Middle Ear Pathology Can Affect the Ear-Canal Sound Pressure Generated by Audiologic Earphones

Susan E. Voss, John J. Rosowski, Saumil N. Merchant, Aaron R. Thornton, Christopher A. Shera, and William T. Peake

Objective: To determine how the ear-canal sound pressures generated by earphones differ between normal and pathologic middle ears.

Design: Measurements of ear-canal sound pressures generated by the Etymotic Research ER-3A insert earphone in normal ears (N = 12) were compared with the pressures generated in abnormally ears with mastoidectomy bowls (N = 15), tympanostomy tubes (N = 5), and tympanic-membrane perforations (N = 5). Similar measurements were made with the Telephones TDH-49 supra-aural earphone in normal ears (N = 10) and abnormal ears with mastoidectomy bowls (N = 10), tympanostomy tubes (N = 4), and tympanic-membrane perforations (N = 5).

Results: With the insert earphone, the sound pressures generated in the mastoid-bowl ears were all smaller than the pressures generated in normal ears; from 250 to 1000 Hz the difference in pressure level was nearly frequency independent and ranged from -3 to -15 dB; from 1000 to 4000 Hz the reduction in level increased with frequency and ranged from -5 dB to -35 dB. In the ears with tympanostomy tubes and perforations the sound pressures were always smaller than in normal ears at frequencies below 1000 Hz; the largest differences occurred below 500 Hz and ranged from -5 to -25 dB.

With the supra-aural earphone, the sound pressures in ears with the three pathologic conditions were more variable than those with the insert earphone. Generally, sound pressures in the ears with mastoid bowls were lower than those in normal ears for frequencies below about 500 Hz; above about 500 Hz the pressures showed sharp minima and maxima that were not seen in the normal ears. The ears with tympanostomy tubes and tympanic-membrane perforations also showed reduced ear-canal pressures at the lower frequencies, but at higher frequencies these ear-canal pressures were generally similar to the pressures measured in the normal ears.

Conclusions: When the middle ear is not normal, ear-canal sound pressures can differ by up to 35 dB from the normal-ear value. Because the pressure level generally is decreased in the pathologic conditions that were studied, the measured hearing loss would exaggerate substantially the actual loss in ear sensitivity. The variations depend on the earphone, the middle ear pathology, and frequency. Uncontrolled variations in ear-canal pressure, whether caused by a poor earphone-to-ear connection or by abnormal middle ear impedance, could be corrected with audiometers that measure sound pressures during hearing tests.

(Ear & Hearing 2000;21:265-274)

The sound pressure generated by an earphone is affected by the acoustic properties of the air space to which the earphone is connected. For example, consider two identical earphones, one coupled to a small closed volume (e.g., a 2-cc coupler) and the other coupled to a larger volume (e.g., a 6-cc coupler). When the same oscillating voltage is applied to both earphones, the earphones’ diaphragms move back and forth almost equally and alternately rarely and compress the air within the volumes. Although sound is generated in both couplers, the peak pressures are not the same. Vibration of the diaphragm creates a greater sound pressure in the smaller cavity because it produces a larger fractional change in volume and thus a larger change in air density. Because identical motion produces a greater sound pressure, we say that the smaller volume is “stiffer” (i.e., has a larger acoustic impedance).

Just as the size (or impedance) of a closed cavity affects the sound pressure generated by an attached earphone, the impedance of an ear affects the sound pressure generated in the ear canal. However, during hearing tests, sound pressure levels in the ear canal are not generally measured. Instead, it is assumed that the earphone’s calibration (sound pressure output per volt input) is effectively independent of the acoustic properties of the ear being tested (see, e.g., Borton, Nolen, Luks, & Meline, 1976).
1989; Burkhard & Corliss, 1954; Shaw, 1974; Wilber, 1994), even for ears with pathologies that significantly alter the acoustic properties of the ear (i.e., its acoustic impedance).

Published views of the importance of abnormal ear impedances for the sound pressure generated by earphones do not provide a quantitative evaluation of this standard assumption. As examples of apparently contradictory results, Kruger and Tonndorf (1977, 1978) suggest that the abnormal impedance of ears with tympanic-membrane perforations may lead to ear-canal pressure levels that are different from normal, whereas Horton et al. (1989) conclude that threshold measurements on ears with conductive hearing loss are the same whether they are obtained with an insert earphone or with a supra-aural earphone. The difficulty in arriving at clear conclusions results from lack of systematic determination of the extent to which conductive pathologies affect the ear-canal pressures generated by audiologic earphones. Here, we determine how much three specific conductive pathologies can change ear-canal sound pressures. In particular, we compare measurements of ear-canal pressure in normal ears to those produced by an insert earphone or a supra-aural earphone in ears with mastoid-bowl cavities, tympanostomy tubes, and tympanic-membrane perforations. Contrary to the standard assumption, we find that the sound pressure generated by earphones can differ considerably in these abnormal ears, which can result in sizable systematic errors in audiologic measurements of hearing level.

METHODS

General Approach

The ear-canal sound pressures generated by both an insert earphone (Etymotic ER-3A) and a supra-aural earphone (Telephonics TDH-49), when driven by the same voltage waveform, were compared for normal and abnormal ears. The pressures were measured with a microphone attached to a probe tube that led into the ear canal.

Subjects

The measurement protocol and procedure were approved by the Human Studies Committee of the Massachusetts Eye and Ear Infirmary.

Normal Ears

Twelve subjects with normal hearing and normal middle ears participated in the study (age range 22 to 33 yr); we report measurements made on the right ear of each subject. Each ear was inspected by an otologist (S.N.M.), who removed any wax and judged the ear's appearance as normal. Audiograms were measured (250 to 4000 Hz) and all thresholds were less than or equal to 20 dB HL. Ear-canal pressure measurements were made on all 12 subjects with the insert earphone and 10 of the 12 subjects with the supra-aural earphone.

Pathologic Ears

Subjects were recruited through the otology service at the Massachusetts Eye and Ear Infirmary. At the time measurements were made, no subject had active middle ear disease, as determined by the subject's otologist.

We studied three pathologies that lower the ear's impedance at most frequencies.

1. "Canal-wall down" mastoid surgery, performed to eliminate middle ear disease, produces a cavity ("mastoid bowl") formed by the drilled-out mastoid and epithympanic spaces, which communicate with the ear canal through a surgically produced opening in the posterior-superior wall of the bony ear canal. In these ears, the "mastoid-bowl" air volume, which typically ranges from 1 to 6 cm³, reduces the net acoustic impedance in the ear canal. For each of our subjects, the otologist (S.N.M.) made a visual estimate of the combined volume of the mastoid bowl and ear canal. Measurements were made on 15 ears with mastoid bowls with the insert earphone (age range 34 to 79 yr) and 10 of these 15 ears with the supra-aural earphone (age range 40 to 74 yr).

2. A tympanostomy tube is a short tube inserted through the tympanic membrane in management of otitis media with effusion. The patent tube connecting the middle ear air space with the ear canal allows aeration of the middle ear and thereby aids recovery from middle ear disease. The direct connection between the ear canal and the middle ear cavity lowers the ear's impedance. Measurements were made on five ears with tympanostomy tubes with the insert earphone (age range 40 to 68 yr) and on four of these five ears with the supra-aural earphone (age range 40 to 64 yr). Four of our subjects had Baxter™ tympanostomy tubes (length = 2.1 mm; diameter = 1.27 mm), and one subject had a Good™ T-tube (length = 12 mm; diameter = 1.14 mm).

3. Tympanic membrane perforations can result from either trauma or middle ear disease, and they occur in a wide range of sizes (i.e., from <1% to 100% of the total tympanic-membrane area). Acoustically, the mechanism of a perforation's effect is the same as a tympanostomy tube, i.e., perforations reduce the ear's impedance via a direct connection between the ear canal and the middle ear cavity. Estimates of
perforation sizes were made by the otologist (S.N.M.) by visual inspection. Measurements were made with both the insert and the supra-aural earphones on five ears with tympanic-membrane perforations (age range 25 to 77 yr).

Stimuli

Broadband stimulus chirps were constructed digitally from a series of 2048 equal-magnitude harmonics of a 24.4 Hz fundamental. Responses to the chirps were sampled at 50 kHz and averaged over 200 repetitions. The rms magnitude of the chirps was less than 75 dB SPL for all ears. We report measurements of components from 100 to 4000 Hz.

Microphone and Earphones

Microphone • A miniature electret microphone (Knowles DB100 3103) attached to a flexible probe (Etymotic Research ER7,14C) was used to sense ear-canal sound pressures generated by the earphones. To determine sound pressure level (dB SPL), the microphone with the probe tube was calibrated in a coupler with a reference microphone whose absolute sensitivity was determined with a Larson Davis acoustic calibrator (CA250). Further calibration details can be found elsewhere (Weiss & Peake, 1972).

Insert Earphone • The insert earphone was coupled through a compressible yellow-foam ear plug (Earlink™) (uncompressed diameter 13 mm, length 12 mm), and the flexible microphone probe tube was also threaded through the foam plug. One end of the probe tube was placed 3 mm beyond the medial end of the yellow foam plug, and the other end was coupled to the microphone (Fig. 1A).

For each ear, a new yellow-foam plug was inserted into the ear canal so that its lateral end was at the entrance to the ear canal. For some of the mastoid-bowel ears, the ear canal was too wide for the standard foam plug; in such cases, a wider foam plug was used (uncompressed diameter 18 mm, length 12 mm).

The measurements were made with two different ER-3A insert earphones. First, a series of five normal subjects, seven mastoid-bowel subjects, and one tympanostomy-tube subject was measured with Earphone A (electrical impedance 50 Ω). Because Earphone A then became unavailable, the remaining measurements were made with Earphone B (electrical impedance 10 Ω). Thus, measurements with earphone B were made on seven normal subjects, eight mastoid-bowel subjects, four tympanostomy-tube subjects, and five tympanic-membrane perforation subjects.

For a given input voltage, the two ER-3A insert earphones generated different output sound pressure levels in either a normal ear or a rigid cavity. However, the ratio of the measurements in a normal ear to those in a small rigid-walled cavity are essentially identical for the two insert earphones. As we express all ear-canal sound pressure levels relative to the level produced by the earphone in a small rigid cavity (namely, $P_{TH}$ from Voss, Rosowski, Shera, & Peake, 2000), effects of this difference are removed in the reported results.

Supra-Aural Earphone • The supra-aural earphone (Telephones TDH-49 with an MX-41/AR cushion) was placed on the pinna of each subject's test ear. The “ear-canal” sound pressure was measured within the earphone cushion's opening at the entrance of the subject's external ear, about 1 mm medial to the earphone speaker. The microphone's flexible probe tube was threaded inside a steel tube that passed through the earphone cushion (Fig. 1B). The flexible probe fit snugly in the steel tube.

Results

Normal Ears

Figure 2 shows the sound pressures generated by the two earphone types in normal ears. In each ear at every frequency, the pressures generated are less than those generated in a small rigid cavity, indicating that for both earphones the output pressure is affected by the acoustic “load” provided by the ears.* For frequencies below about 200 Hz, the standard deviations with the supra-aural earphone (up to 7 dB) are greater than with the insert earphone (about 2 dB). For frequencies above 200 Hz, which are of primary interest, the standard deviation is less than 4 dB with either earphone.

*The systematic fine structure evident in the pressures generated with the supra-aural earphone (e.g., near 1000 Hz) is a feature of the pressure $P_{TH}$ generated in a small cavity.
Ears with Mastoid Bowls

The sound pressures generated in ears with mastoid bowls (Fig. 3) with either earphone differ from the pressures generated in normal ears.

With the insert earphone (Fig. 3 upper), the pressure is generally in the range 5 to 30 dB lower than in normal ears. For frequencies below 1000 Hz, the reduction is roughly independent of frequency in each ear and ranges from 3 to 15 dB. Above 1000 Hz, the pressure generally decreases gradually with frequency, but in two cases it drops rapidly to reach -35 dB.

The 15 pressures shown in Figure 3 (upper) come from ears with mastoid-bowl volumes of different sizes. Because the impedance of a mastoid-bowl ear is largely determined by the bowl’s volume (Voss et al., 2000), we expect the pressure generated in these ears to depend on the volume. Here, categories of estimated mastoid-bowl volumes are indicated in Figure 3. The ear with the largest volume (about 6 cm³) yielded the smallest pressures (for most frequencies). The two ears in the smallest volume category (less than 2 cm³) have pressures that are larger than most of the ears for frequencies below 1000 Hz. These observations are consistent with ear-canal pressure decreasing as the mastoid-bowl volume increases.

With the supra-aural earphone (Fig. 3 lower), the pressures generated in the mastoid-bowl ears have a frequency dependence different from the relatively flat pattern seen with the insert earphone. At frequencies below about 500 Hz, pressures in 8 of 10 ears are reduced by 5 to 25 dB relative to normal. However, these pressures increase with frequency so that between 500 and 1000 Hz, the pressure with a mastoid bowl exceeds normal in most ears. Between about 1000 and 4000 Hz, for each ear the pressure contains at least one maximum that exceeds the standard deviation of the normal population’s pressure. Additionally, between 1700 and 4000 Hz, a sharp reduction in pressure of 5 to 35 dB relative to the normal ears occurs in 9 of the 10 ears; the only ear that does not include a large pressure reduction is the ear (dashed line) with the smallest mastoid bowl of less than 2 cm³. To summarize, with
the supra-aural earphone, the mastoid bowls introduce both sharp increases and sharp decreases in pressure between 1000 and 4000 Hz in addition to decreases below 500 Hz.

**Ears with Tympanostomy Tubes**

With the insert earphone, in all five tympanostomy-tube cases, the low-frequency sound pressure is 5 to 25 dB below that in normal ears; a pressure minimum, below −20 dB, occurs between 100 and 400 Hz in all four cases with a Baxter™ tympanostomy tube (Fig. 4 upper). Above 1000 Hz, in three of the five ears, the pressures are nearly within the standard deviation of the normal measurements but they are 10 to 15 dB below normal in the other two ears.

With the supra-aural earphone, the pressures seem to be less affected by a tube than with the insert earphone (Fig. 4 lower). For frequencies above 500 Hz, ear-canal pressures generally differ from normal by less than 5 dB. Below 500 Hz, there is a systematic reduction in ear-canal pressure that includes a pressure minimum. In three of the four subjects, the low-frequency minimum occurs at the same frequency as the pressure minimum in the insert earphone measurements (see arrows in Fig. 4 at frequencies of 146 Hz, 366 Hz, and 390 Hz).

**Ears with Tympanic-Membrane Perforations**

In ears with tympanic-membrane perforations, the sound pressure generated with the insert earphone appears to depend on perforation size (Fig. 5 upper). Small perforations (1% and 3%) have effects similar to those of tympanostomy tubes: the low-frequency sound pressures are reduced from normal with a pressure minimum below −30 dB. However, larger perforations have effects that are more similar to mastoid bowls: the reduction in pressure has less frequency dependence.

With the supra-aural earphone (Fig. 5 lower) there does not appear to be a clear pattern between
the ear-canal sound pressures and the perforation size. For frequencies below 500 Hz, there is a pressure reduction relative to normal that ranges from a few dB down to –30 dB. Above about 500 Hz, the ear-canal pressures generally differ from normal by less than 5 dB.

In general, the frequency of the low-frequency minima seen with the supra-aural earphone differ from those seen with the insert earphone. However, the minimum with the 3% perforation occurs at essentially the same frequency with both earphones, in agreement with the behavior observed with tympanostomy tubes.

**DISCUSSION**

**General Clinical Implications of Results**

Our results show that, with the attenuator of an audiometer set at a constant value, the ear-canal sound pressures produced by an earphone (either insert or supra-aural) in different ears can vary by up to 35 dB. Because the calibrated earphone used in measuring audiograms is assumed to produce approximately the same pressure in all ear canals, these uncontrolled pressure variations lead to errors in audiograms of up to 35 dB.

As a specific example of the effect of uncontrolled ear-canal pressures on a measured audiogram, consider a hypothetical audiogram measured with an insert earphone in an ear with a mastoid-bowl cavity (Fig. 6). In this example, the “measured audiogram” is independent of frequency (“flat”) at 40 dB hearing level, and for simplicity, the bone-conduction sensitivity is set to 0 dB hearing level. The measurements in Fig. 3 (upper) show that the presence of a mastoid bowl reduces the pressure produced by the insert earphone relative to the pressure produced in a normal ear. With a smaller-than-normal ear-canal pressure produced for a given audiometer attenuation, the hearing loss will be overestimated. The audiogram in Fig. 6 indicates this effect schematically. The line marked “Upper bound for actual hearing levels” approximates the largest pressure deviation from normal that we measured on our population of ears with mastoid bowls so that all pressure deviations that we measured (Fig. 3 upper) fall within the gray shaded region labeled “Range of actual hearing levels.” From this example, we see that our measurements suggest that audiograms measured with insert earphones on mastoid-bowl ears can overestimate the hearing loss by up to 15 dB at the lower frequencies and up to 35 dB at 4000 Hz. The errors discussed here, which can be 35 dB and are commonly 10 to 15 dB, could lead to the inappropriate use of hearing aids, unnecessary surgery, or an incorrect interpretation of the effect of surgery on hearing.

**Acoustic Mechanisms that Cause Variations in Ear-Canal Sound Pressures**

**Approach** • We have developed a quantitative model based on physical acoustics and ear structure that predicts the ear-canal pressures generated by the insert and supra-aural earphones with different pathologic conditions of the ear (Voss et al., 2000). From analysis of the model we compare ear-canal pressures generated in normal ears to pressures generated in ears with reduced impedance (mastoid bowls, tympanostomy tubes, tympanic-membrane perforations), ears with increased impedance, and ear-earphone couplings that include an acoustic leak between the ear and the earphone. Here, we use some of these model results to interpret the results presented above.

**Dependence of the Ear-Canal Pressure on the Ear’s Impedance** • Measurements of the acoustic-source characteristics for both the insert earphone and the supra-aural earphone show that neither earphone acts as an ideal pressure source (Voss et al., 2000), i.e., the ear-canal pressures generated by these earphones depend on the ear’s impedance. Variations in impedance among normal ears appear to affect the sound pressure generated by either
earphone by only a few dB (Fig. 2). In agreement with the results presented here (Figs. 3 through 5), analysis of a structure-based quantitative model (Voss et al., 2000) shows that the pressure generated by earphones can be altered substantially in pathologic ears with reduced impedance.

The result that pathologic conditions have a greater effect on pressure with an insert earphone than with a supra-aural earphone is primarily a consequence of the difference in coupling locations (Voss et al., 2000). The impedance that the earphone drives is different for the two locations. With the insert earphone, there is an ear-canal air volume of approximately 0.5 cm$^3$ between the earphone and the tympanic membrane, whereas with the supra-aural earphone there is a much larger volume of approximately 12 cm$^3$, which includes the concha and air volume under the earphone cushion.† The relatively large external-ear volume with the supra-aural earphone makes the load impedance at the earphone smaller and relatively insensitive to the middle ear's impedance, which is largely controlled by the large external-ear air space.

The model (Voss et al., 2000) shows that the measured changes from normal with the insert earphone can be accounted for by changes in the impedance of the ear. 1) For the case of an ear with a mastoid bowl, as bowl-volume increases the model predicts a systematic reduction in pressure due to the systematic decrease in the ear's impedance. Thus, larger bowl volumes result in greater ear-canal pressure reductions relative to normal. 2) With a tympanostomy tube, the model predicts a resonance between the acoustic mass of the tube (i.e., inertia of air moving through the tube) and the compliance of the middle ear cavity (i.e., elasticity of the enclosed air). This resonance produces a pressure minimum (see Fig. 4) at a frequency below about 500 Hz, where the frequency of the minimum depends on the dimensions of the tube and the volume of the middle ear cavity. 3) A small tympanic-membrane perforation behaves similarly to the tympanostomy tube, with a pressure minimum at a frequency determined by the dimensions of the perforation and the volume of the middle ear cavity; a large perforation behaves more like a mastoid bowl with the middle ear cavity volume acting as a mastoid-bowl volume.

With the supra-aural earphone, the model (Voss et al., 2000) predicts some, but not all, of the measured changes from normal. The model for the supra-aural earphone is consistent with the measurements for ears with tympanostomy tubes and tympanic-membrane perforations. As with the insert earphone, the model predicts a pressure minimum at the resonant frequency between the mass of the tympanostomy tube or perforation and the compliance of the middle ear cavity. Consistent with the measurements, the model predicts smaller differences from normal with the supra-aural earphone than with the insert earphone.

The supra-aural earphone model is not consistent with all of the measured changes from normal. At low frequencies, the model predicts that the pressures in ears with the largest mastoid bowls will be reduced by less than 5 dB relative to normal. However, many of our measurements are reduced by 10s of dBs at the lowest frequencies; reasons for these low-frequency differences between the measurements and the model are discussed in the following section titled “Acoustic Leaks.” At higher frequencies, there are sharp maxima and minima in pressure that are not seen in the normal population. A model of the mastoid-bowl ear connected to the supra-aural earphone shows that these pressure extrema are consistent with resonances that depend on the dimensions of both the ear canal and the mastoid bowl.

Acoustic Leaks • Lack of stability in the acoustic connection of the supra-aural earphone to ears is a problem, especially for low-frequency measurements. As Zwislocki, Kruger, Miller, Niemoeller, Shaw, and Studebaker (1988) write, “Supraaural earphones have low reliability at low frequencies because of variable and unstable coupling between the earphone and the ear. Air leaks occurring between the earphone cushion and the pinna produce variable amounts of sound pressure loss at low frequencies (typically below 500 Hz), accompanied by small, variable amounts of sound pressure enhancement at somewhat higher frequencies (between 500 and 1000 Hz).”

The features described by Zwislocki et al. occur in most of our measurements with the supra-aural earphone on ears with mastoid bowls (Fig. 3, lower). At the lowest frequencies, many of the measurements start 10 to 30 dB below normal and then increase toward normal as frequency increases. Between 500 and 1000 Hz, many measurements show a pressure increase relative to normal. Predictions

†The ear canal has a length of about 28 mm and a diameter of about 7 mm (Wever & Lawrence, 1984). The insert earphone assembly extends about 15 mm into the ear canal; the 12 mm length of the foam plug plus 3 mm for the probe-tube extension. Thus, the ear-canal volume between the foam plug and the tympanic membrane accounts for an air volume of 0.5 cm$^3$. The supra-aural earphone couples to the ear via a cushion that rests along the edge of the pinna. Here, we estimate a total external-ear air volume of 12 cm$^3$, where 1.0 cm$^3$ accounts for the ear-canal volume (Shaw, 1974), 4.0 cm$^3$ accounts for the concha volume (Shaw, 1974), and 7.0 cm$^3$ accounts for the air volume under the earphone's cushion lateral to the concha, which we measured by filling the cushion with water from a calibrated syringe.
with a model of the supra-aural earphone coupled to an ear with a mastoid bowl that includes an acoustic leak at the ear-earphone connection are consistent with the measurements shown here (Voss et al., 2000).

Our data suggest that leaks with the supra-aural earphone are more common in the mastoid-bowl population than in other ears. A possible reason for this difference is an effect of the surgery, which involves an incision behind the pinna. As the incision heals, the scar can pull the posterior portion of the pinna flange closer to the skull. This "bent" configuration may make it more difficult to seal a supra-aural earphone cushion around the pinna flange.

Ears with Abnormally High Impedance

Our measurements demonstrate that ear-canal pressure is affected for three pathologies in which the ear's impedance is lower than normal. Here, we consider, from a theoretical standpoint, how an increased impedance might affect the ear-canal pressure. Pathologies that increase the ear's impedance include 1) otosclerosis (Zwislocki & Feldman, 1970), in which abnormal growth in the otic capsule impedes movement of the stapes; and 2) otitis media with effusion, in which the motion of the tympanic membrane is impeded by middle ear fluids (Berry, Andrus, Bluestone, & Cantekin, 1975).

As the limiting case, consider an "infinite-impedance" middle ear in which the tympanic membrane does not move. In this case, the impedance that the earphone must drive is determined by the air space between the earphone and the tympanic membrane; this air volume places an upper limit on the impedance that must be driven by the earphone. Our model (Voss et al., 2000) predicts that, as a result of this upper limit on the ear's impedance, the ear-canal pressures generated by either earphone in ears with high impedances are within 3 dB of normal. Thus, the large deviations from normal seen in ears with reduced impedances will not, in theory, occur in ears with increased impedance.

Sound Pressures at Locations Distant from the Source

We have focused on variations in the ear-canal pressure generated at the output of an earphone. Interear variations in the pressure generated by the earphone—at the earphone's location—are important to quantify because they are currently assumed negligible when testing hearing. Other fundamental issues that remain to be addressed include 1) determining whether middle ear pathologies affect the ear-canal pressures that result from free-field stim-

uli, and 2) determining how sound pressures, generated by either an earphone or in the free field, vary spatially along the ear canal.

We expect that free-field sources approximate ideal pressure sources for frequencies below 1000 Hz; thus a pressure propagated from the free field to the entrance of the ear canal should be nearly independent of the ear's impedance for frequencies below 1000 Hz. Conversely, as frequency increases, a free-field source does not necessarily behave as an ideal pressure source, and the acoustic properties of the ear (i.e., the ear's impedance) may affect the sound pressure level at the entrance of the concha. In summary, for low frequencies, the pressure at the concha from free-field stimuli is probably similar for both normal and pathologic ears, but for frequencies above about 1000 Hz, the pressure at the concha may differ from normal, depending on the ear's impedance.

Even though the sound pressure at the entrance of the concha is expected to be nearly constant for most ears at most frequencies, the pressure within the ear canal and at the tympanic membrane may vary among both normal and pathologic ears. For example, for both free-field stimuli and earphone-delivered stimuli, at frequencies greater than that for which one quarter of the wavelength of sound approaches the length of the ear canal, standing waves can be generated in the ear canal, and the pressure at the concha or earphone can differ sub-

\[ f_{\lambda/4} = \frac{c}{\lambda/4} = \frac{340000 \text{ mm/sec}}{\lambda/4 \text{ mm}} \]

\( \lambda \) is the wavelength of sound, and \( c \) is the speed of sound in air. For the insert-earphone configuration, the ear-canal length is approximately 10 mm, so that the "quarter-wavelength" frequency \( f_{\lambda/4} \) is about 8500 Hz.
Audiometric Problem and Possible Solutions

The Problem • The practical problem identified by our measurements is that the ear-canal sound pressure level produced by audiologic earphones in pathologic ears can deviate by as much as 35 dB from the expected value, and deviations of 10 to 15 dB are common. Measured hearing levels can therefore be incorrect by as much as 35 dB.

The possibility that variations in impedance of individual ears may cause large variations in the ear-canal sound pressure generated by an earphone has been considered previously (e.g., Norton et al., 1989; Burkhard & Corliss, 1954; Shaw, 1974; Wilber, 1994), but sound pressure measurements with specific middle ear pathologies have not been reported. Norton et al. (1989) explored this issue by comparing audiograms measured with the insert earphone to audiograms measured with a supra-aural earphone for ears with conductive hearing loss. The two earphone configurations gave audiograms that were essentially the same, and Norton et al. (1989) concluded that the insert earphone's output is not sensitive to the ear to which it is coupled. There are two major differences between our measurements and the measurements of Norton et al. (1989). First, our ears with conductive hearing loss are grouped into specific types of pathologies, whereas Norton et al. (1989) lumped all conductive pathologies together; it is possible that the conductive hearing loss in most of Norton et al.'s subjects resulted from pathologies that increased the imped-ance (e.g., middle ear fluid or otosclerosis) rather than from pathologies that decrease the ear's imped-ance at most frequencies. Second, we measured the ear-canal pressures, whereas Norton et al. (1989) compared thresholds with two different earphones: if the two earphone outputs were affected in the same systematic way by a pathologic ear, changes in ear-canal pressure (and thus possible errors in measured thresholds) would go undetected.

Possible Solutions • One approach to eliminating the pressure variations demonstrated here would be to correct audiograms by the mean of the errors illustrated by our measurements in Figures 3 through 5. However, each ear's errors depend on its individual anatomy. For example, ear-canal sound pressure levels depend on the volume of a mastoid bowl or on the diameter of a perforation or tympanostomy tube along with the middle ear cavity volume. Thus, changes in ear-canal pressure from pressure measurements based on averages will not accurately predict the ear-canal pressure for an individual ear.

Another approach is to design audiometers that maintain a constant pressure output from the earphone. This could be done in two ways. First, an earphone that behaves approximately as a constant-pressure source might be designed, as suggested by Burkhard and Corliss (1954). Second, as suggested by Harris (1978, p. 10), an audiometer could be designed to include a feedback system in which a microphone monitors ear-canal pressures that then determine the earphone's input voltage.

As discussed briefly above in the section titled "Sound Pressures at Locations Distant from the Source," the current technique of producing a "known" pressure at the output of the earphone should be reexamined. Future work could investi-gate alternative methods to reference the stimulus pressure, such as either 1) referencing the stimulus pressure to a free-field stimulus, which would mimic most closely a real-world hearing situation; or 2) referencing the stimulus pressure to the pressure at the tympanic membrane, in response to either free-field or earphone-delivered stimuli. In the latter case, methods to measure the pressure at the tympanic membrane would need to be developed (e.g., Huang, Reference Note 1; Siegel & Dreisbach, Reference Note 2). Another approach would be to measure the intensity of the sound in the ear canal, because intensity is nearly unaffected by spatial location (Neely & Gorga, 1998).

Toward a New Configuration • For the technique of producing a "known" ear-canal sound pressure with an earphone, we suggest two features for a new audiometric configuration. First, ear-canal sound pressure should be controlled via a feedback system between a microphone that measures ear-canal pressure and the system that sets the earphone input voltage. Second, the microphone should be as close as possible to the tympanic membrane to reduce effects of spatial variations in pressure along the ear canal (Siegel & Dreisbach, Reference Note 2); an insert earphone could provide convenient conveyance for a microphone probe tube and would preserve the advantages of an insert earphone (Killion & Villchur, 1989).

Acknowledgments:

This work was supported by training and research grants from the NIDCD. We thank Jean Rosowski, M.S., CCC-A, Bob Margo-
REFERENCES


REFERENCE NOTES
