly inexplicable behavior of hearing aids that is encountered when their response is being measured in the ear. A good understanding of vents, including the venting effects of open-canal hearing aids, is essential to hearing aid fitting.

The vent size is selected with the aim of achieving the target gain, but without the ear canal being excessively occluded, and without the hearing aid oscillating. It is often not possible to completely achieve all three aims. These three issues are covered in Sections

5.3.1 to 5.3.3 respectively. Vent size also has implications for the effectiveness of directional microphones, adaptive noise suppression and compression, as discussed in Section 5.3.4.

Vents enable an exchange between air in the ear canal and air outside the ear. This air exchange helps avoid excessive moisture build-up. The venting action can enable people with perforated eardrums to wear hearing aids, provided the perforation is not too large.³⁸

Our understanding of the effects of vents will be greatly increased if we first understand the concept of *acoustic mass*. A vent is a column of air surrounded by the walls of a tube. Air, like any other substance, has mass, and therefore has inertia. For a vent to transmit sound, this inertia has to be overcome (or else the air does not move). Overcoming inertia is much easier at low frequencies than at high frequencies and is much easier for small masses than for large masses. Pick up a small weight, like a pen and shake it sideways in front of you at a rate of once per second (i.e. 1 Hz). Now increase the rate to 3 or 4 Hz. You will notice the increase in force that you have to provide. Now pick up a heavier weight, like a 1-kg (2-pound) bag of sugar or flour and repeat the exercise. The higher frequency will require considerable force, and if you provide only a very small force at the 3 Hz rate, then only a very small motion will result.

The analogy is that the column of air in a vent will not move much and so not transmit much sound if the stimulating frequency is high and if the vent has a large acoustic mass. As shown in the panel, vents have a high acoustic mass if they are long and narrow.

Real vents are not always tubes with the same diameter at all points. The concept of acoustic mass helps us understand how the performance of a vent with a varying diameter differs from that of a constant diameter tube. For a vent like the one shown in Figure 5.9

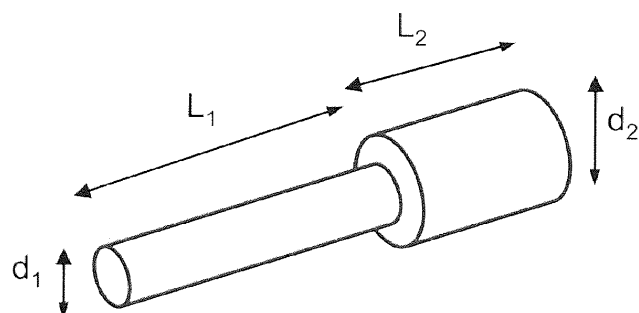


Figure 5.9 A vent made up of two tubes of different lengths and diameters.

Underlying theory: Calculating the acoustic mass of vents from their diameter and length

Although it is never necessary in clinical practice to calculate acoustic mass, the calculation formula is simple and helps our understanding of how changing the vent dimensions will vary the effects of a vent. Acoustic mass is not the same thing as the physical mass of the air in the vent. The acoustic mass of a column of air (i.e. a tube) of length L (in meters) and cross sectional area A (in square meters) is equal to:¹¹³

$$M_a = 1.18 (L/A) \quad \dots\dots 5.1.$$

The units are kg/m^4 , but by analogy with electrical inertia, the units can be referred to as Henrys. The quantity 1.18 is the density of air in kg/m^3 . Because vents are usually circular in shape we can make the calculation more convenient. If the internal diameter of the vent is d (in mm) and the length is l (in mm), the acoustic mass can be calculated as:

$$M_a = 1500l/d^2 \quad \dots\dots 5.2.$$

The acoustic mass of a vent increases as the vent gets longer or narrower. *Thus long vents transmit less sound than short vents, and narrow vents transmit less sound than wide vents.*

As an example, a vent 20 mm long with diameter 2 mm would have an acoustic mass of 8100 Henrys when the end correction is allowed for. As a second example, a 1 mm diameter vent in a hollow canal earmold with a shell thickness of 0.7 mm would have an acoustic mass of only 2250 Henrys.

* To precisely calculate acoustic mass, it is necessary to add a length correction to each end of the vent that opens out into a larger space (such as free air at the lateral end or the residual ear canal at the medial end). Each end correction is equal to 0.4 times the diameter of the tube. Thus, the tube in the example above actually acts like a tube that is 21.6 mm long and the tube in the second example acts like a tube that is 1.5 mm long. The end correction can be neglected for vents that are much longer than they are wide, but otherwise should be included, and the correction is especially important for short or wide vents.

the total acoustic mass equals the sum of the acoustic masses of each segment. In this particular case, the acoustic mass of the narrow segment will be much greater than the acoustic mass of the wider segment, so the total acoustic mass will be approximately equal to the acoustic mass of the narrow segment. The acoustic mass of vents with more than one diameter has a practical application to vents with adjustable apertures and vents that have been widened at one end.⁹⁹⁹

Because it can be difficult to predict exactly what size a vent should be, the clinician may need to adjust the vent after a preliminary fitting has been made on the aid wearer. One way to do this is to enlarge the vent diameter by drilling or grinding, or decrease the vent diameter by filling it with wax or plastic materials that cure, and then re-drilling it if necessary. Vents can be modified more quickly and easily if they are ordered with an exchangeable **vent insert plug**. One such system is shown in Figure 5.10. It comprises a vent tube connected to a widened out cylindrical receptacle at

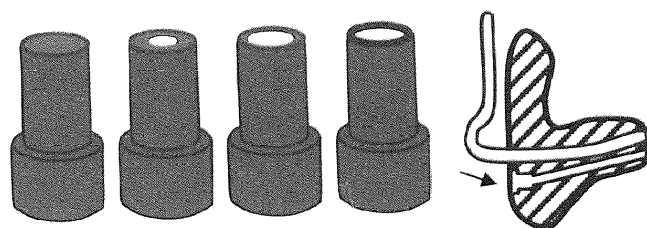


Figure 5.10 The inserts (larger than life-size) from a vent insert system, and the earmold and vent receptacle (approximately life-size) into which they fit. Positive Venting Valve (PVV) and Select-A-Vent (SAV) are two such systems commercially available.

the lateral end of the vent. A “tree” of inserts, any one of which seats firmly in the receptacle, completes the system. The inserts all have the same length (2.5 mm) but differ in the diameter of their internal hole. The different inserts thus change the acoustic mass of the vent but only provided:

- the rest of the vent (the vent tube) is not so long or so thin that its acoustic mass dominates the total mass,³³⁶ and,
- the leakage around the mold or shell is not so big that the size of the vent is inconsequential.

It will commonly be the case that the inserts with the largest and second largest holes will have almost identical effects (because the total vent mass is dominated by the vent tube), and the inserts with the smallest and second smallest holes will have similar effects to each other (because the natural leakage dominates the venting effect). The insert system is nevertheless worthwhile in that it offers an easy way to obtain two or maybe three effectively different vents. If one does need the maximum flexibility in venting, then:

- for the narrowest inserts to be useful, leakage must be minimized by making the mold a tight fit (which may be uncomfortable and is not very sensible if one ends up using a wide insert); and
- for the widest inserts to be useful, the vent tube must be short and wide, which may not be possible if the ear canal is narrow, and the canal has to contain other large objects, like a horn for BTEs or a large receiver for ITEs.

It is thus useful to be able to predict approximately how much venting is necessary, and this is taken up in the next three sections.

5.3.1 Effects of vents on hearing aid gain and OSPL90

Vents (including leaks and open fittings) affect the low-frequency gain and OSPL90 of hearing aids by allowing low-frequency sounds *out* of the ear canal and by allowing low-frequency sounds *in* to reach the residual ear canal volume without passing through the hearing aid amplifier. These are two separate effects of vents, so let us consider them in turn, and then consider their combined effects.

Effects of vents on the amplified sound path

When amplified air vibrations emerge from the sound bore into the ear canal, they generate sound pressure in the canal. It is this sound pressure that is sensed by the eardrum. The smaller the residual canal volume (the space between the sound bore exit and the eardrum), the greater will be the SPL generated. If there is an escape route, such as a vent (including an open canal), some of the injected vibrations will leave by that route rather than contribute to the sound pressure within the canal. How much sound leaves and how much stays? The proportion leaving depends on the impedance of the escape route relative to the impedance of the residual canal and middle ear. The vent pathway, being an acoustic mass, has an impedance that rises with frequency. Conversely, the residual ear canal volume, being primarily an acoustic compliance, has an impedance that falls as frequency increases.

Table 5.1 Effect of different sized vents, in dB, relative to a tightly sealed earmold or shell, on the gain of the amplified sound path. Note that the vent acoustic masses shown do not allow for the effects of leakage around the mold.^{430, 1355, 1816}

Vent size	Vent acoustic mass (Henrys)	Frequency (Hz)								
		250	500	750	1000	1500	2000	3000	4000	6000
Unvented, average fit		-4	-2	-1	-1	1	0	0	0	0
1 mm	26,700	-5	-2	-1	-1	1	0	0	1	1
2 mm	7,000	-11	-3	-1	-1	1	1	1	1	2
Closed dome		-10	-8	-3	-2	-2	-1	1	-2	0
IROS (ITE/ITC)	4,700	-16	-11	-4	-3	2	4	2	-1	0
3.5 mm	2,400	-21	-12	-6	-4	1	2	2	1	1
Janssen (ITE)	2,100	-23	-13	-3	-3	1	6	4	-1	1
Open dome	830	-30	-24	-16	-12	-8	-3	5	0	0

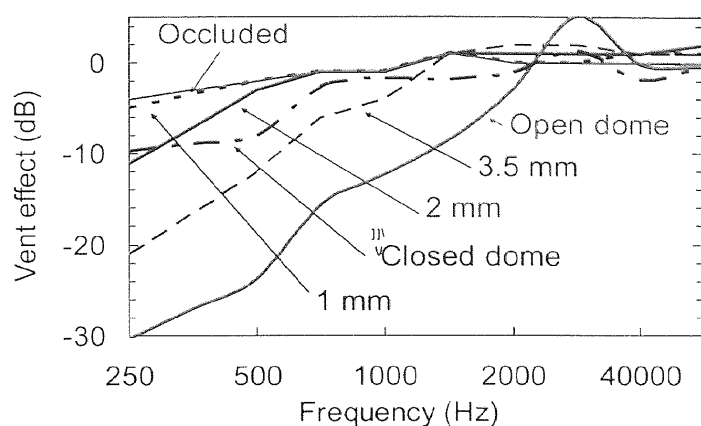


Figure 5.11 Effect of different sized vents on the frequency response of amplified sound, relative to the response with a tightly fitting earmold or earshell.^{430, 431, 1355}

For both these reasons, the vent becomes more attractive as an escape route as frequency decreases. Consequently, for sounds injected into the ear canal by the amplifier and receiver, the vent provides a low cut to the frequency response.

The extent of the low-frequency cut depends on the size of the vent (because the vent size determines its acoustic mass). Figure 5.11 shows the degree to which vents of different sizes cut the low-frequency response of the amplified sound path relative to a tightly fitted earmold or earshell. Because these data are so useful in selecting a vent, they are presented in tabular form at the audiometric frequencies in Table 5.1. The results are consistent with those of Kuk, Keenan and Lau (2009). Vents of other sizes, but with the same acoustic mass, would have the same effect on the amplified sound path.^{b, 998} Calculation of acoustic mass for the closed dome is not appropriate as transmission is affected by the compliance and mass of the dome, as well as leakage around its edge.

Effects of vents on the vent-transmitted (acoustic) sound path

Vents will transmit low-frequency sound waves no matter which end of the vent they enter. Sound waves reaching the head will thus be transmitted directly into the ear canal by a vent. This sound path is totally non-electronic. The range of frequencies over which the vent transmits sounds into the ear canal without

attenuation is the same as the range over which it attenuates sound that has been electronically amplified. In particular, sounds are transmitted into the ear canal without significant attenuation up to the vent Helmholtz resonant frequency (Section 2.2.2). Above that frequency, the vent increasingly attenuates sound directly entering the ear canal from outside the head, so the hearing aid, when turned off, begins to act like an earplug.

Section 4.3.3 introduced the *real-ear occluded gain (REOG)* as the SPL in the canal with the hearing aid turned off, relative to the SPL in the incoming field. The sound wave causing this SPL reaches the canal primarily via the vent (and leakage) path. The REOG is the equivalent of the REAG, but for the *vent-transmitted sound path*, rather than for the amplified sound path. Figure 5.12 shows REOG for several earmold styles. Also shown for reference is an average REUG curve. As vent diameter increases, the REOG curve becomes increasingly similar to the REUG curve. The largest vents (i.e., open-canal fittings) leave the REUG almost intact.^{1105, 1264, 1937} The small acoustic mass caused by sound moving through holes in the dome or other device used to hold the tip of the tube in place moves the open-canal resonance to a slightly lower frequency.

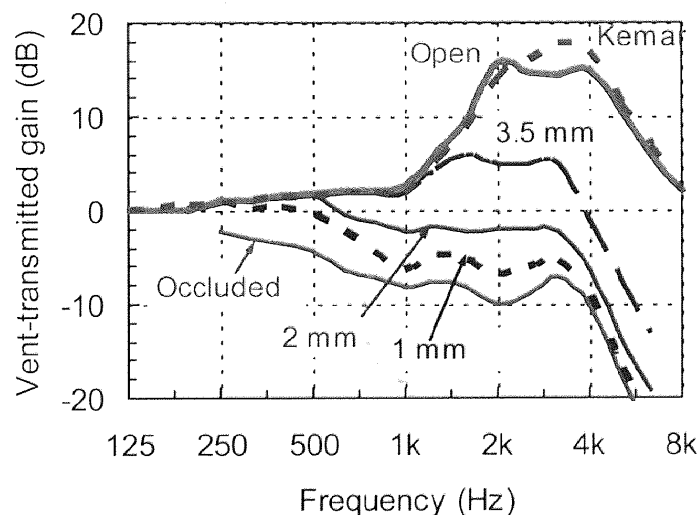


Figure 5.12 REOG of the vent-transmitted sound path for vents of different sizes in an earmold or shell with a mean canal stalk length of 7 mm^{430, 431} and for an open fitting.^{557, 1264, 1937} The dotted blue line shows a typical REUG curve.

^b The data in Figure 5.11 relating to vented earmolds were obtained with vents averaging 17 mm in length. Equation 5.2 can be used to generalize the data to vents of different lengths. For example, if the vent length were to be halved, the acoustic mass (and hence the size of the low cut) would remain constant if the vent diameter were to be decreased by $\sqrt{2}$.

It is also useful to consider the equivalent of insertion gain when the hearing aid is turned off: the *real-ear occluded insertion gain (REOIG)* shows the SPL in the canal with the hearing aid turned off relative to the SPL in the ear canal with no device in the ear. The REIG is simply the insertion gain of the vent-transmitted sound path:

$$\text{REOIG} = \text{REOG} - \text{REUG} \quad \dots\dots 5.3.$$

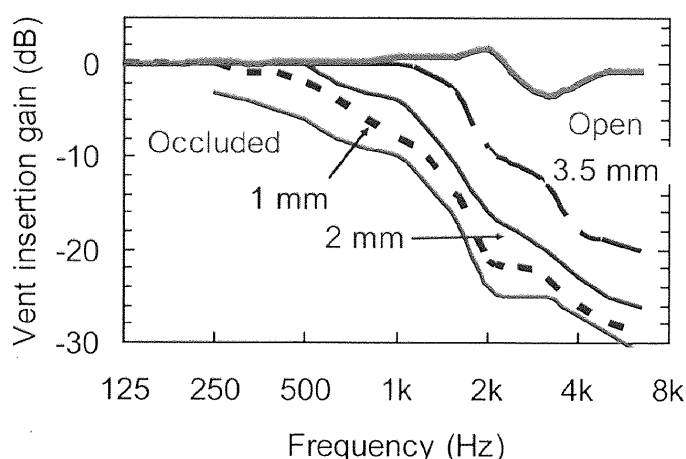


Figure 5.13 Insertion gain of the vent-transmitted sound path (REOIG) for vents of different sizes in an earmold or shell with a mean canal stalk length of 7 mm,^{430, 431} and for an open fitting.^{557, 1264, 1937}

Achieving high-quality, low-frequency sound

If a patient needs a gain of 0 dB below some frequency, no electronics can compete with the low distortion, flat frequency response that a vent can provide.

For such people, an earmold or shell that attenuates sound below this frequency should be used only if:

- The required high-frequency gain cannot be achieved if a vent is used, or
- It is important for the patient to have the benefits of directivity in the low frequencies.

REOIG is shown in Figure 5.13 for various vent sizes, including open fittings. Similar data have been published by Kuk, Keenan and Lau (2009).

Open fittings have close to 0 dB REOIG gain over the entire frequency range. This has a major advantage for people whose hearing is close to normal at any frequency. For people with reverse sloping losses, for example, any mold other than an open fitting will likely cause the complete hearing aid fitting to act as an earplug for the high frequencies because of the restricted bandwidth of the hearing aid amplifier and receiver.

REOIG is also called *insertion loss*, and it is sometimes mistakenly thought that hearing aids have to produce gain equal to insertion loss before they provide any net benefit. This is simply incorrect: as equation 5.3 shows, insertion loss is affected both by the amount that the ear fitting blocks incoming sound (i.e. REOG) and by the loss of the open-canal resonance (i.e. REUG), and only the second of these must be compensated for by the hearing aid gain.^{c, 1264}

Effects of vents on the combined amplified and vent-transmitted sound paths

The hearing aid user does not hear either the amplified sound path, or the vent-transmitted sound path, in isolation.⁹¹¹ Rather, as Figure 5.14 shows, sounds arrive at the eardrum via both routes. The sounds arriving via each path combine in the residual ear canal volume.

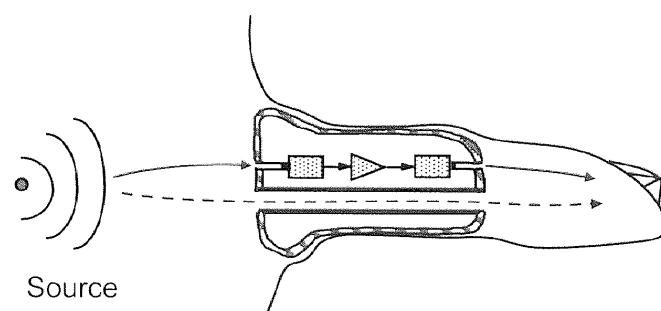


Figure 5.14 Sound travels from a source to the eardrum via the amplified path (solid red line) and the vent or leakage path (dashed blue line). An ITE is shown but the same principle holds for BTE or body aids.

^c As a thought-experiment, imagine improving the fit of an earmold to the ear, and thus reducing leakage around the earmold. Insertion loss will now be larger than before, yet the modification will actually increase the low-frequency gain of the hearing aid

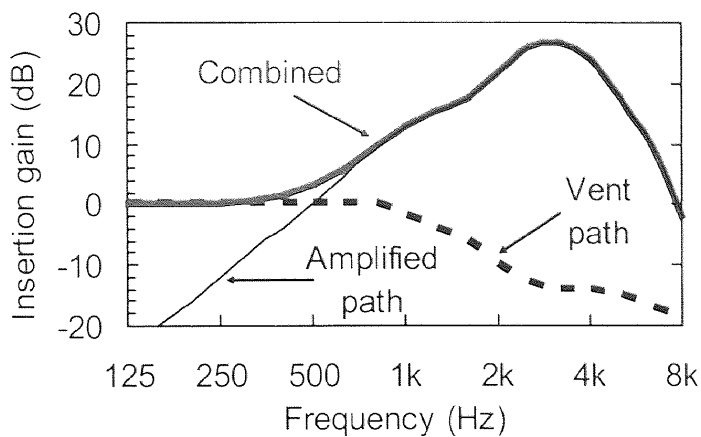


Figure 5.15 Insertion gain of the vent-transmitted path and the amplified path and the way these might combine to form the insertion gain of the complete hearing aid.

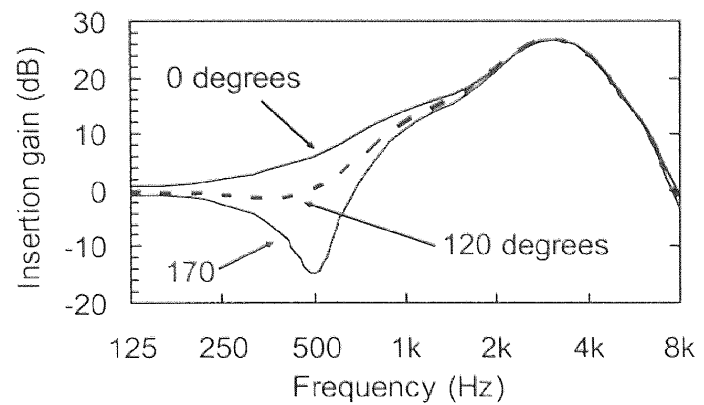


Figure 5.16 Insertion gain of the combined response for phase differences of 0, 120, and 170 degrees between the vent-transmitted and amplified sound paths shown in Figure 5.15. The combined path in Figure 5.15 assumed a phase difference of 90 degrees.

Figure 5.15 shows an example of how the two paths combine.⁴³¹ Notice that whenever the insertion gain of one path exceeds the insertion gain of the other path by 10 dB or more, the insertion gain of the combined paths is almost the same as the insertion gain of the path with the higher gain. This is because the amount of sound arriving via the path with the lower gain is inconsequential compared to the sound arriving via the dominant path. When the insertion gain or real-ear aided gain of the hearing aid, or the 1/3-octave spectrum of a speech signal in the ear canal, is measured, the only curve that is apparent is the combined response. It is evident from Figure 5.15, however, that this combined curve arises from two entirely different paths, and it is useful to divide the response into three separate regions: the *vent-transmitted region*, the *amplified region*, and between these two, the *mixed region*.

In the vent-transmitted region, which can extend up to 1500 Hz in open-canal hearing aids, the microphone, amplifier, and receiver play no part in the sound received. In the amplified region, however, the vent can have an effect if it attenuates part of this region by allowing sound out of the ear canal, as detailed earlier.

In the mixed region, the final result depends on how the vent and amplified paths combine, which in turn depends on the phase difference between the two paths. Figure 5.16 shows how the phase difference directly affects how the two paths can combine in the mixed region. A dip or notch occurs in the combined response when the phase difference between

the two paths is close to 180 degrees. In practice, the notch is rarely more than 10 dB deep, because deep notches require a phase difference of almost exactly 180 degrees at the frequency at which the two paths have identical gains. Minor dips probably do not have any adverse perceptual consequences, although peaks in the frequency response can.⁴⁵⁴ In fact, when a pronounced dip does occur, it provides a convenient marker of the middle of the mixed region.

Because digital hearing aids have significant delay, in the range of 3 to 10 ms,⁴⁵⁰ the relative phase of the amplified and vent-transmitted paths changes con-

Practical tip: Matching a real-ear gain target

- Adding or widening a vent moves the insertion gain towards 0 dB (causing a low-frequency gain reduction in the amplified region, but causing a low-frequency gain increase if the aid was previously acting like an earplug).
- Varying an electronic tone control has no effect in the vent-transmitted region, and therefore may have no effect at all if the tone control only affects the same frequency range as covered by the vent-transmitted region.
- Varying an electronic tone control can have unpredictable effects in the mixed region, with the result depending on the phase relationship between the two sound paths.

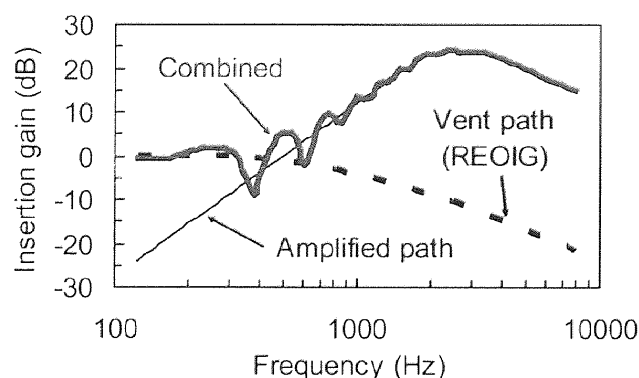


Figure 5.17 Insertion gain of the combined response when sound in the amplified path is delayed by 4 ms with respect to sound in the vent path.

tinuously and rapidly throughout the mixed region. Consequently, the combined response is marked by an alternating series of peaks and troughs, corresponding to in-phase addition and out-of-phase cancellation respectively, over the frequency region for which the two paths have gains within about 10 dB of each other, as shown in Figure 5.17. This modification of sound is called **comb filtering**; the “teeth” of the comb are separated by the inverse of the relative delay of the two paths, in this case 250 Hz arising from a 4 ms delay.

It must be remembered that because vents affect the sound coming out of a hearing aid, they affect the maximum output in the same way they affect the gain. An OSPL90 control, for example, will have no effect on maximum output in the vent-transmitted region.

There has been some research producing conflicting results, for understandable reasons, on whether people prefer the low-frequency response of hearing aids to be achieved by the use of vents or by the use of electronic tone cuts. Conventional electronic low cuts, when combined with a well fitting earmold

will produce negative low-frequency gains (i.e. an attenuation of sound), whereas vents decrease the low-frequency gain only to 0 dB and then provide 0 dB gain for all lower frequencies, as discussed above. Consistent with this, Cox & Alexander (1983) and Kuk (1991) found that vented hearing aids produce superior sound quality. Lundberg et al. (1992), however, used a more complex filter that better simulated the real effect of the vent and consequently found no difference in perceived sound quality. In general, the quality of an amplified sound will also depend on distortion, and this depends on the signal level relative to the level at which the hearing aid saturates. Distortion is never a problem with vent-transmitted sound!

5.3.2 Venting and the occlusion effect

When an ear canal is occluded by a mold or a shell, people with low-frequency hearing thresholds less than about 50 dB HL often complain that their own voice sounds hollow, boomy, like they are speaking in a drum or a tunnel, or that it echoes. These are all descriptions of the **occlusion effect**.

Figure 5.18 shows the increase in SPL, relative to the SPL in an unoccluded canal, measured in one person's ear canal, as the person talked. The subject wore an occluding earmold with no sound bore. The length of the canal stalk was progressively shortened. For these measurements, a reference microphone in front of the subject was used to remove the effects of any variation in vocal effort. Data for the octave centered on 315 Hz are shown, because this is the frequency range in which the occlusion effect was largest. As the canal is progressively blocked by earmolds of increasing insertion depth, the SPL rapidly increases, then decreases slightly, and then rapidly decreases. A similar variation of SPL with canal stalk length has been reported by Mueller (1994) and by Pirzanski (1998). These variations are caused by changes in three things as the canal stalk is lengthened:

Measuring REOG or REOIG

If a probe tube has already been inserted into the ear to measure real-ear gain, then measurement of REOG or REOIG takes only as long as it takes to turn the hearing aid off and hit the “measure” button on the analyzer. The result is instructive as it is immediately apparent how much of the real-ear gain curve is actually the result of sound entering via the vent and hence unaffected by the hearing aid electronics and transducers. Also, the frequency range over which REOIG is close to 0 dB (or REOG is at or above 0 dB) is a good single-figure indicator of “openness” with strong implications for the amount of low-cut filtering, freedom from occlusion, and amount of feedback-inducing leakage for that fitting.

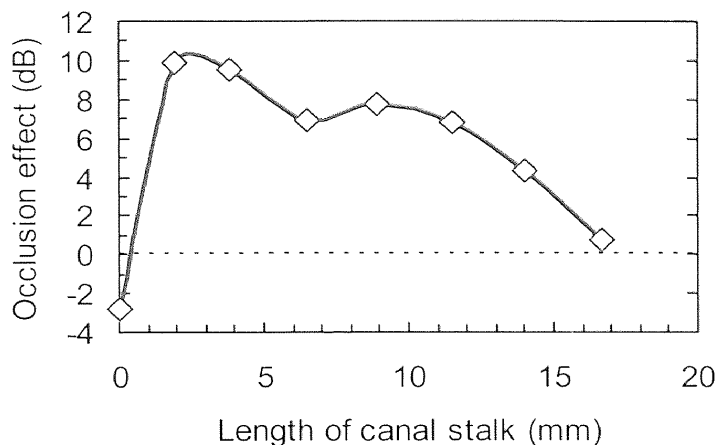


Figure 5.18 Increase in ear canal SPL (relative to no earmold) for the octave centered on 315 Hz when an aid wearer talks. Ear canal length was measured from the ear canal entrance along the center axis of the ear canal. For this person, the transition from cartilaginous to bony canal, as evidenced by the texture of the impression surface, commenced 9 mm into the canal (on the posterior wall, at the second bend) and completed 16 mm into the canal (on the anterior wall).

Experience the occlusion effect yourself

1. First say the vowels *ah*, *ee*, and *oo*. Notice that they sound approximately equally loud.
2. Now block both ear canals by squashing the tragus firmly across the ear canal with your fingers.
3. Repeat the same sounds and notice that the *ee* and *oo* sounds have become much louder than the *ah* sound. The *ee* and *oo* sounds are also much boomier than before.

Go on, do it now!

- The seal to the ear increases, thus trapping more of the bone conducted sound within the residual canal.
- The residual volume decreases, which by itself would lead to a higher SPL.
- The area of the vibrating cartilaginous canal wall that causes the occlusion sound decreases. By itself this would lead to a lower SPL. The decrease in SPL from this cause occurs at a rate faster than the decrease in volume, particularly as the end of the canal stalk approaches the end of the cartilaginous canal. Once the canal stalk fills the cartilaginous portion, only the bony portion of the ear canal remains, and this is not an effective generator of occlusion sound. Because the same (temporal) bone^d surrounds all sides of the bony canal, phase differences between the top, bottom, front, and back walls are presumably minimal.

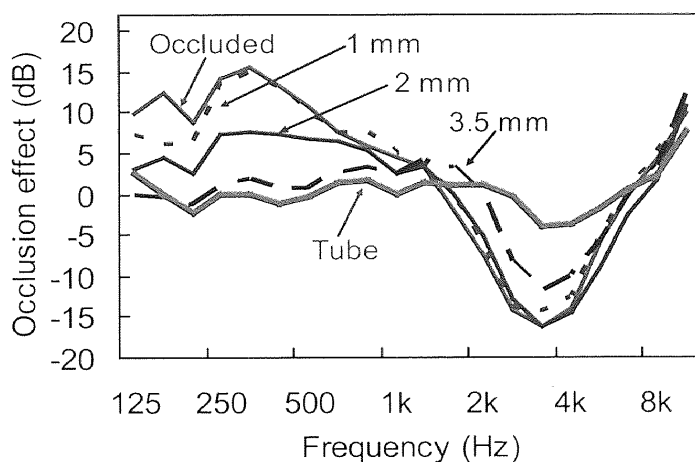


Figure 5.19 The mean increase in SPL (relative to no earmold) in the ear canal for 10 subjects, as they talked while wearing earmolds with vents of different sizes.¹¹⁵⁷

There are at least two ways to decrease the SPL induced by the occlusion effect. The first is to open up the residual ear canal volume with a vent, with the extreme vent being an open-canal fitting.

Figure 5.19 shows the increase in SPL generated in the ears of 10 subjects as they talked while they were wearing earmolds with vents of different sizes.^c Subjects' ratings of the acceptability of their own

^d The *tympenic plate* forms the floor and anterior walls of the bony canal; the *squamous part* forms the roof and posterior walls; but these bones are both parts of one rigid *temporal bone*.

^c The vents and subjects are the same as those for which the data in Tables 5.1 and 5.2 were obtained. Data for an occluded skeleton earmold was very similar to that shown for the occluded carved shell mold. A reference microphone in front of the subject was used to control for any variation in vocal effort.

Why the occlusion effect occurs

As can be inferred from Figure 5.2, the residual ear canal is bounded by the eardrum, the medial end of the mold or shell, and the walls of the canal comprising the cartilaginous section and the bony section. If any one of these boundaries vibrates with respect to the others, the volume of the residual canal changes, and an intense sound pressure is generated within the residual ear canal. What can cause such a vibration? When a person speaks, vibrations in the vocal tract are coupled to all the bones of the skull (including the jaw), and to any tissues connected to these bones.¹⁸⁶¹ Because the jaw has a mass only one fifth of the rest of the skull, and is more loosely connected to the rest of the body, it vibrates to a much greater degree than the rest of the skull. Consequently, in the cartilaginous portion of the canal, the inferior and anterior canal walls (which are in close contact with the jaw) will vibrate with respect to the other two walls (which are in close contact with the temporal bone) thus generating a sound within the residual canal volume. When a person is not wearing a hearing aid this does not create a problem, as there is no enclosed cavity within which significant sound pressure can be generated. The air vibrations created by the vibrating canal wall just leak out into the outside air.

Why is the occlusion effect most noticeable for the *ee* and *oo* vowels? Looked at one way, their first formant is around the frequency of maximum occlusion effect (300 Hz) and so is most reinforced. Looked at differently, these vowels are formed as closed vowels, so there is a higher SPL present in the vocal tract than for open vowels like “ah”.⁹²⁷

voices were significantly correlated to the degree of low-frequency SPL increase ($r=0.63$) and of course to the size of the vent. Such a correlation accounts for only 40% of the variance in reactions to occlusion, and presumably individual differences in the extent of canal wall vibration, ear canal length and volume, canal stalk length, and psychological tolerance to variation in voice quality all contribute to the end resulting perception. Similar results have been shown for CICs and for BTEs with a variety of earmold styles and vent shapes. Whatever the shape of the vent, the occlusion-induced SPL decreases, and perceived own-voice quality increases, as the acoustic mass of the vent decreases.^{902, 997, 998}

The occlusion-induced SPL increases with the acoustic compliance of the ear canal, possibly because those with a large compliance have a larger area of vibrating canal wall, or possibly because the wall vibrates more easily and so transmits more sound into the canal.^{251, 997} Not surprisingly, the perception of occlusion is more strongly connected to objectively measured SPL increase in the ear in which occlusion is greatest than to the SPL increase in the other ear.⁹⁰²

It is clear that a 1 mm diameter vent is not large enough to decrease the occlusion effect because a vent this small does not increase the venting significantly beyond that which occurs by leakage around the mold. Conversely, with the 3.5 mm diameter vent, the open-

ing is sufficiently large to hold the SPL increase to a few dB. With an increase this small, own-voice quality is rated as normal.^{997, 1157} Open-canal fittings, being even more open (see Figures 5.11 to 5.13), produce virtually no occlusion-induced sound.^{902, 998, 1105}

A 2 mm vent is only partially effective in solving the occlusion problem. It decreases the size of the SPL increase but does not eliminate it. For each patient, own-voice quality will become more acceptable as the mold or shell is made more open. A 2 mm vent can be regarded as a good starting point for fixing the occlusion problem, but in many cases, the vent will have to be widened to 3 mm before the patient is satisfied with the sound of his or her own voice. All the diameters mentioned in this and the preceding paragraphs relate to vent lengths similar to those used in the study (17 mm). For very short vents, such as those occurring in hollow canal earmolds, much smaller diameter vents are needed to have the same acoustic mass, and hence the same acoustic effects.⁹⁹⁸

The second way to solve the problem of the occlusion effect is not to create one in the first place! As explained earlier, if the mold or shell completely fills the cartilaginous portion of the canal, there will be less occlusion-generated sound compared to molds or shells that terminate within the cartilaginous portion.^{197, 927} While this sounds like an easy solution, there are practical difficulties for some hearing aid

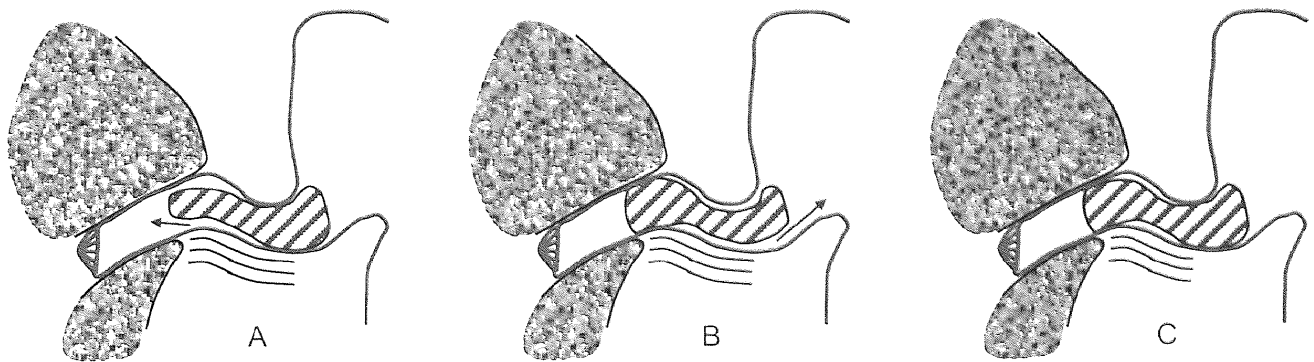


Figure 5.20 Axial view of earmolds or shells that produce a very strong occlusion effect (A), and a very weak occlusion effect (B). The mold or shell shown in (C) will produce a weak occlusion effect and will also have minimal leakage of sound from the hearing aid. In each case, the wavy lines show the vibrating anterior wall and the arrow shows the primary direction in which bone conducted sound will travel once it enters the ear canal. The looseness of fit in each diagram has been exaggerated for clarity.

wearers. First, extra care must be exercised when taking the impression, as detailed in Section 5.8.2. Second, the resulting earshell (or less commonly, earmold) may be difficult for the aid wearer to insert or remove. Third, the earshell may be uncomfortable when worn for long periods if it extends into the bony portion of the canal.¹⁸⁸² Comfort is improved if the shell is made with a soft tip.¹³⁶¹ If the soft material is made of compressible foam, the disadvantage is that the foam has to be replaced regularly, and if it is made of a soft plastic, the life of the earmold or hearing aid may be decreased.

Whatever the length of the canal stalk, it is important that the most medial parts of the earmold or shell be in close contact with the canal walls.^{927, 1491} Earshells that receive a heavy build-up during manufacture cause less occlusion SPL than those made from open-jaw impressions (which achieve a tight fit in the lateral, flexible parts of the canal).¹⁴²¹ Figure 5.20 show three earmolds of the same length. For earmold A, the tight seal near the ear canal entrance and the loose fit more medially traps the vibration-induced sound within the ear canal and so ensures that a high level reaches the eardrum. For earmold B, by contrast, the path of least resistance is outwards, so little vibration-induced sound will reach the eardrum. Earmold C should pro-

duce intermediate effects. Addition of a vent to any of the three will decrease whatever occlusion effect does occur.^f

In the future, *active occlusion cancellation* (see Section 8.5) in an occluded mold or shell may provide a third alternative to ensure that hearing aid wearers are not bothered by the sound of their own voice.

For people with more than about 60 dB loss at 250 Hz and 500 Hz, the occlusion effect should not be a problem.^g These people need significant low-frequency amplification, even for the high input levels typically encountered when the aid wearer talks, so it does not matter if there is an increased sound level when they speak. The only complication is that the hearing aid amplified sound will add (constructively or destructively, depending on the phase relationship) to the occlusion-generated sound, and this can affect the shape of the frequency response in the low-frequency region for the person's own voice. When the electronically amplified sound is out of phase with the bone conducted sound, increasing the degree of low-frequency amplification can cause a *decrease* in the SPL in the residual canal. This may be the reason behind the anecdotal reports of solving the occlusion effect by *increasing* low-frequency gain.¹⁷⁶⁷

^f The level of vibration-induced sound reaching the eardrum may be affected in another way by earmold tightness. It may be that inserting a tight earshell or mold into the canal partly couples the canal walls and so decreases the vibration of the tissues on one side of the canal relative to the tissues on the other side. If so, even the unfilled part of the cartilaginous canal would become a less effective generator of sound. This suggestion is merely an untested supposition.

^g One might expect the occlusion effect to be a much greater problem for patients with low frequency thresholds close to normal than for patients with low-frequency thresholds of 40 or 50 dB HL, as the occlusion-induced sound represents a lower sensation level for the latter group, but this does not appear to be the case.²⁵¹

Alternatively, hearing aid wearers may not have the perception or terminology to adequately differentiate deficient versus excessive low-frequency amplification of their own voice.⁹⁹¹

The clinician can use real-ear gain analyzers to monitor the magnitude of sound when the patient speaks, whether this arises from bone conduction alone or from the combination of bone conduction and amplification.^{1259, 1491} It is unlikely that this measurement is worthwhile doing routinely as, in the end, the amount of occlusion that is acceptable depends on a subjective judgment by the aid wearer rather than on a physical measurement, which in any case is subject to significant measurement error.⁹⁰² Measurement of occlusion would, however, be worthwhile when the aid wearer continues to complain about the sound of his or her voice, even after the clinician believes venting or deep seating should have largely eliminated the occlusion sound build-up. For deeply seated molds or shells, measurement will be possible only if the mold or shell contains a hole through which the probe tube can be placed. The skin of the bony canal does not have sufficient flexibility to enable the probe to be placed between the hearing aid and the canal wall without affecting either comfort or leakage.

One “solution” to the occlusion effect that does *not* work is telling the patient that he or she will get used to the altered sound of their own voice.^{683, 902}

So far, the “occlusion effect” has been defined as the increase in SPL that occurs in the ear canal when the aid wearer talks. Occluded earmolds also create additional low-frequency sound level during chewing, and even walking; the generation mechanism and solutions are the same. Another consequence of a fully occluded earmold or shell is that the lack of ventilation and increase in moisture may increase the likelihood of external ear disease. Information on the effectiveness of ventilation is scarce. One study showed that even a 2 mm vent did not decrease reports of itchiness and moisture in the ear canal.¹¹⁰⁷

5.3.3 Effects of vents and leaks on feedback oscillations

As explained in Section 4.7.1, feedback oscillation occurs when the attenuation of signal leaking from the ear canal back to the microphone is less than the forward gain given to the signal by the hearing aid. Measurements of the amount of signal leaking back at each frequency can therefore be used to deduce the maximum possible insertion gain before feedback oscillation occurs, at least for hearing aids without feedback canceling algorithms (see Section 8.2.3).^h

The maximum possible insertion gain without feedback oscillation is shown in Tables 5.2, 5.3, and 5.4 for BTE, ITE and ITC hearing aids, respectively. (Unfortunately, comparable data are not available for CIC hearing aids.) Feedback cancelling algorithms typically allow about an additional 10 to 15 dB of gain to be obtained. Not surprisingly, the maximum achievable gain decreases as the mold or shell becomes more open. In Table 5.2, data for shell and skeleton styles have been combined because the same maximum insertion gain is possible for both styles. Kuk (1994) and Pirzanski et al. (2000) also reached the conclusion that concha bulk does not affect leakage.

The information contained in Tables 5.2 to 5.4 can be used to select the maximum possible vent size without feedback. It is simplest to first compare the value in the 3 kHz column to the target insertion gain at 3 kHz, as this frequency usually provides the strictest constraint. This occurs because target REAG curves often have a maximum at 3 kHz, reflecting the maximum at this frequency in the REUG curve. Consequently, hearing aids must provide a REAG at least equal to the REUG before they start to give the aid wearer a greater signal level than is received without a hearing aid. The maximum gain is needed at low input levels, so it is this low-level target gain that should be compared to the maximum achievable gain.

^h As explained in Chapter 4, IG equals REAG minus REUG. In turn, REAG equals the microphone location effect from the free field to the microphone plus the hearing aid gain from the microphone to the ear canal. The maximum value of the gain from microphone to ear canal (without oscillation) is approximately equal to the attenuation of the sound leaking back from the ear canal to the microphone. Consequently, the maximum insertion gain equals the leakage attenuation, plus the microphone location effect, minus the REUG. The maximum achievable gain at each frequency can thus be determined. When maximum gain is determined by turning up the gain of a particular hearing aid until it oscillates (e.g. Gatehouse, 1989; Kuk, 1994), the results are applicable only to the frequency at which oscillation first occurs, which depends on the particular hearing aid used.

Table 5.2 Maximum possible insertion gain (in dB) before feedback oscillation, for BTE hearing aids connected to hard acrylic earmolds with vents of different sizes. The data are average results for ten subjects.^{430, 994} Higher insertion gains are possible with tight earmolds, soft earmold materials, and feedback cancellation algorithms.

Vent size	Vent acoustic mass (Henrys)	Frequency (Hz)							
		500	750	1000	1500	2000	3000	4000	6000
Occluded average fit		65	66	64	60	56	41	45	50
1 mm	26,700	65	64	61	58	52	39	45	47
2 mm	7,000	60	60	57	54	49	36	41	48
3.5 mm	2,400	51	53	52	48	43	31	35	41
Tube	800	41	43	42	40	34	23	26	37
Open dome	830	55	49	42	39	31	19	27	30

Table 5.3 Maximum possible insertion gain (in dB) before feedback oscillation, for ITE hearing aids containing vents of different sizes.¹⁸¹⁶ The occluded tight shells had a special build-up during shell construction. Higher insertion gains are possible with feedback cancellation algorithms.

Vent size	Vent acoustic mass (Henrys)	Frequency (Hz)								
		250	500	750	1000	1500	2000	3000	4000	6000
Occluded tight fit		62	56	56	56	47	41	23	24	12
Occluded average fit		62	54	52	49	44	33	24	22	13
1.5 mm	14,200	61	57	54	53	48	37	26	25	15
2 mm	8,000	54	50	46	46	42	33	24	23	13
IROS	4,700	44	42	40	38	38	32	19	16	12
Janssen	2,100	42	41	40	39	36	31	17	16	13

Table 5.4 Maximum possible insertion gain (in dB) before feedback oscillation, for ITC hearing aids containing vents of different sizes.¹⁸¹⁶ The occluded tight shells had a special build-up during shell construction. Higher insertion gains are possible with feedback cancellation algorithms.

Vent size	Vent acoustic mass (Henrys)	Frequency (Hz)								
		250	500	750	1000	1500	2000	3000	4000	6000
Occluded tight fit		58	52	49	52	45	39	31	33	13
Occluded average fit		52	48	44	45	42	37	23	28	11
1.5 mm	14,700	47	47	44	45	39	34	28	31	12
2 mm	7,800	44	41	38	38	38	32	21	27	17
IROS	4,500	39	34	31	31	29	26	15	23	7

The maximum vent size should be selected with considerable caution. For a given vent size, there is some variation between people in the maximum gain achievable without feedback. This variation is greatest for unvented styles because leakage around the mold or shell is more variable than leakage from a vent of known dimensions. Also, when the hearing aid gain is set a few dB below the point at which the aid continually oscillates, sound quality is adversely affected, as explained in Section 4.7.2. The maximum useable gain may therefore be only about 7 dB greater than the values shown in the tables, leaving a 3 to 8 dB safety margin on average when the feedback cancellation algorithm is operating.

The bottom row in Table 5.2 contains data for an open-dome canal fitting from a different data source.⁹⁹⁴ The results should be similar to those for the tube fitting which extended 7 mm past the ear canal entrance. It is unclear why there are large differences in the low frequencies but differences in insertion depth may partly account for the discrepancy. The amount of low-frequency gain that can be achieved before feedback increases with insertion depth.⁹²⁸

It might be expected that the shape of the vent, rather than just its acoustic mass, would have an effect on the likelihood of feedback oscillation. It is sometimes recommended that vents be widened at the medial end rather than the lateral end, so that the vent has a reverse horn shape for sounds exiting from the ear canal. While a reverse horn does decrease the amount of high-frequency sound leaking back to the microphone (relative to a vent that has been widened at the lateral end), the differences are confined to frequencies above 6 kHz.⁴³¹ Consequently, the variation in shape due to the horn effect has little effect on feedback oscillation, because oscillation usually occurs at frequencies below 6 kHz. Reverse horns nonetheless sometimes have a practical advantage in that there may be more space available at the medial end of an ITC hearing aid than is available on the faceplate. The vent can therefore be made more open (i.e. a lower acoustic mass) than would be possible with a constant diameter vent, with a consequent decrease in occlusion but also in maximum achievable gain before feedback oscillation.⁹⁹⁹

Short vents are slightly less likely than long vents to induce feedback oscillation, when both vents have the same acoustic mass and hence produce the same own-voice occlusion.⁷¹⁵ The reason is that the half-

wavelength resonance in long vents occurs within the frequency range in which hearing aids have considerable gain, and this wavelength resonance increases the efficiency with which sounds near the resonant frequency enter, traverse and exit the vent.

A more effective way to decrease high-frequency leakage while maintaining a low acoustic mass to decrease the occlusion effect is to use a cavity vent.¹¹¹¹ This vent comprises a cavity within the earmold, accessed via two small openings at the medial and lateral ends, which combine to form an acoustic low pass filter. It requires a relatively large earmold to be effective, involves a more complex construction technique, and is therefore little used.

5.3.4 Interaction of vents with digital signal processing algorithms

Vents and directivity

Well-designed directional microphones have a directional pattern across the entire hearing aid bandwidth. This directivity, however, will be apparent to the user only at those frequencies where the amplified sound path dominates over the vent-transmitted sound path. To maximize the benefits of a directional microphone, the amplified sound path should therefore extend to as low a frequency as possible, which in turn means the vent should be as small as possible.

Because directionality depends on cancellation of the signal picked up at one microphone port by signal picked up at the other port (Section 7.1.1), vent-transmitted sounds can materially decrease directivity. Even when the aid-transmitted sound is 10 dB more intense than the vent-transmitted sound, the latter can change the direction at which maximum sensitivity occurs, and can significantly increase the response to rearward sounds.

Directivity rapidly disappears as the level of vent-transmitted sound comes within 5 dB of the aid-transmitted sound. Because wide dynamic range compression causes gain to decrease as input increases, aid-transmitted sound dominates vent-transmitted sound over a wider frequency range at lower input levels than at higher input levels. Consequently, the frequency range over which directivity is available is least at high levels, which unfortunately is precisely where it is most needed.¹⁰¹ In short, vents in general and open fittings in particular decrease the effectiveness of directional microphones.

Vents and adaptive noise reduction

Just as with directivity, adaptive noise reduction relies on electronic attenuation of sound (Section 8.1) at specific frequencies, and so applies only to the aid-transmitted sound path. Vent-transmitted sound therefore creates a floor below which sound cannot be attenuated, no matter how poor the SNR is. Open fittings therefore decrease the effectiveness of adaptive noise reduction.

Vents and internal noise

The level of internal noise, like other amplified sound, will be decreased in the low frequencies by vents. For people with near normal low-frequency hearing, perception of internal hearing aid noise will therefore be minimized by making the vent as large as possible.

Vents, compressor action, and battery current

Although a large vent may cause a hearing aid to provide no amplification over an extended low-frequency region, the vent does not affect the sound reaching the microphone, and therefore does not affect the sound reaching any compressors within the amplifier. Consequently, low-frequency sounds may still be activating or even dominating the activity of a compressor, even though all the low-frequency sound heard by the patient arrives via the vent. This is an undesirable situation if the hearing aid has only two or three channels of compression, and hence has compression channels so wide that they encompass both the vent-transmitted region and also the aid-transmitted region. A further disadvantage is that the processing of the low-frequency sounds will consume some battery current, which is wasted if these output signals are inaudible.

Both problems are eliminated by the use of a greater number of compression channels. The gain of all channels in the vent-transmitted region should be set to a low value to minimize battery current used to drive the receiver. In hearing aids intended only for open fittings, the manufacturer may switch off the low-frequency channels completely. Irrespective of how you or the manufacturer sets the compression characteristics in the low-frequency channels, do not expect to see any evidence of compression in the output if these channels are in the vent-dominated frequency region. If they are in the mixed region (the extent of which will vary with gain, and hence with input level), the effective compression ratio will be less than the actual compression ratio operating inside the hearing aid.

5.3.5 Parallel versus Y (or diagonal) vents

Other than their propensity to cause feedback oscillations, one of the biggest difficulties with vents is fitting them in! This is especially a problem at the medial end. Figure 5.21 shows an alternative way to fit in a vent when space is tight. This is called a *Y-vent*, *diagonal vent*, or *angle vent*, as opposed to the *parallel vent* shown in Figure 5.1, and which has been assumed until now. *The Y-vent should be avoided unless there is absolutely no alternative, as it creates two serious problems.*³³⁶ High-frequency sounds propagating down the sound bore will be partially reflected at the Y junction where the sound bore meets the vent tube. This reflection decreases high-frequency gain and also makes high-frequency feedback oscillation more likely.

If a Y-vent absolutely has to be used, the sound bore and the vent tube should intersect as close to the medial end of the mold as possible. Furthermore, the diameter of the sound bore medial to the Y-junction should be widened as much as possible. This decreases the impedance of this section of the sound bore and minimizes the loss of high-frequency energy back up the vent. Of course, if there is room for extensive widening, there is probably room to avoid the Y-vent altogether!

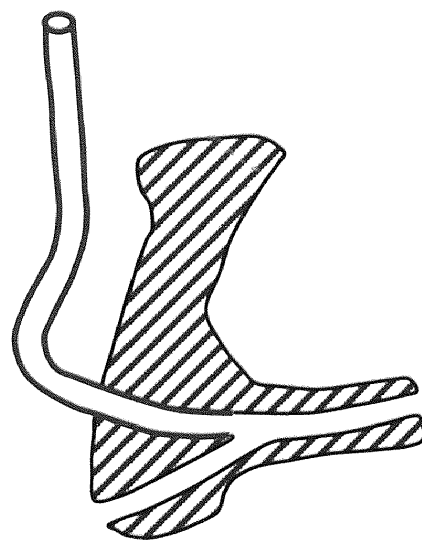


Figure 5.21 Cross section of a Y-vent (or diagonal vent) in a BTE earmold.

5.3.6 Open-canal fittings in summary

Open-canal fittings, when combined with thin tubing and a small BTE, give a very inconspicuous hearing aid, arguably more discreet for patients with hair down to the top of their ears than even a CIC.ⁱ Most of the acoustic properties of open-canal fittings have been covered in appropriate places within this chapter and in Sections 4.2.1 and 4.5.2. The comfort and inconspicuousness of open-canal fittings have made them very successful, although they none-the-less have disadvantages. This section draws together the acoustic characteristics of these devices. Many of these issues are covered in more detail in an excellent review by Mueller and Ricketts (2006).

Gain-frequency response. Open-canal fittings leave the canal sufficiently open that even with the hearing aid turned off, sound at every frequency reaches the eardrum at almost the same level as when no hearing aid is worn. Put more technically, the patient's REOG almost equals REUG, which is equivalent to having REOIG of close to 0 dB at all frequencies. Because the open canal acts as a very large vent, the hearing aid is ineffective at increasing SPL in the ear canal at low frequencies, and is thus limited to providing high-frequency amplification. Compared to using the same amplifier and receiver in a closed fitting, an open fitting will produce about 3 to 5 dB more gain around the resonant frequency of the REOG curve (typically 2000 to 3000 Hz) because the resonance is still present, but much less gain at lower frequencies and about the same gain at higher frequencies (see Figure 5.26). In some mid-frequency region, the sound entering the canal directly has a similar magnitude to the “amplified” sound, so the two paths combine constructively and destructively at adjacent frequencies to produce alternating peaks and troughs in the response. Insertion depth has relatively little effect on the overall gain-frequency response achieved, because its major effect is on the low-frequency gain of the aid-transmitted sound, which is insignificant compared to the low-frequency vent-transmitted sound.

Own-voice occlusion. The open canal allows the sound created by canal wall vibrations to escape, so the open fitting successfully avoids the occlusion effect that makes the aid wearer's own voice unacceptably boomy for more closed hearing aids.

Feedback oscillation. Unfortunately, high-frequency sounds also escape from the open canal, severely limiting the amount of high-frequency gain that can be achieved without feedback oscillation. Fortunately, these hearing aids have become feasible because of the development of feedback cancelling, which digital hearing aids have made possible. Even with feedback cancellation, it is frequently not possible to obtain the prescribed high-frequency gain. However, the ability to avoid occlusion will often outweigh the disadvantage of not achieving the high-frequency gain that is optimal for speech intelligibility.

Microphone directivity and adaptive noise reduction. The second disadvantage of open fittings is that, because the low-frequency sound is dominated by sound directly entering the ear canal, it is not possible to achieve directivity or adaptive noise reduction for low frequencies, where noise is often most intense. In the future, when microphones become much more directional (Section 7.1.4) the loss of this high directivity will be a major disadvantage. Fortunately, new methods for reducing occlusion with a closed earmold may become available (Section 8.5) and open-fittings will possibly become less dominant than they now are, though still much used.

Prescription targets and real-ear gain measurement. A hearing loss of a certain magnitude and configuration requires a specified increase in SPL at the eardrum to compensate, irrespective of how the sound is delivered to the eardrum. The real-ear prescription target for an open fitting is therefore the same no matter whether an open fitting, a closed fitting, or a vented earmold is used (or whether a thick tube, a thin tube, a BTE or a CIC is used). Of course, in all these cases, different coupler gains will be needed to achieve the same real-ear gain. This is not to say that an identical real-ear gain will actually be achieved for an open fitting versus a hearing aid with a minimal vent. When it is not possible to simultaneously avoid own-voice occlusion and achieve the prescribed high-frequency gain, the compromise struck with an open-canal fitting will be in the direction of having no occlusion but not achieving the prescribed gain. Real-ear gain can be verified by measuring REAG or REIG, just as with any other hearing aid. The only change needed is that it is necessary to turn off the control microphone unless the hearing aid is set to a particularly

ⁱ Replacing the open dome with a closed dome or canal-only mold gives just as inconspicuous fitting, of course, as the only change is within the ear canal.

Table 5.5 Typical dimensions (length x internal diameter) in mm of sound bore systems in BTE hearing aids. There is also a tube several mm long and about 1 mm in diameter inside the hearing aid case for BTEs other than the RITE style.

	Earhook BTE	Thin-tube BTE	RITE BTE
Earhook	20 x 1.3	-	-
Tubing	40 x 1.9	55 x 0.8 + 6 x 1.0	2 x 1.2

low gain (Section 4.5.2). Any hearing aid, no matter how open or closed, that relies on feedback canceling to achieve the gain adopted will likely need to be measured with the control microphone turned off.

There has been much ill-advised information written about open fittings, prescription targets and real-ear measurement. There is nothing about preservation of the open ear resonance, and the entry and exit of sound acoustically, that in any way invalidates real-ear prescription targets, or the measurement of REIG, REAG, or REAR speech maps to verify real-ear performance.

In most of the issues discussed above, an open fitting is not fundamentally different from the vented hearing aids that have been used for many decades. It's just that the more open the canal is, the more pronounced each issue becomes. Vented hearing aids also minimize occlusion problems, provide no gain for low frequencies, preclude low-frequency directivity and noise reduction, limit the high-frequency gain that is achievable before feedback oscillation occurs, and undergo constructive and destructive multi-path addition of signals.

5.4 The sound bore: tubing, horns and constrictions

The sound bore provides the path between the receiver and the residual ear canal volume. It has a much greater length in BTE hearing aids than in other types, and hence has a much greater effect on the gain-frequency response for BTEs. There are three types of sound bore systems used in BTE hearing aids, as shown in Table 5.5.

The total length of a BTE sound bore (other than for an RITE) ranges from 60 to 85 mm for adults.³³⁶ For earhook-style BTEs, the final 10 to 20 mm of the tub-

ing is contained within the earmold itself. The sound bore in RITE, ITE, ITC and CIC hearing aids is much shorter, and typically contains a tube from 2 to 10 mm long of diameter 1.0 to 1.5 mm.^j As explained in Section 2.6.2, the sound bore creates resonances, the frequencies of which are determined primarily by the length of the sound bore, but are also affected by its diameter.

So far, all the diameters mentioned in this chapter have been internal diameters, because it is this that affects the passage of sound *along* a tube. The thickness of the tubing wall, and hence the outer diameter, affects the leakage of sound out *through* the walls of tubing. Such leakage can be a problem in high-gain hearing aids, and tubing with extra thick walls is available. Inner and outer diameters of commonly used tubing, along with their NAEL classifications, are shown in Table 5.6. For new tubing, the #13 super thick wall (double wall) tubing provides 2 dB more attenuation of sound leaking through the walls than is obtained

Table 5.6 Diameters, in mm, of commonly used tubing.¹⁹¹³

Tubing type	Inner diameter (mm)	Outer diameter (mm)
#12 Standard	2.16	3.18
#13 Medium	1.93	3.10
#13 Thick wall	1.93	3.31
#13 Super thick	1.93	3.61
#15 Standard	1.50	2.95
#16 Standard	1.35	2.95
Thin-tube	0.80	1.40

^j At least one RITE hearing aid contains a long and convoluted sound bore within the earmold, to achieve a lower resonant frequency than would otherwise occur, and hence create additional OSPL90 and gain in the mid-frequencies.

Theory: How acoustic horns work

Horns help overcome the **impedance mismatch** between the acoustic impedance of a receiver and the much lower acoustic impedance of the ear canal. If the receiver and the ear canal are directly connected together, or are connected via a constant diameter tube, much of the power is reflected back from the medial end of the tube rather than being transferred to the ear canal. By gradually changing the diameter of a connecting tube, and hence its impedance, there is a more gradual transition from the high impedance receiver to the low impedance canal, and hence less power is reflected. This gradual transition is effective only for those high frequencies for which the wavelength is less than or comparable to the dimensions of the tube. Because reflections are less marked, so too are standing waves in the tube. Consequently, the response is less peaky, resulting in improved sound quality.

The effects of horns can be quantified. The approximate boost provided to high frequencies can be calculated from:

$$\text{Boost} = 20 \cdot \log_{10} \left(\frac{d_o}{d_i} \right) \text{ dB} \quad \dots 5.3.$$

That is, horns with the biggest outlet diameters will give the biggest high-frequency boost. However, this boost only occurs for frequencies well above the **horn cut-off frequency**, f_h . Below the cut-off frequency, no boost occurs. For a continuous horn with an exponentially growing diameter, the cut-off frequency can be shown to be:¹¹³

$$f_h = \frac{c \cdot \log_e (d_o / d_i)}{2\pi l} \text{ Hz} \quad \dots 5.4,$$

where c is the speed of sound, and $\log_e$ is the natural logarithm (shown as $\ln$ on most calculators). Thus, the shorter the horn, the higher the cut-off frequency of the horn. As an example, for a horn with an inlet diameter of 2 mm, an outlet diameter of 4 mm, and a length of 25 mm, the horn cut-off frequency is 1520 Hz. The boost *commences* at this frequency and does not reach its full extent until an octave higher than this.

If a horn is made in a stepped manner, as in Figure 5.22, the stepped portion has an additional effect: standing waves will occur within the widened section of tube because reflections occur at each change of diameter. The **quarter-wavelength resonances** caused by these reflections can be used to shape and extend the frequency range of the hearing aid.^{427, 909, 910}

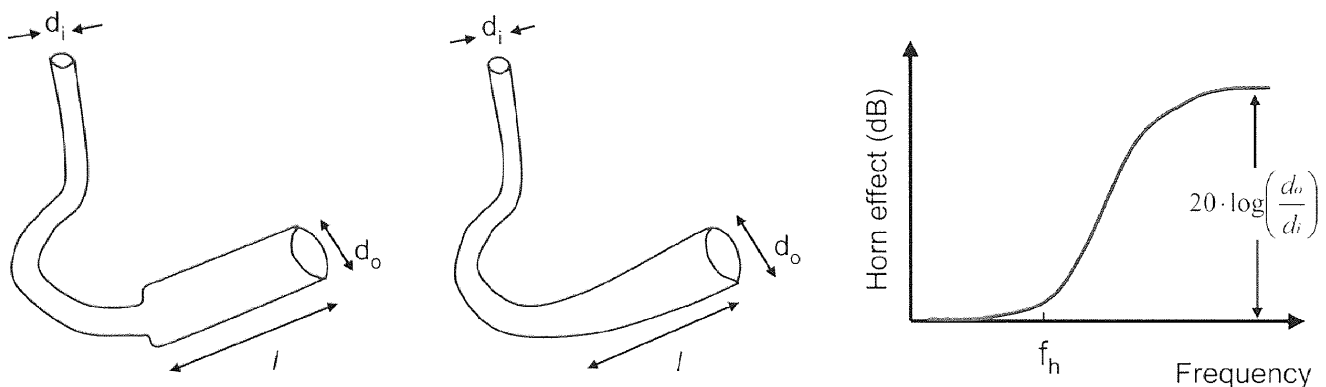


Figure 5.22 Two acoustic horns, one stepped and one continuous, each with inlet diameter d_i , and outlet diameter d_o , and the boost (an increase in gain and maximum output) given to the frequency response by the continuous horn.

with #13 standard tubing.⁵⁵⁰ This difference may seem small but is consistent with the difference in wall thickness. Because a common source of leakage is the junction between the tubing and the earhook, the thicker wall tubing may provide greater advantages over time if it is better able to retain the integrity of this joint.

In areas with high humidity, moisture-resistant tubing should be used. This tubing is made of a different plastic that decreases the likelihood of moisture droplets forming inside. The tubing is stiffer than conventional tubing.

5.4.1 Acoustic horns and constrictions

Varying the internal diameter of the sound bore along its length will modify the high-frequency response of the hearing aid. If the diameter increases (either smoothly or in steps) it is referred to as an *acoustic horn*, and if it decreases it is referred to as an *inverse horn*, *reverse horn*, or *constriction*.

Horns

Acoustic horns increase the efficiency with which high-frequency power is transferred from the receiver to the ear canal, and hence increase both the gain and the maximum output in the high-frequency region. This boost is achieved only above a certain frequency, which depends on the ratio of the inlet and outlet diameters of the horn, and on its length (see panel). The shorter the horn, the higher the range of frequencies affected. Horns attached to a BTE earmold can be much longer than horns contained within ITE hearing aids, and are thus able to boost amplification over more of the frequency range where a boost is often needed. Horns in BTE fittings can typically provide significant boost at 3 kHz and above, while those within ITEs cannot provide any significant boost below 6 kHz.

Horns can be built into BTE earmolds in a number of ways. A simple method is to insert tubing only a few millimeters into the earmold. The outlet diameter of the horn will then be determined by the size of the hole drilled into the medial end of the earmold. Although a horn with one or more steps can be made in this way, the method has two major disadvantages:

- The length of the horn will always be less than the sound bore length of the earmold (typically 15 to 22 mm), so the boost may not extend sufficiently far down in frequency.
- The tubing is poorly retained in the earmold. Furthermore, glue has to be applied at the lateral end of the mold, and over time this will cause the tubing to stiffen, and crack, right at the point where the tubing is most stressed in daily life.

One alternative is to use an elbow securely mounted in the lateral end of the mold, to which the tubing is attached. This has the advantage that the tubing can be replaced without having to replace the mold, or without doing any gluing.

Another alternative is to use a molded plastic horn, such as a *Libby horn*.¹⁰⁶² It is very common for BTE hearing aids to have insufficient high-frequency gain relative to their mid-frequency gain and relative to the prescribed frequency response. Very commonly then, it is desirable to include the widest horn possible. One limiting factor is simply fitting it in, especially if the mold also has to fit a vent.

Figure 5.23 shows two ways in which a Libby 4 mm horn can fit into a mold. In the method on the left, the horn is fully inserted through the mold, for which a hole of approximately 5 mm diameter is required. In the method on the right, however, the final 15 mm or so of the horn is cut off and then the remainder of the horn is glued into the lateral end of the mold. Because

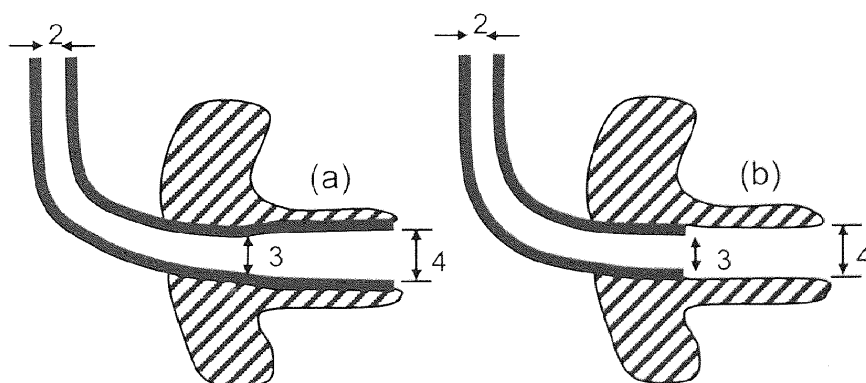


Figure 5.23 A Libby 4 mm horn (a) fully inserted into the earmold, and (b) partially inserted, with the mold forming the final section of the horn. Diameters are in mm.

the mold itself forms the final section of the horn, only a 4 mm hole has to be drilled into the canal portion of the mold. Furthermore, it is the area of the sound bore that matters, not the shape, so an oval-shaped outlet hole can be made if needed.

Using the same method of construction, a 3 mm Libby horn requires only the same space that is needed to fully insert a 2 mm constant diameter tube. The potential disadvantage of this *half-tubing* construction method is that if the horn is glued at the lateral extremity of the mold, the life of the tubing is shortened.

Both the horn effect and the quarter wavelength resonance rely on there being a difference between the inlet and outlet diameters of the horn. Instead of increasing the outlet diameter, the inlet diameter can be decreased relative to a #13 tube. This is the basis of the *Lybarger high-pass tubing* configuration: a tubing of internal diameter 0.8 mm (the same diameter as a modern thin tube) connects the earhook to the final 15 mm section of 1.93 mm diameter tubing. The narrow inlet tubing decreases the mid-frequency gain, however. The small size of the outlet diameter makes it particularly suitable for creating a horn in an earmold for an infant.

Note that amplification at 4 kHz cannot be increased just by *belling* (i.e. gradually widening), or drilling, the last 5 mm of sound bore at the medial tip of an earmold. Such a practice does make a horn, but because it is very short, its major effects will be above 6 kHz. Belling is likely to increase the frequency of the various tubing resonances, which, in a particular fitting, may be advantageous or disadvantageous. Figure 5.24 shows the effects of drilling a 4 mm diameter hole of different lengths at the medial end of an earmold. Notice that the bore has to be at least 10 mm long before a worthwhile effect is achieved at 4 kHz.

An exception to this is when the original, *nominally* constant diameter, tube had been inadvertently constricted at the medial end. The magnitude and extent of high-frequency reduction depends strongly on the degree to which the tube is accidentally constricted when it is glued into a more or less tightly fitting hole in the earmold. A short horn can sometimes provide a significant high-frequency boost, not because of a

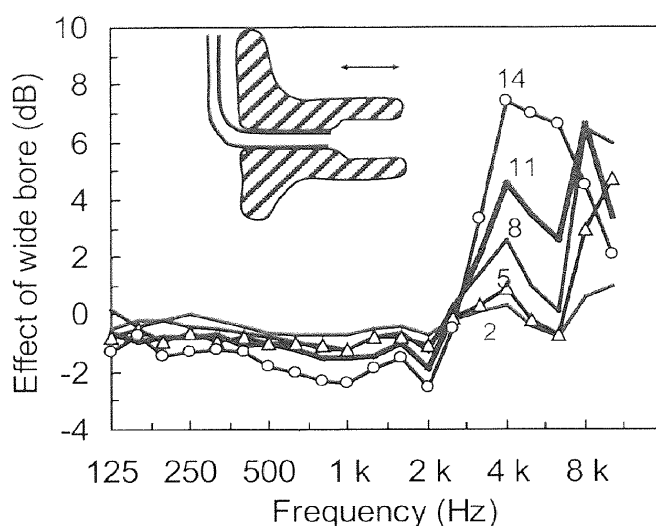


Figure 5.24 The effect of drilling a 4 mm diameter hole at the medial end of an earmold, relative to a constant 2 mm diameter sound bore. The number next to each curve shows the length, in mm, of the widened bore.

horn effect, but because adding the horn removes the constriction.⁹¹⁰ However, horns can also suffer the same fate. If they are squeezed into a hole that is too small for them, the high-frequency boost obtained will be less than that expected.⁹¹⁰

Table 5.7 shows the effect on gain and OSPL90 provided by various acoustic horns relative to a constant diameter #13 tube. The overall high-frequency boost provided by a horn of specified dimensions is reliable – it is an acoustic inevitability – and so does not depend on the characteristics of an individual patient's ears or the model of hearing aid.⁴²⁹ The boost in dB at specific spot frequencies will, however, vary from person to person and from aid to aid. This is because the horn shifts resonant frequencies slightly, as well as providing the overall high-frequency boost. The reason for the small decrease in gain at low frequencies is that horns slightly increase the total volume connected to the hearing aid. The data for the Lybarger high-pass tubing were measured with the one-piece molded plastic version (ER-12 HP).

Thin-tube sound bores do come at a price. As Table 5.7 shows, relative to a wider #13 tube, a constant diameter thin-tube sound bore attenuates high frequencies.^k Thin-tube hearing aids could well use a horn, but so

^k Precise values for the thin tube relative to 2 mm tubing will undoubtedly vary somewhat with the diameter and length of the tubing used, but the general trend of more gain around 750 Hz (caused by a lower resonant frequency) and less gain above 1500 Hz will be generally true.

Table 5.7 Effect on gain and OSPL90 (in dB) of various sound bore profiles relative to a #13 (2 mm) tube of truly constant diameter, for the same receiver.^{428, 429, 1902}

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
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
Thin-tube (0.9 mm)	0	1	4	3	-7	-8	-4	-5	-8
RITC	-1	-4	-5	-7	-10	-6	-3	-6	-6

far none have been made available other than the very short widening at the medial end to which the dome connects. Possibly this is because thin-tube delivery systems were originally developed for use with open fittings, for which the achievable high-frequency gain is severely limited by feedback oscillation. Because of their comfort and appearance, however, thin-tube hearing aids are now also used with closed-canal fittings, so a horn version of the tubing would increase the range of hearing losses for which these hearing aids are effective, and in the process improve sound quality by decreasing the peak-to-trough ratio of the gain-frequency response. Acoustically, the effect would be similar to the Lybarger high-pass tube available decades ago. Manufacturers, please take note!

Constrictions

Constrictions have the opposite effects of horns: they decrease the efficiency with which high-frequency power is delivered to the ear canal. They are rarely needed, partly because hearing loss usually is greatest

at high frequencies, partly because hearing aid receivers become less effective above their primary resonance of 2 to 3 kHz, and partly because multichannel hearing aids make it easy to decrease gain in specific frequency regions. By combining a constriction with a small cavity achieved by widening the sound bore, an even greater degree of high-frequency cut can be achieved.

Figure 5.25 shows the dimensions of three constricting sound bores. The 6C5 and 6C10 configurations are part of a family of sound bores, and are so named because at 6 kHz, they nominally Cut the response by 5 and 10 dB, respectively.⁹⁰⁹ The 6C5 configuration can be made by inserting 14 mm of #16 tubing inside an earmold with a 3 mm horn.⁹¹¹ To make the 6C10 configuration, 13 mm of #19 tubing is inserted inside 13 mm of #13 tubing which is inserted inside a 3 mm horn.⁹¹⁰ The 1.5 LP (low-pass) configuration is available as a one-piece molded tube (ER-12LP). The acoustic effects of constrictions are shown in Table 5.7.

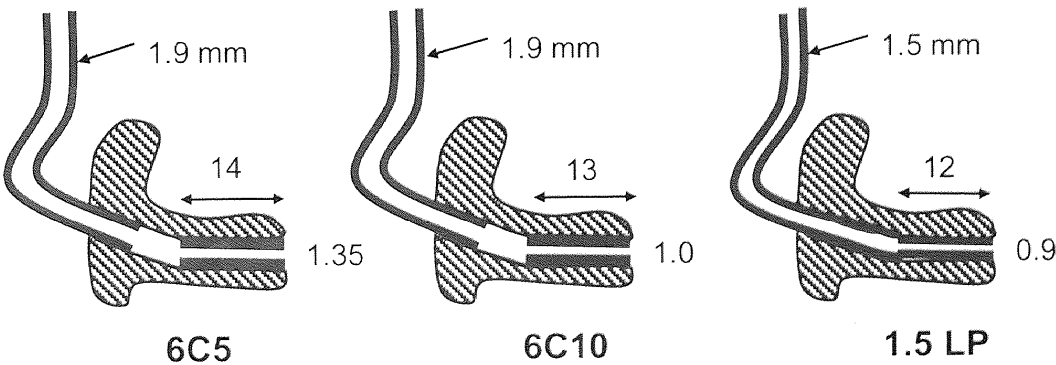


Figure 5.25 The dimensions of the constriction configurations known as 6C5, 6C10, and 1.5 LP.⁹⁰⁹

5.4.2 Tubing insertion depth

For closed and minimally vented hearing aids, increasing the length of the canal stalk decreases the volume of the residual ear canal and hence increases the gain at all frequencies, but a little more for high frequencies than for low frequencies. For open-canal fittings, increasing insertion depth again increases gain across frequency, but this time the effect is greatest for low frequencies, and the mechanism is totally different (see panel). Figure 5.26 shows the SPL change at the eardrum position of a KEMAR manikin as insertion depth increases. As the same receiver and electrical drive level was used for both measurements, the mea-

surements illustrate several other features of open- and closed-dome thin-tube responses:

- Relative to the closed response, the venting effect of the open dome produces a low cut that reaches a slope of exactly 12 dB per octave.
- The high acoustic mass of the thin-tube sound bore moves the first resonance down to a frequency (in this case 500 Hz) much lower than expected from wavelength resonance alone and lower than observed with #13 tubing.
- The open system has a higher output around the canal resonance frequency range of 2 to 4 kHz.

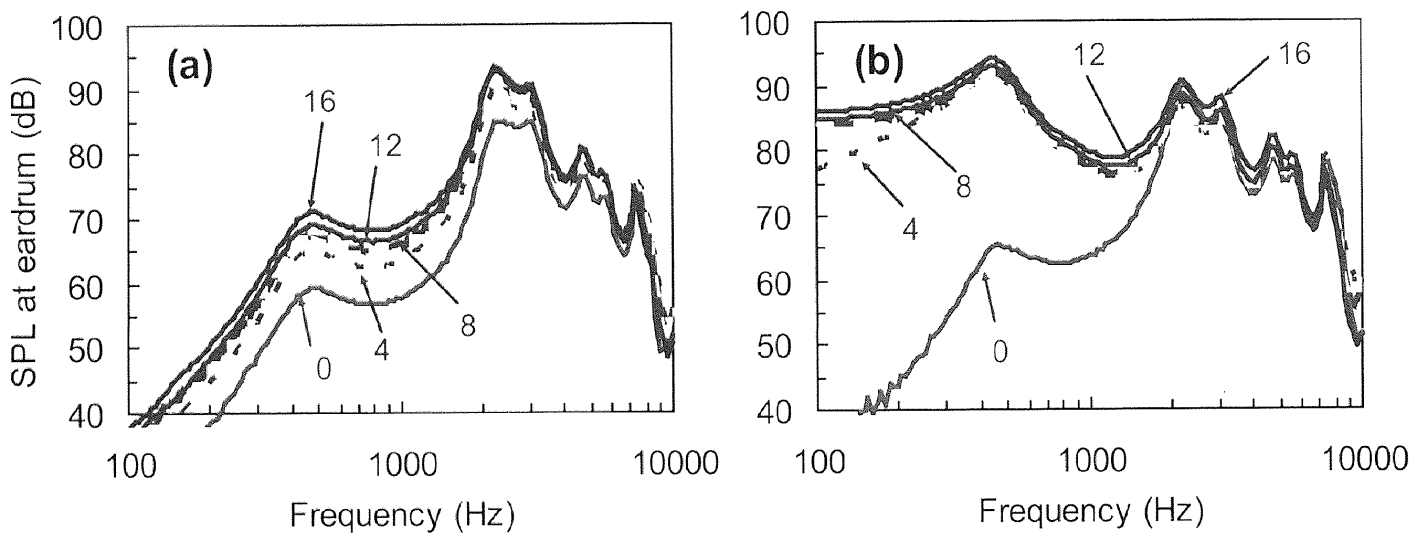


Figure 5.26 Response in an ear simulator of a receiver connected to a thin-tube sound delivery system terminating in (a) an open-dome canal fitting and (b) a closed-dome canal fitting. The numbers in each figure show the insertion depth of the tubing, in mm, past the ear canal entrance. The closed dome did not fully seal the canal for the two shallowest insertions.

Why insertion depth changes ear canal SPL in open fittings

Below about 1500 Hz, the impedance of the vent (i.e. the path from the tip of the tubing to the outside air) is much lower than the residual canal impedance, and so the vent impedance dominates the total impedance and hence determines the SPL in the canal. As insertion depth increases, so too does the length of the vent path, the vent impedance, and hence the canal SPL. For high frequency sounds, deeper insertion still causes the residual canal to have a smaller volume and greater impedance, but this advantage is offset by the tube opening being closer to the eardrum, and hence losing some of the sound pressure increase along the canal that the open-canal resonance provides.

5.5 Dampers

Dampers are used to decrease gain and maximum output at frequencies corresponding to resonances in the sound bore (Sections 2.6.2 and 2.7). Dampers are most effective if they are placed at locations where the resonance causes the fastest flow of air particles. For wavelength resonances, particle velocity is least at the end of the tube that joins to the receiver. In a BTE, the 1, 3, and 5 kHz resonances are therefore damped increasingly effectively as the damper is moved down the sound bore from the receiver towards the lateral tip of the earmold. Conversely, the receiver resonance near 2 kHz is damped slightly more effectively if the damper is placed near the receiver than at the tip of the earhook. Figure 5.27 shows the effect of a 1500-ohm damper placed at the tip (earmold end) and the nub (hearing aid end) of an earhook.

Table 5.8 shows the effect on gain and OSPL90, in dB, of dampers with different impedances when they are placed at each end of the earhook.

In some cases it might be necessary to use dampers at both ends of the earhook to achieve a sufficiently smooth gain and OSPL90 response that is sufficiently close to the target gain.

Dampers can also be placed in the tubing of RITE/ITE/ITC/CIC hearing aids, but they are likely to need replacing more frequently because of blockage by wax and moisture. Some receivers have dampers built into the receiver outlet. In such cases, the entire

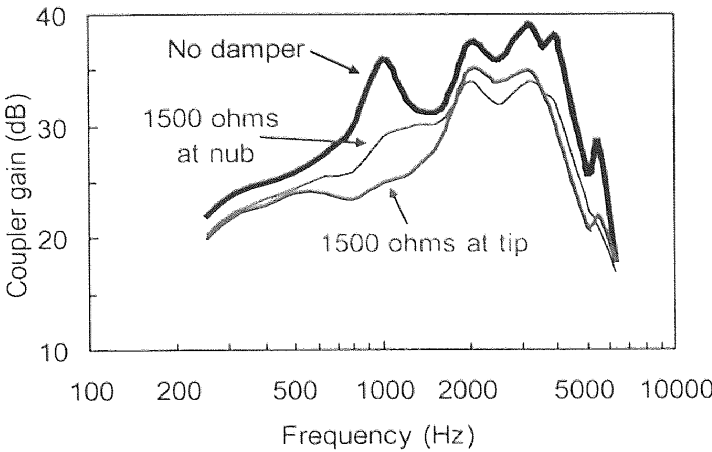


Figure 5.27 Frequency response of a hearing aid with no damper, and with a 1500 ohm damper placed at each end of the earhook.

receiver may need to be replaced when the damper becomes blocked.

Dampers can also be inserted in microphone tubing to decrease the high-frequency response of a hearing aid (typically to prevent feedback). Dampers are available with diameters of 2.08, 1.78, 1.37 and 1.12 mm to accommodate these various applications.¹⁸⁴⁷ For the three smaller sizes, the damping screens are not encased within a metal ferrule.

Dampers are currently not used in thin-tube sound bores, possibly out of concern that they would more easily block with moisture, and possibly because thin tubes inherently have greater damping. (No location

Table 5.8 The typical effect of the dampers placed at the nub or tip end of the earhook of a BTE hearing aid. Values shown are averages across several hearing aids; the attenuation varies slightly from hearing aid to hearing aid. The colors are the coding system used by Knowles Inc. Other values available are 1000 ohms (brown), 3300 ohms (orange), and 4700 ohms (yellow).

Damper impedance (ohms)	Damper position	Frequency (Hz)								
		250	500	750	1000	1500	2000	3000	4000	6000
330 (gray)	Nub	0	0	0	-1	-1	-1	-1	0	0
680 (white)	Nub	0	-1	-1	-3	0	-1	-1	0	0
1500 (green)	Nub	-1	-2	-3	-7	-1	-2	-4	-1	-1
2200 (red)	Nub	-1	-1	-2	-6	0	-3	-3	-4	-1
330 (gray)	Tip	0	0	-1	-3	-1	-1	0	-1	0
680 (white)	Tip	0	0	-2	-6	-1	-1	-1	-1	-1
1500 (green)	Tip	-1	-2	-6	-11	-3	-1	-2	-4	-1
2200 (red)	Tip	-3	-4	-9	-16	-4	-1	-1	-5	-1

Practical tip: Shaping a BTE mid-frequency response with dampers

- To maximally damp 1 kHz and minimally damp 2 kHz, place the damper as close to the earmold as possible. The tip of the earhook is the most practical position. Dampers placed at the medial end of the earmold would be more effective, but quickly become clogged with wax and moisture, and should therefore be avoided.
- To maximally damp 2 kHz, and minimally damp 1 kHz, place the damper as close to the receiver as possible. The end of the earhook where it attaches to the hearing aid case is the most practical position, but only some earhooks have been designed to accept fused mesh and sintered steel dampers in this position.

across the cross-section of a thin tube is far from the wall where damping inevitably occurs when the moving air rubs past the stationary wall). As Figure 5.26 shows, thin-tube sound bores nonetheless have pronounced resonances.

5.6 Specific Tubing, Damping and Venting Configurations

Earmold laboratories and hearing aid manufacturers offer a range of earmolds or sound delivery systems that have particular combinations of tubing, venting and damping. These earmolds or sound delivery systems are given particular names or numbers. Instead of thinking of each of these as a unique style with unique acoustic properties, identify the shape and dimensions of the sound bore, the size of the vent path, and the value and location of any dampers. The acoustic performance of the complete earmold will readily be understood on the basis of these three elements.

5.7 Procedure for Selecting Earmold and Earshell Acoustics

The following steps can be used to select suitable earmold acoustics prior to fitting the hearing aid. The procedure assumes that a tentative choice for the rest of the hearing aid has already been made (see Chapter 11). Sometimes, performing these steps will show that the first tentative choice was not a good one, and that a new choice should be made.

Step 1: Find the maximum vent size possible. The target insertion gain is calculated, and the appropriate one of Tables 5.2, 5.3 or 5.4 is used to find the *maximum vent size* that can be used without feedback. For non-linear hearing aids, the target gain for low-level inputs should be used, as gain is greatest for low-level

inputs. Remember to add an allowance (perhaps 15 dB) if feedback cancellation is available, and subtract a safety factor (perhaps 7 dB).

Step 2: Estimate the minimum vent size needed. Based on the patient's hearing thresholds at 250 and 500 Hz, estimate the *minimum vent size* needed to overcome the occlusion effect. Good research data on this are not available, but as a guide, low-frequency losses greater than 50 dB do not need a vent, and low-frequency losses less than 30 dB must have at least a 2 mm vent, and preferably will have a larger one. Although a 1 mm vent is usually too small to have any effect on occlusion, the inclusion of such a vent will make it easier for the clinician to drill or grind a wider vent if it proves necessary.

Step 3: Decide on the vent size. Given the constraints determined in steps 1 and 2, this will be an easy choice for many patients, as the maximum and minimum vent sizes will be the same, or the maximum vent size will be slightly larger than the minimum. More difficulty will be found for patients with near normal low-frequency hearing thresholds and 60 to 90 dB loss in the high frequencies. The maximum vent size will turn out to be less than the minimum vent size. These are indeed difficult fittings, and will certainly require feedback-canceling algorithms. It is worthwhile ordering adjustable vents for patients with difficult audiograms, and it is probably worth while ordering adjustable vents for anyone where there is not a big range between the minimum vent size and the maximum vent size. Equivalently, for hearing aids with canal fittings rather than earmolds, there are some choices in the degree of openness of the fitting and, if necessary, the fitting can be changed without changing the hearing aid itself. If the result of this step 3 is selection of an open-canal fitting, then step 4 is not necessary, as cosmetic considerations will sug-

Practical tip: Will it fit?

Before finalizing your choice of sound bore and vent, ensure that the larger diameter of the canal stalk on the impression is at least 2 mm bigger than the sum of the sound bore diameter and vent diameter.

gest that a thin-tube bore be used, for which there is no choice of horns or constrictions.

Step 4: Select a sound bore profile. The details outlined in this step are aimed at earmolds for BTE hearing aids, partly because of the limited effectiveness of horns for RITE/ITE/ITC/CIC hearing aids, and partly because selection of the sound bore for these hearing aids is carried out by the manufacturer. For BTEs, the sound bore has the greatest effect on the response shape in the 2 kHz to 4 kHz octave, so selection can be based primarily on these frequencies. First calculate the slope (in dB/octave) of the coupler gain target (i.e. the 4 kHz target gain minus the 2 kHz target gain). Then calculate the maximum slope of the coupler gain of the chosen hearing aid. If the target slope rises more steeply than the hearing aid slope (as will often be the case) then a horn of some type is required. If, in rare instances, the target slope of the response from 2 kHz to 4 kHz is *less* than the hearing aid gain slope, then a constriction of some type is required. If the target slope and the hearing aid slope are approximately the same, a #13 tube is appropriate.¹

The data in Table 5.9 will help you decide which horn or constriction to choose. Simply find the sound bore configuration whose slope in the 2 to 4 kHz octave matches the discrepancy you calculated between the target slope and the slope of the hearing aid you are going to fit. Note that the Lybarger high-pass tube achieves its slope, relative to a #13 tube, by suppressing the mid-frequencies rather than boosting the high frequencies, as shown in Table 5.7. Also note that the 1.5 LP tube achieves its cut from 500 Hz to 2 kHz, and so has little effect on the slope above 2 kHz. If you adopt a simple rule (without doing any calculations) of always choosing the biggest horn that will fit in the ear canal, you will be right most of the time!

Table 5.9 Sound bore profile needed to resolve a discrepancy between a target response slope (calculated as 4 kHz gain minus 2 kHz gain) and the response slope available from the hearing aid in a coupler.

Sound bore profile	2 to 4 kHz slope (dB/octave)
Libby 4 mm horn	12
Libby 3 mm horn	4
CFA #2 horn	7
CFA #3 stepped bore	7
Lybarger high-pass tube	11
#13 glued-tube	-1
6C5	-6
6C10	-7
1.5 LP tube	-1

If the selection of a hearing aid and earmold is based on insertion gain instead of coupler gain, Table 5.9 can still be used to select the sound bore. In this case, base the selection on the discrepancy between the target insertion gain slope and the expected insertion gain slope for the chosen hearing aid.

Step 5: Select a damper. Selection of the damper is most efficiently made after the hearing aid has been fitted. The first reason for this is that Table 5.8 does not show what effect the damper has on the frequencies between the audiometric frequencies. Second, the precise effects of dampers at a given frequency will vary depending on whether that frequency coincides with a peak or with a trough. Third, peaks and troughs in the insertion gain response of a hearing aid will depend on the shape of the individual's real-ear unaided response. Fourth, unlike a vent or a sound bore profile, the size of a damper can be changed at a fitting appointment within a few seconds. It therefore seems easiest to make the first measurement of real-ear gain with whatever damper comes as standard with the hearing aid, and then to vary the damper as needed, guided by the data in Table 5.8 and the information in the panel *Shaping a BTE mid-frequency response with damping*.

¹ The CORFIG figures used in this book for BTE hearing aids are based on the 2 cc coupler response being obtained with a HA2 earmold simulator, but the insertion gain being obtained with a constant diameter (#13) sound bore in an occluded, but typically leaky, earmold. Consequently, when there is no discrepancy between the target coupler response and the actual hearing aid response, the appropriate sound bore is a #13 tube.

Practical tip: Changing dampers quickly

Dampers can be changed quickly and without damaging the damper to be removed if a small stock of spare earhooks for the hearing aids most commonly used is maintained. These earhooks can be pre-loaded with dampers of different sizes.

5.8 Ear Impressions

Although this chapter has commenced with the acoustic effects of earmolds and earshells, there can be no earmold or earshell without first taking an impression. This section describes techniques and materials for making an impression

5.8.1 Standard ear impression techniques

Examine the ear canal. Taking an ear impression begins with an otoscopic examination. It is essential to pull the pinna back and to visualize the eardrum and the canal walls so that any abnormalities are known prior to taking the impression.

- Do not proceed if cerumen is present in amounts large enough to disrupt the accuracy of the ear impression. Opinions vary as to how much this is, but it certainly depends on the accuracy required. More cerumen can be tolerated for a low-gain, vented, BTE earmold or full concha ITE hearing aid than for a high-gain occluded aid or a CIC.
- Do not proceed if there is any visible sign of outer or middle ear infection or inflammation, or a distended or perforated eardrum. Medical clearance should first be obtained in each of these cases.
- Do not make a deep impression if the ear canal widens sufficiently (relative to the outer parts of the canal) that removal of the impression will be difficult. It is common for ear canals to widen slightly in the anterior-posterior dimension just medial to the second bend.³⁶ Ear impression material is able to compress *slightly* during removal (Section 5.8.3), but there is a limit. An extreme case of widening is when a mastoidectomy has been performed to remove diseased portions of the mastoid bone. ENT clearance should be sought before taking an impression of such an ear. An additional block(s) is used to pack the

surgically created cavity prior to inserting the block that protects the eardrum.

- Trim any hair in the concha that is long enough to be cut with scissors, as it will be less likely to distort the impression or to get caught in the impression and make removal difficult.

Insert a canal block. A *canal block* is a small amount of cotton wool or foam that fills the cross-section of the ear canal to prevent impression material flowing further into the canal than is required. Canal blocks are also called *oto-blocks*, *impression pads* and *ear-dams*. The resistance to flow provided by the block enables the impression material to completely fill the canal cross-section right down to the desired length, rather than gradually tapering off in width. A piece of strong thread is knotted around the block to aid in removal, although the thread is usually needed only if the block has to be removed without an impression being taken. Alternatively, the cotton or foam is attached to a tube (see panel and Figure 5.28).

Blocks can be custom-made or, more conveniently, can be purchased in a range of sizes, with pre-tied thread. The correct size must be used: blocks that are too small may get pushed down the canal by the impression material, or allow the material to flow around the block. Blocks that are too large will not go in far enough, and may be uncomfortable. Blocks with decreased thickness in the medial-lateral dimension are available for taking deep canal impressions. The block is most conveniently inserted by pushing it with an illuminated plastic stick, referred to as an *ear-light*, *oto-light*, or *light-stick*. Your little finger should be braced against the side of the head whenever using

Caution: unintended consequences

- A canal block of adequate size *must* be used. Impression material has been known to enter the middle ear cavity, either by entering through an existing undetected perforation, or by the pressure of syringing rupturing the eardrum.^{958, 1564}
- Widened ear canals close to the eardrum, as a result of either an atypically narrow entrance, or of mastoid surgery, can result in ear impression material being so wedged in that surgical removal is needed.^{800, 958}

the ear-light. If pushing the cotton block deeper suddenly becomes easier, beware – the canal may widen suddenly and removal of the impression will be difficult. The depth of insertion of the canal block is very important. Earmold or aid manufacturers can make the finished device with a canal stalk shorter than the impression, but they cannot make it longer. Err on the long side of what you need. The block should be at or past the second bend, unless you are sure you need a very short canal stalk on the finished device. If you wish the earmold or shell to be shorter than the impression you can mark the desired length on the impression.

Mix the impression material. Use only the recommended proportions of the ingredients. Although changing the mixture may let you decrease the viscosity (i.e. make it runnier for easy syringing) or vary the setting time, the change will probably also adversely affect the finished impression. Excessive liquid in a liquid/powder acrylic, for example, will make the impression more readily melt or change shape in heat¹²⁴⁹ and will increase the amount it shrinks.¹⁴ Mixing must be thorough but fast. It should be done with a spatula on a disposable pad or cleanable surface. The reasons for this are to avoid:

- possible adverse health consequences for the clinician arising from repeated absorption of impression chemicals through the skin;
- contaminating the impression material with sulfur-based substances that can leak from hand lotions and from latex gloves;¹⁹¹³ and
- raising the temperature of the impression material, because setting time decreases as temperature increases.

Similarly, the impression material can be scooped into the syringe with the spatula, or by pushing the inverted syringe at an angle around the mixing pad.

Fill the ear. Partially depress the syringe (or gun) until the material is starting to flow out of the tip. Pull the pinna up and back so that the syringe can be inserted as far as possible. Syringe extension tips can be used for long narrow canals. Depress the syringe until the material has covered the syringe tip to a depth of about 6 mm (0.25 inches). Continue to depress the syringe plunger but simultaneously withdraw the syringe tip at the rate required to keep it buried by the same amount. After the canal is filled, and the concha is nearly filled, lower the plunger end of the

syringe and push the syringe tip upwards along the back of the concha (close to the anti-tragus and anti-helix) towards the helix. After the cymba-concha is filled, raise the plunger end of the syringe and push the syringe tip down the front part of the cavum-concha (close to the tragus). Finish syringing when the concha is completely filled and is slightly overflowing on all sides. The earmold/earshell laboratory must be able to recognize all the landmarks on the ear, and this is not possible unless the concha is over-filled. The whole operation should be one complete motion with a constant pressure being applied to the syringe. Finishing in such a way as to give an approximately flat external surface will make it easy to glue the impression to a container for shipping should that be necessary.

Mark the impression. If the hearing aid is an ITE or ITC, and will receive a directional microphone, then scratch a horizontal line across the face of the impression. This line will assist the manufacturer to position the two ports in the same horizontal plane to maximize frontal directivity.

Wait. After 7 to 10 minutes (depending on the impression material and the temperature), test the impression for hardness by momentarily indenting it with a fingernail or other sharp object. If the indent fully disappears, the impression is sufficiently cured. If the canal is particularly twisty, and/or the canal is particularly long, wait a few minutes longer than usual, so that the impression is less likely to tear as it is extracted.

Remove the impression. Have the patient open and close his or her jaw a few times. Pull down, then back, then up on the pinna. These movements help break the bond between the impression and the ear. Extract the helix part of the impression (the *helix lock*). Grasp the impression and pull it out with whatever twisting motions seem to best suit the individual ear.

Inspect the ear. Make sure that nothing has been left behind!

Inspect the impression. Make sure there are no fold marks, gaps, or bubbles. These blemishes can be tolerated in parts of the impression that will be cut away before the finished product is made, but nowhere else. Good quality in the canal stalk is particularly important. If in doubt, make a second impression. Leave the canal block attached to the impression. Its angle relative to the impression will give the manufacturer some clues about the direction taken by the canal medial to the end of the impression material. *Never*

Has the impression reached the bony canal?

For hearing aids that are intended to extend into the bony canal, assess the following:

- If the second bend is not clearly visible in the impression, try again – the impression is too short.
- Inspect the impression under a magnifying glass – skin in the bony canal is smoother and less porous than in the cartilaginous canal, and this difference in texture is observable in a good quality impression.

lengthen the impression by adding impression material after the impression has been removed from the ear. It cannot be done accurately and is likely to result in discomfort and increased feedback.¹⁴²⁰

Annotate and send the impression. Pack the finished impression in a shipping container in a manner suitable for the impression material (Section 5.8.3). Any distortion of the impression during shipping will be reproduced in the final product. Alternatively, scan the impression with a laser scanner and electronically transmit the scanned image to the manufacturer. However the impression is sent, annotate the impression, accompanying documentation, or scanned electronic record with notes on any abnormalities observed in the ear canal or requests for the finished otoplastic to differ from the impression. Mark any hollows in the impression that are caused by bumps in the ear (or else the technician may assume the hollows are the result of a poor impression technique and fill them). If the ear canal is particularly mobile when the jaw moves, mark the mobile region unless the impression has been taken with the jaw open (see later).

Clean up. Appropriate infection control measures are important, as they are for real-ear gain measurement, but it is beyond the scope of this book to cover the degree of risk and type of control measures required. While cerumen itself may not be an infectious substance, it is extremely difficult to ascertain visually whether there is any blood or other fluids mixed in with it.⁸⁸⁹ All cerumen should therefore be treated as potentially infectious.⁸⁹⁰ Extremely high care and fastidious disinfection (or disposal) of equipment should be taken if any infection is evident in the ear or if any procedure inadvertently causes bleeding in the ear canal.

5.8.2 Ear impression techniques for CICs and high-gain hearing aids

CIC hearing aids and high-gain hearing aids may require the earshell or earmold to fit the ear canal more tightly than is necessary for other hearing aids. A tight fit may be needed to avoid feedback oscillation or, in the case of a CIC, to retain the hearing aid in the ear.

CIC hearing aids are retained in the ear by the bends in the ear canal and by the variations in cross-sectional area and shape that occur along the axis of the canal. The widening that usually occurs at the second bend is particularly important.¹⁴²⁰ It is essential, therefore, that impressions for CIC hearing aids be sufficiently deep that they clearly contain the second bend, and preferably extend at least 5 mm past the second bend. With the canal block inserted this deeply, the impression material is able to expand the cartilaginous canal along its entire length, and so provide a more secure fit.¹⁴¹⁹

CIC hearing aids, and to a lesser extent, ITC hearing aids may also require a good fit to ensure that the hearing aid does not work its way out of the ear. Movement of the hearing aid can occur because the ear canal changes shape when the patient moves his or her jaw. In particular, the anterior-posterior dimension of the canal between the first and second bend gradually increases as the jaw opens. As the jaw opens, the condyle of the mandible moves forward, and this pulls the anterior wall of the canal forward.¹³⁶⁰ Averaged across ears, the canal width increases by 10% for a jaw opening of 25 mm measured between the upper and lower incisors.¹³⁵⁹ If the patient's back teeth are missing, the patient has poorly fitting dentures, or the patient has a temporo-mandibular joint disorder with some other cause, the jaw can over-close, and the

CIC impression technique in brief

- Take an impression to 5 mm past the second bend.
- Use a medium-to-high viscosity silicone impression material (e.g. Otoform A/K, Westone, Silicast, Steramold, Otosil, Dahlberg).¹⁴¹⁹
- Use an open-jaw technique.

variation in canal size with jaw motion will be even greater than normal.⁶⁵²

The solution to an overly mobile canal is to take an ear impression with the jaw held open, by having the patient bite on a 25 mm spacer until the material has cured.¹⁴¹⁸ Although it might be thought that the thicker canal stalk in the mold or earshell would be uncomfortable when the jaw is shut, CICs made from open-jaw impressions are reported to be equally comfortable as, or more comfortable than, those made from closed-jaw impressions.⁵⁴⁶ Pirzanski (1997a) comments that discomfort may result from a *loosely* fitting hearing aid because the patient repeatedly pushes it in deeper than it was intended to go, in an attempt to achieve a more secure fit or to prevent feedback oscillation.

Should open-jaw impressions be made for all CIC hearing aids? Possibly, although it seems probable that the need is greatest for those patients whose ear canals change shape the most. The clinician can estimate the degree of movement by observing the canal wall movement with an otoscope or, more intimately, by feeling the degree of motion with an inserted finger.¹¹⁵³

Greatly excessive movement of the canal wall may preclude the use of a CIC hearing aid.⁶⁵² A potential, though untried, solution may be to make the lateral part of the hearing aid a *loose* fit in the canal, but to make the medial part a tight fit within the bony

canal (which does not move). A very soft material for at least the medial part of the hearing aid would be essential for comfort.

An alternative way to make a tightly fitting earmold or shell is to progressively build-up the size of the impression in the ear of the patient. The three-stage impression technique (see panel) uses ear impression material with different viscosities to make a tight but very accurate impression of the ear.⁵⁴³ Each stage expands the walls of canal, with the greatest expansion occurring in those places where the ear has the greatest flexibility.

Both the open-jaw technique and the three-stage technique increase the width of the earmold in the anterior-posterior dimension just inside the ear canal entrance.^{1110, 1419} The relative effectiveness of the two techniques is not known, but the open-jaw technique is considerably faster. A third option is to take a single-stage, closed-jaw impression and have the earmold or hearing aid manufacturer apply special build-up around the aperturic seal region. This is less effective than the three-stage technique because the manufacturer cannot know the flexibility of the patient's ear canal, but even manufacturer's build-up provides enough attenuation for most high gain hearing aids.¹¹¹⁰

Deep-insertion CICs obviously require very deep impressions. The cotton block must be located at

The three-stage technique in brief

1. Take an impression using a viscous (i.e. non-runny) impression material, and with an embedded piece of tubing extending to the cotton block. The embedded tubing provides pressure relief as the impression is being removed from the ear, which is particularly valuable for steps 2 and 3.
2. Apply medium viscosity impression material over the surface of the canal stalk of the impression. Insert the impression, and apply a gentle pressure to it for a few seconds to assist re-distribution of the uncured material. Remove the impression when dry, ensure that the tube is unobstructed, and then re-insert the impression. Use the air pump of an impedance meter to ensure that a static pressure seal can be achieved. There should be no leakage for 5 seconds after applying a pressure of 200 daPa, while the patient opens and closes his or her jaw. If a leak occurs, repeat this step 2.
3. For this step, the patient's head should be turned to the side and resting on a pillow. Insert a new cotton block, at least as deeply as the first one, fill the ear canal with a low-viscosity material, and quickly re-insert the impression, thus forcing out much of the low-viscosity material. The coating left behind on the impression makes a closer match to the fine structure of the ear.

The earmold manufacturer should be instructed not to add any build-up and not to buff the earmold. For further details, see Fifield, Earnshaw & Smither (1980). For a faster, but less accurate procedure, omit step 3.

In summary: Five ways to produce a tightly fitting, but comfortable, earmold or earshell

- Take the impression with the jaw open.
- Take a two- or three-stage impression.
- Request special build-up during earmold construction.
- Use a viscous (non-runny) silicone impression material.
- Pat down the impression material before it hardens.

When used in isolation, items near the top of the list are probably more effective than items near the bottom of the list.¹¹¹⁰ The use of *all* the techniques simultaneously has not been investigated and is definitely *not* recommended.

or within a few mm of the eardrum, and must itself occupy only a few mm. A cotton block designed exclusively for this purpose, as shown in Figure 5.28, uses cotton only about 2 mm deep, securely attached to the end of a hollow plastic tube. During extraction of the impression, the tube allows the pressure medial to the impression to equalize to the ambient air pressure, minimizing pain during removal. Because the cotton block is so close to, or even touching, the eardrum, the impression material should have a very low viscosity to minimize the pressure it can exert against the eardrum during injection of the impression. The medial surface of the cotton block can be coated with lubricant prior to insertion to ease removal when the impression material has hardened.

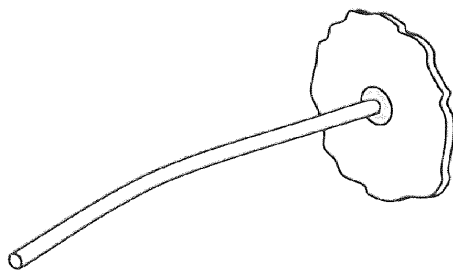


Figure 5.28 A thin cotton block with attached pressure-relief tube, used for taking very deep impressions adjacent to the eardrum.

5.8.3 Ear impression materials

At least three types of materials are used for taking ear impressions. In each case the impression sets when two materials are mixed and undergo a chemical reaction:

- **Acrylic** material (e.g. ethyl-methacrylate) is mixed by combining a liquid and a powder. An example is Audalin™.
- **Condensation-cured silicone** material (e.g. dimethyl-siloxane) is mixed by combining two pastes. Examples are Otoform-K™, Siliclone™, Blue Silicast™, and Micro-sil™.
- **Addition-cured silicone** material (e.g. polyvinyl-siloxane, vinyl-polysiloxane) is mixed by combining two pastes. Examples are Otoform A/K™, Reprosil™, Pink Silicast™, Silasoft™, Mega-Sil™, Dur-a-sil Equal™, Matrics™, Silhouette Plus™.

Ear impression materials must have a certain combination of properties if they are to lead to a tightly fitting, but comfortable, earmold or earshell.

Viscosity. Low viscosity (i.e. runny) materials are easy to syringe and are least likely to expand or distort the ear canal.^m They were previously recommended for making impressions for CIC hearing aids, so as to make the most faithful reproduction of the ear canal. Unfortunately, this recommendation may have overlooked the changes in ear canal size that are caused by jaw motion (Section 5.8.2). Pirzanski (1997a) recommends that low viscosity material *not* be used when a

^m Viscosity is measured in units of mPa s. Unfortunately, values are rarely quoted, so we have to describe viscosity by the ambiguous terms of low, medium and high.

tight fit is required, as it does not sufficiently inflate the cartilaginous portion of the canal. High viscosity material is more likely to push hairs against the canal wall rather than encapsulate them, and so will be less painful to remove from a hairy canal.¹⁴¹⁷ One technique that has been recommended for deeply seated CIC hearing aids is to use a low viscosity material for the bony canal, followed one minute later by a higher viscosity material for the remainder of the impression.¹⁶⁸⁵ The intent is that this combination will expand the cartilaginous canal but not the bony canal. The comfort and feedback advantages of the technique have not been quantified.

Dimensional stability. If an ear impression shrinks in the hours or days following its making, the earmold or earshell made from the impression will also be smaller to the same degree unless some compensatory build-up is applied during manufacture of the earmold or shell. Such build-up typically is applied, but the overall precision of the process from impression to finished earmold or shell is obviously greatest if shrinkage is minimized. In the first 48 hours after the impression is made, the linear dimensions of addition-cured silicone material shrink by 0.1% or less.^{1342, 1343} By contrast, condensation-cured silicones shrink by 0.5%,¹³⁴² and acrylic materials shrink by 2 to 5%.^{14, 1343}

Stress relaxation. When a force is applied to an impression to remove it, it stretches, compresses, and twists as it is pulled through the bends and tight parts of the ear canal. After removal, it is desirable that the impression spring completely back to the size and shape of the ear canal. The extent to which this happens is called its stress relaxation. Silicone materials have excellent stress relaxation properties;ⁿ acrylic materials do not. Forces can also be applied to an impression during shipping, so all impressions should be suitably protected. Crumpled tissues or other lightweight packing material are adequate to protect silicone impressions. Acrylic materials must be more effectively protected against distorting forces, so the concha portion of the impression should be glued to the liner of the shipping container in such a way that nothing can press against the canal stalk.

Tensile strength. Some force has to be applied to the ear impression to remove it from the ear. It would

be a disaster if the impression tore at this stage, so impression materials have to have an adequate tensile strength. Tearing is very rare and is likely to occur only when more medial parts of the canal are considerably wider than more lateral parts or when the impression materials have been mixed in the wrong proportions.

Hardness. Softer impression material is flexible when set and hence easier to extract from the ear than harder impression material. Do not confuse viscosity (how easily the material flows before it is set) with hardness (how easily it deforms after it has set), as these have nothing to do with each other.

Release force. Ear impression materials are designed to conform closely to minute variations in the surface of the ear and ear canal. This makes the impression adhere to the skin so, to make removal possible, a release agent is built into the impression material. This produces the oily feel of a completed impression.

5.9 Earmolds and Earshells

5.9.1 Earmold and earshell construction

Earmolds and earshells (jointly referred to as *otoplastics*) are made, usually by a specialist earmold or hearing aid manufacturer, from the impression obtained by the clinician. The impression can be considered to be a negative of the ear. There are two methods of earmold/earshell construction: the investment method and the computer-aided manufacture method.

Investment method

The impression is placed into liquid silicon or other material that cures around it to make a positive copy of the ear. This positive copy is called the *investment*, and the finished mold or shell is made from this investment. A mold is made by filling the investment with liquid mold material and allowing it to harden, often accelerated by ultraviolet light. A hollow shell is made in the same way, except that most of the mold material is poured out before it hardens, leaving just a thin shell covering the inner surface of the investment. For ITE/ITC/CIC hearing aids, the manufacturer trims the shell to the desired size, inserts the electronic and mechanical parts, attaches the faceplate, and sends the complete hearing aid back to the clinician.

ⁿ Addition-cured silicones appear to have superior stress-relaxation properties to condensation-cured silicones¹³⁴², but data on this are limited.

Some practices are choosing to maximize their involvement in the supply of hearing aids by making molds and shells themselves. The earshells are constructed of plastic that is cured by exposure to a strong source of ultraviolet (UV) light. The electronic parts are purchased by the practice in bulk and come as a faceplate with pre-wired components. The receiver is on a flexible lead so that it can be suitably positioned before the faceplate is attached.

Computer-aided manufacture (CAM)

The starting point for CAM is a standard impression, which must be made of opaque material (e.g. silicon). Instead of making an investment, the manufacturer or the clinician scans the impression with a laser to produce a numerical representation of the three-dimensional surface, and hence of those parts of the otoplastic that contact the ear, in fine detail. For custom devices, the manufacturer technician, or an automated program, then “inserts” (in virtual reality on a computer screen) a computer representation of the hearing aid components (receiver, and faceplate with attached battery compartment, microphone(s) and switch or control). The fit can be confirmed, and the position of the outer surface of the shell determined. Generally, the shell is made as small as possible, while fitting in all the components without the receiver touching the other components.

With all dimensions of the shell now specified, the corresponding numerical values are transferred to a “plastic printer”. The data are used to control lasers that cause a bath of light-sensitive liquid plastic to polymerize (i.e. solidify) in just those positions where the shell or earmold is to be formed. This process is called *stereo lithography*.³⁰⁶ An alternative printing process known as *laser sintering* builds up the shell or earmold by melting nylon powder, which then solidifies in place, in only those positions where solid material is needed. In both processes, the end product is formed one thin layer (a small fraction of a millimeter) at a time.³²⁸

The overall CAM process has rather specifically been dubbed CAMISHA (computer aided manufacturing of individual shells for hearing aids). Advantages of the CAMISHA process are:

- lower labor costs;
- improved ability to visualize the fit of the components within the shell before the final shell is produced, enabling the smallest size possible while still keeping the transducers apart;

- ability to “undo” the process while the virtual impression is being cut down in software to the size of the final product, without having to start all over again;
- ability to achieve a uniformly thick shell, with a consequent increase in available internal space and mechanical strength; and
- ability to remake the hearing aid from the same saved data should that be necessary.

Improved accuracy of reproduction, and hence fit of the finished product, has also been claimed, and this seems likely given that the location and thickness of build-up during manufacture can be controlled much more precisely than is possible with the wax-dipping approach that is used with non-CAMISHA manufacturing.³²⁸

There has been an expectation for nearly a decade that it will be possible to replace impression taking with a direct laser scan of the ear. The problem has been technically tougher than expected, but it does appear that a solution is imminent.

5.9.2 Materials for earmolds and earshells

Material for earmolds and earshells can be classified at a number of levels. Most simply, there are hard and soft materials. Within each of these categories, there are several base plastics. Within each base plastic there are many variations to the mixture that affect the physical properties.

Table 5.10 shows the most common base chemicals used, their range of hardness, and their disadvantages and advantages. The ease with which the materials can be modified refers to the ease experienced by clinicians using the tools commonly found in a clinic. Note that like the other materials, acrylic can be harder or softer. The softer varieties have decreased leakage,¹³⁴⁴ but lose some of the durability advantages of the hard acrylic. The higher leakage of hard plastic earmolds probably arises from their greater shrinking during curing and from the final polishing stage that these materials undergo to give them a pleasing appearance and greater ease of insertion.¹⁴¹⁷ Otoplastics made from very soft materials may be more comfortable than those made from hard materials, but there is no research on this issue.

Otoplastics can contain more than one material. Most commonly this comprises a soft material in the canal stalk, or in just the deepest part of the canal stalk, com-

Table 5.10 Advantages, disadvantages and hardness of different materials used for earmolds and earshells (Source: Microsonic, GN Resound and Westone websites and catalogs).

Type of material	Hardness (Shore durometer scale A)	Advantages	Disadvantages
ACRYLIC (Poly-methyl-methacrylate) Hard acrylic, lucite Super-alerite, heat-cured acrylic Soft acrylic – see text	Hard (off scale)	• Little deterioration or shrinkage with time and use • Easy to grind, drill, re-tube, glue and buff • Smooth surface helps insertion and removal • Easy to clean	• Will not compress to insert past narrow areas in the canal • Leaks easily when the ear canal changes shape • Potential for injury when struck, especially if it shatters
ACRYLIC (Hydroxy-ethyl-methacrylate)	Hard (off scale)	Advantages and disadvantages as for poly-methyl-methacrylate, but used for ITE/ITC and CIC shells	
VINYL (Poly-vinyl-chloride) Rx, Polysheer, Polysheer II, Ultraflex, Superflex, Polyplus, Satin Soft Synth-a-flex II, Formaseal	40 - 50	• Comfortable when a tight fit is needed for high-gain hearing aids • Some vinyls (poly-ethyl-methacrylate) soften at body temperatures and harden at room temperatures, helping insertion	• Shrinks, hardens, and discolors with time, necessitating replacement approximately annually • Tubing is difficult to replace: removal is difficult and new tube needs toxic solvent or locking devices to retain it • Softer vinyls need a toxic solvent to polish them – cannot be worn for 24 hours
VINYL (Poly-ethyl-methacrylate) Vinylflex II, Vinylflex, Marveltex, Marvel Soft, Vinyl Flesh, Formula II, Flexible Plastic			
SILICONE (dimethyl-methyl-hydrogen-siloxane) M-2000, W-1, MSL-90, JB-1000, Softech, Soft Silicone, MDX	20-40	• Comfortable when a tight and/or long canal fit is needed, especially for the softer grades of silicone • Little shrinkage with time • Low incidence of allergic reactions	• Impossible to grind and buff; difficult to drill • Tubing cannot be glued – a mechanical tubing lock is required
SILICONE (poly-dimethyl-siloxane) Medi-Sil II, Mediflex, Emplex, Frosted Flex, Bio-por	50-70		
RUBBER (ethylene-propylene copolymer) Microlite, Excelite		• Soft, lightweight and floatable • Used for swim-plugs	
POLY-ETHYLENE	Hard (off scale)	• Extremely unlikely to produce an allergic reaction • Easy to grind, drill, glue and buff	• Will not compress to insert past narrow areas in the canal • Leaks easily when the ear canal changes shape • Noticeable plastic appearance

The hardness of otoplastics

The material property that most affects the comfort and acoustic performance of an otoplastic is its *hardness*. Hardness is measured by noting how large an indentation occurs when a standard cone- or ball-shaped object is pushed into the material by a standard force. Sharp indentors and large forces are used for hard materials; blunt indentors and small forces for soft materials. The measuring tool is called a *durometer*, and the resulting indentations are expressed as numbers between 0 and 100 on a *Shore hardness scale*. Larger numbers represent harder materials. Each combination of indentor and force gives rise to a different scale. There are many such scales. Scale A is most suitable for the softer otoplastic materials and scale D is most suitable for the harder materials. For example, a reading of 90 on the A-scale is approximately equivalent to a reading of 39 on the D-scale.

Soft materials are intrinsically more flexible than hard materials. Greater flexibility makes earmolds easier to insert in a tortuous ear canal and may make them more comfortable when the ear canal changes shape. Soft materials also provide a better seal to the ear, perhaps because they are not polished during manufacture.¹⁴¹⁷

combined with a hard material in the more lateral parts of the otoplastic. The superior retention, feedback, and perhaps comfort properties of a soft material can thus be combined with the superior durability of the harder material surrounding the lateral parts of the hearing aid. A potential problem is that such mixtures may fracture at the plane where the two materials join.

The advantages of soft materials have to be weighed against the greater deterioration of soft materials with time. Note that a key requirement for comfort is to have some flexibility at the interface between the otoplastic and the ear. If the ear is sufficiently soft and flexible, which is common in older people, none may be required in the otoplastic. Consequently, the balance of advantages may swing in favor of hard materials for such people. Unfortunately, there is insufficient research for anyone to be dogmatic about the best earmold material in different situations.

One option (not commonly used) for ITE/ITC/CIC instruments is the use of a solid otoplastic instead of a hollow shell.³⁷³ The material is a very soft, very flexible silicone of hardness 10-35 (Shore A scale) into which the hearing aid components are embedded. The soft material is bonded to a conventional hard acrylic faceplate. This approach may make it possible to achieve the advantages of a soft material in an adequately durable package, but durability is unlikely to be as great as for a hard-shell device.

The skin of some patients will react to an otoplastic. This may be caused by an *allergic reaction* to the specific material, or may be the result of *prolonged occlusion*, no matter what material is used. A common

cause of allergic reactions is that a small proportion of the original monomer did not cure into a polymer when the earmold was constructed.¹¹⁷⁴ Potential solutions to the problem comprise:

- trying an otoplastic that has been heat-cured rather than cold-cured, as heat-curing decreases the proportion of uncured monomer;
- trying an otoplastic based on a different, low-allergenic chemical, such as silicone or polyethylene;¹⁶⁷⁶
- gold-plating the otoplastic, but some people also have an allergic reaction to gold;¹³⁵⁶
- referring the patient for a contact allergy test, or directly conducting one by taping samples of potential otoplastic material to the skin, so that the presence of a genuine allergic reaction, and the specific allergen, can be detected;^{1174, 1676}
- trying a more open mold, if feasible (as a CROS fitting if necessary – see Section 17.1);
- alternating hearing aid use between ears; and
- when all else fails, using a bone conduction or bone-anchored hearing aid.

Note that the first four solutions will not help if the cause is occlusion, and the next two solutions will not help if the cause is an allergy. None of the first five solutions will help if the cause is physical pressure as a result of a poorly fitting otoplastic, but a simple physical modification of the otoplastic's shape may solve the problem. Note that impression material can also give rise to an allergic reaction.¹⁶¹⁴

5.9.3 Instant earmolds and hearing aids

The earmolds discussed so far are all the results of a two-stage process – an impression is taken and an earmold is made from the impression. An earmold is sometimes needed instantly – for a demonstration, as a temporary solution while waiting for a repair, because the patient is in a hurry, or to improve the efficiency of the overall assessment, fitting and follow-up by combining the assessment and fitting appointments. The following are several ways to achieve an instant otoplastics, the first of which is by far the most common:

- Use a hearing aid designed to be fitted with a stock canal fitting, typically comprising a thin, pre-bent tube (chosen from amongst two to four different lengths) to which an open or closed dome (chosen from amongst two to four different diameters) is attached.
- A temporary earmold can be formed from a foam plug with a tube through it, which can be coupled to an elbow and a tube. These provide a better seal (i.e. less leakage) than a conventional custom earmold,⁶¹² and are more comfortable,¹³⁶¹ but can be more difficult than a custom earmold to insert, and quickly become dirty.
- A custom earmold can be made in minutes by taking an impression using a two-part silicone material (e.g. *Insta-mold*TM). The resulting impression, after some trimming, is the final earmold. A variation from the usual impression-taking technique is that the concha should be filled only to the degree required for the final earmold, and the lateral surface should be smoothed to the finished contour before the impression material hardens. Smoothing can be done with a finger or thumb that has been pre-wetted with a special lotion. Twisting and pushing a special punch through the impression can cut holes for tubing and a vent.
- A modular, prefabricated ITE, ITC, or CIC hearing aid of an appropriate size can be chosen. There are several innovations aimed at improving the comfort and fit of these hearing aids:
 - an articulated joint, in which the orientation of the canal stalk relative to the concha can be altered;
 - replaceable foam sleeves surrounding the canal stalk;
 - a controlled venting path inside the sleeve;

- a disposable soft plastic sheath around a standard module; and
- a hard modular shell combined with a soft, flange-like tip.

If either of the first two options is used, one must be aware that the acoustic performance, and especially the venting effect, may be very different from that which would normally occur with a custom earmold.

5.9.4 Modifying and repairing earmolds and earshells

The most common reasons for modifying or repairing earmolds and earshells are to:

- remove helix locks to ease insertion;
- shorten or taper canal stalks to ease insertion (but see Figure 5.20 and accompanying discussion);
- remove material from the inter-tragal ridge, conchal rim or the canal stalk to eliminate pressure points;
- widen or shorten vents to decrease occlusion;
- constrict vents to decrease feedback;
- thicken canal stalks to decrease feedback; and
- replace loose or hardened tubing.

Earmolds and earshells can be modified in the clinic with suitable tools and materials. For a BTE earmold, a hand-held motor tool is adequate, but to re-obtain the high luster that is usual on ITE/ITC/CIC hearing aids, buffing and polishing wheels are needed. Two such wheels can be mounted on one side of a ¼ Horsepower dental laboratory motor. Buffing compound, obtained from hearing aid manufacturers, is applied to the buffing wheel, but not to the polishing wheel. Drills and small burrs can be mounted on the other side of the motor, and this leaves both hands free to hold the hearing aids. If such a tool is not available, a relatively high luster can be obtained by applying a hypoallergenic clear lacquer. More detailed instructions on modifying shells can be found in an excellent series of practical articles by Curran (1990a, 1990b, 1991, 1992). For CAMISHA shells and molds made by laser sintering, the nylon material is easily melted, so a lower speed grinding tool should be used and less pressure should be applied.³²⁸

Modifying vents

Earmolds or earshells are made less occluding by enlarging the vent diameter, shortening the vent

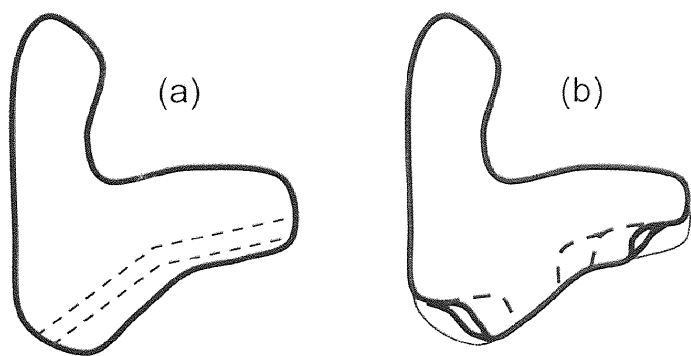


Figure 5.29 An unmodified vent (a) and a shortened vent (b). The dashed lines in (a) indicate the position of the vent. The dashed lines in (b) indicate potential further stages of shortening, and the dotted line indicates the original profile.

length, or a combination of both. Vent diameter is easily enlarged by drilling or grinding. Vent length is shortened by grinding away the mold or shell, from either end of the vent. Figure 5.29 shows how the medial end of the vent can be progressively cut away without affecting the sound bore.

Prior to modifying any custom earshell, view a strong light *through* it to identify the location of the components and to estimate the thickness of the shell walls. Also check that the shell contains a **poured vent** (also known as a **molded vent**) encased in solid plastic, rather than just a vent made of tubing. The modification shown in Figure 5.29 can be performed only if the aid contains a solidly enclosed vent rather than a tube within a hollow shell. Shortening should be performed progressively, each time removing approximately 30% of the remaining vent length. If the vent is shortened so much that the hearing aid oscillates, the remaining vent can be partially filled with earshell build-up material. Tables 5.2 to 5.4 will give some guidance as to whether further shortening is likely to induce feedback oscillations. For hearing aids with vents made only from tubing, grinding trench vents in the canal stalk can increase the effective vent size.

Re-tubing earmolds

Replacing the tubing in a BTE earmold is commonly required and easy to perform. If necessary, ream out the existing hole with a drill bit, motorized reamer, and/or a pipe cleaner dipped in solvent to remove any old glue or debris. To facilitate insertion, the end of the new tubing should be cut at an acute angle. Unless the new tubing is an excessively tight fit in the earmold, the new tubing can be pushed into the mold, as shown in Figure 5.30a. If the point does not emerge

at the lateral end, insert some fine-nosed pliers in the medial end and pull the tubing through. If the tubing fits too tightly to be pushed into the earmold, it can be bent back on itself and pulled through with a loop of fine wire, as shown in Figure 5.30b. Ensure that the lateral end of pre-bent tubing is pointing upwards *just in front* of the pinna. If the tubing points too far backwards, it will place excessive pressure on the front of the pinna when the hearing aid is worn. If it points too far forward, it will tend to pull the hearing aid off the ear.

If the earmold is made from acrylic, the tubing should be glued in. To introduce glue (Cyanoacrylate), bend the protruding tube at the medial end in each direction, and introduce glue into the cracks that open up around the perimeter. Apply glue completely around the perimeter of the tube so that there is no crack for cerumen to penetrate. Finally trim the excess tubing, and optionally withdraw the tubing by 1 or 2 mm. Make sure the glue is thoroughly dry before allowing the patient to handle or insert the earmold. If the tubing is a very loose fit, high viscosity (thick) cement can be used to fill the gap.

If the earmold is made from silicone, the tubing must be held in place mechanically. A collar is slid onto the

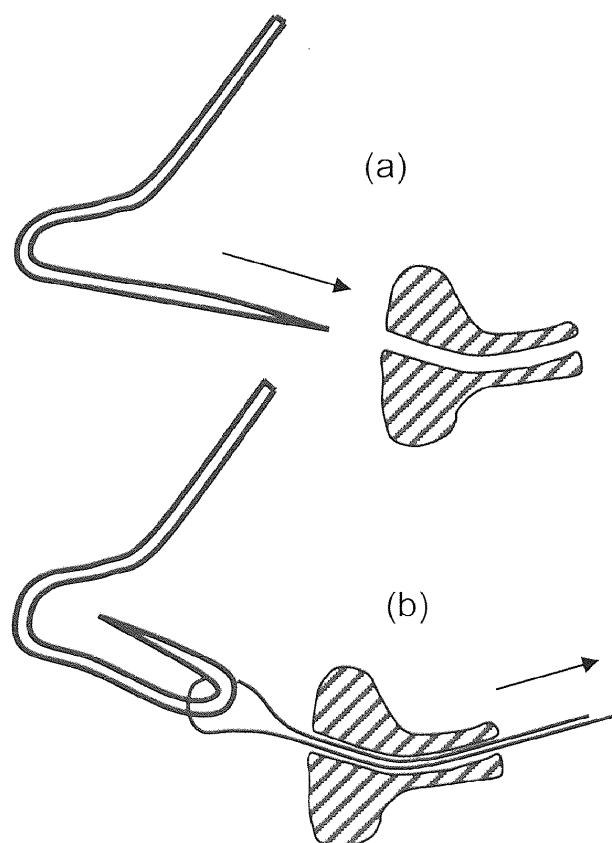


Figure 5.30 Insertion of tubing into an earmold by (a) pushing, or by (b) pulling with a loop of wire.

tubing prior to the tubing being inserted. Some collars are designed to slide in only one direction; these grip the tubing if the tubing is pulled out from the earmold, but this type may constrict the sound bore and decrease the high-frequency response. Other types slide more freely over the tubing and must be glued in place. After fixing the collar onto the tubing at the correct place, the tubing and collar are inserted until the collar is buried a few mm inside the mold material.

Full-length horns (as shown in Figure 5.23a) can be installed in the same manner, except that they are most easily pushed through from the medial end of the earmold. Partly inserted horns (as shown in Figure 5.23b) are preferably installed by pushing the horn in from the lateral end. Glue is applied around the circumference of the medial end of the horn prior to insertion. Provided the horn is inserted very quickly, the glue will act as a lubricant to help insertion.

Building up earshells

Material has to be added to earshells if a grinding operation breaks through the wall of the shell, thus exposing the inner cavity and the electronic components. Material is added by brushing plastic build-up material on to the earshell. A second reason for adding material to either a shell or a mold is to prevent feedback oscillations. If a hearing aid oscillates, despite the vent being plugged, and provided the feedback is not internal, the otoplastics must be made to fit more tightly within the ear, or else a new otoplastic must be made. (See Table 4.12 and 4.13 for diagnosis of feedback cause.) Adding build-up material in the region of the aperturic seal most effectively increases tightness. Build-up material should be applied to the canal stalk in the 6 mm medial to the ear canal entrance, and principally in the anterior-posterior dimension. That is, the narrower diameter of the canal stalk should be enlarged slightly. Different types of build-up material are required for hard versus soft earmolds. High-viscosity material is available for those applications where a thick build-up is required.

5.10 Concluding Comments

By keeping in mind the three key functions of earmolds and earshells listed at the start of this chapter, the clinician can easily understand the characteristics of new designs and styles as they are invented (or re-invented!). The three key questions are:

- How does the diameter of the sound bore change along its length from the receiver to the eardrum, and how long is the sound bore?
- How large (i.e. long and wide) is the vent path, or if there is no intentional opening, how well sealed is the mold or shell to the canal wall?
- How securely will the mold or shell remain in the ear, and how easily can the aid wearer get it in and out of the ear?

If the answers to each of these questions for any new design are compared to the answers for the most similar structure covered in this chapter, the characteristics of any new designs should be able to be predicted with reasonable accuracy.

The importance of selecting earmold and earshell characteristics to achieve a target real-ear gain has diminished with time. Hearing aids almost always have flexible tone controls, which are enabling target gains to be achieved with greater accuracy, assisted by increasingly effective feedback cancellation algorithms, although open fittings still limit the achievable high-frequency gain. For many patients, the freedom from occlusion and physical comfort of an open fitting combine to give higher satisfaction and a lower return rate than is achievable with close fittings,⁶²⁹ even if some compromise in the high-frequency gain achievable has to be accepted. Active electroacoustic methods for reducing the occlusion effect may soon appear, which will remove the tension between eliminating occlusion and feedback simultaneously, while still achieving the prescribed high-frequency gain.

Despite these advances, selection of the vent size will remain important. The vent must be large enough to minimize negative effects of occlusion and maximize physical comfort on the one hand, but small enough to avoid feedback oscillation and maximize SNR improvement on the other hand. All of these hearing aid qualities are affected as one moves along the continuum from a fully closed to a fully open fitting, and these fitting fundamentals apply whether a custom earmold/earshell, or a modular canal fitting is selected. Equally, choosing a physical style that provides enough retention, combined with easy insertion and removal, will remain important for as long as hearing aids are taken on and off by the user.