The etiology of the REUG: Did we get it completely right?

By Marshall Chasin

The outer ear canal is made up of a tube that is closed at the eardrum end (medial) and open at the outer part (lateral). We call such a tube (open at one end and closed at the other), a quarter-wavelength resonator.

Such resonators are found everywhere: First resonance in the behind-the-ear (BTE) hearing aid response, the resonances of a trumpet, clarinet, and even our vocal tract uttering the sound [a] as in "father." The frequency at which such a resonance occurs is the speed of sound (we will assume it to be exactly 340 m/sec or 340,000 mm/sec, even though it actually is slightly slower) divided by four times the length of the tube, or F = v/4L.

There are also higher modes of resonances at three, five, and seven times the main frequency. For example, in a BTE hearing aid tubing, the primary resonance on a specification sheet (or in the real ear) is at about 1000 Hz. There are also *odd*-numbered resonances at 3000 Hz (three x 1000 Hz), 5000 Hz (five x 1000 Hz), 7000 Hz (seven x 1000 Hz), and so on, which are quarter-wavelength-related: odd-numbered multiples of the lower frequency (see Figure 1). This pattern is characteristic of all quarter-wavelength resonances, and all quarter-wavelength resonances come from a tube that is closed at one end and open at the other.

In the early 1970s, KEMAR (Knowles Electronics Manikin for Acoustic Research) was constructed to emulate the average head and upper torso, including the average ear canal.[1] KEMAR has a removable outer ear pinna and, instead of an eardrum, it uses a small half-inch microphone so that accurate measurements can be taken and recorded at the level of the "eardrum substitute."

KEMAR typically uses a coupler or ear canal called a Zwislocki coupler. This is a metal cylinder 21.5 mm long that has, depending on the type, two or four side-branch resonators. This combination of ear canal length (21.5 mm) and half-inch microphone yields a resonance of 2700-3000 Hz, just like the adult human ear. However, the adult ear canal is typically 6.5 mm longer than KEMAR's 21.5 mm, yet both resonate at 2700-3000 Hz as their first quarter-wavelength resonance.

The trick that Burkhard and Sachs used in 1973 was to give the diaphragm of the microphone a compliance that adds some "acoustic length" to the 21.5-mm tube, essentially causing it to behave as if it were 31 mm long.[1] Even the real human ear isn't that long. It averages 28 mm, and the normally compliant human eardrum adds a few more millimeters of acoustic length to the measured length. The ear canal is a quarter-wavelength resonator and, like the tubing resonances in a BTE hearing aid, is given by the equation, F=v/4L (F = 340,000 mm/sec ÷ [4 x 31 mm] = 2700 Hz).

KEMAR just needs to make a larger correction, since half-inch microphones have significantly more compliance than typical eardrums. Some people with very flaccid tympanic membranes (type AD tympanograms) have outer ear canal resonances on the order of 2500 or 2600 Hz, since they function as if they were slightly longer tubes (i.e., have more "acoustic length").

So far, this description of the etiology of the REUG could come from a first-year audiology textbook and contains nothing new. The first resonance, together with a second resonance at about 5500 Hz, makes up the REUG or real-ear unaided gain. The REUG is what people with normal hearing typically hear through when they perceive speech and music. For hearing aid wearers listening in the "real world" (or in sound field audiometry), the REUG typically needs to be subtracted from the REAG (real-ear aided gain) to get the real, useful, or insertion gain. Real-ear measurement systems have been used since the early 1980s to accomplish this and are a mainstay for those who work

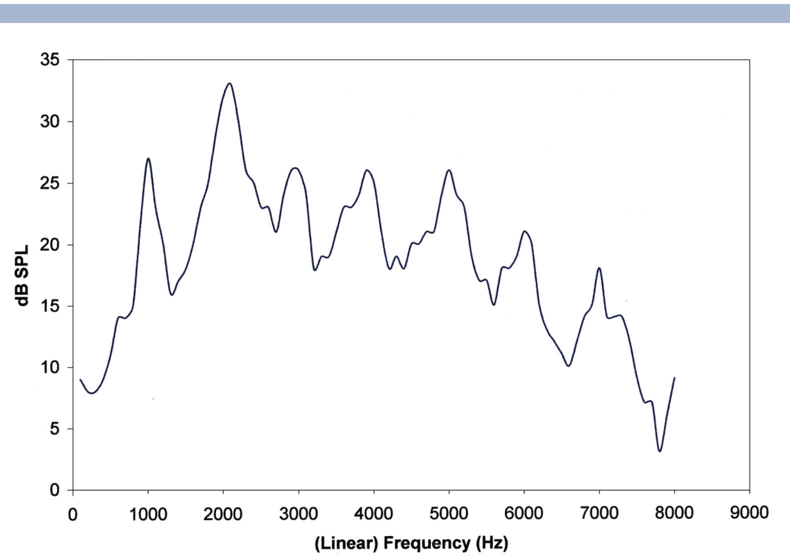

Figure 1. *Five-resonance pattern of a typical BTE with resonances 1, 3, and 5 being quarter-wavelength resonances.*

with hearing aid amplification (and hearing protection) assessment.

THE SECOND RESONANCE

Now let's consider the second resonance at 5500 Hz in the REUG. Traditional textbooks, based on the work of Burkhard and Sachs[1] and of Shaw,[2] state that this higher frequency resonance, like the 2700-Hz resonance, is lost upon insertion of an occluding hearing aid or the use of an earphone or hearing protector. This second resonance is thought to be related to the volume of air resonating in the concha of the pinna.

Unlike the ear canal resonance, which is a quarter-wavelength resonator (at 2700 Hz), the concha resonance at 5500 Hz is believed to be related to the volume of air "resonating" in the concha bowl. Like the ear canal quarter-wavelength resonance, the 5500-Hz resonance magnitude is highly dependent on angle and azimuth.[2] In both cases, the sound field is enhanced (amplified) at these two frequencies.

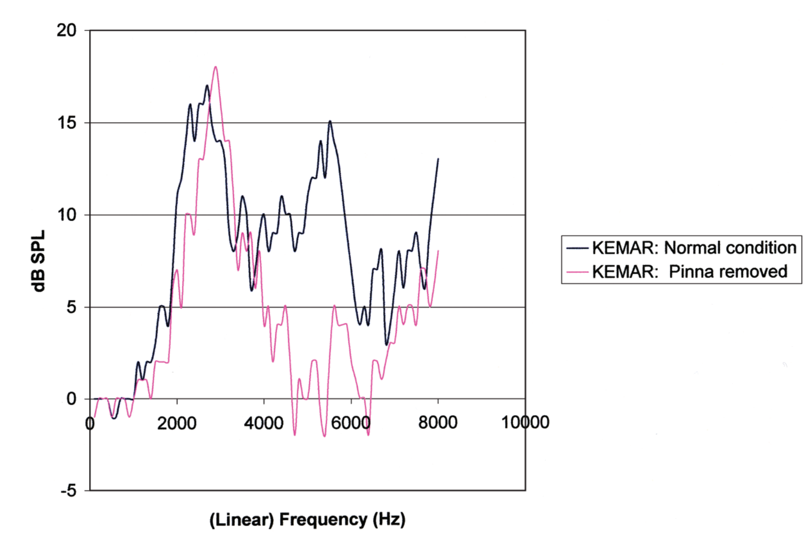

Figure 2. *KEMAR response with and without the outer pinna removed showing the destruction of the 5500-Hz concha-related resonance. Note that without the pinna, a few mm of length were removed so the resonance frequency was slightly higher than the expected 2700 Hz.*

Shaw demonstrated that when the meatal opening was occluded (with a small plug in the ear canal), the higher frequency resonance was still observed (but not the 2700-Hz resonance), which he attributed to the concha volume.[2] Certainly this is one source (and for some people the main source) of the 5500-Hz resonance. However, there may be other sources, which, depending perhaps on the shape of the ear canal, may be more dominant.

It is true that when the outer ear pinna is removed from KEMAR, the resulting REUG has a relatively unaffected ear canal resonance, but the 5500-Hz resonance is missing entirely (see Figure 2). But, as will be demonstrated, if an experiment could be performed on a real ear, the same thing would not always happen.

KEMAR uses a perfectly cylindrical tube, which should have a quarter-wavelength resonance with a frequency completely dependent on the effective length of the tube. However, human ear canals are more conical and tend to narrow significantly at the eardrum. A conical tube (such as an oboe or saxophone) yields resonances that tend to be consistent with a half-wavelength resonator. A half-wavelength resonator will have a resonant frequency at twice that of a quarter-wavelength resonator for a given length.

A half-wavelength resonator is given by the equation F = v/2L and integer multiples of this frequency (see Figure 3 for a comparison with a quarter-wavelength resonator model). For example, if the effective length (L) of a tube was 31 mm (as in many adult ear canals), then F = 340,000 mm/sec ÷ (2 x 31 mm) = 5500 Hz. It is true that half-wavelength resonators typically are observed in tubes that are either open at both ends or closed at both ends. The ear canal is open at the meatal opening end and closed at the eardrum end, so it should be a quarter-wavelength resonator, and indeed it primarily is (2700-Hz resonance).

However, if the tube is conical, as in a saxophone or an ear canal, there is a heavy dependence on the half-wavelength model with the equation F = v/2L and integer multiples of this frequency. Note that the 5500-Hz resonance is about twice the frequency of the 2700-Hz resonance (ear canal tube quarter-wavelength resonance). This relationship is precisely what one would expect from a semi-cylindrical and semi-conical tube resonant pattern where one resonant peak is exactly double the lower one. The human ear canal is indeed semi-cylindrical and semi-conical.

Although surgically removing a patient's pinnas is not feasible, an experiment was conducted on 30 willing subjects in which we placed earmold impression material in the concha bowl to remove it from the outer ear acoustical system. Care was taken not to obstruct the ear canal in any way. Real-ear measurements (REM) were taken at 0° azimuth and 0° altitude using a swept warble signal at 70 dB SPL. This is the exact opposite of what Shaw did 30 years ago when he removed the ear canal tube from the experiment by plugging it at the meatal opening.[2]

Figure 4 shows one response (seen in 13 of the 30 subjects) with the concha bowl completely occluded with earmold impression material showing *no* appreciable destruction of the so called "con-

Quarter wave length resonator :

F = v/4L

and odd numbered multiples (1, 3, 5, …)

Half wave length resonator :

F = v/2L

and integer multiples (1, 2, 3,…)

V = speed of sound (340,000 mm/sec)
L = Length of tube (mm)
F = resonant frequency (Hz)

Figure 3. *Formulas of both the quarter- and half-wavelength resonators. Note that for a given length (L), the half-wavelength model generates a result that is double that of the quarter-wavelength model.*

cha-related volume resonance." There was a slight decrease in the frequency of both the 2700-Hz and 5500-Hz wavelength resonances. As in Figure 2, this occurs because the earmold impression material adds several millimeters of length to the ear canal. (When the pinna was removed from KEMAR in Figure 2, this extra length was removed from the system so the KEMAR ear canal resonance was slightly higher in frequency).

In the other 17 subjects (56%), there was an appreciable degradation of the 5500-Hz "concha-related" resonance. Possibly in these subjects, concha volume was significant enough to be a measurable (or dominant) factor. It is also possible that their ear canals were more cylindrical than the typical human ear canal. The 17 subjects who demonstrated a significant loss of sound energy in the 5500-Hz region are consistent with previous data such as those of Shaw,[2] and in these cases, this resonance may indeed be primarily concha related.

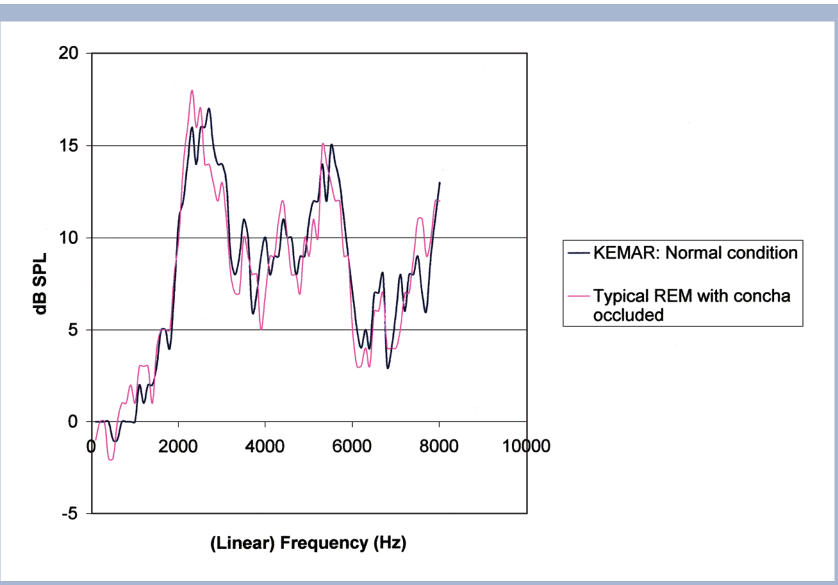

Figure 4. *A typical response seen in 13 of the 30 subjects with minimal concha resonance alteration. The normal KEMAR response with an intact concha from Figure 1 is also shown for comparison purposes. Note that in the other 17 subjects there was degradation of the "concha resonance" similar to that found in KEMAR.*

The results shown in Figure 4 demonstrate that at least for some people (13/30 subjects), the "concha-related" 5500-Hz resonance is not solely related to their concha volume, but related also to their ear canal length and to having an anatomically conical ear canal, which narrows gradually from the lateral meatal opening to the medial tympanic membrane. (For other people, the 5500-Hz resonance may be solely related to their concha volume.)

If this is indeed the case, then arguments made by some hearing aid manufacturers and dispensers that not occluding the concha has the advantage of allowing more high-frequency sound pressure to be received at the hearing aid microphone (at 5500 Hz) may not be true in all people. Such arguments are often used to support the use of completely-in-the-canal, canal, and mini-canal hearing aids. While these styles of hearing aids do have many advantages, both acoustic[3,4] and cosmetic,[5] for some people, preserving the concha resonance may not be one of them.

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