

THE "HOLLOW VOICE" OCCLUSION EFFECT

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THE PROBLEM

Someone wearing a hearing aid with an unvented or minimally vented earmold is in all probability going to complain that his voice sounds hollow or boomy. And he's absolutely right. If you measure the sound pressure in his ear canal with a probe microphone, you'll find typically 90 to 100 dB SPL developed at the lower frequencies. Occluding the ear canal gives rise to what is called an "occlusion effect", which amplifies the low-frequency sound of the talker's own voice by sometimes 20 to 30 dB.

The worst of it is that the amount of amplification depends on which vowel is being spoken. The closed vowels like /i/ (English EE or Danish "i") and /u/ (OO or "o"?) have a large amount of amplification, whereas the open vowels such as /a/ (AH or "a") often have very little amplification. The result is not only a voice that sounds boomy, but the vowels themselves can become almost indistinguishable in the ear canal. (The three vowels /i/, /a/, /u/ sound like /u/, /u/, /u/ in the case of the recorded demonstration obtained from the ear canal of Dr. Laura Ann Wilber, who collaborated with me in studying the occlusion effect.)

It is no wonder that people complain, if they find themselves listening to 90 to 100 dB sound pressure levels at low frequencies every time they talk, and all they hear is /u/ even when they are saying /i/!

WHERE IT COMES FROM

The vibrations set up in the jaw and surrounding flesh by your own voice are fairly weak for open vowels such as /a/, but quite intense for the closed vowels /i/ and /u/, as you can easily feel for yourself if you vocalize with your chin on your hands and your elbows on a table. This difference comes about because the "back pressure" built up during vocalization with a restricted mouth opening is surprisingly high: I measured 142 dB SPL for /i/ and 138 dB SPL for /u/ when I put a small probe microphone into the back of my mouth. The pressure developed with an open mouth is relatively low, however. I measured only 116 dB SPL in the back of my mouth for the open vowel /a/.

These intense low frequency vibrations cause the cartilagenous walls of the ear canal to dilate and pump sound into the ear (recall that the temporal-mandibular joint of the jaw

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rests right next to the wall of the ear canal). This sound easily "spills out" the open ear, but is amplified by 20 to 30 dB or more when trapped inside.

A similar phenomenon occurs during bone conduction testing, giving rise to an increased sensitivity if the ear is occluded. Khanna, Tonndorf and Queller (1976) made probe-microphone measurements of the sound pressure developed behind earplugs, confirming that the effect in this case was due to sound transmission into the ear canal from vibration of the fleshy (cartilaginous) portion of the ear canal walls induced by a flesh- or bone-conducted vibration. (In the case of supraaural earphones, the relative vibration between the head and the earphone probably causes the predominant pumping action, rather than canal-wall vibration.)

The increased ear canal SPL due to the occlusion effect is restricted to low frequencies. The effect is similar to adding a strong low frequency "first formant" to all closed vowels, which is probably why they sound so unnatural.

FOUR WAYS OF DEALING WITH THE PROBLEM

There are two old and two new ways of handling the occlusion effect problem.

1. The traditional way is to use enough venting to reduce the low-frequency pressure buildup.
2. When the amount of venting necessary to reduce the pressure buildup to acceptable levels causes feedback whistling before adequate gain is obtained, the other traditional solution is to leave the earmold relatively unvented and take the authoritarian approach (see Figure 1), telling the wearer: "That's OK, don't worry about a thing. Just wear it a while and you'll get used to it." (which most, but not all, of them do).



FIGURE 1
 AUTHORITARIAN
 APPROACH TO
 SOLVING THE
 PROBLEM
 (MUELLER, 1987)

3. A recent innovation is the "Macrae vent", a two-stage acoustic low-pass filter that lets the low frequency sounds spill out relatively freely while preventing the feedback-causing high frequency sounds from leaking out.

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4. Finally, what now appears practical in many cases is to make use of a 1953 report of Jozef Zwislocki that a deeply-sealed eartip prevents the soft-tissue canal wall from vibrating and/or prevents the resulting sound from reaching the eardrum.

These are discussed in turn.

A VENTING EXAMPLE

A couple of years ago, a prominent trial lawyer in the U.S. was referred to me by his hearing aid dispenser as "the court of last resort" after he had unsuccessfully tried nearly a dozen binaural hearing aid fittings. He had an unusual hearing loss, as seen in the audiogram shown in Figure 2, and was experiencing great trouble understanding testimony in the typically reverberant courtrooms where he practices. Almost more important, however, was the fact that when wearing hearing aids his own voice "sounded so bad I would get half way thru my summary and have to fight off saying 'the hell with it' and sitting down."

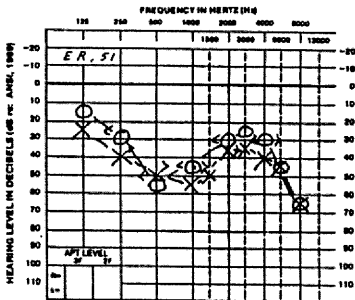


FIG. 2 AUDIOGRAM OF A 51 YEAR OLD TRIAL
LAWYER AFTER A DOZEN UNSUCCESSFUL
HEARING AID FITTINGS

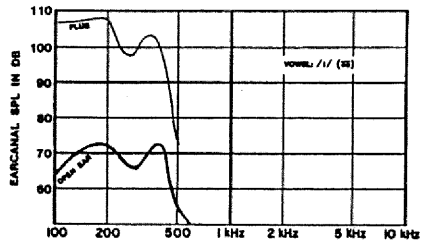


FIG. 3 SPL IN 100HZ BW IN CLOSED
VS OPEN EAR

When I placed a probe microphone thru his earmold and listened (with an earphone connected to the probe-microphone amplifier) to the sound in his earcanal, I had to agree: His voice, normally rich and resonant as one would expect from an accomplished forensic speaker, took on a guttural, unnatural quality totally unlike its normal character.

He was able to vocallize a continuous /i/ (eeeeeeee in English) long enough to permit, with the help of a B&K 2020 tracking filter, a complete, continuous sweep, 100 Hz-bandwidth analysis of the SPL developed in his earcanal. Figure 3 shows the extreme differences in SPL levels developed behind a sealed earmold and in his open earcanal. With his physiology, he developed an overall SPL of nearly 110 dB behind an unvented earmold, and was obviously not a candidate for a sealed-earmold construction! (Nor had one ever been tried, to my knowledge. All the earmolds I saw were vented to one degree or another).

After a good deal of perseverance on both our parts (approximately 9 hours of continuous experiments), and no small measure of luck on my part, he went away with a satisfactory fitting. The luck came when, almost by chance, I was able to balance the low-frequency amplification of his voice due to the occlusion effect with the mid- and high-frequency amplification of his voice due to the hearing aid. In keeping with normal scientific writing, however, the results will be presented in the "I knew it all along" fashion.

The first choice was the hearing aids themselves, a choice which had been made in advance. Given this lawyer's reverberant working environment, binaural directional-microphone hearing aids were the only choice one could imagine. Indeed, Hawkins and Yacullo (1984) have documented a 6 to 8 dB improvement in signal to noise ratio required for 50% word intelligibility in a reverberant environment with binaural directional aids compared to monaural non-directional aids having identical frequency responses. (Not all "directional" hearing aids are very directional, incidentally, so care in choosing superior designs is advisable.)

The use of directional hearing aids immediately presented a frequency response problem, however, because the normal insertion-gain response of these (and most) directional-microphone hearing aids rises at 6 dB/octave or greater.

Once again, Sam Lybarger's twin-diameter high-pass eartube came to the rescue (we have these eartubes molded and readily available so we can include them with our high-pass earhooks). Its tiny initial diameter acted as described elsewhere in these Proceedings to boost the lows and flatten the mid-frequency response, while the final horn-resonator section extended the real-ear high-frequency response out to nearly 7 kHz. The resulting insertion-gain response curve the lawyer obtained is shown in Figure 4, and appears ideally suited to his unusual hearing loss. Note especially the extended high-frequency bandwidth, which is crucial to obtaining maximum intelligibility in noise and reverberation (Skinner, Karstaedt and Miller, 1982).

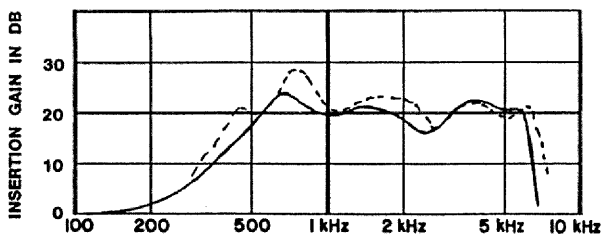


FIGURE 4 TWO ESTIMATES OF REAL-EAR RESPONSE OF MAICO MCO 33 WITH LYBARGER DUAL-DIAMETER HIGH PASS EARMOLD

Another important thing to note in Figure 4 is the gain he chose for normal conversational speech, about 20 dB.

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A fresh pair of earmolds had been ordered for him with a "Select-A-Vent" construction and a short, fat vent hole (8 mm long by 3 mm diameter). Figure 5 shows the effect of various SAV inserts with that vent construction, measured previously on KEMAR using an experimental simulation of a flat-frequency-response hearing aid with external audio input. (These measurements followed almost exactly the elegant method reported 13 years ago in these Proceedings by Sam Lybarger. The term "vent response" is also his.)

Most importantly, Figure 6 shows that the effect of venting on the SPL developed in his ear canal was identical to the effect of venting on the output of the hearing aid. This result was expected on a theoretical basis, of course, but it was pleasant to have it confirmed so nicely experimentally.

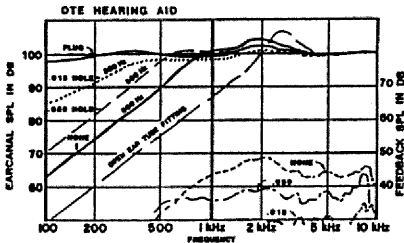


FIG. 5 EFFECT OF VENTING
ON HEARING AID OUTPUT

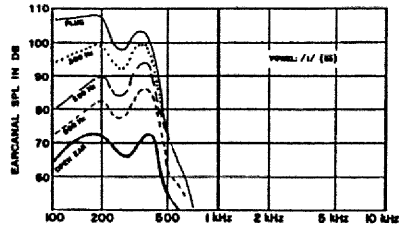


FIG. 6 EFFECT OF VENTING
ON OCCLUSION EFFECT

By choosing the SAV insert which reduced the amplification of the low-frequency sound of the lawyer's voice to the same 20 dB gain he chose for the hearing aid at mid and high frequencies, the results shown in Figure 7 were obtained: Nearly the same spectral balance for his voice in the aided condition as he normally obtained in the unaided open-ear condition. Listening to the output of the probe microphone in his ear canal provided

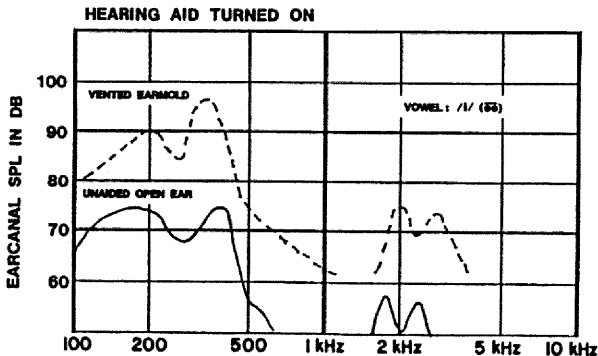


FIGURE 7 ER'S OWN-VOICE-PRODUCED EARCANAL SPECTRA

confirmation that not only the /i/ vowel but his entire speech now sounded more normal. The most important confirmation, of course, had to come from him. He was delighted.

In writing this up, I am complying with his request in a thank-you letter he sent: "I write to you in the hopes that if someone else with a similar problem comes to you, you can use the clinical experience gained from me to apply to them. It is interesting that the hearing aids singularly do not work well; but if they are worn binaurally, with the highs and lows which you introduced into the machines, then they work most efficiently. I went to the movies the other night (the film *The Mission*, which was filled with running water and a lot of native noises), and must tell you that I heard around 80% of the film, which for me is a significant increase."

MACRAE VENT

In the previous example, the amount of insertion gain required was only 20 dB, so that feedback presented little problem. Figure 5 shows the relationship between venting and the amount of sound leaking out of the vent and picked up at the microphone of a BTE hearing aid. Here, again, these data were measured following the method described in these Proceedings 13 years ago by Sam Lybarger. (At one time or another, most of us get the feeling we are simply re-discovering something Sam knew 50 years ago. I have a copy of some horn-earmold-acoustics calculations he made back in the 1930's that appear quite correct.)

For example, the data in Figure 5 indicate that with no SAV insert (the curve labeled "NONE" on the figure), 48 dB SPL is picked up by the microphone from the open vent leakage at 2 kHz when the hearing aid is producing 104 dB SPL at the eardrum. Thus if the hearing aid is set to greater than 56 dB of gain between microphone and eardrum, and the phase is right, whistling can be expected. Allowing a 5 dB safety margin, and allowing for the roughly 11 dB gain of the unaided ear at 2 kHz, a maximum of 40 dB insertion gain should be obtainable at that frequency.

In practice, the overall gain available with that much venting is often less than 40 dB, perhaps due to a peak in the hearing aid frequency response. In those cases where greater gain is needed than can be obtained with sufficient venting to relieve the occlusion effect, the two-stage filter earmold construction described by John Macrae can be used to good advantage. Its construction, venting properties, and reduced feedback SPL at high frequencies are shown in Figures 9 thru 11.

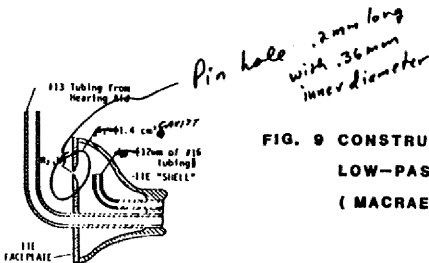


FIG. 9 CONSTRUCTION OF MACRAE
LOW-PASS VENT
(MACRAE, 1982)

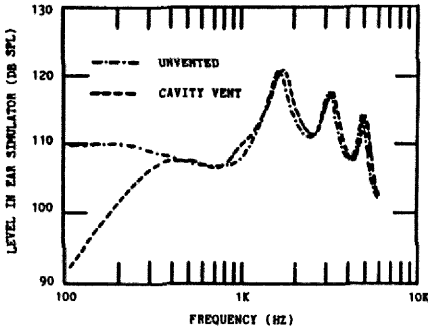


FIG. 10 EFFECT OF MACRAE VENT
ON HEARING AID OUTPUT

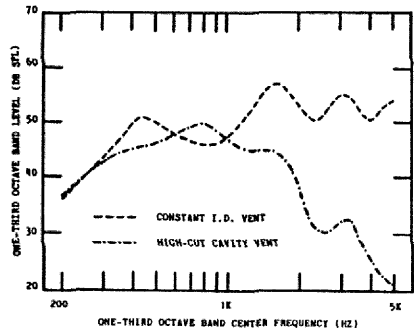


FIG. 11 EFFECT OF MACRAE VENT
ON FEEDBACK SPL

DEEPLY SEALED EARMOLDS

In 1953 Zwislocki described the effect which would be created when one inserted a plug into the ear during bone conduction testing. He showed that placement of the plug in the fleshy (cartilaginous) part of the ear yielded more sound in the ear canal than if the plug were inserted more deeply into the bony (osseous) portion of the ear canal. He referred to the process as "obduration" of the ear canal.

Later, Zwislocki showed that an insert earphone eartip inserted deeply into the canal would reduce, if not remove, this predominately low-frequency occlusion effect and thus he recommended the use of insert earphones for masking when testing bone conduction. Berger & Kerivan (1983) recently reconfirmed that deeply inserted eartips (E-A-R plugs in this case) minimized the occlusion effect for bone conduction.

A couple of years ago, my colleagues and I had rediscovered the importance of deep eartip insertion in order to maximize interaural attenuation with insert earphones. (Killion, Wilber and Gudmundsen, 1985). A modular canal hearing aid developed by Voroba (1987) had, in some versions, a soft rubber bulbous tip that sealed deeply in the ear canal. One of the first things noticed by some hearing aid dispensers was that fewer patients complained about the sound of their own voices. In thinking about this, we realized that this new aid's deeper placement into the ear canal might be diminishing the occlusion effect.

In a series of experiments with custom earmolds made using soft vinyl materials, we explored the practicality of a deeply-sealed earmold as a solution to the hollow voice problem. These are described in detail in Killion, Wilber & Gudmundsen (1988), but will be summarized here.

Figure 12 shows the wide variety of occlusion-effect SPL's we obtained during the course of our experiments. Figure 13 summarizes our basic findings: Earmolds which sealed near the canal entrance and did not seal near the bony portion of the

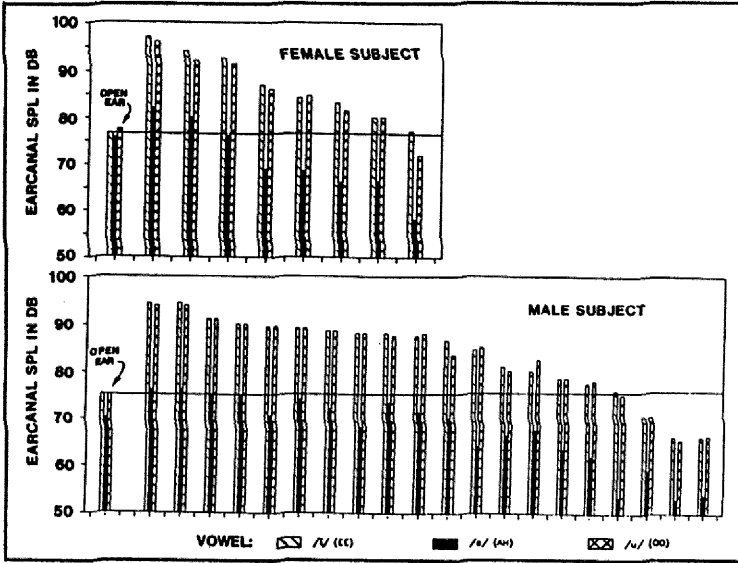


FIG. 12 Ear canal SPLs developed during vocalization behind a variety of unvented earmold constructions investigated in these experiments. Open ear SPLs shown for comparison.

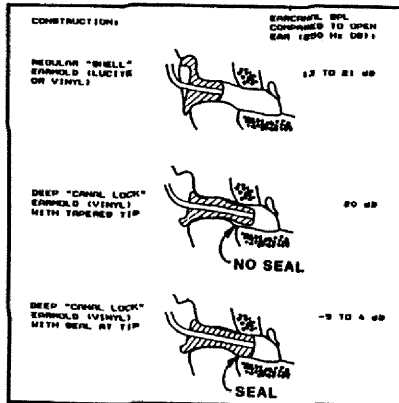


FIG. 13 Illustration of findings from these experiments: earmolds with deep seal gave minimal occlusion effect; earmolds without deep seal gave large occlusion effect.

earcanal gave a large amount of occlusion effect, typically 20 dB or so (the left bars in Figure 12). This was true even if the earmold had a long tip (the middle drawing in Figure 12), some of which gave the largest occlusion effect SPL's. If the seal occurred deeply, however, the occlusion effect virtually disappeared, typified by the right bars in Figure 13.

We were able to further confirm the deep-canal seal as a solution to the occlusion effect problem with probe-microphone measurement on patients whose earcanals had been surgically modified in order to accept deep-canal hearing aids; surgery developed by Dr. Rodney Perkins of California. With the deep-canal aids in place, the occlusion effect on these patients also virtually disappeared.

Since the time that paper was written, several people have been successfully fit with deep-sealed soft vinyl earmolds. The most exciting to me personally have been two musicians from the Chicago Symphony, who were recently fit with ER-15 "musician's earplugs" (Killion, DeVilbiss & Stewart, 1988) in deeply sealed earmolds. Both of them play instruments which cause substantial jaw vibration, so that with shallow earplugs the sound of their own instrument was sometimes amplified by the occlusion effect so that it was much louder in their head than the rest of the orchestra. They report that these are the first earplugs that allow them to hear the rest of the orchestra properly while playing their own instrument. (The same ER-15 15 dB attenuators in shallow earmolds are not nearly so satisfactory to them, indicating that the occlusion effect is an important part of the problem for musicians who play instruments that vibrate the lips or chin.)

OBTAINING DEEPLY SEALED EARMOLDS

Not surprisingly, perhaps, we found that it was not easy to obtain deep seal earmolds. We first made a deep impression and mailed it to one of the earmold labs that had often made extremely careful experimental earmolds for us in the past, asking that the finished earmold tip be kept as long and full as possible since we were planning to use it in an experiment. This resulted in an earmold that was not as deep as the impression had been. We repeated, this time with all three of us having deep impressions made and sending them with a very special request and telephone call to another lab. Again, the resulting earmolds barely reached the bony portion of the earcanal, and in one case did not look like a similar impression stored at the lab. (In all fairness, in these early experiments we used

powder-and-liquid impression material and trusted them to the temperature and humidity vagaries of the mail.)

At last Fall's speech and hearing convention, two of us discussed our problem at length with representatives from various earmold labs, and arrived at what we have dubbed the "Byron McKellip" procedure. A cotton otoblock is prepared with one end of a soft rubber probe tube inserted into the middle of the cotton and sewn into place with the normal thread, taking care that the tube remains open. The otoblock is then inserted as deeply as possible into the canal and a deep silicone impression is obtained. The cotton otoblock is used because it squeezes easily into a smaller size and still prevents the impression material from oozing through. (Foam otoblocks take up too much room to allow a really deep impression unless cut about half in length.) The rubber tube allows air to flow out while the impression is being taken and, more importantly, air to flow back in when the impression is being removed. Without the tube, the suction that is created when removing the impression can be painful (if not potentially dangerous). The use of silicone impression material helps assure that it will not lose shape during shipment.

Using this impression technique, and asking for "soft vinyl canal-lock style earmolds with eartip to the full length of the impression (20 to 22 mm in this case) and a seal at the tip end only", we ordered four earmolds (from two different earmold laboratories). All four were a success! In Figure 12, the two rightmost (lowest-occlusion-effect) bars for the female subject and two of the three rightmost bars for the male subject show the SPL's measured with these four earmolds. The figure at the bottom of Figure 13 illustrates these earmolds.

Since that time, I have usually not bothered with the rubber tube during impression taking, but I have been extremely cautious in removing the impression--slowly--and have usually had the patient remove it carefully himself. A willingness to remake the impression and earmold as often as required to get it right is a good attitude to adopt before you start, although it is not unusual to obtain good, low-occlusion-effect, comfortable earmolds on the first try.

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