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SOUND LEVELS IN A 2-cc CAVITY, A ZWISLOCKI COUPLER, AND OCCLUDED EAR CANALS

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ABSTRACT

Probe-tube measurements of the differences in sound levels at three locations in ear canals were compared to the differences in levels measured at analogous positions in a Zwislocki coupler and a 2-cc cavity. The results support the recommendation of Sachs and Burkhard that probe tube measurements should not be made with the probe tube flush with the earmold tip and close to the sound inlet bore. In real ear canals the transfer functions to the eardrum presented by Bruel, Frederikson, and Rasmussen and by Studebaker agree well with each other but differ somewhat from the one used by Sachs and Burkhard. In agreement with Bruel et al., the data of this study reveal a plateau in the relationship between real ear and 2-cc cavity responses between about 1.6 and 4.0 kHz, the relative intensity level of which may depend upon residual ear canal volume.

In 1971, Zwislocki reported the development of a new coupler which could be used in measuring the electroacoustic performance of hearing aids. The impetus for developing a new coupler arose from general dissatisfaction with 2-cc couplers as a basis for predicting sound levels developed by hearing aids at the tympanic membrane.

Limited data exist regarding the extent to which the Zwislocki coupler predicts sound levels in real ear canals occluded by an earmold. Furthermore, consensus has not been reached on the magnitude by which 2-cc couplers underestimate the sound levels generated by hearing aid receivers in ear canals or how the magnitude of the difference varies with frequency.

Efforts to establish the relationship between sound levels in acoustic couplers and in ear canals at the tympanic membrane must involve consideration of the relationship between the sound pressure level (SPL) observed at the measurement location in the ear canal and that developed at the eardrum. There are two conditions wherein sound levels are not equal across couplers and/or ear canals which are of particular concern in this study. First, the SPL at any two points in a space such as an ear canal or a coupler differs whenever the distance between the two points becomes an appreciable fraction of a wavelength. The SPL difference is greatest when the distance between the two points is equal to a one-quarter wavelength. Second, when the probe-tube tip of the measurement system and the tip of the sound-inlet tube are placed close together, significant perturbations may occur in the apparent frequency response (Ingard, 1948; Sachs and Burkhard, 1971). According to Sachs and Burkhard (1971), the frequency region and magnitude of these perturbations depend on such factors as the size of the tubes, the distance between the tubes, and the acoustic character of the space in which the observations are made. In the situation where the probe tube and the sound-inlet tube both terminate at the end of an earmold and where the observation is made in a 2-cc cavity, the effect takes the form of a notch in the frequency region above 3 kHz.

The purpose of this study was to evaluate the extent to which sound levels generated by a hearing aid receiver-earmold combination in a Zwislocki coupler and a 2-cc cavity simulate the sound levels generated at the eardrum in the occluded ear. A second purpose was to determine the extent to which measurements made at two commonly used positions differ from those at the coupler microphones and at the eardrum. Measurements were made in ear canals and couplers

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with the probe tube tip terminated flush with the earmold tip and with it placed 5 mm beyond the earmold tip. Measurements were also made at a point very near the coupler microphone in each coupler. Real ear transfer functions from the midcanal position to the eardrum from three studies were compared. One of these was used to correct the 5-mm data from this study to eardrum pressure levels. Measurements were confined to the high frequencies because the measurement techniques were time consuming and because the effects of interest in this study, specified above, influence that frequency region.

Method

In order to study the pressure distribution in the two couplers and the ear canals, probe-tube measurements were made at three locations in the couplers and at two locations in the ear canals. One set of measurements was made with the probe tip flush with the earmold tip and adjacent to the sound-inlet tube (the 0-mm position) in the manner used by a number of previous investigators (Nichols et al., 1945; Studebaker and Zachman, 1970; Lybarger, 1966). A second set of measurements was made with the probe tip extended 5 mm beyond the earmold tip and sound-inlet bore in the manner suggested by Sachs and Burkhard (1971). These two sets of measurements were made in both couplers and ear canals.

A third set of measurements was made in the couplers with the probe tip located 1 mm from the respective coupler microphones (the coupler bottom position). An effort to derive analogous measurements in the ear canal (i.e., within 1 mm of the eardrum) in the present study was not successful but was subsequently accomplished by Studebaker (1974), using methods and probe tubes very similar to those used in the present study. For these reasons and because, as will be shown, the data of interest from the two studies produced similar results, the results of that study will be used to assist in the evaluation of the results of the present study.

Subjects. The right and left ears of eight male, normal-hearing subjects between the ages of 22 and 30 years were used. Each subject had pure-tone, air-conduction thresholds no poorer than 10 dB (ANSI, 1969). Bone-conduction thresholds were within 10 dB of the air-conduction thresholds for the octave frequencies from 0.25 to 4 kHz. Each subject was free from external and middle ear pathology as determined by an otological evaluation and by testing with an electroacoustic impedance bridge.

Earmolds. Impressions were made of the right and left ears of each subject. Earmolds were fabricated from the impressions by an earmold laboratory. Each earmold accommodated a 25-mm length of Tygon sound-inlet tubing with an inside diameter of 2 mm.

A bore for the probe tube was drilled in each of the earmolds parallel to the bore which housed the sound-inlet tube. The orifice of this bore terminated adjacent to and on a plane with that of the sound-inlet orifice. The distance between the center of the sound-inlet orifice and the center of the probe-tube orifice was 3 mm.

Probe-Tube System. Probe-tubes used in this investigation were formed from a malleable, heat-shrinkable polyolefin tubing. A stainless steel tube with an outside diameter of 1 mm was inserted inside a length of the heat-shrinkable tubing. Heat was then applied. After shrinking, the metal tube was removed. The result was a fairly rigid but flexible tubing with an outside diameter of about 2 mm and an inside diameter of 1 mm. The frequency response of the probe-tube system was checked four times during the course of the investigation. Through a series of measurements it was determined that the presence of the probe tube or its location in the cavity had no practical effect upon the SPL measured at the coupler microphone diaphragms under any of the measurement conditions which followed. It was also determined that signal transmission through the walls of the probe tube had no significant effect on the measurement under any of the conditions used.

Signal Generation. The output of a beat-frequency oscillator was directed to a high quality 1-dB step attenuator. The output of the attenuator was directed through an isolation pad to a power amplifier. The output of the amplifier (across which was paralleled an 8-ohm, 100-watt resistor) was directed to a Bruel and Kjaer (B & K) button type earphone (type HT 0003). The earphone's electrical input impedance was measured as being 980 ohms at 1.0 kHz.

The sound-inlet tubing in each earmold was connected to the system by means of a plastic adaptor which accommodated the nubbin of the earphone.

Measurement System. The 3- × 18-mm bore of the standard HA-2 coupler was replaced in this study by the earmolds themselves which were placed directly on a 2-cc cavity machined to the exact specifications of the HA-2 cavity by the University of Oklahoma's Instrument Shop.

An "ear-like" coupler was also manufactured by the Instrument Shop for this investigation according to specifications reported by Zwislocki (1971). After its manufacture, it was sent to Dr. Zwislocki's laboratory for evaluation. It was reported to have met design specifications in all respects.[1]

For the measurement of sound levels through the earmolds at the three measurement positions in the couplers and at the two measurement positions in the ear canals, a probe tube was inserted into the 2-mm probe-tube adapter of the B & K assembly which was used with a B & K type 4132 ½-inch microphone and cathode follower. SPLs were observed using a B & K type 2603 microphone amplifier and a Hewlett-Packard model 302 wave analyzer.

For the ear canal measurements, an apparatus was

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[1] B. Klock, personal communication, 1972.

constructed to secure the subject's head firmly. The basic support structure was a dental chair, modified so that the headrest butted against the side of the subject's head. An adjustable rubber headband was fastened to the headrest in order to fix the subject's head in position. An adjustable clamp assembly was attached to the headrest side of the apparatus in order to hold the cathode follower and microphone assembly securely.

Measurements in the Couplers. The receiver-earmold combinations were mounted on the 2-cc cavity and on the Zwislocki coupler and were sealed using a silicone putty. Measurements were made for 15 discrete frequencies in the range from 0.8 to 6.4 kHz from the probe-tube microphone with the probe-tube tip placed at each of three positions (0 and 5 mm from the earmold tip and 1 mm from the coupler bottom) in each coupler.

Sixteen earmolds were used in this portion of the study. The voltage to the input terminals of the receiver was adjusted to that which produced 100 dB SPL at 0.8 kHz in the 2-cc cavity by the receiver when coupled to a single particular earmold. All subsequent coupler measurements were made with the same voltage across the terminals of the receiver.

Measurements in the Ear Canals. Each earmold was seated in the subject's ear canal and sealed with petroleum jelly. For each measurement, the same voltage appeared across the input terminals of the hearing aid receiver. Measurements were made in ear canals for the same 15 frequencies in the range from 0.8 to 6.4 kHz at the 0- and the 5-mm positions in the right ears of four subjects and in the left ears of four subjects.

Results

The mean sound levels resulting from probe-tube measurements at the 0-, 5-mm, and coupler bottom positions in the two couplers are shown in Figures 1 and 2. The data obtained in the real ears are shown in Figure 3. The data plotted in these figures are the differences between the levels recorded by the probe tube at the 5-mm position (reference line) and those observed at the 0-mm and coupler bottom positions.

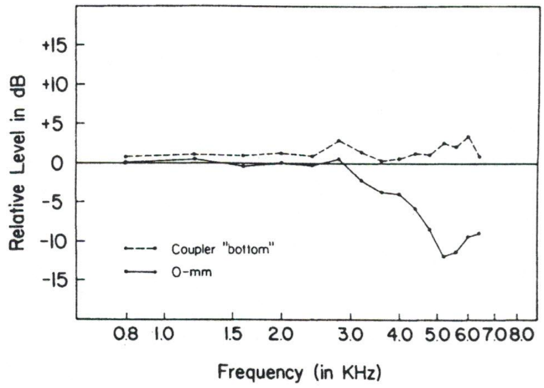

Fig. 1. Pressure levels measured at the 0-mm and coupler bottom probe positions plotted in relation to the levels observed at the 5-mm probe position in a 2-cc cavity.

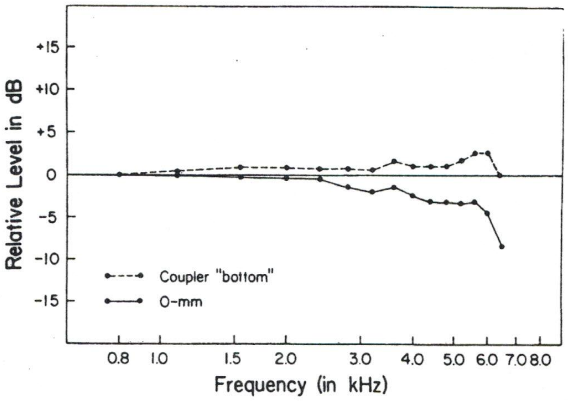

Fig. 2. Pressure levels measured at the 0-mm and coupler bottom probe positions plotted in relation to the levels observed at the 5-mm probe position in a Zwislocki coupler.

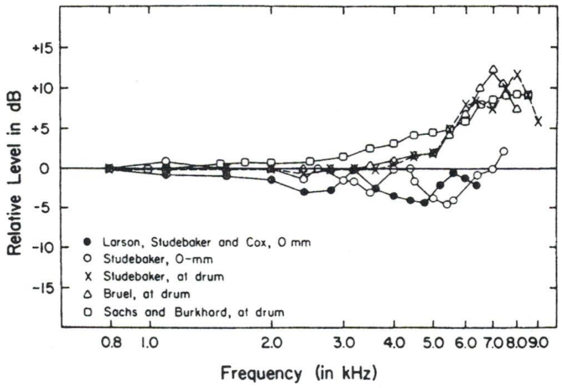

Fig. 3. Pressure levels measured at the 0-mm probe position plotted in relation to the levels observed at the 5-mm probe position in ear canals in two studies, and the difference between the pressure levels observed at the 5-mm probe position and at the eardrum by Studebaker (1974). Also shown are the ear canal transfer functions derived by Sachs and Burkhard (1972) and reported by Bruel et al. (1976).

Coupler Results. The data presented in Figures 1 and 2 show that sound levels observed in both couplers at positions proximal to the sound-inlet bore are lower than sound levels measured at the 5-mm position. Levels observed at the coupler bottom position are slightly higher (mean difference < 1.5 dB). In Figure 1, which shows the results from the 2-cc cavity, only very small differences are seen among the sound levels measured at the three positions up to 2.8 kHz. Above 2.8 kHz the results from the 0-mm position dropped sharply reaching values 10–12 dB lower than at the 5-mm position in the frequency range from 4.4 to 6.4 kHz.

Figure 2 shows the relative levels at the same three measurement locations in the Zwislocki coupler. Again, through 2.8 kHz the levels recorded at the three positions are similar. The levels recorded at the coupler bottom position are about 1 dB above those recorded at the 5-mm position through 4.8 kHz. The differences between the 0- and 5-mm results are not as large as those observed in the 2-cc cavity. Nevertheless, the levels recorded at the 0-mm position are increasingly discrepant from the levels measured at the 5-mm position above 2.4 kHz, and decrease 3.5 dB between 4.4 and 5.6 kHz before dropping sharply to 9 dB down at 6.4 kHz.

Real Ear Results. Figure 3 shows data which provide comparison of pressure levels observed in real ear canals. The 0-mm data obtained in this investigation are shown to fall below the 5-mm data (the reference line).

Also shown in the figure are two sets of data derived from the previously unpublished data first presented by Studebaker in 1974.[2] The first set of data (plotted as the *open circles*) are the results obtained by Studebaker at the 0-mm position relative to those obtained at his 5-mm position. The similarity between the overall patterns and the direction and extent of the differences between the 0- and 5-mm conditions in the two studies is apparent, even though the pattern seems to have been shifted to a somewhat higher frequency in the Studebaker study. Considering that many factors can affect measurements of this type and that the measurements were made at different times and places with different subjects by different investigators, the agreement seems quite good. For this reason it was felt justifiable to combine the results from these studies as a basis for the discussion which follows.

Studebaker's second set of data (the ×'s plotted above the reference line in Figure 3) shows the difference between the pressure levels measured at the 5-mm position and those measured within approximately 1 mm of the eardrum. Virtually no difference in the data between these positions was observed up to about 4.9 kHz. Above this frequency the level at the eardrum in relation to that at 5 mm rises slowly at first, and then more rapidly, finally reaching a peak at 8.0 kHz.

Two other sets of data are shown in Figure 3. These are transfer functions which have been used to represent the difference in levels at the eardrum and at measurement points approximately midway along the length of the ear canal. One was used by Sachs and Burkhard (1972) and the other was reported by Bruel et al. (1976). These curves will be referred to in the "Discussion" section.

Variability. The inter-earmold standard deviations for the coupler measurements in this study were never greater than 2.5 dB at any frequency and were generally 1.25 dB or less. The inter-subject standard deviations associated with the real ear data ranged from 2.0 to 7.5 dB and were generally 6.5 dB or smaller. They were about the same magnitude for both 0- and 5-mm positions and were larger above 2.4 kHz than below that frequency. The observed variability was similar in magnitude to that observed in one other investigation (Zachman, 1969); somewhat larger than that observed by Sachs and Burkhard (who observed standard deviations up to 5.0 dB); and considerably larger than that observed by McDonald (1970) who did not observe standard deviations in excess of 3.5 dB.

Discussion

Coupler Results. Sachs and Burkhard (1971) studied the effect of position of the probe tube in relation to the sound-inlet tube on measurements made in hard-walled cavities. The data obtained at the 0-mm position in the 2-cc cavity in this investigation and reported in Figure 1 are very similar to their results. Sachs and Burkhard explained the result at the 0-mm position on the basis of an extension of Ingard's (1948) theory of the radiation of sound in cylindrical cavities. For low frequencies, they reasoned, the reactance of a cavity is negative. However, at positions near the sound-inlet tube there is a positive reactance (or inertance). It follows, as they point out, that the total transfer reactance for particular frequencies will be zero at particular locations in the cavity. At that frequency, the sound pressure level developed will be substantially lower. As measurements are made at points farther away from the sound-inlet tube, the affected frequency increases. The data obtained in the 2-cc cavity in this investigation are supportive of Sach's and Burkhard's observations on the form and extent of this artifact.

Perturbations observed in the Zwislocki coupler under these same conditions differ some-

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[2] The original data were in the form of sweep frequency tracings from each ear of five subjects at the 0- and 5-mm positions and from each of three subjects at the "at drum" position. The at drum position was estimated to be approximately 1 mm from the eardrum.

what from those observed in the 2-cc cavity. As Sachs and Burkhard point out, the affected frequency is governed by several geometric parameters, the most important of which is the ratio of cavity diameter to cavity length. For this reason, the affected frequency region will change even with identical sound-inlet tube and probe-tube locations and relationship if the cavities are of dissimilar size or configuration. The data reported in Figure 2 suggest that the affected frequency for the Zwislocki coupler was higher than in the 2-cc cavity and was probably above the uppermost frequency observed in this investigation. A second, possibly significant factor, is that although the 2-cc cavity is purely a reactive device, the acoustic load offered by the Zwislocki coupler is both reactive and resistive. Therefore, when the positive and negative reactances cancel at some point in the space of the cavity the sound level will not decrease as much because of the sound pressure developed across the residual resistive component of the acoustic impedance.

The differences observed between the 0- and 5-mm measurement positions in the real ear canals (Fig. 3) were smaller but more irregular than seen in either coupler. The differences never exceeded 5 dB and, with few exceptions, generally did not exceed 3 dB. The increased irregularity may result, in part, from the considerably greater variability of the data upon which these means are based and/or upon the relatively complex acoustical conditions in the real ear canal. Whether such magnitudes have practical significance may depend upon the application to which the data are put. Nevertheless, because such effects are easily avoided, it seems a prudent policy to advance the probe-tube tip some 5 mm beyond the termination of the sound-inlet tube when making measurements in ear canals or couplers as Sachs and Burkhard suggested.

Also shown in Figures 1 and 2 is a small consistent difference between the results measured at the 5-mm position and the position 1 mm from the coupler microphones. The effect, which is generally 1 dB or smaller with a tendency to get somewhat larger in the high frequencies reaching up to 2.5 to 3.0 dB above 5.0 kHz, is probably an artifact produced largely as a result of placing the probe tip 1 mm from the vibrating microphone diaphragm. Under this circumstance, the diaphragm acts as a nearby signal source. The magnitude of the observed effect and its general increase with frequency suggest that a local area of slightly higher impedance has been created between the probe tip and microphone diaphragm at this distance of separation, thereby increasing slightly the pressure level at the tip of the probe tube. An additional factor possibly contributing to the difference in the 2-cc cavity was suggested by Sachs.[3] Owing to the spreading inertance around the sound-inlet bore, as discussed above, the probe-tube microphone at the 5-mm position will measure 0.4–1.1 dB less than the coupler microphone in the 2-cc coupler at frequencies above 4.0 kHz. No differences will be observed at that position in the Zwislocki coupler or at lower frequencies in either coupler. It was concluded that these effects can be ignored and that the levels at the 5-mm position in the couplers are for all practical purposes equal to those measured using the coupler microphone.

Ear Canal Results. In order that the results of various studies using somewhat different techniques can be compared, and so that these results can be compared to the results obtained in couplers, it is desirable to express all results as "eardrum" sound pressure levels. However, in order to derive eardrum sound pressures it is necessary to know the differences in level between the particular observation position used and the eardrum position as a function of frequency. Plotted above the 5-mm reference line in Figure 3 are data representing the differences between the levels observed at the 5-mm position and at a position about 1 mm from the eardrum by Studebaker (1974). He concluded that there were no practical differences between the levels at the two positions up to 4.5 kHz. Above that frequency the difference increases more and more rapidly reaching a peak at 8.0 kHz.

Also included in Figure 3 are the analogous values reported in two other investigations (Sachs and Burkhard, 1972; Bruel et al., 1976). Agreement between the Bruel et al. results and those of Studebaker are excellent except for the resonant frequency value. However, this difference is minor and can be explained by a difference in the measurement position in the ear canal of only about 1.5 mm. Sachs and Burkhard (1972) did not actually measure this difference but noted a notch in their 5-mm data at 8 kHz. On this basis they concluded that the differences between the levels at their measurement position and those at the eardrum, had they been measured, would have peaked at 8.0 kHz.[4]

[3] R. Sachs, personal communication, 1973.

[4] The difference in SPL between the measurement location and the eardrum will reach a maximum when the

The transfer function used by Sachs and Burkhard (reported in Fig. 3) was derived from the function reported by Zwislocki (1970) for the midear canal-eardrum level differences observed in open ear canals. The Zwislocki function peaked at 7.0 kHz, whereas Sachs and Burkhard observed a notch at 8.0 kHz. Therefore, they adjusted the Zwislocki values upward to compensate for the difference in apparent measurement location (i.e., the data indicate that Sachs and Burkhard made their measurements approximately 1.5 mm closer to the eardrum than did Zwislocki or Bruel et al., and at about the same distance from the eardrum as Studebaker).

There are several small, but possibly significant, differences between the Sachs and Burkhard and the Bruel et al. and Studebaker results. These are that the transfer function used by Sachs and Burkhard (and built into the Zwislocki coupler) begins at a lower frequency, it is several dB greater from 3.0 to 5.0 kHz, and it rises into a less sharp peak at the resonant frequency. Although these differences are small in magnitude they may be of theoretical importance. They will be discussed further in the next section.

Coupler and Ear Canal Comparisons. Many comparisons have been made between results obtained in real ear canals and in 2-cc couplers or cavities (Nichols et al., 1945; Wiener and Filler, 1945; Lybarger, 1966; Studebaker, 1974; Sachs and Burkhard, 1972; Bruel et al., 1976) and between real ears and Zwislocki couplers (Sachs and Burkhard, 1972; Lybarger, 1975; Bruel et al., 1976). The present study provides additional data on these relationships. Figure 4 presents the differences observed in this study between the results observed at the coupler microphone of the 2-cc cavity and the levels observed at the 5-mm position in the ear canals (corrected for probe-tube response). Also included in the figure are the analogous data for the same test position reported by Sachs and Burkhard (1972). Both sets of data are uncorrected for the transfer function to the eardrum. (Because the present study was concerned only with the high frequencies, only that portion of the data of Sachs and Burkhard is reproduced here.) The excellent agreement between the results of this study and those of Sachs and Burkhard from 1.6 kHz upward is evident. The agreement at the lower frequencies is not good although support can be found in the literature for the results of either study.

Bruel (undated) has characterized the relationship between 2-cc coupler and real ear results as consisting principally of two plateaus. He reasoned that, given a high impedance source with particular volume velocity output, the SPL of low frequency signals in the ear canal is determined by the residual ear canal volume plus the equivalent volume of the eardrum. Above this frequency the eardrum becomes mass controlled and the level of the signal in the ear canal is determined principally by the residual ear canal volume. By converting the observed pressure level changes (in dB) into volume ratios it is possible to derive absolute equivalent volumes for the ear canal (from the level of the upper plateau) for the eardrum (from the difference between the levels at the upper and lower plateaus) and the total volume equivalent of the canal and eardrum together (from the pressure level at the lower frequencies).

The data of this study, that of McDonald and

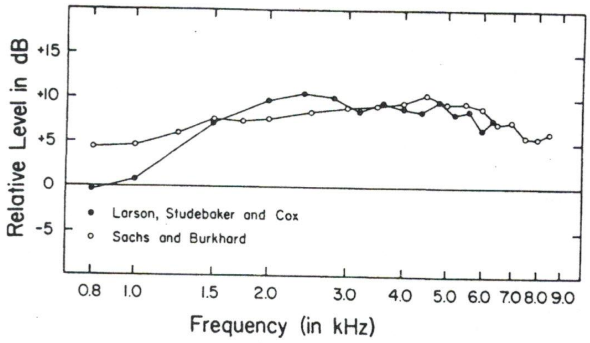

Fig. 4. Pressure levels observed at the 5-mm probe position in ear canals plotted relative to the levels observed at the microphone of a 2-cc cavity in this study and those observed by Sachs and Burkhard (1972).

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measurement location is one-quarter wavelength from the eardrum. Observation of a pressure minimum at some particular frequency means that the observation point is then one-quarter wavelength from the reflection surface. Moving the observation point closer increases the frequency at which the minimum is observed. Assuming the speed of sound in the ear canal to be 352 m/sec, a pressure minimum at 8.0 kHz indicates that the measurement position was 11 mm from the eardrum, a very reasonable value. Such quarter-wavelength resonances are not seen in the couplers because at the 5-mm position the probe-tubes were closer to the coupler microphones (about 7.9 mm in the Zwislocki coupler and 3.0 mm in the 2-cc cavity). For this reason, measurements made in real ears must be adjusted by the transfer function in order to obtain levels which are comparable to measurements made from coupler microphones which are already analogous to eardrum pressure levels. Probe microphone results measured in couplers would require correction for this factor if the frequency of the test signal was made very high.

Studebaker (1970), Lybarger (1975), Nichols et al. (1945), and the uncorrected data of Sachs and Burkhard (1972) (shown in Fig. 4), all appear to support the existence of a pressure level plateau between about 1.5 and 4.0 kHz. However, a transfer function correcting the results to eardrum sound pressure levels must be applied to the data before a conclusion can be reached. The transfer function derived and used by Sachs and Burkhard tends to obscure the appearance of an upper frequency plateau because of the relatively larger correction values from about 2.0 to 4.0 kHz and contributes to the conclusion that the relationship between real ear and the 2-cc cavity pressure levels rises monotonically as a function of frequency above 1.0 kHz (see Lybarger, 1975). Application of the directly measured transfer function of Studebaker (which is supported by the Bruel et al. data) tends to preserve the appearance of a plateau in the frequency region from 1.6 to 4.0 kHz. It is for this reason that the exact shape of the transfer function in the real ear occluded by an earmold takes on some theoretical importance.

Presented in Figure 5 are the following data: the differences between the 2-cc cavity results and the ear canal results measured at the 5-mm position (from Fig. 4) observed in this study and corrected by the Studebaker transfer function; the Sachs and Burkhard (1972) data, also from Figure 4, corrected by the Studebaker transfer function; and the Bruel et al. (1976) idealized curve corrected by their transfer function (their values must be used to correct their data to eardrum pressure levels because of the somewhat different measurement location they used). Finally, the figure shows the differences between the levels observed in the 2-cc cavity and the Zwislocki coupler used in this study as observed from the respective coupler microphones. The differences in levels observed in the two couplers are very similar to those observed by Sachs and Burkhard (1972) and by Lybarger (1975) (mean difference < 1.3 dB never exceeding 3 dB), indicating the adequacy of the Zwislocki coupler used in this study. In spite of differences, the overall similarity of the configuration of the various curves in Figure 5 is evident. The data appear to support a relatively constant level relationship (plateau) between real ear and 2-cc cavity results in the 1.6–4.0 kHz region.

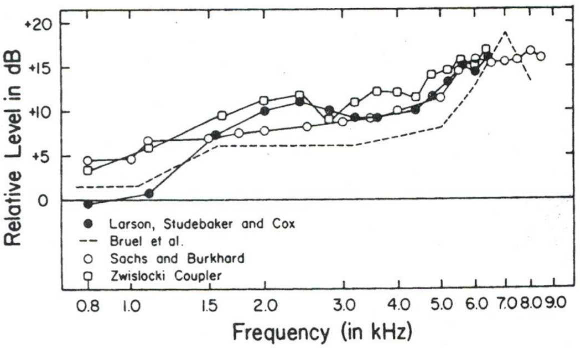

Fig. 5. Pressure levels measured at a midear canal position corrected to eardrum pressure levels through the application of transfer functions. All data are plotted relative to results observed at the microphone of a 2-cc cavity. The data of this study and of Sachs and Burkhard are corrected by the Studebaker (1974) transfer function.

One justifiable adjustment improves the quantitative similarity of the curves shown in Figure 5 as well. Bruel et al. (1976) noted that the total enclosed volume (residual ear canal volume plus eardrum equivalent volume) for their two subjects equaled 1.72 cc. The two subjects were 55–60 years of age and were probably both males. By contrast the subjects used by Sachs and Burkhard (1972) were made up of nearly equal numbers of males and females and were generally younger (mean age about 36 years). The total enclosed volume observed by Sachs and Burkhard was 1.2 cc, a rather small value. Nevertheless, if it is assumed that the ear canals of the Bruel et al. subjects were somewhat larger than a more representative sample by as little as 0.2–0.3 cc, the differences between the Bruel et al. results and those of the others and the Zwislocki coupler-2-cc coupler difference shown in Figure 5 virtually disappear. (Such a reduction in ear canal residual volume would cause the Bruel et al. results to be about 1.4 dB higher at the low frequencies and about 2.5 dB higher at the high frequencies.) On the basis of this evaluation it was concluded that the pressure level at the eardrum of the frequencies from about 1.5 kHz upward can be predicted with reasonable confidence from the results shown in Figure 5, assuming that the residual ear canal volumes fall in the approximate range of from 0.6 to 1.0 cc. Unfortunately, the situation in the lower frequencies remains less certain.

The data obtained in the lower frequencies in this study appear to agree fairly well with Bruel et al. (1976) and with certain earlier studies (Nichols et al., 1945; Lybarger, 1966) and seem to suggest relatively large total ear canal-eardrum volumes for the subjects used in these studies. However, the high pressure levels observed at the high frequencies seem to rule out large residual ear canal volumes in this and some of the earlier studies. The relatively low pressure level, low frequency results seen in these studies cannot be attributed to the low impedance signal sources and probe tubes they used because this would have the effect of reducing the apparent level difference between the upper and lower frequency plateaus, not increasing it as seen here. Finally, it is not possible to attribute the relatively large pressure level differences between upper and lower plateaus to large eardrum equivalent volumes in the subjects used in these studies because unreasonably large equivalent volumes would be required. A review of the techniques used in this and other investigations suggests unintentional leaks around the earmold in spite of such precautions as sealing the earmolds in the ear canals with petroleum jelly or similar substances, as the cause of the low frequency results of this and other studies. In support of this hypothesis is the fact that a common feature of those studies (Sachs and Burkhard, 1972; McDonald and Studebaker, 1970; Bruel et al., 1976), which did not observe reduced low frequency levels, is that they all used head-borne measurement equipment. The implication is that the other arrangements which support the equipment on stands, clamps, or chair backs, result in significant acoustic leaks with at least some subjects at least some of the time, no matter how carefully the earmold is coated or how rigidly the head is clamped. However, this does not mean that such data are entirely invalid. Earmolds as normally worn are leaky to varying degrees and, as such, these data may bear a closer relationship to results achieved in actual use than those obtained in a tightly sealed condition. An analysis of this factor, of how it may have affected published data in this area, of the effects of earmold modifications, and of how acoustic leaks may influence the electroacoustic performance of hearing aids under normal use conditions is the subject of a forthcoming paper.

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