J Am Acad Audiol 12: 150–154 (2001)

Estimating the Location of Probe Microphones Relative to the Tympanic Membrane

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Abstract

This experiment investigated the accuracy with which the location of a probe tip relative to the tympanic membrane can be estimated by means of standing waves. The ear canal length of each ear of six adult subjects was measured with a probe tube using a tactile method. A 6-kHz warble tone was then generated, and the position of the standing wave notch in the ear canal was determined using a probe microphone by noting the place where the sound pressure level was at a minimum. The distance of the notch from the tympanic membrane was then calculated. The mean distance of the notch from the tympanic membrane was found to be 14.1 mm. It was concluded that this technique is reliable and suitable for clinical use when it is important that the probe tube be placed within a known distance of the eardrum for accurate measurement of real-ear aided gain.

Key Words: Probe microphone, real-ear aided gain, standing waves

Abbreviations: REAG = real-ear aided gain

Some hearing aid prescription procedures prescribe a target real-ear aided gain (REAG) rather than an insertion gain. REAG is defined as the sound pressure level near the eardrum minus the sound pressure level at some reference point in the sound field outside the head. Because of standing waves in the ear canal, sound pressure level at the eardrum is different from sound pressure level at other points in the ear canal. To verify that the target REAG has been achieved, it is therefore important that the probe tube be placed within a known distance of the eardrum (Dirks and Kincaid, 1987). The maximum allowable distance from the eardrum depends on the highest frequency to be measured and the accuracy required. For an error of 4 dB caused by standing waves for measurements up to 6 kHz, for example, the probe tube should theoretically be located within 8 mm of the eardrum (Dillon, 2001). This article investigates the accuracy of an acoustic method for positioning the probe tube that is suitable for clinical use.

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The cause of standing waves is well understood. In a tube that terminates in a high acoustic impedance (such as a closed end), sound waves will be reflected at the high impedance end and will travel back along the tube. The sound pressure at any point in the tube will thus equal the combined pressures of the incident and reflected waves. At a distance one quarter wavelength back from the closed end, the reflected wave will have traveled one half wavelength longer than the incident wave. Because the two waves are 180 degrees out of phase, the net pressure at this point equals the difference between the pressure of the two waves. Thus, there is less sound pressure at this point in the tube than at any other point.

The distance at which this minimum occurs is readily calculated for a tube that is truly closed at one end. The wavelength of sound equals c/f, where c is the speed of sound (assumed to be 355 m/sec in the ear canal) and f is the frequency. The distance of the minimum from the eardrum therefore equals $c/(4f)$. For a frequency of 6 kHz, for example, the distance is 14.8 mm.

Eardrums do not, however, have infinitely high impedance. Furthermore, unless the impedance of the eardrum is totally resistive, the wave will undergo a phase shift as it is reflected. Consequently, at the point at which the incident and reflected waves are 180 degrees out of

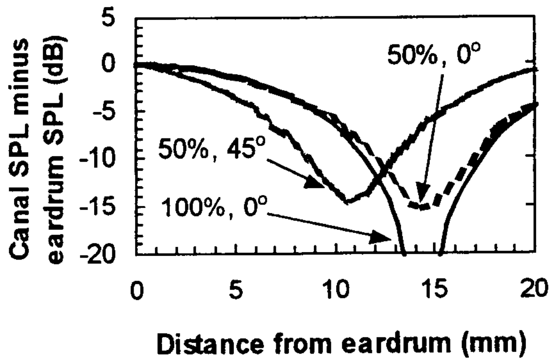

Figure 1 Calculated pattern of sound pressure level in the ear canal versus distance from the eardrum at a frequency of 6 kHz. The solid curve is for total reflection from the eardrum with no phase shift at the drum, the dashed line is for 50 percent power reflected from the drum with no phase shift, and the speckled line is for 50 percent reflected with a 45-degree phase shift at the drum. Reprinted from Dillon (2001) with permission.

phase, the reflected wave will have traveled further than the incident wave by some distance other than one half a wavelength. Therefore, the point in the tube at which the minimum occurs, and the entire pattern of sound pressure level versus distance, will be different from the simple case of a closed end. Figure 1 shows the computed pattern of sound pressure level versus distance for three cases. Notice that if there is no phase shift, the minimum falls in the expected location, even for a partial reflection. When there is a 45-degree phase shift at the drum, however, the position of the minimum shifts. A phase shift of 45 degrees is chosen as an example but is within the range of phase shifts reported by Voss and Allen (1994) at 6 kHz.

Although reflections are the cause of the variation in sound pressure level with distance, these reflections can also be used to help locate the tip of the probe tube. Sullivan (1988) suggested that if the position of the minimum can be determined, the distance of the probe from the drum can then be inferred from the quarter-wave formula. Once the distance of the probe tube from the eardrum is known, the probe tube can be inserted to any desired distance from the drum by moving it in or out by the difference between the desired and actual locations. Sullivan demonstrated that for a 6-kHz warble tone, the mean distance from the tympanic membrane to the standing wave notch, for six subjects, was 14.7 mm. This is in excellent agreement with the theoretically expected value of 14.8 mm.

Gerling and Engman (1991) compared four procedures for placement of the probe tube. In one of the methods, they determined the position of the 6-kHz standing wave notch and inserted the probe a further 10 mm. For 20 ears, they found that the mean distance of the probe from the eardrum was 2.75 mm. Thus, the mean distance of the standing wave notch from the eardrum was 12.75 mm. When they repeated the study, the mean distance of the notch from the eardrum was 12.4 mm. There was no statistical difference between the first and second results; therefore, they concluded that the procedure was repeatable.

Voss and Allen (1994), however, performed extensive measurements of the complex reflectance of the eardrum and found significant phase shifts above about 4 kHz. They comment that "it is incorrect to assume that the eardrum is rigid and that the distance to the drum may be estimated from the quarter wave formula." Gilman and Dirks (1986) also showed that the phase angle of the eardrum impedance affected the distance of the notch from the eardrum.

This observation leaves the clinician with great uncertainty as to whether the probe tube can be located by acoustic means to achieve accurate measurements of the high-frequency gain of hearing aids. The aim of this research was to investigate independently the accuracy with which the distance between the probe tip and the tympanic membrane can be determined by means of the standing waves.

METHOD

Subjects

Subjects were three male and three female adults, all with normal hearing. Both ears of each subject were used.

Procedure

Subjects were seated in front of a Rastronics PR20 portaREM insertion gain analyzer directly facing the loudspeaker (0-degree azimuth) and with the test ear 50 cm from the loudspeaker. A 6.21-kHz warble tone at 60 dB sound pressure level was generated.

A probe tube, with hairs protruding 3 mm from the tip and with colored bands marked at 5-mm intervals along the length, was slowly inserted into the ear canal until the subject reported hearing the hairs scraping on the tym-

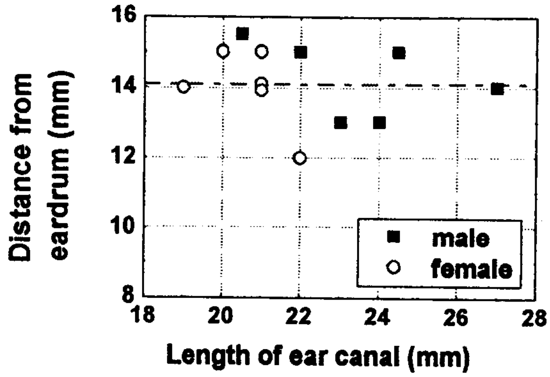

Figure 2 Measured position of standing wave notches for six subjects. The dotted line shows the mean distance of the notches from the tympanic membrane.

panic membrane. The length of the ear canal, as judged by the scale drawn on the probe, was noted. The probe tube was slowly withdrawn until the sound pressure level in the eardrum was lowest. The probe tube was moved in and out slightly until the exact position with the lowest sound pressure level was determined. The distance of the probe tip from the canal entrance was noted. The distance of the standing wave notch from the eardrum was calculated by subtracting the second measurement from the first measurement.

RESULTS

The results are shown in Figure 2. It can be seen that measured positions of the standing wave notches are between 12 and 15 mm from the tympanic membrane and that all but one of the measured positions are within 1.5 mm of the predicted position (14.8 mm). The mean distance of the notch from the tympanic membrane is 14.1 mm (SD = 1.1 mm).

DISCUSSION

The measured positions of the standing wave notches are in close agreement with the predicted position for 11 of 12 of the measurements. This would appear to indicate that the phase shift at 6 kHz is generally not large enough to have a significant effect on the position of the standing wave notch. Measured sound pressure levels are most inaccurate when the probe tube is further from the ear than expected. The greatest discrepancy observed in this direction was 1.5 mm. Were the clinician to be aiming for a location 8 mm out from the eardrum, the actual location would be 9.5 mm. For this distance, the expected error (assuming no phase shift in the drum impedance) is 5.5 dB at 6 kHz and only 2.2 dB at 4 kHz (Dillon, 2001). These worst-case errors are not sufficiently great to discourage use of the procedure.

One measurement was 2.8 mm from the predicted position. This subject had an unusually sensitive ear and had difficulty tolerating the deep insertion of the probe tube during the tactile positioning part of the procedure. It is likely that in this case, the probe tip did not reach the tympanic membrane, with the result that the length of the canal was slightly underestimated. If, as we suspect, the probe did not scrape the eardrum during the tactile positioning, the larger error of nearly 3 mm is caused by an error in the reference position rather than an error in the acoustically determined position. As tactile positioning is not required (or recommended) for clinical use of the standing wave procedure, the larger apparent error would have no impact when the standing wave procedure is used. If, instead, the error was caused by a phase shift in the drum impedance, the result is that the probe tip would be nearly 3 mm closer to the drum than expected. An error in this direction reduces the effect of standing waves on the sound pressure level measured and, again, has no clinical impact. Larger errors in the same direction would cause the clinician to inadvertently push the probe against the drum, but no such larger errors were observed in this experiment.

Because of the reasonably good agreement with the theoretically expected value, we conclude that the phase angle of the impedance, at a frequency of 6 kHz, is not generally large enough to invalidate the method. Although only 12 ears from six subjects were used in this experiment (because the experimental procedure is a little invasive), the results agree with those reported for 6 ears by Sullivan (1988).

Even in the absence of errors caused by non-zero phase of the eardrum impedance, we would not expect perfect agreement with the distance estimated from the quarter-wave equation. The eardrum is not at right angles to the center axis of the ear canal, as shown in Figure 3. Consequently, the effective acoustic position of the eardrum will be at some unknown point between the top of the drum and vertex. Similarly, the physical length of the ear canal

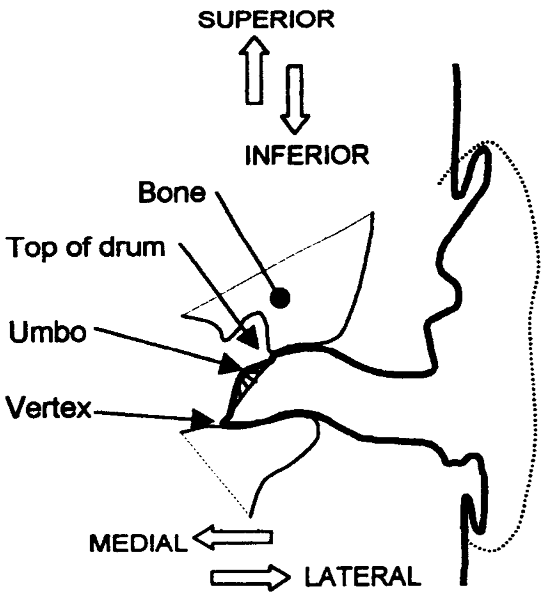

Figure 3 Diagram of the ear canal showing the acute angle of the drum relative to the canal axis.

as determined by the drum-scraping method used to validate the acoustic method will depend on which point of the drum is first touched by the probe-tube hairs. Touching the eardrum at the vertex will typically require an insertion depth approximately 7 mm greater than that needed to touch the top of the eardrum (Salvinelli et al, 1991). Given the twisting motion continually applied to the probe during insertion, however, the point of contact was more likely to be near the top of the drum than the vertex, so the uncertainty in the physical length should be considerably less than ±3.5 dB. Because both the acoustic length and the physical length of the ear canal are therefore poorly defined, we would not expect the two methods to agree perfectly.

A frequency of 6 kHz appears to be a good choice for this measurement. For frequencies lower than 6 kHz, the minimum will occur further from the eardrum, thus requiring a relatively large movement of the probe tube from the position of the minimum to the desired measurement location. Furthermore, although this experiment only evaluated the method in open ear canals, the location of the minimum depends only on the impedance of the drum relative to that of the ear canal. Thus, it occurs in the same location for occluded ears. For a frequency of 6 kHz, the minimum will often fall within the portion of the canal that is unoccluded, even when the outer part of the canal contains an earmold or earshell, at least for earmolds or earshells that do not extend beyond the second bend of the ear canal. Were a lower frequency to be used, there would often be no actual minimum within the unoccluded part of the canal. That is, the pressure would decrease monotonically from the drum to the medial tip of the earmold.

For deeply seated hearing aids, the accuracy of the method is uncertain. A frequency higher than 6 kHz would be required to position the minimum within the unoccluded portion of the ear canal. Based on the measurements of Voss and Allen (1994), however, the use of a frequency higher than 6 kHz would increase the likelihood that reactive components (i.e., a non-zero phase) in the drum impedance would affect the inferred position of the eardrum.

The 6-kHz method has some advantages over an alternative method based on standing waves and frequency spectra that has been used in prior research and that is recommended in manuals for some real-ear gain equipment. Chan and Geisler (1990) estimate position from the eardrum on the basis of the frequency of a notch in the frequency spectrum. That is, the probe is inserted some unknown distance, the notch frequency is observed, and the quarter-wave equation is used to calculate the distance from the eardrum. Chan and Geisler comment that notches in the frequency spectrum can also be caused by pinna resonances. To this we would add room resonances and loudspeaker resonances. They suggest that the resonances caused by factors outside the ear canal can be removed if the spectrum is measured at two points in the canal and the difference of the spectra is computed. They comment that this is simpler than the single-frequency method proposed by Sullivan (1998), because Sullivan's method requires measurements to be made at multiple positions.

Based on our experience, Sullivan's method merely requires a single smooth, continuous insertion and then withdrawal of the probe tube while observing the real-ear gain analyzer screen. The position of the sound pressure level minimum is well defined and, as this experiment has shown, is at the distance expected from the eardrum. The question of spurious minima at other frequencies does not arise because only a single-frequency stimulus is used.

Finally, we note that a probe position close to the eardrum is not required if insertion gain, rather than REAG, is prescribed and measured.

For that reason, insertion gain is recommended for routine clinical measurement of adult hearing aid wearers. For infants and for adults with unusual real-ear unaided gain characteristics (e.g., following surgery), REAG has several advantages over insertion gain (Dillon, 2001). When REAG is to be measured, the 6-kHz method evaluated in this article is recommended. The accuracy of the 6-kHz method has not been evaluated on children, but we are not aware of any reason why it would be less accurate for small ear canals.

CONCLUSIONS

The distance of a probe tube tip from the eardrum can be estimated reliably by finding the position at which the sound pressure level in the ear canal is at a minimum for a 6-kHz warble-tone stimulus presented from a loudspeaker. Once the location of this minimum is found, the tip of the probe tube can be moved to any desired location by further inserting the probe tube a known distance. Insertion by a further 6 mm, for example, would position the probe tube 8 mm, on average, from the eardrum.

Acknowledgment. Portions of this research were presented at the conference Hearing Aid Amplification for the New Millennium, November 15–19, 1999, Sydney, Australia.

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