

Revised estimate of minimum audible pressure: Where is the "missing 6 dB"?^{a)}

Mead C. Killion

Industrial Research Products, Incorporated, A Knowles Company, Elk Grove Village, Illinois 60007
(Received 18 November 1976; revised 9 November 1977)

Eardrum pressures at hearing threshold have been calculated from both earphone data (ISO R389-1964 and ANSI S3.6-1969) and free-field data (ISO R226-1961). When head diffraction, external-ear resonance, and an apparent flaw in ISO R226 are accounted for in the free-field data, and real-ear versus coupler differences and physiological noise are accounted for in the earphone data, the agreement between the two derivations is good. At the audiometric frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz, the estimated eardrum pressures at absolute threshold are 30, 19, 12, 9, 15, 13, and 14 dB SPL, respectively. Except for the effects of physiological noise at low frequencies, no evidence of the "missing 6 dB" is seen, an observation consistent with the experimental results of several recent studies.

PACS numbers: 43.66.Cb, 43.66.Sr

INTRODUCTION

The term "Minimum Audible Pressure" (MAP) was first used by Sivian and White (1933) to describe threshold determinations "in terms of the pressure amplitude at the observer's eardrum." Unfortunately, the term MAP has also sometimes been used to mean the *coupler* pressure corresponding to the threshold calibration of a given earphone. To avoid confusion, in this paper the term MAP will be used only with regard to eardrum pressure; the term "Minimum Audible Pressure in a Coupler" (MAPC) will be used when reference to coupler pressures is intended. (MAPC so defined is equivalent to the "reference equivalent threshold sound pressure level" of ISO R389-1964 and the "reference threshold level" of ANSI S3.6-1969.)

Since the Sivian and White study, numerous studies of both earphone MAPC and free-field MAF (Minimum Audible Field, the threshold sound pressure at the listener's position [listener absent] due to a sound source in front of that position) have been made, and international standards exist for both MAPC and MAF (ISO R389-1964 and ISO R226-1961, respectively). In addition, several independent studies of the relationship between free-field pressure and eardrum pressure, and between earphone-coupler pressure and eardrum pressure, have been made. A comprehensive compilation of all available data on the ratio of eardrum pressure to free-field pressure was published by Shaw in 1974, along with a self-consistent set of "best-fit" average curves for both free-field-to-eardrum and earcanal-entrance-to-eardrum transfer ratios.

By combining the available psychoacoustic and physical acoustic data, following the procedure discussed by Pollack (1949), it is possible to arrive at a single estimate of MAP. This paper reports one such estimate. Although the author has found the present estimate quite useful on several occasions, it will undoubtedly require revision as more direct evidence becomes available. The chief purpose of this paper is not to recommend

acceptance of the present MAP estimate, but to demonstrate that the apparent differences in commonly accepted threshold values for earphone and free-field listening are easily reconciled.

I. NEW ESTIMATE OF MAP

Figure 1 shows the result of the present study as a single estimated eardrum pressure (MAP) curve. Vertical bars at each of the standard audiometric frequencies indicate the differences between the average data derived from earphone MAPC studies and from free-field MAF studies. Agreement between the two approaches is excellent between 1000 and 3000 Hz (typically less than 1.5 dB difference between the two determinations), and not as good at lower and higher frequencies. At very low and very high frequencies (below 100 Hz and above 8000 Hz), the curve of Fig. 1 was estimated from the studies discussed in Sec. IC, below.

The remainder of this paper contains a discussion of the derivation of Fig. 1 and of possible explanations for the less-than-perfect agreement between the two approaches at both low and high frequencies. The reader uninterested in the details may skip to the Discussion and Recommendations.

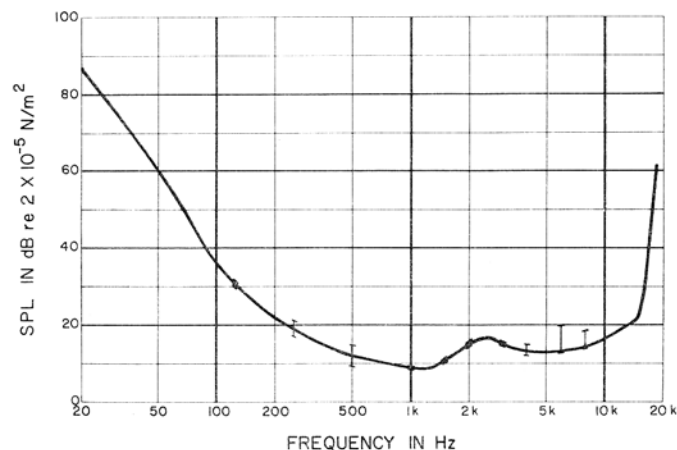


FIG. 1. The present estimate of monaural Minimum Audible Pressure at the eardrum. Vertical bars indicate the difference between the averages of MAF-derived and MAPC-derived data.

^{a)} Presented 19 November 1976, at the 92nd meeting of the Acoustical Society of America, San Diego, CA.

A. The estimation of MAP from MAF data

The sound pressure level in a free field of a sinusoidal, 0°-incident sound wave which is just audible to an observer is usually referred to as his Minimum Audible Field (MAF). The measurement of sound pressure level is made with the subject absent, at a point corresponding to the center of the subject's head. The corresponding eardrum pressure, therefore, will be generally higher due to head and ear diffraction and resonance [see, for example, Wiener and Ross (1946) and Shaw (1974)].¹

Three important MAF studies cover the audible frequency range: the Sivian and White study (1933), the British study of Churcher and King (1937), and the British National Physical Laboratory (NPL) study of Robinson and Dadson (1956). In addition, the 0-dB-loudness-level curve of Fletcher and Munson (1933) provided an estimate of MAF based on an extrapolation back to zero from suprathreshold loudness measurements performed with field-calibrated earphones.

In the late 1950's, international agreement was reached on a standard curve for absolute binaural threshold (and equal-loudness contours) for normal, young ears. The result was ISO R226-1961, whose threshold values are shown in Fig. 2.

With the exception of the data at low frequencies, the ISO R226 values appear to represent a reasonable consensus of the available data. At low frequencies, however, the available data suggest that the ISO values are too low. Figure 3 shows a comparison of the various 100-Hz MAF values obtained at six different laboratories. In the three cases where the original study determined a monaural threshold, 2 dB has been subtracted to obtain an estimate of the binaural threshold.² Five out of six laboratories obtained results indicating the normal binaural MAF at 100 Hz is within 2 dB of 33 dB SPL. This is discrepant from the 25 dB SPL at 100 Hz given in ISO R226-1961.³ [The 100-Hz MAF estimate of 37 dB obtained by Fletcher and Munson (1933) was not included in Fig. 3 because it was an indirect estimate.]

Since the weight of evidence at 100 Hz is in support of the original Sivian and White and the later Churcher and King studies, it seems reasonable to take an aver-

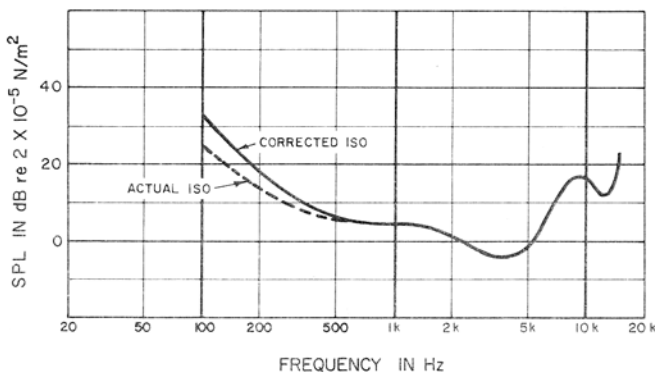


FIG. 2. Binaural Minimum Audible Field (0° incidence) from ISO R226-1961, with low-frequency correction. (See text.)

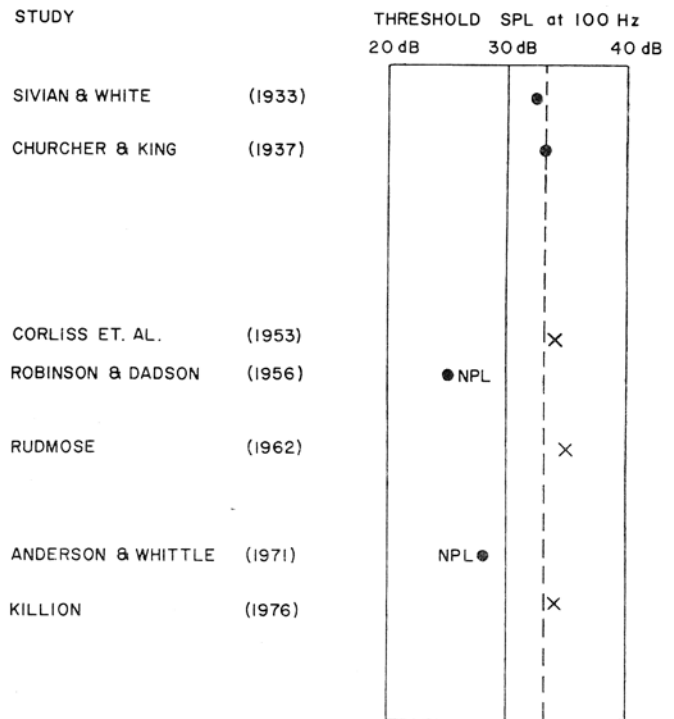


FIG. 3. 100-Hz free-field thresholds (MAF) obtained at various laboratories: (●) binaural; (x) monaural minus 2 dB.

age of their data in the 100–400 Hz region to obtain a “corrected R226 curve.” The data shown in Table I and as the solid curve in Fig. 2 were obtained in that manner: At 500 Hz and above they are identical with ISO R226, whereas between 100 and 400 Hz they are the average of the (dB) values shown in Fig. 10 of the 1933 Sivian and White paper and in Fig. 9 of the 1937 Churcher and King paper. (In the 200–400-Hz region, the curve changes less than 0.5 dB at any frequency if the Robinson and Dadson and the Fletcher and Munson data are included in the average.)

To convert the MAF data in Table I to MAP (eardrum-pressure) data requires only the subtraction of the eardrum-pressure/free-field-pressure ratio (in dB) given by Shaw (1974). In addition, a decision must be made as to how much correction should be applied to convert the resulting binaural data to monaural data. A “monaural disadvantage” of 2 dB was added² to obtain the final estimate of MAP shown in Table I and as the dashed curve in Fig. 5.

B. Estimation of MAP from earphone-MAPC data

Although the term MAP was originally used by Sivian and White to describe threshold “in terms of the pressure amplitude at the observer's eardrum,” it has since been used by others to refer to earphone thresholds where the pressure developed with the “threshold voltage” applied to the earphone is measured in what was intended to be an ear-like reference coupler such as the NBS-9A. This has been a perversion of the original meaning, since the pressure measured in the reference coupler often bears little resemblance to the pressure at the observer's eardrum. Unfortunately, the

TABLE I. Derivation of minimum audible pressure at the eardrum from minimum audible field data. Data are in decibels.

Freq. (Hz)	A MAF (ISO R226 corrected)	B P_D/P_{FF} at 0° ^a	C MAP (binaural)	D MAP (monaural)
100	33		33	35
150	24		24	26
200	18.5	0.5	19	21
300	12	1.3	13.3	15.3
400	8	1.6	9.6	11.6
500	6	1.7	7.7	9.7
700	4.7	2.8	7.5	9.5
1000	4.2	2.6	6.8	8.8
1500	3	5.0	8.0	10.0
2000	1	12.0	13.0	15.0
2500	-1.2	16.8	15.6	17.6
3000	-2.9	15.4	12.5	14.5
3500	-3.9	14.8	10.9	12.9
4000	-3.9	14.2	10.3	12.3
4500	-3	12.8	9.8	11.8
5000	-1	10.7	9.6	11.6
6000	4.6	7.4	12.0	14.0
7000	10.9	4.3	15.2	17.2
8000	15.3	1.8	17.1	19.1
9000	17	-0.7	16.3	18.3
10 000	16.4	-1.6	14.8	16.8

^a P_D/P_{FF} is the ratio of eardrum pressure to free-field pressure as given by Shaw (1974).

^bA constant 2 dB was added to convert binaural to monaural thresholds; thus, the MAP derived in Column D is the sum of Columns A and B plus 2 dB.

term MAP has been used in the latter sense for so long that it now seems to be part of the entrenched jargon of psychoacoustics and audiology.

As the pioneers in audiology quickly discovered, the coupler pressure corresponding to threshold depended on the earphone system used with the audiometer. Moreover, an enormous amount of work went into the determination of the "normal threshold," resulting first in the 1951 ASA standard Z 24.5 and later in the revised values found in the ISO R389-1964 standard. A round robin of loudness balances and threshold comparisons between various laboratories preceded the agreement on ISO R389-1964 (Weissler, 1968), a relatively self-consistent international standard listing the coupler pressures corresponding to threshold for one "standard earphone type" from each of five different countries. The U.S. standard earphone was the Western Electric 705A which, unfortunately, is no longer in production. A substantial additional amount of work within the United States resulted in ANSI Standard S3.6-1969, which included a suggested calibration of four additional earphones; three Permaflux earphones and the Telephonics TDH-39. (Each earphone is to be mounted in an MX41/AR earphone cushion and the reference pressure measured in the NBS-9A coupler.) Additional earphone-coupler combinations are included in the 1975 edition of ISO R389.

Both the TDH-39 and the Beyer DT-48 earphone have MAPCs specified in terms of NBS-9A coupler pres-

sure. By applying the data obtained by Shaw (1966) on the ratio of canal-entrance pressure to NBS-9A pressure for these two earphones, these MAPC values can be converted to represent ear-canal-entrance pressures. By further applying Shaw's 1974 data on the ratio of eardrum pressure to ear-canal-entrance pressure, one obtains the calculated MAP at the eardrum. Table II shows these calculations for the TDH-39 and the DT-48 earphones.

In addition to these data, a careful study of the thresholds of 25 male and female subjects ranging from 18 to 26 years of age was reported by Albrite *et al.* (1958) using the WE 705A headphone. In that study, the actual sound pressure level developed in front of the earphone grill was measured with a probe microphone. As would be expected from physical considera-

TABLE II. Derivation of Minimum Audible Pressure at the eardrum from MAPC data on three earphones. Data are in decibels; data marked with an asterisk are extrapolated.

Freq. (Hz)	A P_C^a (MAPC)	B P_E/P_C^b	C P_D/P_E^c	D P_D/P_C	E MAP ^d
TDH-39					
125	45	-19*	0	-19*	26
250	25.5	-7	+0.2	-6.8	18.7
500	11.5	+2.5	+0.7	+3.2	14.7
1000	7	+3.0	+1.2	+4.2	11.2
1500	6.5	+2.5	+2.4	+4.9	11.4
2000	9	+3.5	+3.8	+7.3	16.3
3000	10	-1.5	+8.5	+7.0	17.0
4000	9.5	-4.5	+10.2	+5.7	15.2
6000	15.5	+1.0	+3.7	+4.7	20.2
8000	13	+4.5	+1.5	+6.0	19.0
DT-48					
125	47.5	-16.5*	0	-16.5*	31
250	28.5	-5.5	+0.2	-5.3	23.2
500	14.5	0	+0.7	+0.7	15.2
1000	8	0	+1.2	+1.2	9.2
1500	7.5	+1.5	+2.4	+3.9	11.4
2000	8	+3	+3.8	+6.8	14.8
3000	6	+0.2	+8.5	+8.7	14.7
4000	5.5	0	+10.2	+10.2	15.7
6000	8	+8	+3.7	+11.7	19.7
8000	14.5	-3.5	+1.5	-2.0	12.5
705-A					
125		42	0		42
250		26	+0.2		26.2
500		16	+0.7		16.7
1000		7	+1.2		+8.2

^aThe earphone-MAPC data represent NBS-9A coupler pressure as found in ANSI S3.6-1969 for the TDH-39 earphone in MX41/AR cushion, and from ISO R389-1964 for the Beyer DT-48 earphone in the supra-aural cushion.

^bShaw (1966).

^cShaw (1974).

^dThe sum of columns A-C.

tions, and as was experimentally verified by Villchur (1969), the pressure measured at that location and the pressure measured at the entrance to the ear canal are essentially identical at 1000 Hz and below. Thus, at the four audiometric frequencies below 1500 Hz, the data of Albrite *et al.* can be converted directly to eardrum pressure, using only the correction given by Shaw (1974). These data are also found in Table II.

1. Potential errors

For the low-frequency data in Table II, the correction from the NBS-9A coupler to the ear-canal-entrance data of Shaw (1966) represents an average of ten subjects. The value used at 125 Hz was extrapolated (on a 12-dB/oct slope) from Shaw's curve at 200 Hz and above. Even at 250 Hz, however, Shaw found an 18-dB range across the ten subjects due to the well-known cushion-fit variability. Villchur (1970) reported a range of over 25 dB at 125 Hz for the TDH-39/MX41-AR on 13 subjects—a number in substantial agreement with the 27-dB range at 100 Hz previously reported by Burkhard and Corliss (1954) for the PDR-8/MX41-AR combination. It is not too surprising, therefore, that the three estimates of eardrum pressure shown in Table II have a 16-dB range at 125 Hz, and that even at 250 Hz there is a 7-dB difference between the extremes of the three estimates.

The 125-Hz and 250-Hz thresholds are essentially masked thresholds due to the physiological noise generated under the earphone cushion. Based on the data of Rudmose (1962) at 100, 200, and 400 Hz, an interpolated value of 4.5 dB at 125 Hz and 1 dB at 250 Hz is obtained for the threshold elevation due to the physiological masking when using the TDH-39/MX41-AR earphone. This correction was simply applied to the overall averages in Table II. In light of the variability among estimates at these frequencies, a more elaborate analysis hardly seems justified.⁴

Shaw's data on the ratio of coupler pressure to ear-canal-entrance pressure was obtained with a modified NBS-9A coupler, where the 1-in.-diam laboratory standard microphone was replaced with a rigid plate containing the small inlet of the same probe tube used for measuring ear-canal-entrance pressures. This had the great advantage of eliminating the possibility of error due to the use of two different microphone setups, with their differing frequency responses, sensitivities, etc. When the frequency is high enough, however, the standing waves set up in any coupler can cause a difference between the pressure in the center of the coupler (at the probe pickup point) and the pressure averaged over the active diaphragm area of standard microphones. An estimate of the possible effect of such standing waves in the NBS-9A coupler indicated that there might be a small effect at the 6- and 8-kHz audiometric frequencies, but that it was unlikely to have altered the data at the lower frequencies. This conclusion was checked experimentally by the author recently, with the finding that the maximum error below 10 kHz is of the order of a few tenths dB as long as the 9A coupler length is increased by the amount necessary

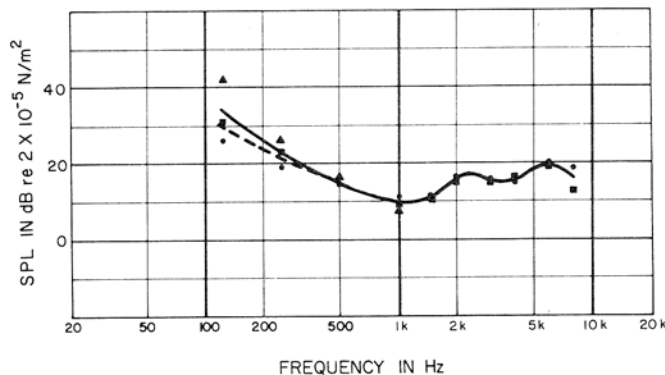


FIG. 4. MAP calculated from earphone-MAPC data (solid curve) and corrected for the effect of physiological noise below 500 Hz (dashed curve). Data on individual earphones are shown for the TDH-39/MX41-AR (\bullet), DT-48 (\blacksquare), and 705A (\blacktriangle).

(around 2 mm) to compensate for the equivalent volume of the standard 1-in. microphone. (Shaw's data were obtained with such a coupler modification.) Without such a modification, the error can exceed 0.5 dB at low frequencies and 1.0 dB (in the opposite direction) at high frequencies.

The acoustic impedance of the particular TDH-39 and DT-48 earphone samples used at various laboratories might have differed enough to affect the data at high frequencies. Although often ignored, variations in source impedance are always a potential source of error when probe-tube determinations of the real-ear response of one sample of an earphone type are compared to threshold or loudness balance data obtained using a different sample(s). (Note that this error can occur even when the number of human subjects appears adequate to rule out significant real-ear sampling errors in both cases.)

The application of the earphone to the ear changes the dimensions of both the outer ear and the ear canal itself. The change in pinna and concha shape are taken care of automatically in the data since Shaw's sound pressure measurements were made at the ear canal entrance. The constriction of the ear canal, however, can cause changes of up to at least 5 dB in the ratio of eardrum pressure to canal-entrance pressure at frequencies in the 3-6-kHz region, as shown by Villchur (1969).⁵

2. The final earphone-derived MAP estimate

Figure 4 shows the earphone-derived MAP estimates of Table II, with the data derived from each of the three studies plotted separately. The dashed curve below 500 Hz shows the effect of correcting the average for physiological noise, as discussed above. The close agreement above 250 Hz suggests that earphone-sampling errors were not significant. Because of the other potential errors discussed above, however, one concludes that only in the region between 500 and 3000 Hz should one expect to find a correspondence between the MAP derived from earphone MAPC data and from free-field MAF data. Nonetheless, the data at all audiometric frequencies have been averaged (the Albrite

et al. data were included only at 1000 Hz and below for the reasons given above) and corrected for physiological noise. The averaged data are shown in Table III and plotted as the dotted curve in Fig. 5.

C. MAP above 8000 and below 100 Hz

For completeness, the present MAP estimate has been extended above 8000 and below 100 Hz, as shown by the heavy dashed curves in Fig. 5. These extensions were based directly on the studies described below.

Northern *et al.* (1972) reported a study of high-frequency audiometric threshold levels in the 8000–18 000-Hz range. The result of that study was a set of recommended high-frequency threshold values expressed in terms of eardrum SPL. The heavy dashed curve above 8000 Hz in Fig. 5 (and the extended solid curve above 8000 Hz in Fig. 1) follows their recommendations directly.

Corso (1958) and Yeowart and Evans (1974) reported independent studies of low-frequency thresholds. In both studies, unusual care was taken to avoid contamination of the results due to physiological noise, harmonic distortion, and vibrational artifacts. At most frequencies, the two studies agree within a few dB. The heavy dashed curve below 100 Hz in Fig. 5 (and the extended solid curve below 100 Hz in Fig. 1) was drawn smoothly through data points from the two studies.

D. The new estimate

Figure 5 shows a comparison between the calculated MAP derived from free-field MAF data (thin dashed curve) and from earphone MAPC data corrected for physiological noise (dotted curve). There is a difference of 6 dB at 500 Hz, but the rest of the data in the 500–3000 Hz region—where both transformations are on solid footing—is in excellent agreement: The maximum difference is 1.6 dB, and the average difference is 1.2 dB ignoring sign and 0.4 dB including the sign of the differences. As expected, the data at 4 kHz and above do not agree as well, although even here the average difference is less than 4 dB ignoring sign and less than 2 dB including the sign of the differences. By what must be sheer coincidence, the data at 250 and 125 Hz

TABLE III. Average of three earphone-derived MAP estimates shown in Table II.

Freq. (Hz)	Average	Correction for physical noise	MAP
125	33	-3.5	29.5
250	22.7	-1	21.7
500	15.5	0	15.5
1000	9.5		9.5
1500	11.4		11.4
2000	13.9		13.9
3000	15.9		15.9
4000	15.5		15.5
6000	20.0		20.0
8000	15.7		15.7

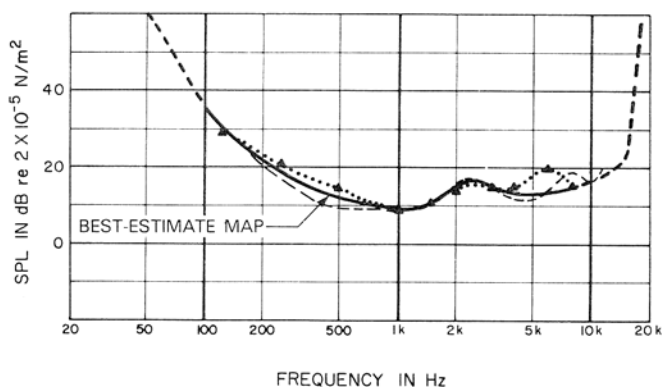


FIG. 5. MAP estimates derived from earphone-MAPC data corrected for physiological noise (triangles and dotted curve) and free-field MAF data (light dashed curve). Solid curve represents the present estimate of MAP shown in Fig. 1. The extensions below 100 Hz and above 8000 Hz (heavy dashed curves) are discussed in the text.

are also in excellent agreement.⁶ The solid curve shown in Fig. 5 is the (author's) best-estimate MAP curve of Fig. 1. In arriving at this estimate, little weight was given to the MAPC-derived data in the 3000–6000-Hz region for the reasons discussed in Sec. IB 1. Above 6000 Hz, the curve was drawn to blend smoothly with the high-frequency MAP recommendations of Northern *et al.* (1972), which were based on direct measurements of eardrum pressure.

It is interesting to note that the solid curve in Fig. 5 is not far from the probe-tube MAP data obtained by Sivian on eight ears (1928, unpublished) and reported in a little-noticed series of paragraphs in Sivian and White (1933). The probe tube was located 1–1.5 cm from the eardrum in two sets of experiments they described as follows:

The results given in Fig. 9 represent the average of two determinations. In both, the ear is exposed to a fairly loud tone from a loudspeaker, and the pressure in the ear canal is measured with a search tube.

From the attenuation of the loudspeaker current required to produce threshold, the MAP values are computed. The chief assumption is that the search tube pressures are equal to the drum pressures.

In a second procedure, a telephone receiver is made to produce in the ear a loudness sensation equal to that caused by the loudspeaker. The receiver current is then attenuated to threshold. From this attenuation, and from the above search tube pressure measurement, the absolute MAP value is derived.

Since the attenuation measured by both methods were found to agree fairly well, it was considered justifiable to average the results.

Figure 6 shows a comparison between Sivian's data and the MAP curve derived in the present study. Sivian's data are plotted as reported. Correction for the mid-canal location of his probe tube would improve the agree-

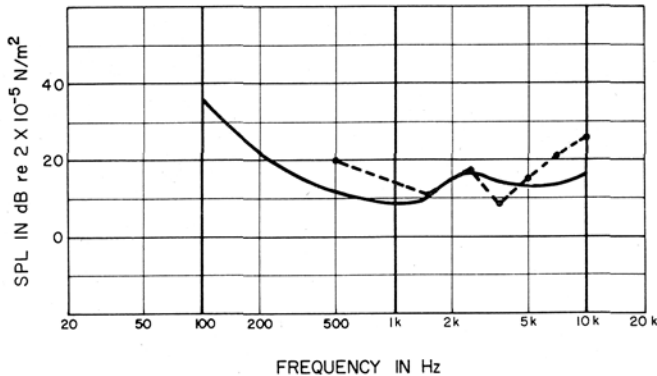


FIG. 6. The 1928 probe-tube MAP data of Sivian (dashed curve) compared to the present MAP estimate (solid curve).

ment at high frequencies between Sivian's data and the present estimate.

II. DISCUSSION

The comparison of eardrum pressure at absolute threshold derived from available MAF and MAPC data reveals a good agreement. It is no surprise that threshold occurs at a constant eardrum pressure; this has been generally accepted as fact since the so-called "missing 6-dB problem"⁷ was put to rest by the studies of Rudmose (1962, 1963), Shaw and Piercy (1962), Shaw (1969), Villchur (1969, 1970, 1972), Anderson and Whittle (1971), Tillman *et al.* (1973), Morgan and Dirks (1974), and Stream and Dirks (1974). It is somewhat surprising, however, to see such close agreement between two sets of psychoacoustic data, each of which was arrived at in such a roundabout way.

The combined middle- and inner-ear response appears to have a dip in sensitivity (increase in threshold) near 2700 Hz, where head and ear diffraction effects produce the maximum eardrum pressure (not at a 4 kHz as has sometimes been erroneously reported). One wonders if the outer-, middle-, and inner-ear system was simply designed so that all the elements cooperated to produce the best overall performance compromise, or if the 2500-Hz "hump" seen in the MAP curve of Fig. 1 is simply an artifact of some sort. The excellent agreement between the two MAP derivations in the 2500-Hz region lends credence to the former hypothesis, although careful probe-tube monitored threshold measurements performed by the author on one (!) ear showed no signs of such a hump.

One potential explanation for the increased threshold near 2500 Hz is masking due to the Brownian noise pressure at the eardrum, which exhibits a substantial peak at the 2700-Hz resonance of the outer ear. Recent estimates by Shaw (1976) of the real part of the acoustic impedance seen looking out from the eardrum permit the estimate of a noise spectrum level of -29 dB SPL at the eardrum at 2700 Hz. Preliminary noise measurements made with a low-noise XD-985 subminiature microphone (Killion, 1976) at the eardrum position of a KEMAR manikin (Burkhard and Sachs, 1975) appear to confirm this tentative estimate, although a

microphone with a substantially lower noise level will be required to obtain precise confirmation. A spectrum level of -29 dB SPL at the eardrum at 2700 Hz is 24 dB below the approximately -5 dB SPL spectrum level which would be required to explain the 16-dB value for MAP at 2700 Hz shown in Fig. 5. The effect of Brownian noise pressure at the eardrum thus appears inconsequential even for an extremely acute ear, a conclusion consistent with the estimates of other authors. (A somewhat expanded discussion of real-ear noise sources and their effects can be found in Killion, 1976.)

Although no estimate of the noise pressure produced by the damping resistance in the TDH-39 earphone has been attempted, it seems most unlikely that it would be significant. Peaks in noise pressure would be expected at the resonances of the earphone, however, and the primary resonance of the TDH-39 does occur at roughly 3 kHz.

Noise-induced hearing loss might provide an explanation for the reduced sensitivity in the 2500-Hz region, except such loss normally occurs a half-octave above the frequency of maximum stimulation (Davis *et al.*, 1950). With the typical 2700-Hz resonance frequency for the outer ear, the greatest noise-induced hearing loss might be expected to occur near 4 kHz. Recent temporary-threshold-shift (TTS) experiments performed by Caiazzo and Tonndorf (1977) appear to confirm the hypothesis that the characteristic 4-kHz notch of noise-induced hearing loss is mainly related to outer ear resonance: By artificially doubling the length of the ear canals of 15 subjects, they found a maximum TTS at 2 kHz under the same noise-field conditions which produced a maximum TTS at 4 kHz with the subjects own (unaltered) ear canals.

Perhaps the 2500 Hz sensitivity dip will ultimately be explained by the characteristics of the eardrum-to-basilar-membrane transformation. As shown by Dallos (1973), a similar sensitivity dip in the MAP curve for the cat can be nicely explained on the basis of the middle-ear transfer characteristics.

III. RECOMMENDATIONS

Several suggestions previously made by others perhaps bear repeating here. Following the recommendations of Corliss and Burkhard (1953), the standardization of audiometric zero levels would be substantially simplified if audiometric zero levels were expressed in terms of eardrum pressures instead of coupler pressures corresponding to a specific earphone. This would allow use of a relatively simple probe-microphone procedure (such as described by Villchur and Killion, 1975) to establish threshold norms for a new earphone system.⁸ The same procedure should also allow validation and/or correction of the MAP estimate given in this paper.

Similarly, anyone contemplating psychoacoustic experiments in which the absolute level of the stimulus (or the relative level between two stimuli having different frequencies) is important would do well to include some means of determining that level on an individual

basis. And given the large variations in earphone cushion fit from trial to trial shown by Villchur (1970) for the TDH-39 in either the MX-41/AR or the Zwislocki cushion, a single-sitting determination of the level appears risky if more than one experimental session is contemplated. As Munson and Wiener (1950) observed, many apparently anomalous results in the literature of psychoacoustics can be explained if the failure of the experimenters to obtain real-ear measurements of stimulus levels is taken into account.

Lastly, the overwhelming weight of experimental evidence indicates that anyone finding a "missing 6 dB" in his data would do well to look for (a) inadequate determination of actual stimulus levels, (b) physiological noise, (c) transducer distortion, (d) mechanical vibration coupled to the subject, or one of the several other artifacts which Rudmose (1962, 1963) uncovered in ten years of work on the subject. There *are* very real differences between MAF and MAP—differences which must be taken into account in the calibration of speech audiometers, for example—but they are readily accounted for by the physical factors involved. In short, nothing is really missing.

ACKNOWLEDGMENTS

The author is indebted to Wayne Rudmose for several fascinating discussions on the "missing 6 dB" problem, and to Edgar Villchur and Mahlon Burkhard for extensive suggestions made regarding an earlier draft of this paper.

¹Additional variations in eardrum pressure are caused by the exact vertical location of the subject, reflections from the chair, reflections from the subject's shoulders, arms, legs, etc. These have not always been well specified, as discussed by Shaw (1974).

²Fletcher and Munson (1933) found a 1.8-dB average difference in acuity between the best ear and the average of both ears for frequencies below 2000 Hz, but only a slight difference between the binaural and best-ear threshold. Assuming Pollock's (1948) finding of an 0.8-dB improvement in binaural versus best-ear threshold when the sensation levels at the two ears differ by 3 dB, one could refine the average-binaural-advantage estimate to approximately 2.6 dB. (The 1.8-dB difference of Fletcher and Munson is equivalent to an average sensation-level-difference of 3.6 dB between ears receiving binaural stimulation at equal intensity levels.) Assuming an across-the-board binaural advantage of 2 dB appears sufficiently accurate for our purposes, however.

³The ISO standard relied heavily on the Robinson and Dadson study at frequencies below 300 Hz. One explanation for the apparent flaw in the NPL determination may be that vibrations transmitted through the observer's chair caused a reduced "threshold." Rudmose (1962) found that the standard free-field audiometry setup could sometimes produce artificially low thresholds at low frequencies; the summation of the direct airborne stimulus and the tactile stimulus caused by chair vibrations allowed the subject to hear a below-threshold airborne stimulus which he could no longer hear when the chair vibrations were eliminated. One cannot help noticing a similar discrepancy in the earphone study reported by Albrite *et al.* (1958): Although both NPL and NBS obtain the same "threshold voltage" on a 4026A earphone they exchanged, the probe-tube real-ear average sound pressure measured by NPL was some 12 dB less at 125 Hz than a similar mea-

surement made on the same earphone by NBS (see Figs. 4 and 6 of that paper).

⁴Other investigators have obtained higher estimates of the masking due to physiological noise. Villchur (1970) obtained 6 dB at 125 Hz and 5 dB at 250 Hz for the MX41/AR cushion. At the same time, Villchur appears to have obtained lower real-ear response levels in his measurements of the TD-39/MX41-AR combination (his Fig. 2) than the values used in Table II. The two effects would tend to cancel, i.e., the final threshold estimates based on Villchur's data would be similar to those obtained here. Anderson and Whittle (1971) obtained 11 dB of masking due to physiological noise at 125 Hz, although this estimate was obviously influenced by the unusually low MAF values they obtained (see Fig. 3, this paper). In any case, only Rudmose (1962) appears to have taken great pains to isolate his subjects from mechanical vibrations, so only his data are used here. It is of some comfort to note that the resulting MAP estimate of 29.5 dB at 125 Hz (Table III) is nearly identical to the 15-subject average of 30.6 dB obtained by Corso (1958) at 125 Hz, since the large-volume construction of Corso's electrodynamic driver should have resulted in greatly reduced physiological noise (see Rudmose, 1962; and Shaw and Piercy, 1962).

⁵We assume here that subjects whose canals collapse almost completely under earphones—representing roughly 4% of the population according to Hildyard and Valentine (1962)—were excluded from all studies on the basis of audiometric findings.

⁶Given the enormous variations in the earphone data at low frequencies, one is reminded of the remark made by Lagrange, the great mathematical analyst, about Newton's treatment of calculus: "All of Newton's ideas were in error; but due to God's infinite kindness, the errors all cancelled!"

⁷The term "the missing 6 dB" was apparently first used by Munson and Wiener (1952), who reported the vexing results of nearly twenty years of experiments undertaken to uncover the reason for the apparent difference in earcanal pressure between equally loud earphone-generated and loudspeaker-generated suprathreshold tones at low frequencies; where "... a person familiar with Thévenin's theorem but otherwise naive would expect the two pressures to be the same..." Successive experimental refinements produced a progressive decrease in the 100-Hz pressure difference obtained by Munson and Wiener, but it took a substantial amount of additional investigation by Rudmose (1962, 1963) before some of the more subtle experimental difficulties were finally identified. At higher frequencies, of course, the difference has always been of the order of that expected due to diffraction and ear-canal resonance effects; so nothing was generally considered "missing" above a few hundred Hz, although "the missing 6 dB" has occasionally been invoked by writers to explain unusual experimental results.

⁸It would not solve the problem of variability due to the age and sex of the subject, as discussed by Erber (1968), of course.

Albrite, J. P., Shutts, R. E., Whitlock, M. D., Cook, R. K., Corliss, E. L., and Burkhard, M. D. (1958). "Research in normal threshold of hearing," *AMA Arch. Otolaryngol.* **68**, 194-198.

ANSI (1969). "Specifications for audiometers," S3.6-1969 (Am. Natl. Stand. Inst., New York).

Anderson, C. M. B., and Whittle, L. S. (1971). "Physiological noise and the Missing 6 dB," *Acustica* **24**, 261-272.

Burkhard, M. D., and Corliss, E. L. R. (1954). "The response of earphones in ears and couplers," *J. Acoust. Soc. Am.* **26**, 679-685.

Burkhard, M. D., and Sachs, R. M. (1975). "Anthropometric manikin for acoustic research," *J. Acoust. Soc. Am.* **58**, 214-222.

Caliazzo, A. J., and Tonndorf, J. (1977). "Ear canal resonance and temporary threshold shift," *J. Acoust. Soc. Am.* **61**, S78(A).

- Churcher, B. G., and King, A. J. (1937). "The performance of noise meters in terms of the primary standard," *J. Inst. Electr. Eng.* [1889-1940] **81**, 57-90. (See their Fig. 9.)
- Corliss, E. L. R., and Burkhard, M. D. (1953). "Probe tube method for the transfer of threshold standards between audiometer earphones," *J. Acoust. Soc. Am.* **25**, 990-993.
- Corliss, E. L. R., Burkhard, M. D., Thompson, R. P., Smith, E. L., Marchetti, A. A., Koidan, W., Dunn, G. H., and Peterson, K. (1953). "Progress on Methods for Calibration of Hearing Diagnostic Instruments," *Natl. Bur. Stand. Rep.* 2312, 1-33 (Washington, DC).
- Corso, J. F. (1958). "Absolute threshold for tones of low frequency," *Am. J. Psychol.* **71**, 367-384.
- Dallos, P. (1973). *The Auditory Periphery* (Academic, New York), pp. 117-126.
- Davis, H., Morgan, C. T., Hawkins, J. E., Jr., Galambos, R., and Smith, F. W. (1950). "Temporary deafness following exposure to loud tones and noise," *Acta Oto-Laryngol. Suppl.* **88**.
- Erber, N. P. (1968). "Variables that influence sound pressures generated in the ear canal by an audiometric earphone," *J. Acoust. Soc. Am.* **44**, 555-562.
- Fletcher, H., and Munson, W. A. (1933). "Loudness, its definition, measurement, and calculation," *J. Acoust. Soc. Am.* **5**, 82-107.
- Hildyard, V. H., and Valentine, M. A. (1962). "Collapse of the ear canal during audiometry," *Arch. Otolaryngol.* **75**, 422-423.
- International Organization for Standardization (1961). "Normal equal-loudness contours for pure tones and normal threshold of hearing under free-field listening conditions," R226-1961 (available from American National Standards Institute, New York).
- International Organization for Standardization (1964). "Standard reference zero for the calibration of pure tone audiometers," R389-1964 (available from American National Standards Institute, New York). Now available as ISO R389-1975 (E).
- Killion, M. C. (1976). "Noise of ears and microphones," *J. Acoust. Soc. Am.* **59**, 424-433.
- Morgan, D. E., and Dirks, D. D. (1974). "Loudness discomfort level under earphone and in the free field: The effects of calibration methods," *J. Acoust. Soc. Am.* **56**, 172-178.
- Munson, W. A., and Wiener, F. M. (1950). "Sound measurements for psychophysical tests," *J. Acoust. Soc. Am.* **22**, 382-386.
- Munson, W. A., and Wiener, F. M. (1952). "In search of the Missing 6 dB," *J. Acoust. Soc. Am.* **24**, 498-501.
- Northern, J. L., Downs, M. P., Rudmose, W., Glorig, A., and Fletcher, J. L. (1972). "Recommended high-frequency audiometric threshold levels (8000-18 000 Hz)" *J. Acoust. Soc. Am.* **52**, 585-595.
- Pollack, I. (1948). "Monaural and binaural sensitivity for tones and for white noise," *J. Acoust. Soc. Am.* **20**, 52-57.
- Pollack, I. (1949). "Specification of sound-pressure levels," *Am. J. Psychol.* **62**, 412-417.
- Robinson, D. W., and Dadson, R. S. (1956). "A re-determination of the equal-loudness relations for pure tones," *Br. J. Appl. Phys.* **7**, 166-181.
- Rudmose, W. (1962). "Pressure vs free-field thresholds at low frequencies," *Proc. 4th Int. Congr. Acoust., Copenhagen*, Paper H52.
- Rudmose, W. (1963). "On the lack of agreement between earphone pressures and loudspeaker pressures for loudness balances at low frequencies," *J. Acoust. Soc. Am.* **35**, S1906(A).
- Shaw, E. A. G., and Piercy, J. E. (1962). "Audiometry and physiological noise," *Proc. 4th Int. Congr. Acoust., Copenhagen*, Paper H46.
- Shaw, E. A. G. (1966). "Ear canal pressure generated by circumaural and supra-aural earphones," *J. Acoust. Soc. Am.* **39**, 471-479.
- Shaw, E. A. G. (1969). "Hearing threshold and ear canal pressure levels with varying acoustic field," *J. Acoust. Soc. Am.* **46**, 1502-1514.
- Shaw, E. A. G. (1974). "Transformation of sound pressure level from the free field to the eardrum in the horizontal plane," *J. Acoust. Soc. Am.* **56**, 1848-1861.
- Shaw, E. A. G. (1976). "Diffuse field sensitivity of the external ear based on the reciprocity principle," *J. Acoust. Soc. Am.* **60**, S102(A).
- Sivian, L. J. (1928) (unpublished.)
- Sivian, L. J., and White, S. D. (1933). "On minimum audible sound fields," *J. Acoust. Soc. Am.* **4**, 288-321.
- Stream, R. W., and Dirks, D. D. (1974). "Effects of loudspeaker position on difference between earphone and free-field thresholds (MAP and MAF)," *J. Speech Hear. Res.* **17**, 549-568.
- Tillman, T., Olsen, W., Killion, M., and Block, M. (1973). "MAP vs MAF for Spondees: Nothing's really missing," presented at *Am. Speech Hear. Assoc.*, Detroit (12 Oct. 1973) (unpublished).
- Villchur, E. (1969). "Free-field calibration of earphones," *J. Acoust. Soc. Am.* **46**, 1527-1534.
- Villchur, E. (1970). "Audiometer-earphone mounting to improve intersubject and cushion-fit reliability," *J. Acoust. Soc. Am.* **48**, 1387-1396.
- Villchur, E. (1972). "Comparison between objective and threshold-shift methods of measuring real-ear attenuation of external sound by earphones," *J. Acoust. Soc. Am.* **51**, 663-664(L).
- Villchur, E., and Killion, M. C. (1975). "Probe-tube microphone assembly," *J. Acoust. Soc. Am.* **57**, 238-240.
- Weessler, P. G. (1968). "International Standard Reference Zero for Audiometers," *J. Acoust. Soc. Am.* **44**, 264-275.
- Wiener, F. M., and Ross, D. A. (1946). "The pressure distribution in the auditory canal in a progressive sound field," *J. Acoust. Soc. Am.* **18**, 401-408.
- Yeowart, N. S., and Evans, M. J. (1974). "Thresholds of audibility for very low-frequency pure tones," *J. Acoust. Soc. Am.* **55**, 814-818.