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SPECTRAL CHANGES PRODUCED BY EARPHONE-CUSHION REPRODUCTION OF HEARING AID-PROCESSED SIGNALS

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ABSTRACT

This investigation was conducted to assess the extent to which hearing aid-processed signals present an acoustic signal to the subject which has a frequency response equivalent to that which the hearing aid itself would have provided. The frequency response of a hearing aid receiver which was coupled directly to the ear canal ("aided" condition) was compared with the frequency response of the same receiver when its output was recorded on magnetic tape and then presented to the subject via a TDH-49 earphone ("pseudoaided" condition). Results indicated that when the earphone was mounted in an MX-41/AR cushion or either of two circumaural cushions, the spectrum of the sound arriving at the subject's eardrum in the pseudoaided condition was substantially different from the spectrum delivered in the aided condition.

A procedure frequently used in the hearing aid research of the past 15 years included what has come to be known as "hearing aid-processed" test signals. In this procedure the test signal (usually speech) was typically presented to a hearing aid situated alone in a sound field. The output of the hearing aid was delivered to a 2-cc coupler and then recorded on magnetic tape. Later, the tape-recorded signals were presented to the experimental subjects via earphones, usually mounted in MX-41/AR supra-aural cushions. This method was used because it appeared to offer the advantage of holding constant the test stimuli presented to the subjects—a feat which is relatively difficult to accomplish when the hearing aid itself is placed on the subject's ear.

Numerous studies have been published in which hearing aid-processed test signals formed a part of the research protocol. They include studies which investigated methods of hearing aid selection (Zerlin, 1962; Witter and Goldstein, 1971, Jerger et al., 1966), as well as aspects of hearing aid performance such as harmonic distortion (Bode and Kasten, 1971; Jirsa and Hodgson, 1970), frequency response (Jerger and Thelin, 1968; Harris et al., 1961), and telephone input (Sung and Hodgson, 1971; Hodgson and Sung, 1972), to name only a few.

At least two studies have been reported in which hearing aid-processed signals were evaluated to determine their acceptability as test signals in hearing aid evaluation procedures (Revoile, 1971; Harris and Hodgson, 1974). In both studies, one speech discrimination score was obtained with the speech test material "processed" through the hearing aid, tape-recorded, and subsequently played back to the subject via an earphone (this was called the "pseudoaided" condition by Harris and Hodgson). A second score was obtained with the speech test presented to the subject actually wearing the hearing aid (the "aided" condition). After comparing these scores, both studies reported no statistically significant difference between them. The authors concluded that the use of signals which had been "preprocessed" through a given hearing aid and delivered via an earphone was functionally equivalent to using the hearing aid itself to deliver the signals to the subject's ear.

It should be noted, however, that these investigators reached their conclusions on the basis of

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the results of speech tests which are well known to be relatively insensitive to small but possibly significant differences in hearing aid characteristics. Further, neither of these studies, nor any of the other cited investigations, reported measurements of the spectrum of the signal delivered to the subject's ear in either of the two conditions.

Ideally, the spectrum of the signal received by a subject in the pseudoaided condition should be the same as the spectrum received in the aided condition. If this ideal is not achieved, or closely approximated, the usefulness of the hearing aid-processing method as a tool for research or hearing aid evaluation is severely limited. Thus, the purpose of the present study was to compare the acoustic spectra of a hearing aid receiver's output at the eardrum in each of two conditions, aided and pseudoaided.

Procedure

Most of the data were generated and analyzed using a method developed by Studebaker (1975, 1976) which employs a broad band noise as the signal delivered to the test device. The output spectrum of the test device (equivalent to its frequency response) was derived by the use of a real-time analyzer. (See Studebaker, 1975, 1976 for detailed descriptions of the method.)

This investigation was comprised of two independent studies. Although there were some differences in the instrumentation used on the two occasions, the changes, which were made on the basis of convenience, are not considered to have affected the experimental outcome.

The experimental conditions are shown schematically in Figure 1. In the aided condition, a hearing aid receiver was coupled directly to the ear canal using a conventional earmold. A flat spectrum thermal noise was delivered to the receiver and the spectrum of the sound occurring at a point 5 mm beyond the tip of the earmold was observed using a probe microphone. In the pseudoaided condition, the hearing aid receiver was placed on a 2-cc coupler. Again, the thermal noise signal was delivered to the receiver. The output of the receiver generated in the coupler was recorded on Memorex tape using an Ampex 440 tape recorder. (The frequency response of the recorder-tape system was flat within ±0.5 dB up to 10,000 Hz.) This recorded output was then played back from the tape to a TDH-49 earphone mounted in an MX-41/AR supra-aural cushion. The spectrum of the sound produced by this transducer was observed at the entrance to the ear canal using a second probe microphone. The instrumentation for the pseudoaided condition was selected to replicate,

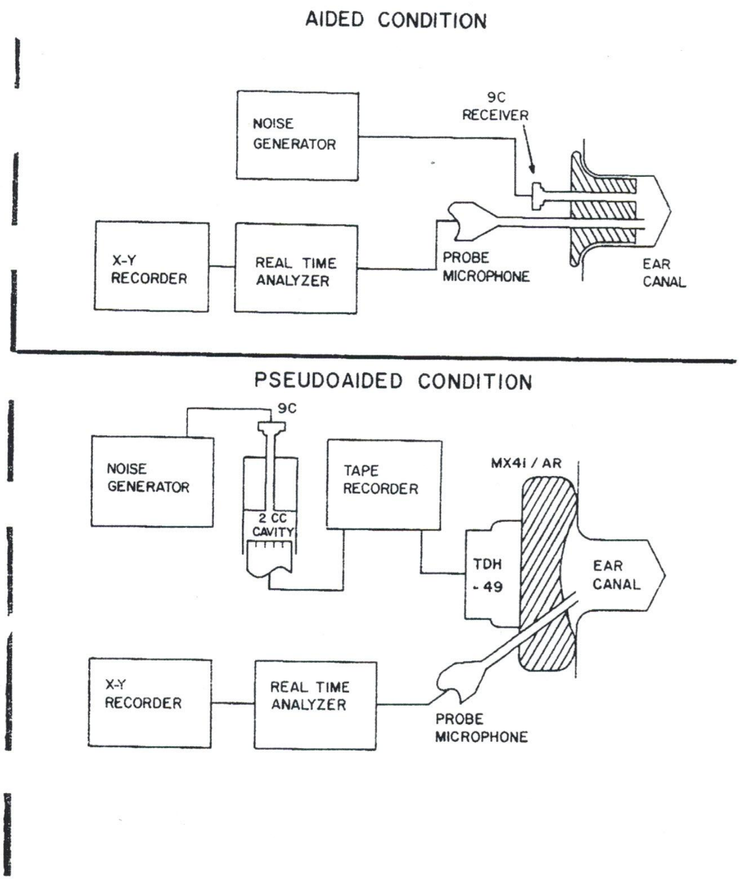

Fig. 1. Block diagram of the apparatus.

as closely as possible, the conditions used in the majority of studies which utilized this research protocol.

A hearing aid receiver was used in this study instead of a complete hearing aid because the receiver is more convenient, gives a better low frequency response and is more easily controlled. The results, nevertheless, may be generalized to the situation in which the complete hearing aid is used. Also, the tape recorder was not always a part of the instrumentation (even though it is essential in conceptualizing the purpose of the study) because the process of recording and reproduction of a signal using high quality tape and a properly adjusted tape recorder does not change the spectrum of the signal in the frequency region of interest.

Nine young adults served as subjects in the first study and five young adults served in the second study. All subjects appeared to have normal hearing, although possession of normal hearing was not a selection criterion.

Results and Discussion

In each study an average curve was derived for each of the two conditions. However, before the aided curve could be compared with the pseudoaided curve it was necessary to apply two different frequency response corrections to the data. First, inasmuch as different probe tubes were used in the two conditions, it was necessary to correct the data in each condition for the effects introduced by the transmission characteristics of the particular probe tube used. Second, because measurements in the two conditions were taken at two different points in the ear canal, and under different conditions of ear canal occlusion, all of the data were converted into eardrum sound pressures.

In the aided condition no corrections were necessary to convert the data obtained 5 mm beyond the earmold tip into eardrum sound levels, as data from our laboratory (Studebaker, 1974) indicated that sound pressures in the ear canal behind a standard earmold are essentially uniformly distributed up to at least 4000 Hz. However, in the pseudoaided condition, it was necessary to apply a correction to convert sound pressures measured at the ear canal entrance into sound pressures occurring at the eardrum.

Villchur (1969) has shown that the transfer function from the ear canal entrance to the eardrum, when the ear is covered with an earphone, has essentially the same configuration as the transfer function measured when there is no ear covering. For Villchur's three subjects, the transfer function from the ear canal entrance to the eardrum, measured under earphones mounted in MX-41/AR cushions, was shifted downward in frequency from the free-field transfer function by an average of 6%, but was otherwise unchanged. Hence, to derive a set of corrections representing the average transfer function from ear canal entrance to eardrum under an earphone mounted in MX-41/AR cushions, the average free-field transfer function (Wiener and Ross, 1946) was shifted downward in frequency by 6%. This cor-

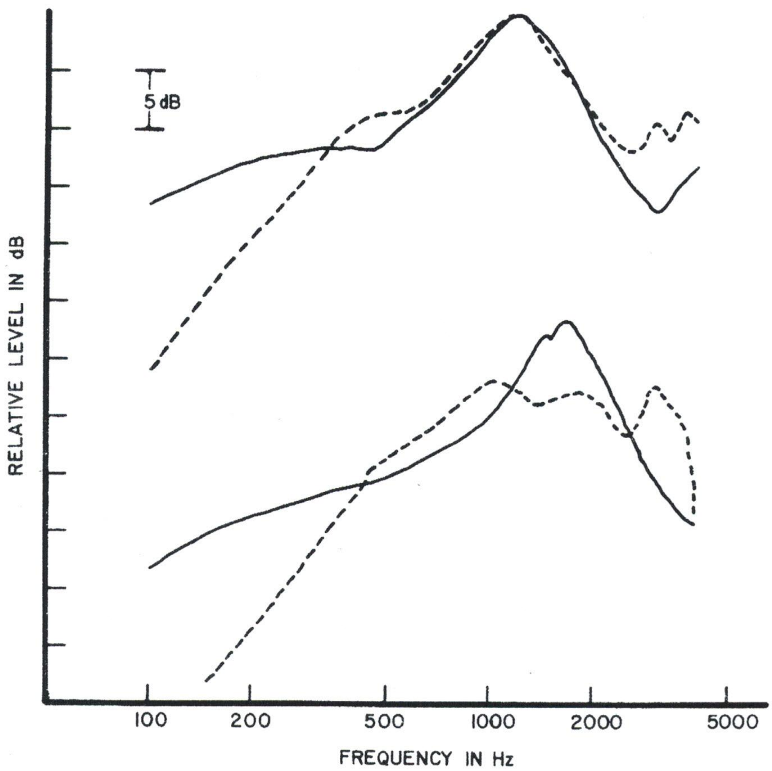

Fig. 2. Results of two studies comparing the spectrum of a "hearing aid-processed" signal (*dashed line*) with the spectrum of the same signal when the hearing aid receiver was coupled directly to the ear canal (*solid line*). All data are transformed to eardrum sound levels.

rection factor was applied to the curves derived from pseudoaided measurements to convert these data to eardrum sound levels.

The curves for the aided and pseudoaided conditions could then be compared. Figure 2 shows the corrected results obtained in each of the two studies. Aided condition data are shown by the *solid line* and pseudoaided condition data by the *dashed line* for each study. The vertical positioning of the solid line with respect to the dashed line is quite arbitrary. They were placed in the relationship shown on the basis of experience with the types of curves generated in sealed versus leaking cavities as they show a considerable similarity to these types of curves, and because it seems probable that acoustic leakage from under the earphone is responsible for the difference in results in the low frequencies.

In order to facilitate the comparison between the two test conditions in each of the studies, the same data are shown in Figure 3 in terms of the differences between aided and pseudoaided curves. The aided condition is the *zero reference line* and the *dotted and dashed lines* show the extent to which the pseudoaided condition data differed from the aided condition data in each of the two studies.

It is obvious that the outcomes of the two studies are not exactly the same. The explanation for these differences is not precisely known but, as data presented later indicate, the variability of signals generated in the ear canal by an earphone mounted in a supra-aural cushion is quite large, both across subjects and as a function of the pressure of the earphone against the head. The effects of this variability can be seen in all frequency regions. In addition, as numerous previous investigators have noted (Shaw, 1966; Harris, 1971), probe tube measurements at the entrance to the ear canal are subject to considerable variability above 2.5 kHz, no matter how careful the experimental technique.

There are, nevertheless, noteworthy similarities in the overall pattern of the results of these two studies. In the pseudoaided condition there appears to be a low frequency filtering effect in combination with a more or less broad resonance between 400 and 1000 Hz. This is a pattern similar to the acoustical effect produced by a vent or leak in a conventional earmold or in a coupler. Repeated observations of this effect and its manipulation have led the authors to the conclusion that there is a significant leak under the supra-aural cushion which acts like an earmold vent and which is responsible for the effects shown in Figure 3 below 1000 Hz.

An additional feature seen in both studies is the resonance observed in the pseudoaided condition data in the vicinity of 3000 Hz. This is the ear canal resonance which has been shown by Villchur (1969) to be present when supra-aural earphones are used. By contrast, when the ear canal is made shorter by the presence of an earmold, this resonance is shifted to a much higher frequency. As a result, it is not visible in the aided condition data.

Thus, there appear to be two main factors operating to modify the frequency response of a signal produced by an earphone mounted in an MX-41/AR cushion on a real ear. First, there is a

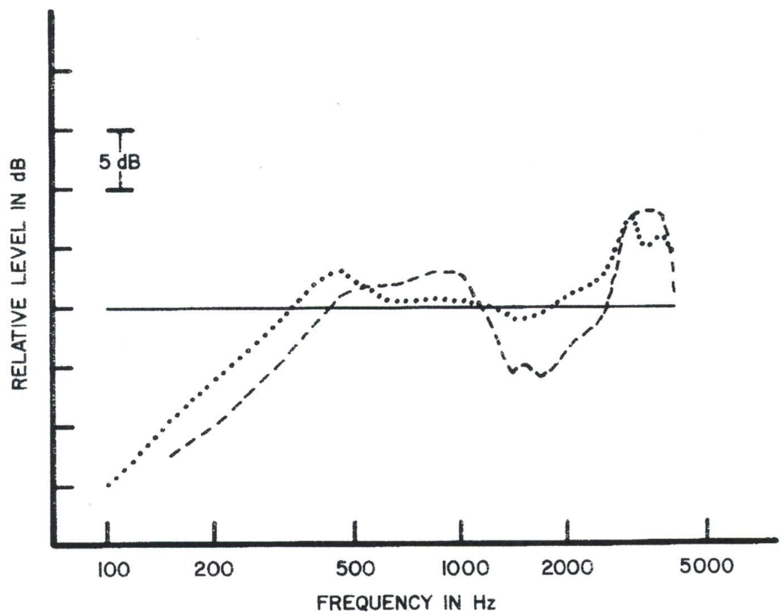

Fig. 3. Results of two studies showing the spectrum of a "hearing aid-processed" signal relative to the spectrum of the same signal when the hearing aid receiver was coupled directly to the ear canal (*solid reference line*). All data are transformed to eardrum sound levels.

leak under the supra-aural earphone cushion which, by shunting low frequencies and producing a midfrequency resonance, creates an effect very similar to that produced by an earmold vent. Second, the use of an earphone allows the ear canal to resonate about as it normally would in an uncovered condition, thus providing a boost in the 3000-Hz frequency region which is not present when earmolds are used. The net result is that the output of a hearing aid which has been recorded and then presented to an ear via an earphone in an MX-41/AR supra-aural cushion has a spectrum at the eardrum which is substantially different, in low, mid-, and high frequency regions, from the spectrum at the eardrum when the hearing aid is coupled directly to the ear canal by a conventional earmold.

Punch and Studebaker (1975) reported a study on this question. Figure 4 shows the average of these two studies in comparison with the data generated by Punch and Studebaker (1975). In order to make this comparison, it was necessary first to convert the Punch and Studebaker ear canal entrance measurements (obtained in the pseudoaided condition) into eardrum sound levels as discussed earlier. As with the comparison between the two studies within this investigation, the differences between studies are apparent, but again the overall patterns are similar. This finding helps to confirm the basic form of the difference between aided and pseudoaided conditions, and underscores the variability of that difference.

Incidentally, it was possible to simulate these results quite closely by substituting a Zwislocki coupler for the real ear and introducing a sizable vent underneath the MX-41/AR cushion as it was placed on the coupler. The absolute size of the effects depended on the size of the vent, but the similarity of the obtained patterns to those shown in Figures 3 and 4 was obvious.

Results Obtained with Two Circumaural Earphone Cusions. In order to investigate the influence of cushion design on the pseudoaided condition results, the output of a TDH-49 earphone mounted in the supra-aural cushion was compared with the output of the same earphone, mounted in each of two circumaural earphone cushions. The two circumaural cushions chosen were the one supplied by HC Electronics with their FM Auditory Trainer and one designed by Zwislocki (1955) and manufactured by Grason Stadler. These two circumaural cushions were chosen because they are widely available in speech and hearing clinics. Figure 5 shows the three cushions.

The data were obtained by spectrally analyzing the output of the TDH-49 earphone, driven by a flat spectrum noise input signal, with the earphone mounted in each of the three cushions and placed over the subjects' ears in the usual way. The signal at the ear canal entrance was recorded via a single probe tube microphone for all cushion conditions.

A curve averaged across subjects was derived for each cushion. The results are shown in Figure 6. The *solid line* is the output for the supra-aural cushion (average of seven subjects), the *dotted and dashed lines* represent the output of the two circumaural cushions (averages of seven and five subjects, respectively). These curves have been matched arbitrarily at 1000 Hz to facilitate the comparison between them. It is evident that the spectrum of the sound arriving at the entrance to the ear canal was not greatly changed when

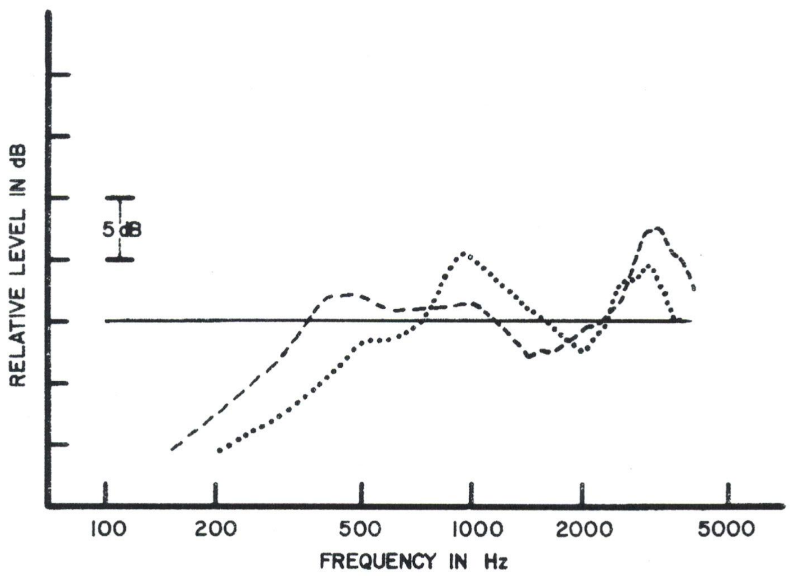

Fig. 4. Average spectrum of a "hearing aid-processed" signal (*dashed line*) compared with similar data from Punch and Studebaker (1975) (*dotted line*). Both curves shown relative to the spectrum of the same signal when the hearing aid receiver was coupled directly to the ear canal (*solid reference line*). All data are transformed to eardrum sound levels.

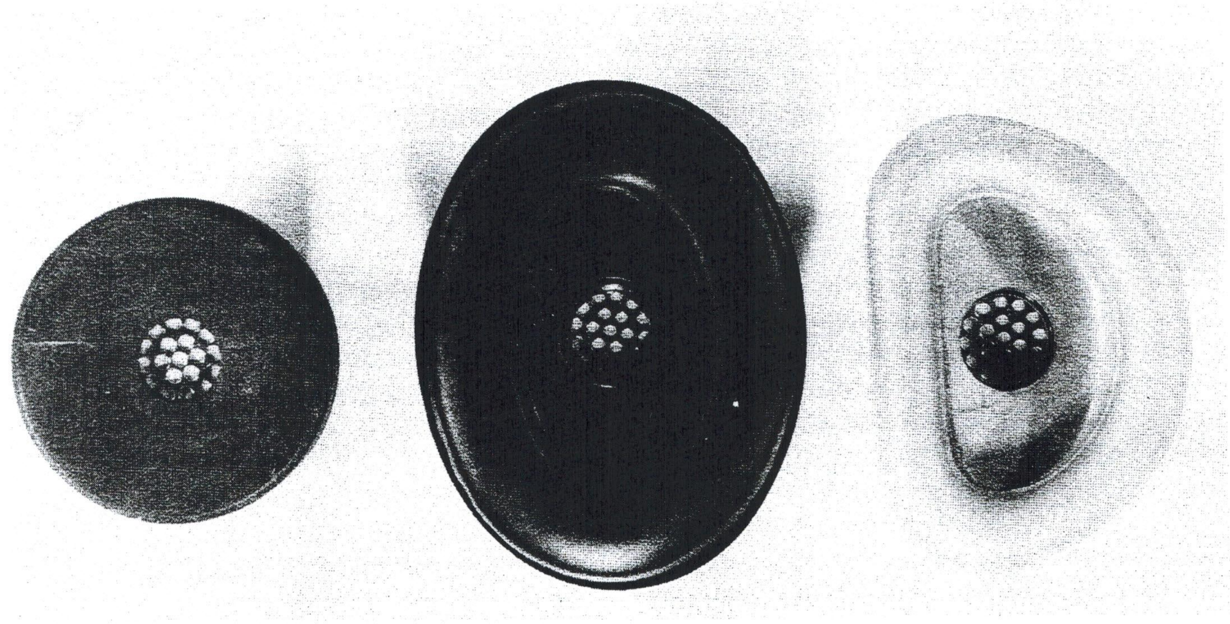

Fig. 5. Supra-aural and circumaural earphone cushions used in the investigation, *Left,* MX-41/AR; *middle,* HC Electronics; *right,* Grason-Stadler.

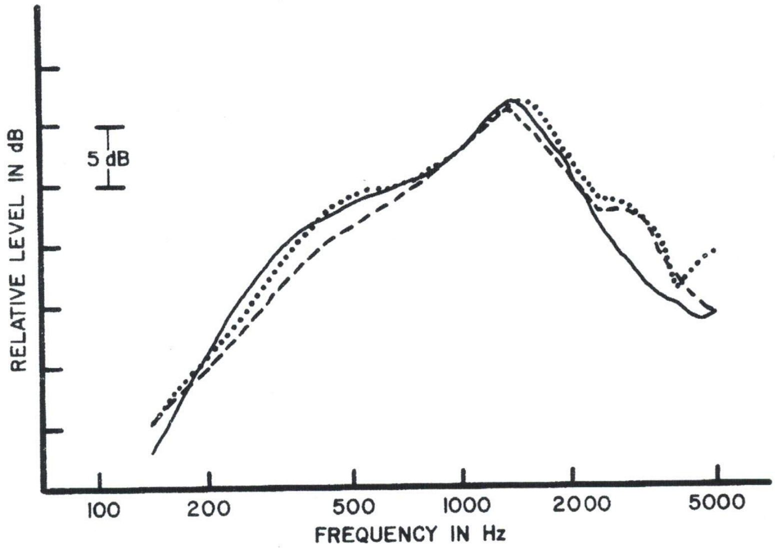

Fig. 6. Spectrum of signal at ear canal entrance with TDH-49 earphone mounted in MX-41/AR supra-aural cushion (*solid line*), HC Electronics circumaural cushion (*dotted line*), and Grason-Stadler circumaural cushion (*dashed line*).

either of these circumaural cushions was substituted for the supra-aural cushion. The average differences do not exceed 3 dB below 2500 Hz, or 5 dB from 2500 to 5000 Hz. This indicates that, on the average, the use of these circumaural cushions would not be an effective means of reducing the low frequency leakage which was noted when the supra-aural cushion was used.

It is perhaps important to note, however, that the small size of these circumaural cushions may be a significant factor. The two cushions used in this study do not enclose more than abut 30 cm^3 of air. Shaw (1966) has reported data on circumaural cushions enclosing 120 to 270 cm^3 in which there does not appear to be any significant low frequency leakage. However, neither the small nor the larger earphone cushions would change the high frequency canal resonance.

Reliability of the Hearing Aid Processed Signal. As noted earlier, "hearing aid processing" was used so that the signal delivered to the subject could be held constant. One factor which must be considered is the intersubject variability of the acoustic seal as revealed by the variability of the low frequency results. We have observed repeatedly that the amount of low frequency leakage achieved with a given earphone cushion varies widely across subjects. For example, Figure 7 shows the results of a study using an MX-41/AR cushion, where the cushion was carefully adjusted by the experimenter. The curves have been normalized in the 1500-Hz region. Each

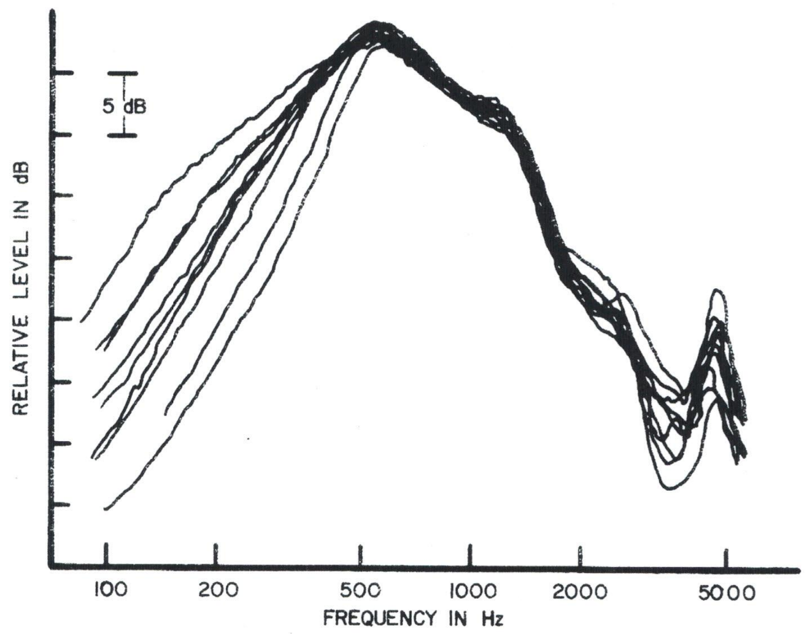

Fig. 7. Spectrum of signal at ear canal entrance for each of nine subjects when the TDH-49 earphone was mounted in an MX-41/AR supra-aural cushion.

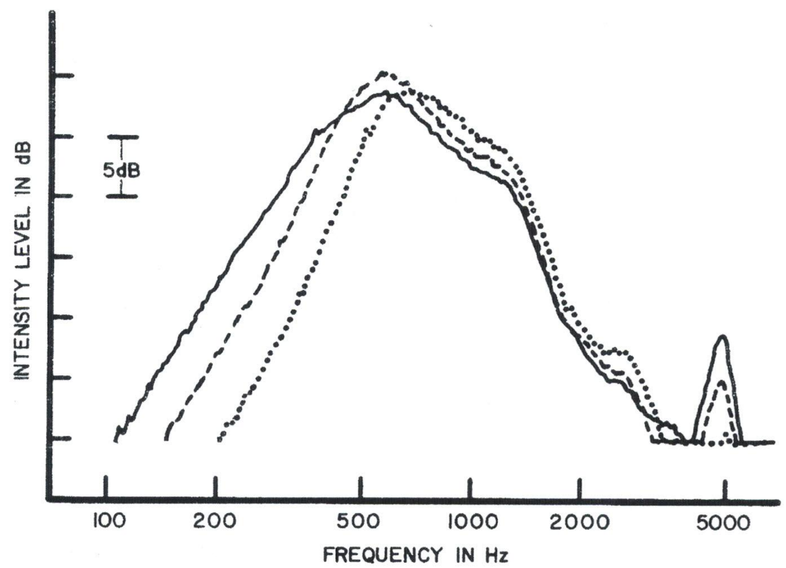

Fig. 8. Spectrum of signal at ear canal entrance with three levels of tension on the earphone headband for one representative subject; tight headband (*solid line*), average tension (*dashed line*), loose headband (*dotted line*).

line represents a different subject. The range of the results for nine ears was 18 dB at 200 Hz. When the subjects adjusted the cushion themselves for best fit, the range for seven ears at 200 Hz was still 10 dB. Similar data obtained with the two circumaural cushions on five and seven ears, respectively, indicated that the range was 5 to 7 dB at 200 Hz. Values of the same order of magnitude have been reported by Villchur (1970).

For a given subject, the tightness of the earphone headband can be another important factor. With an MX-41/AR cushion the level at 200 Hz may be changed by 5 to 15 dB or more when the headband is changed from relatively loose to relatively tight. Figure 8 shows an example of these changes on one representative subject. The dotted curve was obtained with a loose headband, the dashed curve with average tension, and the solid curve was obtained with a tight headband.

The large variability associated with placement of an earphone over the external ear indicates that accurate prediction of the spectrum of the signal delivered to the eardrum is very difficult for the individual subject even when the average values are known.

Conclusions

The results of this investigation indicate that when the earphone used to deliver hearing aid processed speech to a subject is mounted in an MX-41AR supra-aural cushion, the spectrum of the sound arriving at the average subject's eardrum is substantially different in low, mid-, and high frequency areas from the spectrum of the signal delivered when the hearing aid receiver itself is coupled to the ear canal by an earmold.

A comparison of the supra-aural cushion with two different circumaural cushions revealed that although the low frequency variability was somewhat reduced with these circumaural cushions, the average results were approximately the same with all three cushions. Also, the discrepancy in the high frequency region would remain with these cushions. Finally, the variability of the signal spectrum across subjects and as a function of earphone pressure on the head is very substantial, making accurate prediction of the spectrum of the signal delivered to the eardrum very difficult in the individual case even when average values are known.

The conclusion reached on the basis of these findings was that the reproduction of hearing aid-processed signals through an earphone in an MX-41/AR cushion or in circumaural cushions similar to the types reported here does not result in a signal at the eardrum which is spectrally similar to the signal provided when the hearing aid itself is worn. Furthermore, the large variability associated with placement and fit of earphone cushions on real heads is a serious limitation in the use of this technique in any research procedure which requires careful control of the spectrum of the test stimulus presented.

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