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# Comparison of Probe Insertion Methods on Estimates of Ear Canal SPL

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**Abstract**

Real-ear sound pressure levels (SPLs) were compared among three methods used for positioning a probe microphone in the ear canal. The probe insertion techniques included (1) an acoustic method that incorporates use of the quarter-wave antiresonance property of the ear to determine acoustically the location of the probe tube relative to the eardrum; (2) a constant insertion depth method (25 mm from the intratragal notch); and (3) the earmold +5-mm method, which places the probe 5 mm beyond the tip of the earmold, thereby avoiding problems associated with the transition region where sound exits from the bore of the earmold into the larger ear canal. Measurements were obtained at 32 test frequencies in 24 adults with normal middle ear impedance. Results indicated that the SPLs measured by the acoustic method were modestly higher than those measured by the other two methods. This result was most evident in subjects with long ear canals (> 25 mm) and at high test frequencies (3.0 to 6.3 kHz).

**Key Words:** Acoustic method, constant insertion depth method, earmold +5-mm method, insertion gain, probe insertion depth, probe-microphone real-ear measurements

During the past decade, the use of probe-microphone real-ear measurements has had a significant impact on the evaluation of hearing aid systems. The probe-microphone method is especially appealing because of its objectivity and, unlike coupler-based methods, provides the real-ear sound pressure level (SPL) in an individual's ear canal. In clinical practice, probe-microphone techniques have most often been used for the relative measurement of the real-ear gain of a hearing aid, that is, to measure insertion gain or the difference in decibels (dB) between the hearing-aided and unaided (open ear) conditions. For this relative measurement of gain, the ear is treated as a transmission line, and the position of the probe within the ear canal is not of paramount concern as long as the probe tip location is identical for both the aided and unaided measurements. It is, of course, advisable that the probe tube be positioned at least 4 to 5 mm beyond the medial tip of the earmold to avoid the transition field that occurs when sound is radiated into the ear canal from the smaller earmold duct. In this transition area, radial waves are created, which interact with the plane waves emanating from the hearing aid and may produce nulls or variations in measurement of ear canal output near the earmold duct (Burkhard and Sachs, 1977).

As probe-microphone systems have become commercially available, clinicians and investigators have attempted to extend probe methods beyond the relative measurements of insertion gain (Mueller et al, 1992). Probe measurements, for example, have been proposed for a variety of goals, such as determining SPL output in an open or hearing-aid–occluded ear canal at levels that correspond to subjective comfort or discomfort. In addition, probe measurements have been advocated to measure the real-ear SPLs in the ear at the saturation level of a hearing aid (so-called saturation SPL, SSPL90). For these applications, the SPL is measured in the ear canal and usually referenced to a constant SPL input located in the sound field, or with a reference

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microphone located on the patient's head or at a position equivalent to the location of the microphone of the hearing aid. For these special applications, the positioning of the probe to establish the SPL in the ear canal becomes a critical procedural consideration. Specifically, unless the probe tip is located near the eardrum, the SPL measured in the canal may vary considerably because of interactions that occur between the reflected waves from the eardrum and the incident acoustic waves from the hearing aid (occluded measurement) or the speaker (open-ear measurement). The interaction between the reflected waves with the incident waves sets up standing wave patterns that cause pressure amplitude variations to occur in different parts of the canal. In the frequency region of most hearing aids (0.2–8.0 kHz), the standing wave patterns generally follow the physical principles observed in a rigid-walled cylindrical tube. The pressure amplitude of the standing wave is determined primarily by the probe location in the canal, the termination (eardrum) or the impedance at the eardrum, and the frequency of the test signal.

Although the existence of standing waves in the ear canal has been recognized for a number of years (Bekesy, 1960), their practical effect on real-ear measurements has only recently been studied under hearing aid conditions by Gilman and Dirks (1986) using an occluded ear simulator, by Dirks and Kincaid (1987) in KEMAR, and by Chan and Geisler (1990) using open and occluded human ears. The data from these studies suggest that, unless the probe tube is positioned near the eardrum, the measured SPL can vary by as much as 12 to 14 dB in an "average" adult ear as a function of frequency and probe placement. Because the SPL measured in the ear canal is dependent on the position of the probe tube within the canal, it is essential to know the location of the probe relative to the eardrum. This problem could be solved either by determining the length of the individual canal and then inserting the probe to an appropriate depth or, alternatively, by establishing the distance of the probe tip from the ear drum. The methods developed to achieve these solutions are not especially applicable for clinic use. For example, Beranek (1949) suggested the use of the so-called "thud" method, in which the probe is advanced into the canal until the individual reports a sensation approximating a dull thud as the probe touches the eardrum. This method can cause physical discomfort to the patient and, considering potential tester liability, is not advocated for clinical use. An optic method (Zemplenyi et al, 1985) using a high-powered stereoscopic operating microscope has also been developed to determine the length of an ear canal. This technique, although useful in research, requires a high-powered microscope and skill in its operation.

Recently, Chan and Geisler (1990) developed an acoustic method to estimate the distance of the probe tip from the eardrum using principles derived from one-dimensional wave theory. The theory indicates that, for any one frequency component of the signal, the pressure amplitude reaches a minimum at a distance from the termination (eardrum) that is approximately equal to one-quarter of the wavelength of that signal component (Shaw and Teranishi, 1968; Gilman and Dirks, 1986). In the acoustic method, the quarter wavelength corresponding to this notch frequency is measured and used to estimate the distance of the probe from the eardrum. Specifically, the estimated distance of the probe from the eardrum is equal to the speed of sound in air (c) divided by four times the notch frequency (f), (i.e., distance = c/4f). With modern-day computer technology, detection of the notch frequency from a measured spectrum and the necessary calculations required to determine the distance of the probe from the eardrum can be automated for clinical implementation.

In the current study, real-ear measurements obtained via the acoustic method are compared to similar results obtained from two clinical procedures advocated for probe-microphone measurements. In the first procedure, referred to as the constant insertion depth method, the probe is placed at a constant depth from the intratragal notch based on average adult canal and concha length (Hawkins et al, 1991). In the second procedure, referred to as the earmold +5-mm method, the probe is positioned along the side of the earmold and then extended 5 mm beyond the sound bore to avoid the transition region where the signal from the small earmold duct enters the larger canal. These clinical methods have the advantage of simplicity, but both are based on average canal and concha lengths, and individual differences generally are not involved in the basic determination of probe insertion depth. The acoustic method, however, has the potential to locate the probe tip at a known distance from the eardrum regardless of the length of the ear canal.

Although the acoustic method, theoretically, is the more precise and sophisticated of the aforementioned procedures, even the constant insertion depth or earmold +5-mm methods can be used to position the probe within 5 to 6 mm of the eardrum for average adult ear canals. For long ear canals, however, the more clinically applicable methods are likely to result in probe placements that are more distant from the eardrum. To assess the relative effects of these methods on real-ear SPLs, comparative probe-microphone measurements were obtained from the open ears of individuals with normal middle ear impedance.

## METHOD

### Subjects

The subjects for this experiment were 24 adults (12 males and 12 females). Each subject exhibited normal middle ear admittance as measured by tympanometry. Prior to the experiment, the test ear of each subject was examined otoscopically and wax deposits were removed upon detection.

### Procedures

Subjects were tested in a double-walled, sound-insulated test room. The data for each method were collected with a probe-microphone assembly, which was incorporated in an Aurora Audiodiagnostic Workstation (Nicolet Instrument Corp.). The test signal was a pseudorandom noise with a uniform spectrum up to 10.0 kHz. The noise was delivered from a small loudspeaker (Realistic Minimus-7), which was located on an adjustable stand. The loudspeaker was placed 1.2 feet from the center of the subject's head at ear level at a 45° azimuth. The noise presentation level was 70 dB SPL.

The probe-microphone assembly contained two microphones; a soft silicone probe tube was attached to one microphone, which was used to measure the SPL in the ear canal, while a second microphone was located approximately 1 cm above the apex of the pinna of the test ear and was used as a reference microphone. The probe microphone was attached to a headband assemblage, which held a micrometer that permitted the tester to insert the probe tube in 1-mm steps into the ear canal.

The probe-microphone system was calibrated with respect to the reference microphone prior to each experimental session. The calibration response was stored by a computer, which was part of the Aurora system, and the output SPL of each probe measurement was compensated with this calibration correction. The probe output response was digitized at a sampling rate of 20 kHz. The output response was averaged 128 times in the time domain, and the amplitude frequency spectrum was displayed on a computer monitor with 12th-octave resolution over the frequency range from 0.2 to 6.3 kHz. A hard copy of the actual SPL values was also obtained and used for analysis. Two trials were conducted for each of the probe methods conducted over two test sessions. All procedures were performed with the test ear unoccluded. There were three probe-microphone test conditions: (1) the acoustic method, (2) the constant insertion depth method, and (3) the earmold +5-mm method. Details concerning the specifics of the acoustic method can be found in Chan and Geisler (1990) and will only be described briefly in this paper.

***Acoustic Method.*** As indicated earlier, the location of the first standing wave minimum can be predicted to occur at one-quarter wavelength the distance from the eardrum. For the acoustic method, initial measurements are made to identify the frequency where this minimum occurs. From that information, the distance of the probe from the eardrum is calculated. Reflections from the pinna and concha can produce confounding effects in the amplitude spectra, which also appear as notches or minima in the spectrum. These notches can be confused with the quarter wavelength minimum. To eliminate this problem, the Chan and Geisler method incorporates an acoustic algorithm that requires obtaining two amplitude spectra with the probe placed sequentially at two different locations (5 mm apart) in the canal. The first measurement is made with the probe located at a distance of 15 mm from the canal entrance and the second at a distance of 10 mm from the canal entrance. Insertion of the probe tube is easily accomplished by use of a calibrated micrometer, which is attached to an adjustable headband. Fourier spectra are calculated from the averaged spectrum obtained at each location, and the amplitude spectra from the two locations are then subtracted from each other. Those elements common to both probe locations, such as the effects of the pinna and concha, are eliminated; however, the quarter wavelength notch, due to the standing wave, will change in a predictable fashion as the probe is moved from one location to another. The resulting difference curve contains a prominent peak and notch at identifiable frequencies. The peak corresponds to the quarter

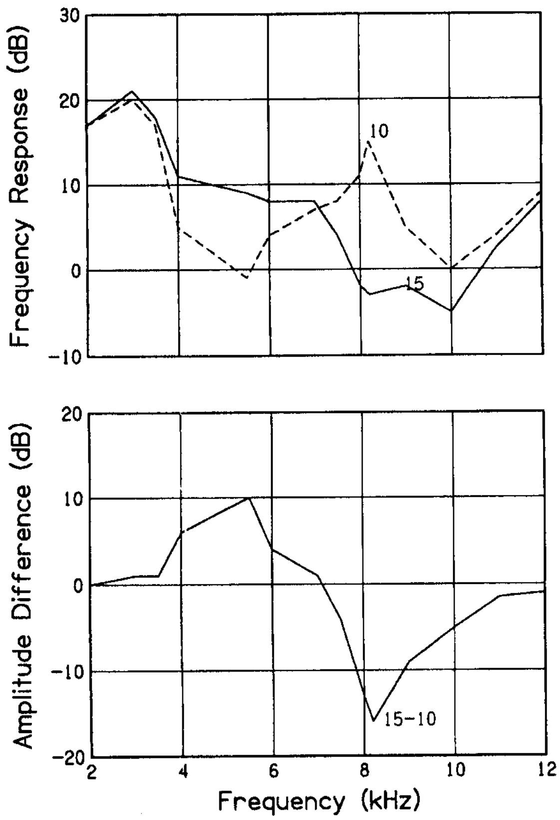


**Figure 1** The top panel contains the simulated frequency response characteristics measured with the probe inserted 15 mm (solid line) and 10 mm (dashed line) from the canal entrance. The bottom panel contains the difference spectra (15–10 mm) between the frequency responses shown in the top panel. The simulation was replotted from data reported by Chan and Geisler, 1990 (Fig. 4, p. 1241).

wavelength minimum at a distance of 15 mm from the canal entrance, whereas the notch corresponds to the placement of the probe placed 10 mm from the canal entrance.

A simulated graphic representation of the method is provided in Figure 1 for clarification. The upper panel of this figure contains two simulated but realistic frequency response spectra. The first is obtained with the probe inserted 10 mm (dashed line) and the second with the probe inserted 15 mm (solid line) from the canal entrance. The typical normal canal resonances are evident for both response curves at approximately 3.0 kHz. For the curve recorded with the probe inserted 10 mm into the canal, a relatively sharp notch occurs at 5.5 kHz. A second notch appears at ~10.0 kHz. By following the solid curve obtained with the probe inserted 15 mm into the canal; two notches are again observed, first at ~8.0 kHz and second at ~10.0 kHz (near the same frequency where the second notch occurred on the 10-mm curve). The problem is to identify the quarter wavelength notch in each spectrum because the pinna and/or concha can also produce confounding effects in the amplitude spectrum, which also appear as notches. It is, however, only the notch created by the quarter wavelength at the minima of the standing wave that can be used to predict the position of the probe relative to the eardrum. As indicated earlier, this minima is found by subtracting the 10-mm response from the results found at 15 mm. Those elements common to both probe locations, such as the effects of the pinna and concha, are eliminated, but the quarter wavelength notch will change in a predictable manner as the probe is moved to a new location. The difference curve is illustrated in the bottom panel of Figure 1. The prominent peak at 5.5 kHz reflects the quarter wavelength notch that occurred when the probe was inserted 10 mm into the canal. The notch at 8.2 kHz reflects the quarter wavelength notch obtained from the 15-mm measurement. The notch at 10.0 kHz was observed in both curves and was eliminated by the subtraction process, suggesting that these notches were due to factors other than the standing wave minimum. According to theory, a notch located at 5.5 kHz indicates that the probe tip is approximately 15.5 mm from the eardrum for this measurement. Because the probe is already 10 mm into the canal, it can be inserted another 10.5 mm to place it 5 mm (15.5–10.5 mm) from the eardrum.

Computer software is designed to store the spectra, detect the peak or notch, and perform the necessary calculations required to determine the probe distance from the eardrum when the probe was located either 15 or 10 mm from the canal entrance. Adjusting the headband assembly on the patient and positioning the probe via the calibrated micrometer are the most time-consuming aspects of this method. In contrast, running the actual tests and collecting the data needed to calculate the probe distance from the eardrum are under computer control and, therefore, require little time for completion.

***Constant Insertion Depth Method.*** The constant insertion depth method (Hawkins et al, 1991) is a practical clinical method in which the probe is located in the ear canal at a depth of 27 mm past the intratragal notch (various depths have been recommended but 27 mm is considered to be a conservative distance). For an average adult, the distance between the intratragal notch and the canal entrance is ~8 to 10 mm, and an average ear canal length is ~24 mm in length. Thus, the distance from the intratragal notch to the eardrum in an average adult ear is ~32 to 34 mm. Using the constant insertion depth method, the probe would be located within 5 to 7 mm of the eardrum on an average ear. The actual distance of the probe from the eardrum will be either closer or farther than the average, depending on the length of the individual canal under test. This method is straightforward but, of course, represents a compromise based on average concha and ear canal lengths.

***Earmold +5-mm Method.*** For the earmold +5-mm method, the probe length is determined by placing the tube along the side of the earmold and then extending it an additional 5 mm beyond the sound bore. This method ensures that the insertion depth of the probe is adequate to avoid the transition region where the small earmold duct interfaces with the larger ear canal. The disadvantage with this technique is that the depth of probe insertion depends on earmold length. For the current study, some subjects included hearing aid users whose earmolds were used in estimating the length of the probe. For subjects who were not hearing impaired, earmolds had to be made prior to obtaining the real-ear measurements. Most earmolds extended 8 to 10 mm into the canal; thus, on average, the probe tip was located 15 mm into the canal (i.e., ~8–9 mm from the eardrum).

## RESULTS

### General Descriptive Data

Recall that the distance of the probe from the eardrum is estimated by the acoustic method from two preliminary measurements obtained with the probe located at 10 and 15 mm from the canal entrance. The length of an individual ear can be calculated by adding the measured probe distance from the eardrum (determined from the acoustic method) to the known distance of the probe from the canal entrance (either 10 or 15 mm). Following this calculation scheme, the mean ear canal "acoustic length" for the 24 subjects was 23.8 mm, with a standard deviation of 2.1 mm. The ear canal lengths ranged from 20.1 mm to 27.6 mm. These results are generally representative of adult canal lengths reported by other investigators (e.g., Zemplenyi et al, 1985).

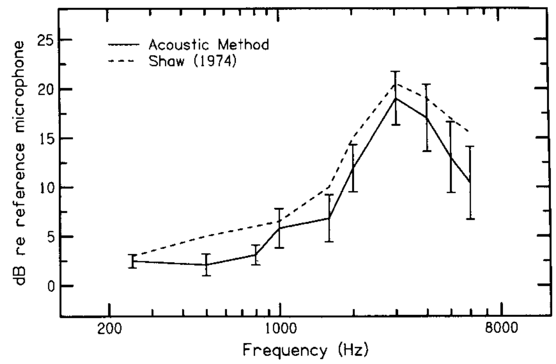


**Figure 2** Mean gain levels (in dB) re: the signal at the reference microphone (70 dB SPL) for 24 subjects using the acoustic method. Bars indicate ±1 standard deviation at selected test frequencies. The Shaw (1974) free field-to-eardrum transfer function at 45° azimuth is shown for comparison.

Figure 2 illustrates the means and standard deviations of the real-ear response at selected test frequencies obtained with the acoustic method. The results are shown in dB gain relative to the level of the soundfield signal at the reference microphone (70 dB SPL). The ear canal response follows the well-known shape of open ear canal characteristics; the response varies as a function of frequency with the peak observed near 3.0 kHz. The intersubject standard deviations, displayed as vertical lines in the figure, ranged from 0.4 dB at 0.25 kHz to 7.5 dB at 5.0 and 6.0 kHz. Similar variability was also observed with the constant insertion depth and earmold +5-mm methods. For comparison, Figure 2 also displays the free field-to-eardrum transfer function found in the classic results of Shaw (1974) for a loudspeaker located at an azimuth of 45°. The results obtained with the acoustic method were lower in amplitude than the Shaw data at most test frequencies. Comparable disparities between the Shaw transfer function and real-ear probe measurements have also been reported by Ickes et al (1991) and Fikret-Pasa and Revit (1992). The differences between the Shaw results and the data collected with the probe-microphone systems are related to the differences in the location of the reference microphone in each study. Shaw used a substitution method in which the reference microphone was located at the center of the head with the subject absent. In the current study and the comparable probe-microphone investigations, the reference microphone was located either on the head of the subject or on a KEMAR manikin just above the pinna. The differences between the Shaw data and the results in the

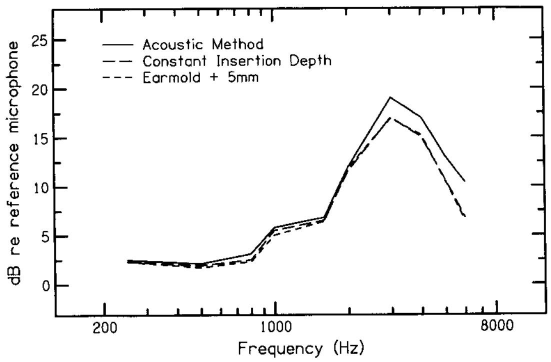


**Figure 3** Mean gain levels (in dB) re: the signal level at the probe microphone for 24 subjects for three experimental methods.

current investigation would be slightly larger than those shown in the figure at the high frequencies if the comparisons had been made to data obtained with the constant insertion depth or earmold +5-dB methods (the latter results are shown in Fig. 3).

There has been some interest among testers to compare a subject's individual real-ear unoccluded response to available average-ear data (such as the Shaw curve), and then estimate this difference to be the real-ear-to-coupler conversion for more accurate individual predictions of the desired hearing aid response. The data shown in Figure 2, along with the data provided from other comparable studies, suggest that the use of this calculation will lead to errors.

## Effects of Method and Frequency

In order to determine the influence of method on the probe-microphone response, a repeated measures analysis of variance (ANOVA) was performed on the real-ear SPL data obtained from the 24 subjects for each of the three methods across 30 test frequencies (responses included each 12th-octave interval from 1.0 kHz through 6.3 kHz). Responses below 1.0 kHz were not included in the analysis because the wavelengths of those frequencies are so long relative to even long ear canals that no differences could reasonably be expected regardless of probe location (see Fig. 3, Gilman and Dirks, 1986). The data from the two sessions were averaged because preliminary analysis indicated no significant trial effects.

The mean frequency response characteristics for the three experimental methods are displayed in Figure 3. A two-way ANOVA with repeated measures indicated significant effects both for method ($F [2,46] = 9.27$, $p < .001$) and frequency ($F [29,667] = 67.39$, $p < .0001$), as well as a significant interaction between method and frequency ($F [58,1334] = 4.03$, $p < .0001$). Post hoc analysis using Fisher's least significant difference (LSD) test indicated that a 1.03-dB difference between methods at a particular frequency was statistically significant. The figure shows that the acoustic method produced modest but significantly greater SPLs at all frequencies above 2.5 kHz than either the constant insertion depth or earmold +5-mm methods. The average response characteristics of the latter two methods are virtually identical throughout the frequency range tested.

## Effects of Ear Canal Length

Although the acoustic method produced significantly larger SPL output in the high test frequencies as compared to the other methods, the differences averaged across the major test frequencies (> 1 kHz) were modest (average difference = 2.1 dB). Additional inspection of the individual data did, however, suggest a strong bias in comparative results related to the acoustic length of the subjects' ear canals; larger response outputs were observed more consistently for subjects with long ear canals. In order to test for this effect, the subjects were rank ordered according to ear canal length and then divided arbitrarily into three equal groups with eight subjects per group. Subjects in the "long canal" group exhibited ear canal lengths ranging from 25.2 to 27.6 mm, the "medium canal" group encompassed a range from 22.0 to 24.8 mm, and the "short canal" group ranged from 20.1 to 21.4 mm.

Figure 4 illustrates the mean gain levels (re: the reference microphone) for each method as a function of ear canal length (upper panel = long canals, middle panel = medium canals, lower panel = short canals). A between-subjects, repeated measures ANOVA indicated a significant interaction between canal length, method, and frequency ($F[58,1218] = 1.81$, $p < .0001$). Specifically, greater SPLs were evident in the high frequencies, especially for subjects with the long ear canals. Post hoc analysis using Fisher's LSD test indicated that a difference of 1.02 dB or greater between methods was statistically significant ($p < .05$). As can be seen in Figure 4, the acoustic method produced significantly greater gain in the long canals at frequencies 3.0 kHz and higher. A smaller, but significant, increase in gain was observed in

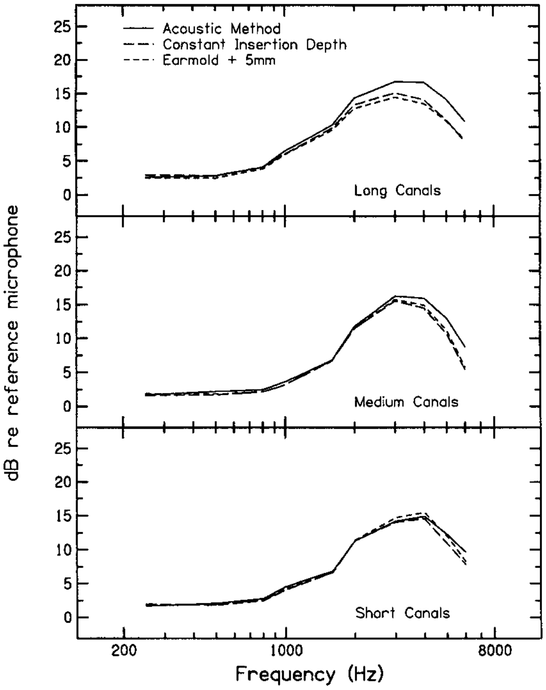


**Figure 4** Mean gain level (in dB) measured by the probe microphone for the three experimental methods for subjects grouped according to ear canal length: long canals (top panel), medium canals (middle panel), and short canals (bottom panel).

the medium canals at frequencies 4.0 kHz and higher for the acoustic method. There was virtually no difference in response curves between the three methods for subjects with the short ear canals.

## DISCUSSION

The general outcome of the current investigation indicates that the acoustic method results in modest but significantly greater real-ear SPL output for high-frequency signals (> 3.0 kHz) when compared to two commonly used clinical procedures. The acoustic method provides the advantage of accurate placement of the probe near the eardrum regardless of ear canal length. This precision may be especially desirable in research studies where the length of the ear canal is an important variable, particularly when the absolute measurement of SPL is critical. The method can, of course, be used for obtaining insertion gain with high precision because the probe can always be located near the eardrum where small variations in probe position between aided and unaided conditions have little effect on the gain measurement. This benefit, inherent in the acoustic method, may be particularly important when fitting completely-in-the-canal or peritympanic instruments where the hearing aid depth is often only 7 mm from the eardrum (Staab, 1994). In such instances, the probe would need to be extremely close to the eardrum to avoid the transition sound field for either insertion gain or absolute measurements of real-ear SPL. With the acoustic method, the probe could be consistently positioned within a few millimeters from the eardrum without fear of grazing it. Whether the probe tip can be located at a sufficient distance from the earmold duct with all deep-canal fittings requires further investigation and clinical experience.

Despite the advantages of the acoustic method, the improved accuracy of this method contrasted to that of the other clinical procedures is modest at best, and limited primarily to long ear canals and at high test frequencies. The constant insertion depth method will presumably remain the clinical technique for probe insertion both because of its simplicity and the generally equivalent results compared with the acoustic method in the low and mid frequencies for a majority of subjects. In fact, as long as the relative measurement of insertion gain continues to be the primary application of probe-microphone systems, each of the methods compared in this study can be used effectively as long as the probe remains in the same location for the open-ear and aided-ear measurements.

The acoustic method, although the most accurate of the three methods compared in this study, may also have several potential disadvantages for routine clinical use, at least in its current stage of development. First, the method is more time consuming than the other methods, principally because two additional acoustic measurements are required to estimate the distance of the probe relative to the eardrum before the response curve itself can be measured. Considering the rationale on which the acoustic method was based, it would be difficult to identify "short cuts" in the procedure and still maintain accuracy. On the other hand, the advantage of achieving more precise measurement of real-ear responses in a majority of patients might reasonably justify the additional time required to perform the procedure even in the clinical setting.

The second disadvantage of the acoustic method concerns the calculation scheme necessary for determining the probe distance from the eardrum. These calculations are complex and require that special software be developed for practical implementation. Fortunately, this development would essentially be a one-time expense.

The third disadvantage pertains to the requirement of a headband assemblage incorporating a micrometer for precise 1-mm step probe insertion. Although the Aurora system was equipped with this device, commercial probe units in present use do not employ a precision micrometer for probe insertion. Despite the fact that such a device would increase the cost of the test unit, the micrometer would permit small and known insertion changes to be made without the fear of possibly grazing the eardrum in short canals. The use of a micrometer would also be beneficial in those instances when the tester's hand may be unsteady or when the probe tube sticks to the tester's fingers and prohibits desired small changes in probe insertion depth. The extra benefits of flexibility and ease of probe insertion with a micrometer should be taken into consideration by manufacturers of probe-microphone systems, regardless of whether the acoustic method or one of the other clinical procedures is used.

In summary, results from this investigation indicate that the SPLs measured by the acoustic method were modest but significantly greater than those measured by the commonly used constant insertion depth and the earmold +5-mm clinical methods. This small magnitude of difference, however, was observed only in the high frequencies (> 3.0 kHz) in subjects with long ear canals. These findings apply to probe-microphone measurements where the position of the probe in the canal is vulnerable to standing waves. When specification of probe location in the canal and/or measurements of absolute SPL near the eardrum are necessary, however, the acoustic method is the only procedure of the three compared in this study that potentially provides both sets of information with high accuracy.

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