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THE USE OF CIRCUMAURAL EARPHONES IN AUDIOMETRY

by

J. Donald Harris, Ph.D.

Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF022.01.04-9004.10

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SUMMARY PAGE

THE PROBLEM

To explore ways of standardizing the measurement of the sound pressure level generated by an earphone in several of the circumaural noise-attenuation ear cushions now being proposed for communication circuits and for audiometry.

FINDINGS

Either a flat-plate acoustic coupler, or a probe-tube microphone, may be used to standardize sound pressure level for a circumaural ear-muff; however, this is true only over the frequency range 500-3,000 cycles per second. If such an earphone/cushion combination is used for pure-tone audiometry at any higher frequencies, recheck tests using the standard audiometric earphone/cushion unit must be performed on certain individuals.

APPLICATIONS

The information presented in this report will be useful for communications engineers wishing to compare the sound pressure levels in the ear canal generated at various frequencies by a variety of earphone/earmuff combinations, and for otologists, audiologists, and safety engineers throughout the Department of Defense, who are involved in the individual and group testing of hearing.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MF022.01.04-9004—Optimizing of Special Senses in Submarine and Diving Operations. The present report is No. 10 on this Work Unit. It was approved for publication on 15 July and designated as Submarine Medical Research Laboratory Report No. 540.

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GLOSSARY

1. A.S.A. Type 1 Coupler: the American Standards Association (A.S.A.) standard coupler for mating an earphone to a microphone.

2. Audiometric "0": Zero Hearing Level on a standard audiometer.

3. dB: decibel

4. gr: gram

5. HL: Hearing Level (number of decibels above audiometric "0").

6. Hz; kHz; Herz; or cycles per second (kiloHerz, or thousands of c/s).

7. ISO: International Standards Organization.

8. MX-41/AR cushion: a sponge neoprene cushion fitted to the above phones; standard in this country.

9. 9A Coupler: The American National Bureau of Standards standard coupler for mating an earphone to a microphone.

10. SPL: Sound pressure level in decibels above 0.0002 microbar.

11. TDH-39; TDH-49; PDR-8 earphones: These are American standard units for audiometry.

12. U.S.A.S.I.: United States of America Standards Institute (formerly A.S.A.).

13. V: volt

14. VTVM: vacuum-tube voltmeter.

15. W.E. 640AA: Model No. of an American standard Western Electric Co. condenser microphone.

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THE USE OF CIRCUMAURAL EARPHONES IN AUDIOMETRY

I. INTRODUCTION

Some earphones standardized for audiometry neglect the problems of comfort and sound attenuation, simply providing a hard surface to be placed against the pinna. Examples are the Standard Telephones and Cables, Ltd., Model 4026A British Standard audiometric phone, and the Western Electric Model 552. However, most audiometric coupling between the phone and the eardrum now involves the comfort of a soft cushion, and another trend is more and more to devices which in addition may significantly reduce the masking effect of ambient sound. Quite a few devices are now commercially available and advertised to reduce unwanted sound in audiometry, but so far, no procedure has been generally adopted whereby the acoustic output of these phones can be stated in terms of rendering possible a direct comparison with current audiometric earphone standards.

The knowledgeable reader may pass over the following description of three general methods by which the acoustic output of any earphone can be standardized for audiometric purposes:

(a) **Psychoacoustic.**

For each of a number of earphones and earphone-cushion combinations, the voltage over a broad frequency region is known which yields audiometric "0" (modal value of an adequately large sample of young normal ears). ISO Recommendation R389[1] gives the SPLs developed by five standard phones from five different countries, each for an acoustical coupler mated to it, when the appropriate voltage is applied to the phones.

Taking any earphone from these five as reference, any other earphone-cushion combination can be used in audiometry if it is first loudness-balanced against the reference phone (see Martin and Touger[2] for an early discussion). For example, Delaney and Whittle[3] from new data on loudness balancing at threshold, applied threshold voltage to each of six phones and report reference equivalent threshold SPL as developed in each of three acoustic coupler systems. From these data, audiometric "0" in the Telephonics TDH-39 and TDH-49 phones, in MX-41/AR cushions, the commonest earphone/cushion in this country, is known by psychoacoustic comparison with the standard Western Electric Co. 705A.

The difficulty comes in considering a phone-cushion combination incompatible with any current standard coupler. Of course, any particular system can be standardized by the psychoacoustic technique, but if the phone should age or otherwise change, or a companion unit of the same model be somewhat different, or should the manufacturer change, unannounced, the acoustics of the unit (either the phone, the cushion, or the manner of mounting the phone in the cushion) a completely new and time-consuming psychoacoustic loudness balancing has to be performed.

(b) **Probe Tube Microphone Pickup at the Ear Canal.**

At the first glance it would seem possible to insert a small acoustic probe under any phone-cushion combination, position the tip at the entrance to the meatus, and specify exactly the SPL at audiometric "0" (Corliss and Burkhard[4]). However, especially at the lower frequencies, the difference may be considerable between the SPLs measured on the same earphone at the same voltage by probe tube and by acoustic coupler. Dadson and King[5], for example, report a difference between data from a probe microphone and from an artificial ear of about 10 dB at 250 Hz. Furthermore, it has been demonstrated (Harris[6]) that there may be systematic differences in the SPLs measured by probe microphone at the entrance to the meatus between two types of phone, even though both phones are at equal loudness. Delaney, Whittle, Cook and Scott[7] have shown that the equivalent threshold SPL for a British standard 4026A earphone in the new National Physical Laboratory artificial ear may match very closely that from probe measurements on human heads, but for the 9A coupler the differences were commonly 2-3 dB, and, in the British Standard artificial ear, even more (up to 7 dB at 8 kHz).

The truly relevant question then becomes, can one, for any new type of phone-cushion combinations, first find threshold voltage by direct psychoacoustic judgment (balancing against a standard phone), and then store the acoustic output in terms of the SPL measured by a probe at the entrance to the ear canal, when the device is properly energized and mounted on a "typical" human head. If such a real-ear probe method can be shown reliable, the problems of a closed acoustic coupler are avoided altogether.

(c) **Closed Acoustic Coupler SPL.**

The use of closed acoustic couplers and of artificial ears has been mentioned as applicable to only some earphone-cushion combinations. In the case of the especially troublesome large circumaural cushions, Shaw and Thiessen[8] initiated the practice of inserting a calibrated microphone flush with the surface of a large flat metal plate to accommodate any circumaural system. The earphone is simply centered over the microphone. Charan, et al.,[9] have shown that such a coupler has no more, and usually fewer, resonant and anti-resonant peaks, for various circumaural phones, than flat plate couplers similar in design but with the microphone depressed so as to incorporate the 6-cc cavity either of the 9A or the A.S.A. Type I coupler.

The relevant questions are, can any flat-plate coupler accept any circumaural phone-cushion combination; and do any differences in SPL among phone systems reflect with any precision those differences determined to exist, using the psychoacoustic threshold procedure. The data of Charan, et al.[9] indicate that only for frequencies below 2 kHz is it possible to state, from the data on one flat-plate coupler, what the SPL may be for the same voltage to that phone-cushion combination on another flat-plate coupler. Differences among couplers up to 10 dB (unacceptable for most audiometry) are common in the 4-8 kHz region.

However, if one can adopt the compromise of fixing upon one particular flat-plate coupler, the problem is considerably simplified, since one avoids the problems of the differences among couplers. The relevant question then becomes, can voltages to a particular type of phone-cushion combination on a particular flat-plate coupler be stated in SPL, so that differences in SPL generated by two different specimens of the same combination will reflect real-ear differences in psychoacoustic threshold, within, say, a precision of ± 2 dB through 8 kHz.

II. PURPOSE OF THIS STUDY

In order to perform threshold audiometry in certain workspaces, and particularly in group audiometry where a certain inherent workspace noise level is generated, it is highly desirable to use some sort of phone-cushion unit which maximally attenuates ambient noise.

Writing Group S3-1-W-37 of the U.S.A. Standards Institute (see Benson, et al.,[10]) has noted that the uncertainties both of probe tube and of flat-plate coupler measurements are such that the routine replacement of current standard audiometric units by some sort of circumaural unit is at present unjustified.

In this laboratory we have had considerable experience with three such circumaural units, on which data are in our files from all three standardizing methods, psychoacoustic, probe microphone, and flat-plate coupler. This report explores the success achieved by each of these methods, and presents some inter-relationships. Finally, recommendations are made in the light of these data how such units can, with certain precautions, be useful in an audiometric program.

III. METHOD

A. Devices Tested.

The same Permoflux PDR-8 earphone was used throughout. It was incorporated sequentially into the following cushions:

Device No. 1: MX-41/AR (this is the usual audiometric device).

Device No. 2: In an MX cushion, and further mounted locally in a Willson Products Corp. "Sound Barrier" noise-attenuation ear defender. The MX cushion is recessed just below the hard plastic septum under the fluid-filled outer cushion.

Device No. 3: Maico Co. "Auraldome" audiometric unit; this is essentially a David Clark Co. "Straightaway" ear defender fitted with a soft rubber mounting flange to fix a PDR-series phone near the opening of the main cavity. Air ports are provided to the cavity in the rear of the phone.

Device No. 4: Tracor, Inc. "Otocup"; when it arrived from the supplier it housed a Telephonic TDH-39 phone in an MX cushion beneath a fluid-filled outer cushion similar to but larger than Device No. 2; but the MX cushion is cut to be flush with the hard plastic septum of the cavity, and glued in place, and an attempt is made to seal the unit against the side of the head in front of the pinna with a soft-semi-circular ridge about ¼ inch in cross-section glued to the MX cushion.

Device No. 5: Same as Device No. 4, but as it arrived from the supplier there was no ridge, and a metal spring system pressed the MX cushion, which was shaped to fit the septum aperture, slightly forward.

For Devices 3-5, which arrived with TDH-39 phones, our PDR-8 replaced the originals.

B. Equipment.

1. Psychoacoustic Method.

For audiometry, a Grason-Stadler Bekesy audiometer was used in standard fashion.

2. Probe-Tube Method.

A probe tube of conventional design, 0.07 inch i.d., 3.5 inch long, filled tightly with wool yarn was affixed by way of a brass fitting with minimum volume to a Western Electric 640AA microphone. This probe was kindly made in our shop by Mr. E. Graber, Fort Collins, Colorado, formerly of Vicon Corporation. A bend in the tip of the tube was created after the suggestion of Shaw[11], the better to position the tip in the ear of a human head. Associated preamplifier, filters, and VTVM calibrated in SPL were from Western Electro-Acoustic Laboratories. Output was led to a General Radio Model 1521A graphic level recorder.

SPL was presented flat through 0.2 — 10 kHz either from a loudspeaker or earphone, by means of a mechano-electronic attachment to a General Radio Model 1304 oscillator, made by Dr. Scott Reger (see Appendix).

Calibration of the probe tube was performed (1) conventionally in a free field and (2) in a modified 9A coupler. The two methods agreed within the limits of our creating a flat SPL throughout the constantly-changing frequency range. In the second method of calibration, a PDR-8 phone in an MX cushion was fitted to the coupler, a brass plug exactly replaced the microphone, and a straight probe tube passed through a hole drilled through the center of the plug, the tip flush with the top of the plug. The probe tube response was taken to be the difference between the SPL as usually measured in the 9A coupler vs the probe reading from that coupler.

3. Flat-Plate Coupler Method.

A flat-plate coupler for the 640AA microphone was made following the design of Shaw and Thiessen[8], but incorporating a thin ring of rubber in the cavity filled by the microphone, for a somewhat improved seal. Atherley, et al[13] showed, while our work was in progress, that a somewhat superior flat-plate coupler incorporates a ¼-inch microphone recessed at the end of a 1-inch artificial meatus, the meatus packed with material to decrease resonance.

(a) In one set of measurements, the SPL in the flat-plate coupler was sampled by the probe tube slipped under the circumaural cushion, the tip centered just over the brass plug replacing the 640AA.

(b) In another set of measurements, the probe tube was held firmly in place against the heads of ten unselected young men, flat against the side of the head on the forehead, and the tip at the entrance to the cartilaginous meatus, while a selection of devices was energized.

In both cases, sweep-frequency measurements were recorded at a constant 0.5 V to the driver.

IV. PSYCHOACOUSTIC COMPARISONS

A. Results.

1. Threshold Determinations.

Six laboratory subjects traced Bekesy thresholds twice each for each ear, using Devices Nos. 1, 2, and 3. Because of its special interest to us, 13 subjects were utilized for Device No. 5.

Plots of mean thresholds at a selection of frequencies are in Fig. 1, referred in each case to the thresholds for the standard audiometric Device No. 1.

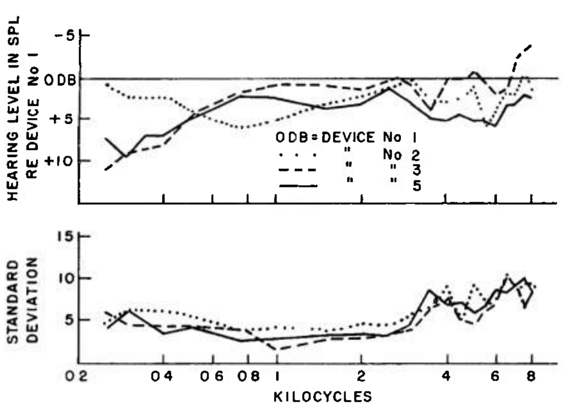

Fig. 1: Békésy Threshold SPL for Various Devices Compared to the Standard Device (Identical Driver Throughout), and Standard Deviation of Differences.

Device No. 2: Results confirm an earlier report of Myers[14] that the audiometric standard unit can simply be incorporated into a Willson "Sound-Barrier" ear defender, and mean thresholds at the octaves of 0.25 kHz remain within ± 5 dB.

Device No. 3: Results show a good coincidence (± 5 dB) in mean audiograms between Devices Nos. 1 and 3, except that a correction of 11 dB must be made for the fainter thresholds of Device No. 3 at 250 Hz.

Device No. 5: Results are as with Device No. 3 except that only 7 dB correction must be applied at 250 Hz. These corrections corroborate those of Millner[15] who found a necessary correction of 10 dB at 250 Hz, but only 3 dB at 500 Hz; Coles[16] found differences of 7.5 and 3.0 dB in one model, but only 4.0 and 1.0 dB in another model, at 250 and 500 Hz respectively.

2. Variance of Thresholds from Device No. 1.

Figure 1 also contains the standard deviations for all ears, of the distribution of differences between threshold using Device No. 1 vs the others, regardless of sign. For Device No. 2, with which the thresholds at audiometric frequencies differ never more than 5 dB from the standard unit, nevertheless a glance at the standard deviations indicate that differences between the thresholds from Devices 1 and 2 usually run about 5 dB or over, and in fact approach 10 dB at 4+ kHz. Obviously, especially for the high frequencies, the small differences in mean thresholds are no guarantee at all, in the case of the individual subject, that the devices are interchangeable in audiometry. Five or six subjects out of each hundred with Device No. 2 will yield audiograms at 4, 6, and/or 8 kHz which will differ by more than 15 dB from audiograms they would have yielded had they used the standard Device No. 1. Two or three of these will be in the direction of yielding spuriously acceptable audiograms by some criterion, although had they used Device No. 1 they would have failed that criterion.

Variations from Device No. 1 in our sample were not different in any meaningful pattern among the devices tested. Test-retest variance within the device was likewise not found significantly different (in agreement with Coles[16]).

3. Attenuation of Ambient Noise.

Inasmuch as the information bears upon the use of these devices in audiometry, we reproduce here some previously released data. Using the U.S.A.S.I. Standard method, Myers[17] determined the sound attenuating properties of Devices Nos. 2, 3, and 4, both with and without the PDR-8 driver mounted inside. Figs. 2 and 3 show these data. The effect of inserting a PDR-8/MX unit into the

"Sound Barrier" muff (Device No. 2) is to reduce the attenuation provided at 1 kHz and below, to a level as low as that provided by the MX cushion alone. Device No. 4 with phone provides generally the most attenuation of all; with this device, inserting the driver rather adds to than subtracts from the protective function, (see Table I).

V. PHYSICAL COMPARISONS: PROBE MICROPHONY

A. Introduction.

The subject reclined on a hard table and the probe tube in a flexible mount was positioned as close as possible to the side of the head, with the tip at the entrance to the ear canal. The probe was long enough and held rigidly enough so that placing the devices one after the other on the head disturbed the essential geometry a fairly small amount. Four entirely different probe tube positionings were accomplished on heads of ten young men, for Devices Nos. 1, 2, and 3. Fifteen subjects were used with No. 5.

B. Results.

With the standard Device No. 1, the real-ear response is flat ±2 dB from about 0.6 kHz (see Fig. 4). Devices Nos. 2, 3, and 5 are

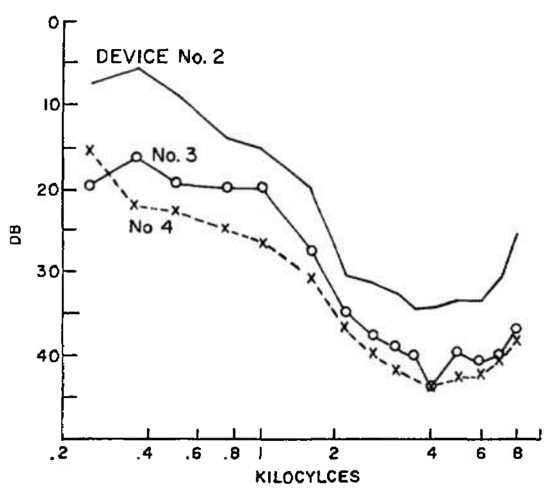

Fig. 2. Attenuation for Pure Tones of Three Circumaural Devices.

very generally similar. The drop at lower frequencies for Device No. 1 is caused by acoustic leakage around the probe tube (we did not penetrate the cushions with the probe); for Nos. 3 and 5 it is caused by the

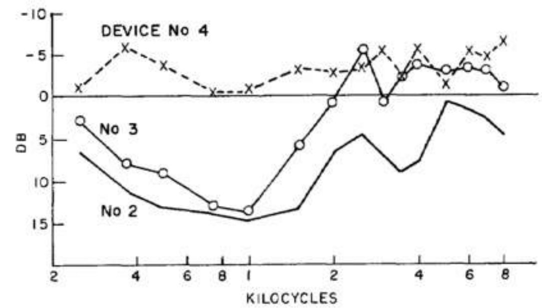

Fig. 3. Effect of Incorporating a PDR-8 Driver (Devices Nos. 3 and 4) or a PDR-8 Driver/MX Cushion Unit (Device No. 2). NOTE: Entry is reduction in attenuation due to phone, or phone/cushion in the case of Device No. 2.

large volume of air ensonified. Noteworthy is the fact that the 6-kHz coupler peak well-known to develop with this phone in the 9A coupler did not develop, and the 3-kHz peak was somewhat reduced.

Figure 4 also shows that there is not much to choose among the devices in the matter of individual differences; all devices yield approximately the same variance.

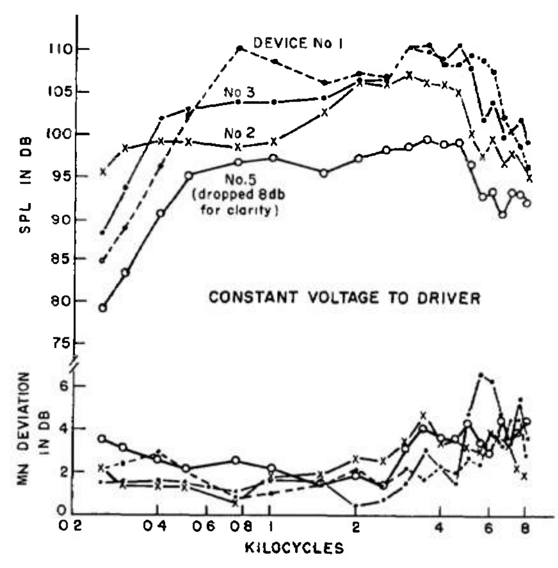

Fig. 4: SPL Measured by Probe Tube Microphone at Entrance to Ear Canal (Real-Ear Response), and Mean Deviations (N:10-15 men)

C. DISCUSSION AND TENTATIVE CONCLUSIONS

The mean SPL at the entrance to the ear canal of normal young men can be measured, with precision adequate for some audiometric purposes, by a probe microphone, over the frequency region 0.5-8 kHz. The average deviation among subjects will be of the order of 5 dB or less, thus the "true" mean can be estimated within 1-2 dB. These data are similar to those of Forshaw[18] who found between subject (N:16) standard deviations of up to 3.6 dB for probe tube measurements under a Sharpe HA-10 phone. Further, Shaw[19] found that the intra-subject standard deviations of SPL at 8 kHz under the earphones were for his 10 subjects estimated to be 1.32 to 2.4 dB for two configurations of Sharpe units, and generally less at lower frequencies.

The conclusion that a true mean SPL can be measured by the probe method with adequate precision does not mean, however, that for all audiometric frequencies it is justifiable to state an individual subject's audiometric threshold in terms of a reading from a probe tube inserted under the earphone cushion. Error variances are too great at 4+ kHz to render this solution advisable.

VI. PHYSICAL COMPARISONS: FLAT-PLATE COUPLER METHOD

A. Introduction.

A first attempt with circumaural earphones (Sharpe HA-10-C) to store audiometric threshold in terms of SPL in a flat-plate coupler (design of Shaw and Thiessen[8]), was made by Stein and Zerlin[20]. It might have proved possible to use these data in audiometric practice, since thresholds collected with a standard device on these subjects were reported in terms of SPL in a standard coupler; and although the notation of the ordinate is somewhat ambiguous, one infers the possibility of correcting the flat-plate coupler SPLs for differences between acuity of these particular subjects and that represented by audiometric "0."

However, Tillman and Gish[21] do not corroborate these flat-plate coupler SPLs for the HA-10 earphone. After correcting for acuity differences between their subjects and Stein and Zerlin's subjects with the usual TDH/MX unit, they still found substantial differences between either of their Sharpe models and Stein and Zerlin's unit. For their HA-10-B unit a modal difference of about 20 dB was in the direction of their unit producing that much more flat-plate coupler SPL for equal voltage to the driver. It is impossible from these data alone to judge whether the difference results from acoustic differences between HA-10 units, differences in acoustic coupling to real heads, coupler-earphone interactions, or coupler differences.

We compared flat-plate coupler SPL's developed by the five devices. Device No. 1 was centered over the microphone using predrawn lines on the flat plate, 500 gr vertical thrust added, and by monitoring and tracking SPL output from the microphone a graph was drawn on the Reger mechanoelectric attachment, from which later a constant SPL of 95 dB could be assured as the frequency was swept over the range 0.2-8 kHz. Then, in sequence, Devices 2, 3, and 5 were centered on the coupler and a graph drawn for each, representing differences in output from that of Device No. 1. Fig. 5 shows these data.

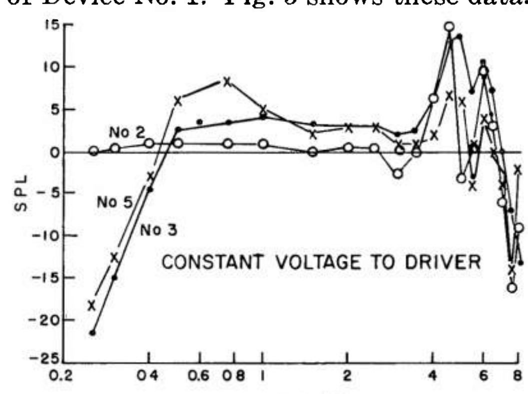

Fig. 5. SPL on Flat-Plate Coupler Developed by Various Devices, Compared to Standard Device No. 1.

B. Results.

For all circumaural devices, the coupler-device interactions at 4+ kHz render specific comparisions practically impossible, as all previous writers have testified. More or less sharp peaks are observed for all devices at about 4.5, 6, and 7.5 kHz, but the exact frequency varies with the device.

C. **Discussion.**

1. **Effect of Thrust.**

In work with a flat-plate coupler, the necessity to specify exactly the total thrust is shown by Fig. 6. Here the "0" line represents the SPL developed by Device No. 5. The entry is the relative SPL developed in Device No. 4 (exactly similar to No. 4 but without the rubber ridge touching the cheekbone). Differences between these two devices are seen to depend partly upon the thrust added, from 350-1000 gr, at frequencies higher than 4 kHz.

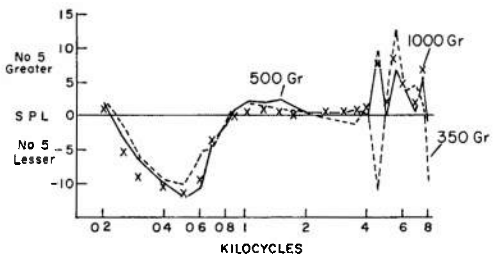

Fig. 6. Comparison of Output of Device No. 4 with that of No. 5 for Three Weights Added to Cushion.

2. **Effect of Probe Tip Position.**

It is not quite immaterial whether these measurements are made with the microphone embedded in the flat-plate coupler, or with a probe tube inserted under the cushion and the tip centered over a dummy microphone. At low frequencies the exact position of the probe tip is negligible, but at higher frequencies this is not the case. Figure 7 shows that for Device No. 5, moving the probe tube tip 0.5 in. off center can affect a high-frequency reading by c. 10 dB. The tip exerts an erratic effect above 4.5 kHz. Evidently, in any future attempt at standardization, the probe tip position would have to be fixed. It would probably be best simply to use the microphone embedded in the coupler.

VII. INTER-METHOD COMPARISONS

A. Threshold Estimates by Probe Tube in the Ear Canal vs 9A Coupler.

Figure 8 gives the two estimates for several devices. Our data on the PDR-8/MX unit corroborate in general the first attempt to compare coupler and probe methods, using identical voltage to the PDR-8 driver (c.f. Corliss and Burkhard[4]. Fig. 2, where consistent differences of 5 dB or more occurred through the audiometric range.) Entries in Fig. 8 are SPLs calculated for voltage corresponding to mean audiometric threshold for a group of 10 normal-hearing young adults. The heavy line is for the driver and MX cushion in a 9A coupler, the light lines for SPL calculated at the ear canal for identical voltage to the driver in Devices 2, 3, and 5.

It is clear that an estimate of threshold SPL at the ear canal matches in no device the SPL developed by the same driver/voltage in the 9A coupler. Variances associated

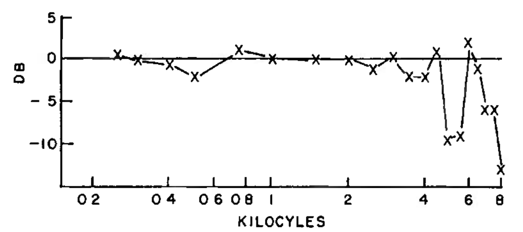

Fig. 7: Shows Equivalence of Position of Probe Tube Tip Through 4 kHz in Measuring SPL under Device No. 5 on Flat-Plate Coupler. NOTE: Entry is amount by which probe tip 0.5-inch off center yields greater SPL than when tip is centered.

both with acoustic characteristics of the coupler at 6 kHz, and with use of probe tube microphony a low as well as high frequencies, tend to obscure similarities in the two estimates using these devices.

B. Threshold Estimates by Flat-Plate Coupler vs 9A Coupler.

But if probe tube microphony cannot solve all the problems of specifying SPL on actual human heads at audiometric "0" for all kinds of earphone/cushion systems (see again Fig. 8 for the differences among devices as to ear canal SPL for constant threshold loudness), then may one look forward to a generalized coupler, in lieu of the human head, able to accept all earphone/cushion systems.

(It is practically immaterial whether the SPL on the flat-plate is measured by a microphone flush with the surface or by a probe tube slipped under the cushion; Fig. 9 shows one such comparison for Device No. 5.)

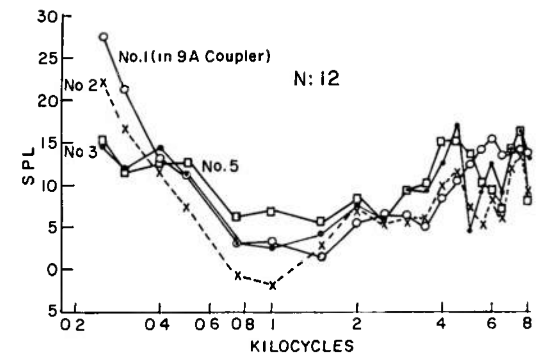

Fig. 8: SPL at Mean Békésy Threshold Measured by Probe Tube Microphone at Entrance to Ear Canal on Devices Nos. 2, 3, 5 Compared to Threshold SPL from Device No. 1 in NBS 9A Coupler.

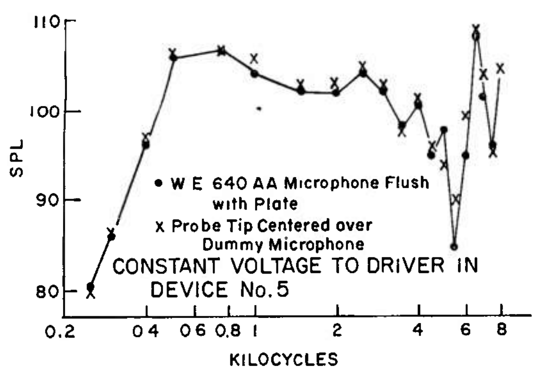

Fig. 9. Shows Equivalence of Methods of Measuring SPL Developed in Flat-Plate Coupler.

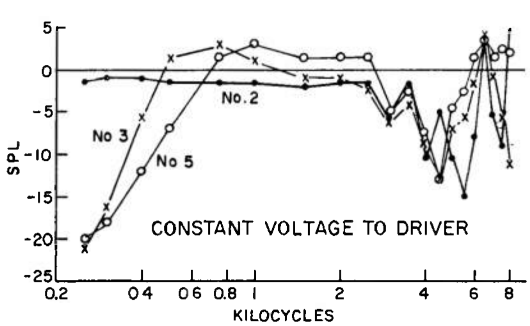

Fig. 10. SPL in Flat-Plate Coupler of Various Devices Compared to SPL in 9A Coupler of Device No. 1.

Fig. 10 shows the now-familiar lack of correspondence between the two estimates of threshold SPL at the extreme frequency regions.

C. Threshold Estimates by Flat-Plate Coupler vs Probe Tube in the Ear Canal.

The relevant question is, can one, with the same probe tube, measure SPL under the same circumaural muff at constant voltage to the driver, whether the muff is placed on a human head or on a flat plate. Representative data, from Devices Nos. 3 and 5, in Figs. 11-12, show this cannot be done above 3 kHz without correcting for serious coupler resonance.

D. Evaluation of Methods of Calibrating Circumaural Earphone/Cushion Units for Use in Audiometry.

No one questions that psychoacoustic loudness balancing from a standard to a new unit provides the most valid data to standardize a new unit. At least, threshold determinations (= balancing at "Zero" loudness) should probably be performed. The simplest solution, the flat-plate coupler, has been shown to contribute resonances with which it would be difficult to deal. The measurement of SPL in the ear canal by probe tube microphony avoids some of the objectionable resonances of any closed coupler, and on a dozen heads can yield mean data flat ± 5 dB over the whole audiometric range 0.5-8 kHz; variance among heads is such that the standard error of a mean SPL for con-

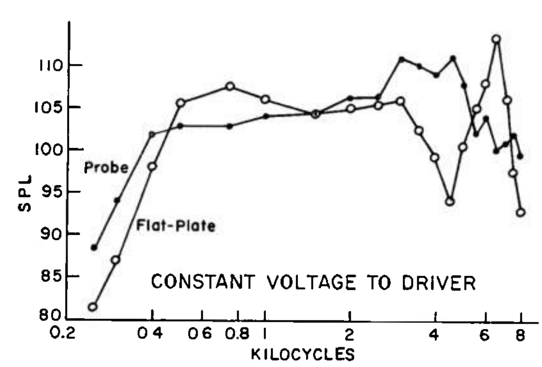

Fig. 11: Comparison of SPL Developed by Device No. 3 on a Flat-Plate Coupler and on Human Heads.

stant voltage need be only 1-2 dB. Thus probe tube microphony should be explored further in connection with proposed new audiometric transducer units. Such data

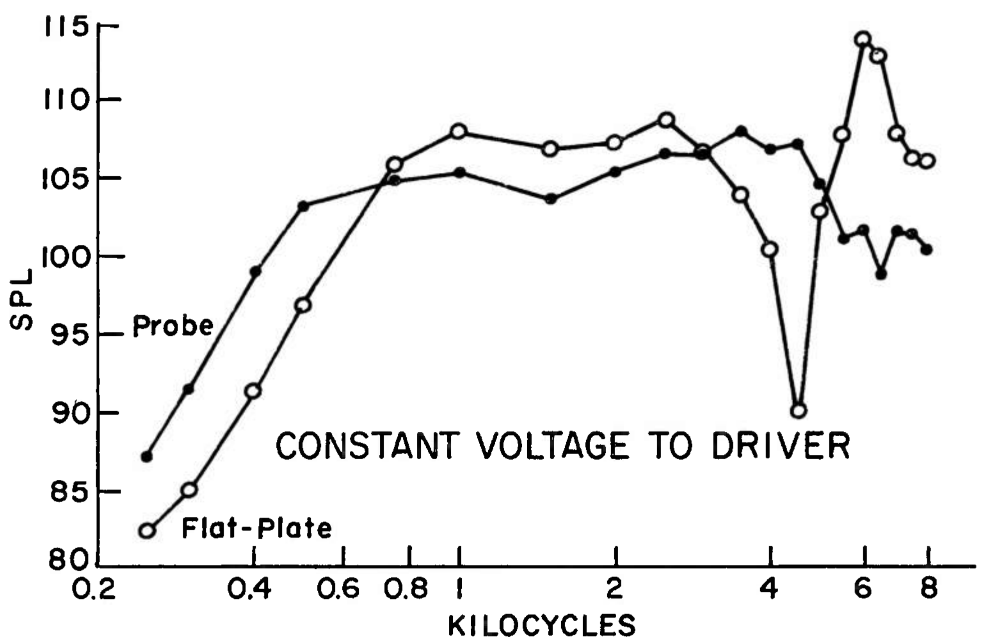

Fig. 12: Comparison of SPL Developed by Device No. 5 on a Flat-Plate Coupler and on Human Heads.

would, however, have to have independent validation — our Fig. 8 shows serious (i.e., erratic) deviations between the SPL developed by the now-standard Device No. 1 in the now-standard 9A coupler, vs the SPL developed in the ear canal when the same driver/voltage was used with Devices 2-5.

Figs. 11-12 show that there is little to choose between the flat-plate coupler method vs the probe microphone method of storing SPL; the human head introduces a leak at low frequencies, but smooths out some resonances and antiresonances at high frequencies. The especial resonance of the human meatus is seen at 3-4 kHz.

For the purpose of stating the SPL for a particular individual at the entrance to the meatus, a direct measurement by probe tube is much the preferable; but for the purpose of storing the acoustic output of a circumaural device for a certain driver voltage, at these frequencies, the coupler is much the preferable.

The best compromise, though perhaps unwieldy, would be to store the output up to three kHz in a flat-plate coupler, and above one kHz with the use of a selection of normal human heads used as passive couplers. Probably it will shortly be within the state of the art to create a standard artificial head incorporating flexible pinnae and a fixed probe tube which could serve all frequency regions.

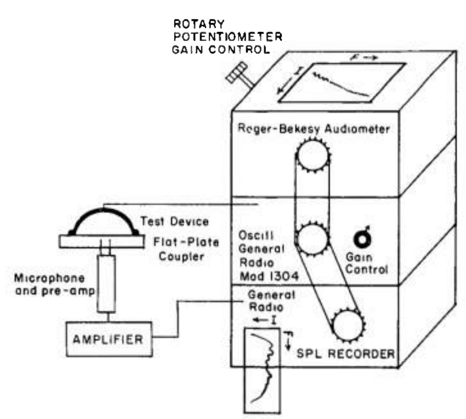

Fig. 13: Block Diagram of Apparatus for Adjusting Voltage to Devices 2-5 to Compensate for Frequency-response of Device No. 1.

E. Comparisons Among Devices as to Suitability for Audiometry.

Each of these devices has some merit for audiometry, with proper precautions. The most economical device and the one with simplest calibration corrections is Device No. 2. However, it offers little or no advantage in attenuation over the standard Device No. 1, and may be dismissed from further consideration.

Device No. 3, suitably calibrated, most reduces the disparity between audiograms from the Standard Device No. 1. Device No. 5 has good attenuation; Device No. 4, with phone, provides the most attenuation of all; with this device, inserting the driver rather adds to than subtracts from the protective function.

None of these devices can be considered interchangeable with the standard unit, even after intensity calibration corrections, above three kHz. In order to use these devices in audiometry, and for some purposes their use is imperative, data should be monitored and certain patients who may well be misclassified should be rechecked using the standard device.

A few specific suggestions may be helpful to some readers: where threshold audiometry is impossible because the ambient noise exceeds the U.S.A.S.I. specifications for such workspaces[22], a change to such a device as No. 5 may render threshold audiometry quite possible. This is also true where the self-noise created by persons in group audiometric situations can mask thresholds with Device No. 1, but perhaps not with Devices Nos. 3-5.

It is only necessary to consider the audiogram above three kHz as a screen, and to set up a recheck procedure for certain individuals. First of all, it must be understood that after acoustic correction any of these devices will, for the majority of individuals, yield the same threshold as the standard unit. However, the precision of the average individual's threshold, in terms of what it would have been with standard Device No. 1 will have deteriorated. Harris and Myers[23] showed that the test-retest deviation at all frequencies of Device No. 1 was only ± 2 dB; but the present data show a deviation of ±5 dB from device to device through 3 kHz, rising to 8-10 dB from 4-8 kHz. Furthermore, the occasional subject (16%) whose

Table I. — Maximum Allowable SPLs in an Audiometric Workspace, for no Masking above the Zero Hearing-Loss Setting of an Audiometer (ASA-1951 Standard) when using Devices 3-4.

Audiometric Frequency	.250	.500	.750	1	1.5	2	3	4	6	8
Relevant Octave-Band	.15 .30	.3- .6	.6- 1.2	.6- 1.2	1.2 2.4	1.2 2.4	2.4 4.8	2.4 4.8	4.8 9.6	4.8- 9.6
Maximum Allowable Spectrum Level for PDR MX Unit*	18	15	12	12	11	16	18	23	25	30
for Device No.3	29.8	26.1	22.9	15.8	15.4	21.7	21.9	31.3	30.3	33.6
for Device No.4**	25.2	29.4	27.8	22.5	18.7	23.4	24	31.7	32.2	35.1
Max. Allowable Octave Band Level for PDR MX	40	40	40	40	42	47	52	57	62	67
for Device No.3**	51.8	51.1	50.9	43.8	46.4	52.7	55.7	65.3	67.3	70.6
for Device No.4**	47.2	54.4	55.8	50.5	49.7	54.4	58.0	65.7	69.2	72.1

* From USASI Specification S3.1-1960, designed for audiometry with standard phone/cushion.

** Corrected for differences in attenuation for Devices Nos. 3 and 4 as established by Myers, versus the attenuation for the PDR/MX unit (see Zwislocki, [12] - Fig. 12).

threshold with any of Devices Nos. 2-5 at some frequency may differ in a critical direction by more than one or two standard deviations, will have to be given special attention.

Suppose, for example, it is important to know whether an ear exceeds a 30-dB Hearing Level (HL) at 8 kHz. Then suppose that by group audiometry using Device No. 3, a subject scores 15 dB HL. Now with the standard deviation of differences of 8.5 dB for Device No. 3 vs Device No. 1, there are 16 chances in 100 that the "true" reading (i.e., with Device No. 1) would be $15 + 8.5 = 23.5$ dB or worse, and 2.5 chances that it would be $15 + 17 = 32$ dB or worse. The exigencies of the situation, particularly the cost of accepting an ear which would fail with the standard unit, must dictate whether the payment of time to recheck with the standard unit all ears with hearing levels of 15 dB or worse at 8 kHz is in fact worth the cost.

We conclude that if the audiometric situation dictates the use of these circumaural Devices Nos. 3-5, and some situations certainly do, the practice is justified only if one institutes monitoring of data and recheck audiometry using a standard device in an acceptable workspace.

VIII. SUMMARY AND CONCLUSIONS

Four common circumaural devices incorporating the identical Permoflux PDR-8 phone were compared with a standard audiometric unit: (a) Békésy thresholds were collected on 12 ears of 6 laboratory subjects, (b) SPL outputs on a flat-plate coupler incorporating a W. E. 640AA microphone were studied with a graphic level recorder, and (c) SPL outputs at the entrance to the meatus were recorded by probe tube microphone for ten normal adult male heads.

It was desired to know whether any or all of the four devices could simply replace the standard device, with some acoustic corrections for mean deviations from the standard device.

It was found by psychoacoustic threshold-testing that all four devices yielded the same means ± 5 dB through 0.5-8 kHz, but that the standard deviation of individual differences between any device re the standard device was 5-10 dB at 4 kHz and above for all devices; thus for an appreciable number of individuals the devices are not in fact interchangeable in audiometry.

Attempts to specify threshold SPL produced by each device by probe tube microphony at the entrance to the external meatus were only partially successful. Mean data were stable through 0.5-8 kHz, but again individual variances at 4 kHz and above indicate that equal loudness does not yield exactly equal SPL at the probe tip.

A suggestion was made to standardize a flat-plate coupler with the edge of the W. E. 640AA microphone flush with the surface. However, although such a coupler can well store mean threshold SPL for any circumaural device, acoustic interactions between device and coupler render specific comparisons among devices of little use at 4+ kHz without psychoacoustic corroboration.

If reliance is to be placed on physical rather than psychoacoustic methods of using circumaural devices, a flat-plate coupler should be used to store mean threshold SPL; but to state the threshold SPL developed in a particular ear, a probe microphone should be used. An appropriately constructed artificial head is suggested as a future compromise.

The circumaural devices tested, with their greatly superior noise attenuation, can with certain precautions be used in screening audiometry where the noise levels cannot possibly be reduced to acceptable levels. The increase in permissible noise levels is documented here. The precautions to be taken are that any ear which does not exceed by about 15 dB any desired criterion hearing loss, at 4, 6, and/or 8 kHz, must be rechecked with the standard device in an acceptable workspace.

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APPENDIX

Creating Voltage to Devices 2 . . . 5, Adjusted for Output in SPL of Device No. 1 (see Fig. 13)

Note: A single motor drives both paper tapes on similar log frequency scales.

Step 1: Device No. 1 is placed on the flat-plate coupler, and as frequency is slowly swept upward, the gain control of the oscillator is adjusted manually to yield a horizontal line (constant SPL) on the General Radio graphic level recorder. At the same time, the pen of the Reger-Békésy attachment automatically produces a voltage change at the output of the rotary potentiometer, which is recorded on log-frequency paper.

Step 2: Device No. 2 . . . 5 replaces No. 1, and frequency is turned back to 200 Hz.

Step 3: Frequency is slowly swept upward, while experimenter manually adjusts the rotary potentiometer so that the Reger-Békésy pen traces the same path as in Step 1. This presents to Device No. 2 . . . 5 the same voltage program as had been the case in Step 1. Simultaneously, the pen of the General Radio graphic level recorder traces the SPL produced by Device No. 2 . . . 5.

Step 4: Difference between the horizontal tracing of SPL on the General Radio recorder in Step 1, and the tracing in Step 4, is a picture of the difference in frequency response of the two devices when both are presented with the identical voltage.

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13 ABSTRACT

Four circumaural muffs were compared with the phone/cushion device now standard for audiometry, the Willson "Sound-Barrier", the Maico "Auraldome", and 2 versions of the Tracor "Otocup". Psychoacoustic loudness balancing by normal subjects was performed, and physical measurements by probe-tube microphone and by flat-plate coupler. Neither physical method was related closely enough at 4+ kHz to the fundamental loudness balancing to serve as an independent calibration system for all circumaural muffs. Need was expressed for a standard artificial head incorporating flexible pinnae and a fixed probe microphone. At present, circumaural devices can reasonably be used from 0.5-3 kHz, but at 4+ kHz any audiometry should be considered only a screening procedure, with individual recheck using the standard device in an acceptable workspace to examine all ears which do not exceed by 15 dB any criterion set by the demands of the situation.

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