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Earmold Modification Effect Measured by Coupler, Threshold and Probe Techniques[1]

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Abstract. The validity of probe tube microphone measurements in providing data indicative of the magnitude of the change in subjects' thresholds resulting from changes in earmold configuration was investigated. The relationship between these measures in the real ear canal and the changes observed in 2-cm^3 and Zwislocki couplers under similar circumstances of earmold modification was also measured. Standard, vented and 'open' earmold conditions were utilized. Threshold and probe-tube measurements were made. Statistical evaluation revealed that these two techniques did not produce significantly different results except at 125–165 Hz, where noise masking may have been a factor influencing the threshold data. Neither coupler as used gave an accurate quantitative estimate of the in-use effects of vented earmolds or the open earmold configuration, but the Zwislocki coupler gave a better approximation than the 2-cm^3 coupler.

Many investigations have compared sound level measurements made in real ears with measurements made in metal couplers. A major finding of these studies is that measurements made in 2-cm^3 couplers, while useful for exchange of information, do not yield results which are accurate representations of a hearing aid's output when it is working into a real ear canal. WIENER and FILLER [1945], using a probe tube microphone measurement technique measured the frequency response curves of several insert receivers

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and supra-aural earphones on real ears and compared these data with corresponding frequency response curves obtained on 2- or 6-cm^3 metal couplers. Their results revealed, (1) that resonances which are prominent in coupler measurements are greatly reduced in size or even absent when the same receiver is attached to a real ear, (2) that the frequency location of a vent-related resonance may vary somewhat between coupler and real ear and from individual to individual, and (3) that real ears often exhibit leakage effects which result in the loss of low-frequency energy and sometimes in mid-frequency resonances compared to coupler frequency responses. Similar data showing differences between coupler and real-ear responses of hearing aids or earphones have been reported by BURKHARD and CORLISS [1954] and VAN EYSBERGEN and GROEN [1959] among others.

More recently, a number of similar studies have been carried out with the purpose of assessing the effects of earmold modifications on the frequency response of hearing aids on real ears and couplers. Two different measurement methods have been used to obtain the real-ear data: probe tube microphone sound level measurements and psychoacoustic measurements of either auditory threshold or loudness level. The probe tube microphone measurement technique, for example, was used by EWERTSEN *et al.* [1957], STUDEBAKER and ZACHMAN [1970], and MACDONALD and STUDEBAKER [1970]. These investigations all reported effects of changes in earmold structure on sound levels in the ear canal as a function of frequency. Psychoacoustic measurements (threshold or loudness level) have also been used to assess effects of earmold modifications in real ears by investigators such as GREEN and ROSS [1968], WEATHERTON and GOETZINGER [1971], JACOBSEN *et al.* [1972], and COOPER and O'MALLEY [1975].

Whether these two methods of real ear measurement yield equivalent data has not been assessed. Two of the investigations cited above [STUDEBAKER and ZACHMAN, 1970; COOPER and O'MALLEY, 1975], each using a different method of real-ear measurement, compared the obtained real-ear data with measurements made in 2-cm^3 couplers. The results of these two studies are similar in certain respects. For example, both studies found that vent effects measured in a metal coupler have steeper low-frequency slopes and more prominent vent-associated resonances than when measured on real ears. On the other hand, the results of the two studies are by no means completely consistent. Since both investigations were concerned with the assessment of the effects of earmold vents in real ears relative to the same effects in a standard coupler, one might anticipate that the data should be more similar across studies than they appear to be.

A few studies in related areas are relevant to a discussion of the equivalency of these two measurement methods. SHAW [1966] reported probe microphone measurements of sound pressure level at the ear canal entrance at threshold under four different earphone/cushion combinations which indicated that, at a given frequency, the sound pressure levels at threshold almost all fall within a range of 4 dB with all earphones and cushions. This result suggests that a threshold level tone at a given frequency occurs at a sound pressure level at the eardrum which is fixed for each individual (within limits set by the test-retest variability). HARRIS [1973], however, reported data which supported his contention that a constant sound pressure level at a given frequency when produced by different earphones, does not necessarily yield sensations of equal loudness. WIENER and FILLER [1945] compared earphone frequency response curves derived using a loudness balance technique with probe microphone measurements of the frequency response curve of the same earphone made at the ear canal entrance. They expected that the sound pressure at the eardrum should be equal for the two measurement methods. However, they found that the 'differences exceed(ed) the expected experimental inaccuracies'. The results of these studies are equivocal regarding the relationship between the data from probe tube microphony in the external ear and psychoacoustic measurements derived from responses of the subject whose ear is serving as the termination cavity.

Purpose of the Study

An investigation was performed in which both probe tube microphony and threshold measurement methods were used to obtain real-ear data on the same subjects. The purpose was to describe the relationship between sound level changes measured with a probe tube microphone in the ear canal and concomitant changes in threshold which occur when standard earmolds are replaced by vented or open earmolds.

The effects of these same earmold modifications were measured using a Zwislocki coupler [ZWISLOCKI, 1970] and a 2-cm^3 cavity in place of the real ear canals. The Zwislocki coupler has been shown to simulate the behavior of real ears more closely than does the 2-cm^3 coupler cavity when a standard unvented earmold is used [SACHS and BURKHARD, 1972; LYBARGER, 1975]. Thus, a further goal of this study was to evaluate the extent to which the Zwislocki coupler simulates real-ear performance for purposes of evaluating the effects of modified earmolds.

Materials and Methods

Subjects. 11 subjects served in the vented-earmold portion of the study; 7 subjects served in the open-earmold portion. Only one ear of each subject was used since, as BURKHARD and CORLISS [1954] have shown, the two ears of a single individual tend to be a 'matched pair'.

All subjects appeared to have normal hearing. However, since each subject served as his own control, possession of normal hearing was not a requirement for subjects. The only criterion used in the selection of subjects was that they have an ear canal large enough to accommodate an earmold which could be modified in the way required by the investigation (this criterion did not necessitate particularly large ear canals.)

Earmolds. The earmolds were made by two of the authors. For subjects serving in the vented-earmold part of the study, a single earmold was made. A sound input bore was drilled through the earmold with a side-branch vent entering this bore. The length of the vents ranged from 4.1 to 7.6 mm. In addition, a bore was drilled through each earmold to accommodate the probe microphone tube (fig. 1).

For subjects serving in the open-earmold part of the study, two identical earmold impressions were taken. One impression was worked into a standard (unvented) earmold with sound input bore and probe tube bore diameters the same as for the side-branch-vented mold. The other impression was so constructed that the sound input tube bore was located as close as possible to the superior wall of the canal and the probe tube bore was located as close as possible to the inferior wall of the canal. The space between these two tubes was then evacuated as completely as possible leaving only enough earmold material to hold the input and probe microphone tubes. This earmold is referred to as the 'open' earmold (fig. 1).

Psychoacoustic thresholds. The subjects were seated in a sound-treated room (Industrial Acoustics Company, 1200 series). The signal was introduced to the ear canal via an Audivox (Western Electric) 9c receiver. The receiver was coupled to the sound input tube of the earmold by an input tube the length of which was held constant across conditions for a given subject, but which varied a few millimeters across subjects. The test signal was a sweep-frequency pulsed pure tone generated by the Grason-Stadler E800 'Békésy' audiometer modified to give constant voltage output as a function of frequency at any given pen (attenuator) position. Subjects traced their thresholds in the conventional manner from 100 to 10 000 Hz. The probe tube microphone was kept in place during the threshold measurements.

When the effect of the side-branch vent was being investigated, the same earmold served for both standard (unvented) and vented conditions. The threshold was first traced with the vent open (vented condition). Then the vent was plugged at its lateral end and the threshold was retraced with the earmold thus transformed into a standard (unvented) mold (standard condition). Plugging a side-branch vent at its lateral, rather than its medial end, introduces a resonance into the 'standard' mold transmission characteristic. However, under the conditions of this study, this resonance occurred well above the frequency region of interest. This procedure was adopted because it permitted all the data to be collected in vented and standard (unvented) conditions for a given ear without removal of the earmold. Each subject was given 30 s of practice in tracing his/her 'Békésy' threshold before data collection was begun.

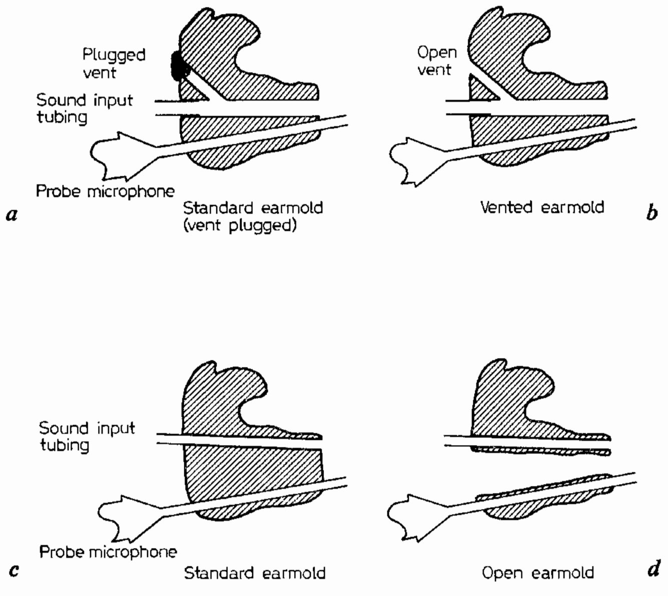


Fig. 1. Cross-sectional drawings of earmolds made for subjects in the vented-earmold part of the study (a, b) and in the open-earmold part of the study (c, d).

When the effect of the open mold was being investigated, separate earmolds were used for the standard and open conditions as described above. Threshold tracings were obtained as described for the vented earmold.

Probe microphone measurements. For all measurems, theent probe tube was extended through the earmold to a depth of 3–5 mm beyond the earmold tip. The probe tube conducted the signal in the ear canal to a Brüel & Kjaer 1.3-cm pressure microphone. After passing through a high-pass filter set at 60 Hz, the level of the signal was read on a Brüel & Kjaer voltmeter, type 2425 (fig. 2).

In all conditions, probe microphone measurements were made immediately following the corresponding psychoacoustic threshold measurements. The test signal was switched to the continuous mode and the level of the signal was increased so that the voltmeter reading was well above the ambient noise level.

When the effects of the side-branch-vented earmold were being investigated, the sound pressure levels of test signals were observed at 21 frequencies, approximately equally spaced on a logarithmic scale from 125 to 2 000 Hz. When the effects of the open earmold were being investigated, the levels of tones were measured at 25 frequencies, approximately equally spaced on a logarithmic scale from 220 to 6 000 Hz.

Coupler measurements. Because earmolds were used as a part of the input system for these measurements, the portions of the 2-cm^3 and Zwislocki couplers which simulate the sound input bore of the earmold were eliminated, leaving only the cavity portion of each

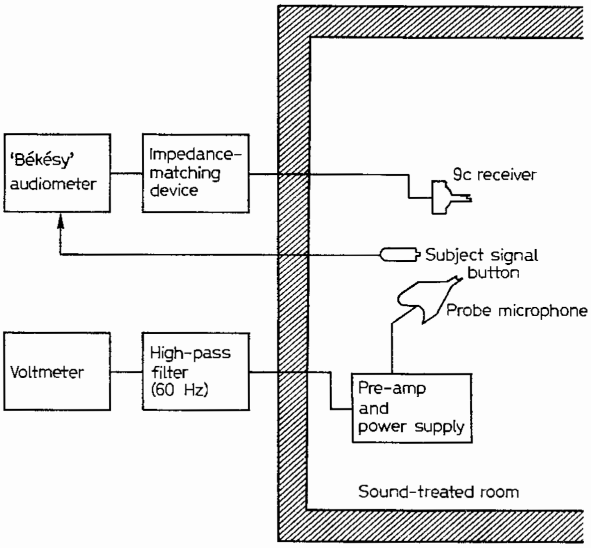


Fig. 2. Instrumentation for threshold and probe tube microphone measurements.

coupler. In the case of the 2-cm^3 coupler, a 2-cm^3 cavity identical to the one incorporated in the standard HA-2 coupler was used.

For all standard, vented and open earmolds, sweep frequency response curves were obtained with the earmolds mounted on the 2-cm^3 and Zwislocki cavities. The input and measurement systems were identical to those used during real ear measurements with the exceptions that the input pure tone was generated by a General Radio Audio Frequency Generator, type 1304-B and the output from the probe microphone was recorded graphically using a General Radio Level Recorder, type 1521-B.

Results and Discussion

Data Treatment

All data were transformed into differences (in decibels) at the selected frequencies. For both the side-branch-vented earmold and the open earmold, the differences between the modified earmold and its corresponding standard earmold were derived for each of four sets of data: (1) psychoacoustic thresholds; (2) probe microphone measurements of ear canal sound level; (3) measurements of level in 2-cm^3 cavity, and (4) measurements of level in Zwislocki coupler.

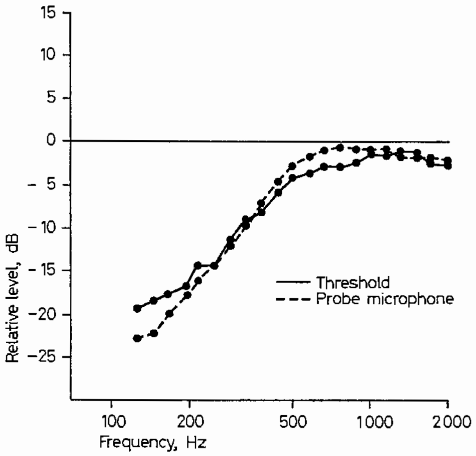


Fig. 3. Mean differences between levels observed with vented earmold and levels observed with corresponding standard earmold for the two real-ear measurement methods.

Ear Canal Measurements Compared with Psychoacoustic Thresholds

Figure 3 shows the differences between the levels observed with the vented earmold and those with its corresponding standard earmold for psychoacoustic thresholds and for ear canal probe microphone measurements. If probe microphone measurements in the ear canal and psychoacoustic threshold measurements are both valid indicators of the effective signal level reaching the cochlea of the subject, the derived differences for the two measurement methods should be of similar magnitude at each frequency. Hence, the subtraction of threshold vented-standard difference from probe microphone vented-standard difference at the same frequency should yield a result which is not significantly different from zero.

This hypothesis was tested using a t test for correlated samples [FERGUSEN, 1966, p. 169]. The results indicated that 16 of the 21 frequencies did not give significantly different results by the two measurement methods at the 5% level of confidence. Significant differences between psychoacoustic threshold measurements and probe microphone measurements did occur at 125 and 145 Hz and also in the frequency region encompassing 660–880 Hz. The difference at the two very low frequencies is in the positive direction indicating that the vented-standard difference in probe microphone measurements was greater than the vented-standard difference in threshold measurements. This finding is consistent with the hypothesis that physiological noise resulted in more masking in the unvented-earmold condition than in the vented-earmold condition. The probe microphone results, since the measurements were taken at levels well above the observed noise floor were not affected by physiological noise. The mean difference of 3.6 dB at 125 Hz is nearly the same as the 4.7 dB at 125 Hz reported by VILLCHUR [1970], who compared a closed (unvented) with a vented supra-aural earphone.

The difference between probe microphone and threshold measurements in the 660- to 880-Hz region is in the negative direction, indicating that the vented-standard difference in threshold measurements was greater than the vented-standard difference probe microphone measurements. It seems probable that the origin of this difference was an interaction between the resonance of the measurement system (i.e. the probe tube microphone) which occurred in the frequency region 600–1 000 Hz, and the resonance associated with the vent which occurred in this same frequency region. This effect was not observed in the data obtained using the open earmold where the resonance associated with the vent occurred at a frequency much higher than the resonant frequency of the measurement system. However, even though the two measurement methods yielded statistically different data in this frequency area, the absolute magnitude of the differences between measurement methods did not exceed 2.5 dB.

Figure 4 shows the differences between sound levels observed with the

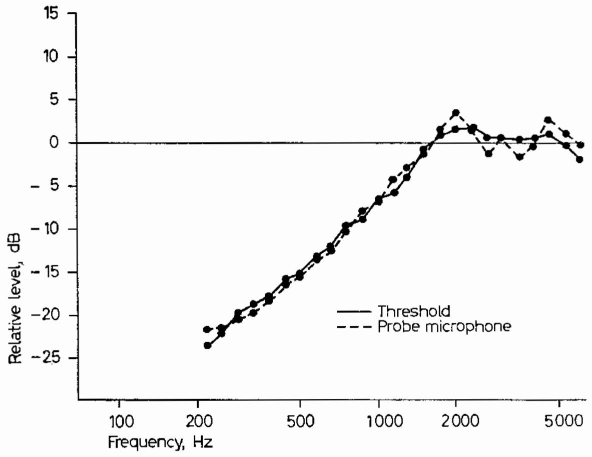


Fig. 4. Mean differences between levels observed with open earmold and levels observed with corresponding standard earmold for the two real-ear measurement methods.

open earmold and those observed with its corresponding standard earmold for threshold and probe microphone measurements. Measurements made at frequencies below 220 Hz are not reported because they were clearly contaminated by the ambient noise level. Again, the differences observed between the two sets of measurements were treated statistically using the t test for correlated samples. At 24 of the 25 tested frequencies, the data from the two measurement methods were not significantly different at the 5% level of confidence. A significant difference was observed at 3 500 Hz ($p<0.05$). However, since 25 t tests were performed on these data, it is likely that one value of t which is significant at the 0.05 level will occur by chance alone. It is also possible that the significant difference was the result of an, as yet, unidentified factor. In either case, since the absolute magnitude of the difference was less than 2 dB, it was an error which is quite tolerable for most purposes.

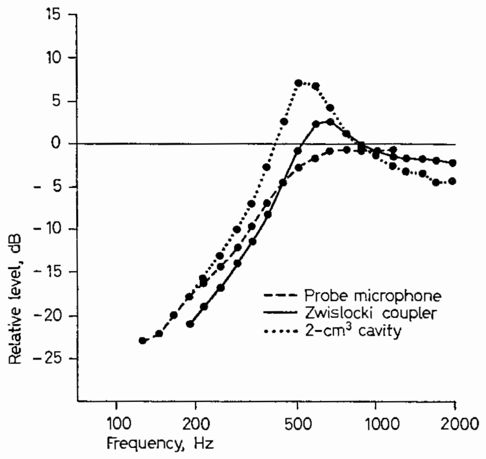
Reliability of the Real-Ear Measurements

In order to assess the reliability of the real-ear measurements, 5 of the subjects in the vented-earmold group were re-tested. The time that elapsed between first and second test sessions varied from ½ day to 38 days. For probe microphone measurements, the mean change from the first to the second test for all frequencies was $-0.8 \pm$ SD 0.6 dB. For psychoacoustic threshold measurements, the mean change from the first to the second test was $0.13 \pm$ SD 1.7 dB.

On the basis of these findings, the reliability of these measurements was judged to be quite acceptable.

Ear Canal Measurements Compared with Coupler Measurements

Figure 5 shows the mean differences between the levels observed with the vented earmold and those observed with its corresponding standard earmold for both couplers. The analogous differences measured in the real ear canal using the probe microphone have been included for reference. Figure 6 shows the corresponding data for the open earmold. These two figures, while they differ in detail, are similar in general tendencies. The comparison of measurements made in the real ear with measurements made in the 2-cm^3 cavity revealed effects very similar to the ones reported by previous investigators: that is, (1) a tendency towards an upward shift in location of vent-related resonance in the real ear; (2) a considerable damping of the vent-related resonance by the real ear, and (3) a steeper slope in the low-frequency filter effect for 2-cm^3 coupler measurements than for real-ear measurements.



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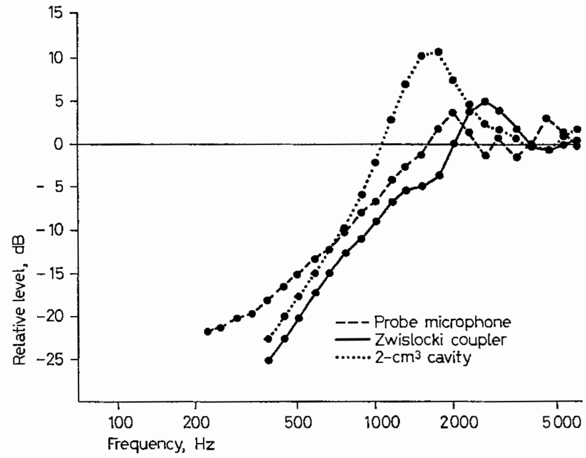

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Fig. 5. Mean differences between levels observed with vented earmold and levels observed with corresponding standard earmold for measurements made in 2-cm^3 cavity, Zwislocki coupler, and real ear canals (probe microphone).

Fig. 6. Mean differences between levels observed with open earmold and levels observed with corresponding standard earmold for measurements made in 2-cm^3 cavity, Zwislocki coupler and real ear canals (probe microphone).

A comparison of measurements made in the real ear with measurements made in the Zwislocki coupler revealed that the vent-associated resonance is located at a higher frequency. The extent to which the location of this resonance approximates its location in real ears will depend upon the extent to which the effective volume of the Zwislocki coupler in any given frequency region approximates the average equivalent volume of the group of real ears with which it is compared. As figure 5 shows, the resonance associated with the vented earmolds, as measured in the Zwislocki coupler, coincides closely with the average resonant frequency of the same earmolds measured on one group of real ears used in this study. On the other hand, figure 6 shows that the vent-associated resonance observed with the open earmolds measured on a different group of real ears occurred at a somewhat lower frequency than the analogous resonance observed using the Zwislocki coupler.

When the earmolds are evaluated using the Zwislocki coupler, the vent-associated resonances are considerably more damped than the same resonances observed using the 2-cm^3 cavity. However, the real-ear resonance appears even more damped, particularly in the vented-earmold group (see below for a further discussion of this point).

Finally, the slopes of the low-frequency filter effects observed when measurements were made in the couplers are steeper than the slopes observed for real-ear measurements. In the vented-earmold condition (fig. 5), the slope for the Zwislocki coupler is very similar to the slope obtained using the 2-cm^3 cavity. For the open earmold (fig. 6), the slopes for the Zwislocki coupler and 2-cm^3 cavity are also very similar below 1 000 Hz. Between 1 000 and 2 000 Hz, there are irregular features in the curve obtained from the Zwislocki coupler which make the interpretation of the slope difficult in this region.

Comment

The evaluation of the effects of earmold modifications using the Zwislocki coupler yielded data which resembled real-ear behavior more closely than did data from the 2-cm^3 cavity. However, noteworthy differences were observed between the real-ear and Zwislocki-coupler data, particularly with respect to the height of the vent-related resonance and the slope of the low-frequency roll-off.

However, it would be premature to conclude that the Zwislocki coupler is unsuitable for making such measurements. It seems possible that the differences observed between real-ear data and Zwislocki-coupler data may be explained in terms of the relative quality of the acoustic seal realized on the coupler and the real ear for measurements in the standard (unvented) condition. It is a simple matter to achieve an excellent acoustic seal when an earmold is placed on a metal coupler. However, an equally good acoustic seal is difficult to achieve when the same earmold is worn in a real ear. The result is that standard (unvented) earmolds almost always 'leak' low-frequency acoustic energy to some extent under normal everyday, in-use conditions. The net effect of a relatively 'leaky' standard earmold condition in real ears would be to cause a less steep low-frequency slope and a vent-related resonance with more apparent damping than would be obtained with a standard earmold condition which had no acoustic leak. Preliminary data obtained on real ears and using an electrical-analog circuit support this hypothesis. Further investigations of this factor and of methods to modify the Zwislocki coupler to simulate the 'leaky' standard earmold condition are underway.

Conclusions

On the basis of the data obtained in this investigation, it was concluded that measurement of the sound level changes in the real ear canal via a probe tube microphone yields data which are excellent indicators of the changes in effective signal levels which occur as a result of earmold modifications. However, there are some precautions which should be exercised in the use of this technique. When probe microphone measurements are made in a frequency region encompassed by a major resonance of the probe microphone measurement system, the data may be influenced to some extent by the presence of the resonance, especially if a major resonance feature of the data (e.g. a vent resonance) occurs in the same frequency region. The amount of error introduced by this effect is not large and can be minimized by manipulation of the probe microphone system so that its resonances fall outside the frequency range of interest. In addition, where circumstances permit some loss of signal level, or where a high degree of repeatability and comparability of results over time is not essential, probe tube resonances could be damped by the use of acoustical damping material.

With regard to the threshold technique, the study verifies VILLCHUR's [1970] finding that real ears experience additional threshold masking by physiological noise at very low frequencies when the ear is fully occluded. Probe microphone measurements performed at higher levels are not subject to the influence of this noise. However, this effect poses a problem only when real-ear measurements are made at very low frequencies.

It is evident that in response to earmold modifications, the Zwislocki coupler simulates the behavior of real ears considerably better than does the

2-cm^3 cavity. Nevertheless, noteworthy differences were found between real-ear and Zwislocki-coupler data. A possible explanation for these differences may lie in the complete absence of an acoustic leak (to simulate that which often does occur in the real ear) when a standard (unvented) earmold is sealed onto the Zwislocki coupler. At present, the similarity between Zwislocki-coupler data and real-ear data does not appear as close as could be desired, but further improvements in technique may result in a change in this conclusion.

Résumé

Nous avons étudié la validité de mesures faites à l'aide d'un microphone à sonde pour mesurer l'amplitude des changements de seuil d'audition résultant de modifications de la forme des embouts. Nous avons mesuré également le rapport entre des mesures prises dans un conduit auditif réel et dans un coupleur de 2 cm^3 et dans un coupleur Zwislocki pour les mêmes conditions de modifications d'embouts. L'étude a été faite avec des embouts normaux, perforés et ouverts. Des mesures des seuils d'audition ont été faites ainsi que des mesures par sonde. L'exploitation statistique des résultats a montré qu'il n'y a pas de différence significative entre les résultats obtenus avec ces deux méthodes, sauf entre 125 et 165 Hz, où l'effet masquant du bruit de fond a pu avoir une influence sur la mesure des seuils d'audition. Aucun des deux coupleurs n'a pu donner une approximation quantitative précise de l'effet réel des embouts perforés ou ouverts, mais l'approximation était plus grande avec le coupleur Zwislocki qu'avec le coupleur de 2 cm^3.

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