

Noise of ears and microphones*

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Although it is well known that the internal noise of the human ear is less than that of many microphones, little has been published since Baerwald (1940) directly comparing the noise level of ears and microphones. When a microphone is to be used in a hearing aid, it is of interest to know how soft a sound the wearer can hear if he turns the gain up far enough. If the noise spectrum of the microphone is known, the "aided pure-tone threshold" which can be achieved with that microphone can be calculated by utilizing the extensive literature on the masking of pure tones by noise. Following French and Steinberg [J. Acoust. Soc. Am. **19**, 90-119 (1947)], one can turn the tables and calculate the apparent noise spectrum of the ear considered as a microphone. Such a calculation indicates that an acute young ear has an apparent noise level equivalent to that of a microphone with an *A*-weighted noise level of about 20 dB SPL. Experimental verification has been obtained on a new hearing aid microphone designed to be quieter than the human ear. A brief comment on the clinical implications of these results for hearing aid evaluation is included.

Subject Classification: [43]65.50, [43]65.80; [43]85.62.

INTRODUCTION

If a person with normal hearing puts on a hearing aid, goes into a quiet room, and turns up the gain, he hears a hiss or "shhhhh" sound. If the room is quiet enough, that hiss is simply the amplified noise of the microphone and input stage of the hearing aid. The noise puts a limit on how quiet a sound can be heard using that hearing aid.

In a similar way, if a person with normal hearing goes into a very quiet room *without* a hearing aid and listens carefully, he also hears a hiss—the hiss due to the apparent noise level in his own ears. In both cases, the threshold of hearing appears to be limited by noise—whether that of the microphone or that of the real ear. Thus it seems reasonable to attempt a comparison between the two.

Some years ago the author had calculated that the noise level of subminiature magnetic microphones was roughly comparable to that of a human ear in the speech band. Their limited bandwidth (typically 500-4000 Hz), however, made direct comparison with a human ear difficult. The introduction of wide-band subminiature ceramic microphones (Killion and Carlson, 1970), and more recently, wide-band, subminiature, electret-biased condenser microphones (Killion and Carlson, 1974a, b), made a direct comparison with human ears somewhat easier, but listening tests confirmed that these microphones were slightly noisier in the speech band than the previous subminiature magnetic microphones.

The unusually low noise we were able to achieve in a recently designed subminiature electret-biased condenser microphone prompted the present study. A careful investigation demonstrated that the noise level of this new microphone was, indeed, lower than the apparent noise level of a good young human ear in the following sense: By turning the gain up on a hearing aid using this microphone, the wearer could hear sounds which were slightly quieter than those which could have been heard by a good young ear. A corollary of this conclusion provided a convenient benchmark for comparing the noise of microphones and ears; namely, that a good

young human ear has an apparent noise level equivalent to that of a microphone with an *A*-weighted noise level of about 20 dB SPL.

Before going any further, a comment about what was *not* considered should be made: No attempt was made here to study the *audibility* of microphone noise. Although the question of when microphone noise becomes audible is of some importance when selecting microphones for studio applications, the answer is critically dependent on the amount of acoustical gain (or more commonly, acoustical loss) inserted between the microphone and the ultimate listener. In contrast, the present results are essentially independent of acoustical gain if enough gain is used to make the microphone noise clearly audible. The present results are also relatively independent—within limits—of the frequency response of the overall system. Thus they may be applied directly within the passband of most hearing aid systems.

This paper is divided into three sections. Section I gives a theoretical derivation of the pure-tone hearing threshold determined by the masking of the microphone noise. Calculation of the pure-tone thresholds that can be achieved with two microphones—the laboratory standard 640AA and the new XD-985 microphone—is included. Section II contains the theoretical derivation of the apparent noise level of the ear considered as a microphone. Section III describes the experimental results on a hearing aid microphone designed to be quieter than the human ear. An Appendix contains a limited discussion of the sources of microphone noise and the apparent noise level in real ears.

The reader interested primarily in the experimental results may, with impunity, skip over Secs. I and II and start with Sec. III.

I. MICROPHONE NOISE AND "AIDED THRESHOLDS"

A. Critical bands applied to microphone noise spectra

When a microphone is used along with a reproducer and an amplifier of sufficient gain, the "aided" pure-tone threshold will be determined by the masking created

by the amplified microphone or amplifier noise and not by the listener's own threshold. If we assume that the amplifier and reproducer contribute no noise of their own, then the noise of the microphone itself becomes the limiting factor.

Assuming the noise spectrum of the microphone is reasonably smooth, the extensive literature on the masking of pure tones by noise can be applied to calculate the aided threshold determined by the microphone noise. In particular, what Fletcher (1940) first called critical bands provide the "equivalent bandwidth" of the ear as a detector of pure tones imbedded in wide-band noise. Most of the early attempts to measure the critical band, in fact, were actually measurements of the difference in decibels between the level of a pure tone and the spectrum level (at the frequency of the pure tone) of a wide-band noise which would just mask that tone. This difference (equal to ten times the log of the "Fletcher critical band") has more recently been called the critical ratio by auditory theorists. Figure 1 shows the critical ratios corresponding to the Fletcher critical bands reproduced in ANSI S1.13-1971 from Fletcher's 1953 *Speech and Hearing* textbook. Essentially identical values were obtained by Hawkins and Stevens (1950).

If, at a given frequency, the spectrum level¹ of the microphone noise (expressed in equivalent SPL) is known, the best possible aided pure-tone threshold obtainable in a system using that microphone can be calculated simply by adding the critical ratios shown in Fig. 1 to the spectrum level of the microphone noise.² For example, a microphone with an equivalent 1-kHz spectrum level of -13 dB would be expected to produce an "aided" pure-tone threshold of +5 dB *re* 0.0002 dyn/cm²; about the same as the monaural minimum audible field (MAF) for an acute young ear. (The critical ratio at 1 kHz is +18 dB, whence we have $-13 + 18 = +5$ dB.)

Since microphone noise is often given in one-third octave bands, the one-third octave band level has been added to Fig. 1 by way of a dot at each of the standard one-third octave frequencies. Table I shows the difference (column D) between the one-third octave levels

TABLE I. Comparison between one-third octave band levels and critical ratios.

A	B	C	D
One-third octave center frequency (Hz)	One-third octave band level (dB above spectrum level)	Critical ratio (dB above spectrum level)	Difference between critical ratio and one-third octave band level
100	+13.6	+19.4	+5.7
125	14.6	18.2	+3.6
160	15.6	17.5	+1.9
200	16.6	17.2	+0.6
250	17.6	17.1	-0.5
315	18.6	17.0	-1.6
400	19.6	17.0	-2.6
500	20.6	17.1	-3.5
630	21.6	17.2	-4.4
800	22.6	17.6	-5.0
1000	23.6	18.0	-5.6
1250	24.6	18.5	-6.1
1600	25.6	19.2	-6.4
2000	26.6	19.9	-6.4
2500	27.6	20.9	-6.7
3150	28.6	21.8	-6.8
4000	29.6	23.1	-6.5
5000	30.6	24.6	-6.0
6300	31.6	26.1	-5.5
8000	32.6	27.7	-4.9
10 000	33.6	29.2	-4.4

of Fig. 1 and the critical ratios shown in Fig. 1 and is useful for directly converting one-third octave microphone noise levels to the "aided" pure-tone thresholds which will be determined by the noise of that microphone. Using the same example as above, a microphone with a 1-kHz spectrum level of -13 dB would have a one-third octave noise level of +10.6 dB at 1 kHz. By Table I we subtract 5.6 dB at 1 kHz from the one-third octave noise to obtain the "aided" pure-tone threshold (or what we will henceforth call the "aided MAF) of +5 dB SPL. For convenience, the values of the critical ratio at each one-third octave center frequency are also shown (column C) in Table I. Where required, these have been extrapolated from the published values.

Since our prime concern here is in microphones intended for use in hearing aids, some comment should be made about the applicability of the critical ratios shown

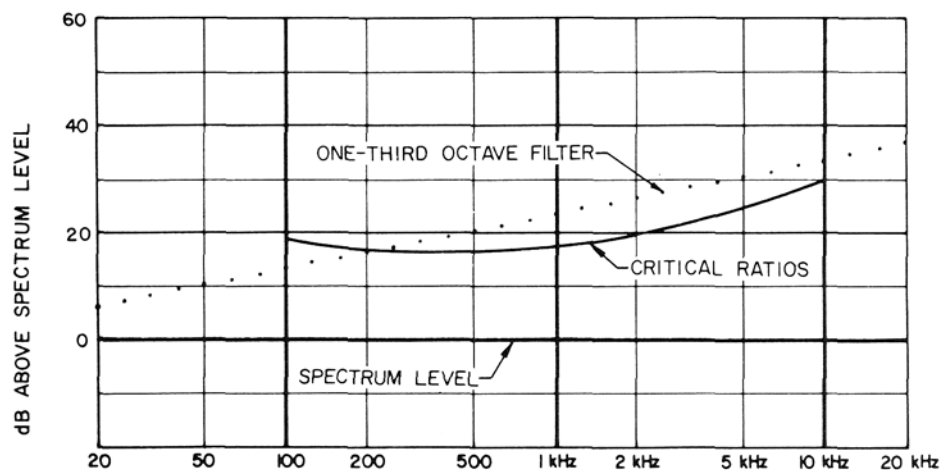


FIG. 1. Level of Fletcher critical bands (critical ratios) and one-third octave bands for smooth wide-band noise.

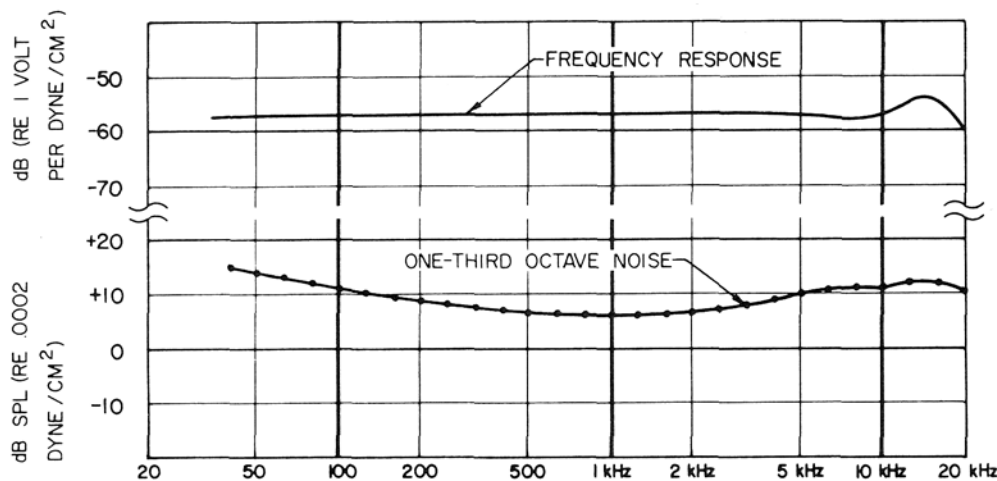


FIG. 2. Frequency response and one-third octave noise of XD-985 subminiature microphone. Noise shown is equivalent 1 kHz SPL of output noise voltage.

in Fig. 1 to impaired ears, particularly since most of the early work on critical bands (ratios) was done on normal subjects. The work of Palva, Goodman, and Hirsh (1953) and the more recent study of Jerger, Tillman, and Peterson (1960) indicates that the critical ratios of Fig. 1 are applicable to both normal and impaired ears as long as patients with neural lesions are excluded.

B. Aided MAF calculated for two microphone types

As an example of the application of Fig. 1 and Table I, the aided MAF has been calculated for two commercially available microphones. One of these is the laboratory standard WE 640AA capacitor microphone.³ The other is the Knowles XD-985 subminiature (0.312 × 0.218 × 0.163 in.) electret-biased condenser microphone, designed recently for hearing aid research. The noise level assumed for the 640AA was that which can be obtained using a quiet preamplifier such as described by Killion (1967), and the combined noise spectrum shown in Fig. 9 of that paper was used for the present calculation.⁴ The frequency response and one-third octave noise spectrum of the XD-985 subminiature microphone are shown in Fig. 2. Those familiar with wideband hearing aid microphones will notice that the XD-985 does not have the tailored frequency response normally

associated with such microphones. The XD-985 was designed for use in a "master hearing aid" where the desired frequency response shaping was to be added electronically under the control of the experimenter. It is basically similar to the microphone described by Killion and Carslon (1974a, b), but is 80% thicker and uses a special ultralow noise preamplifier.

Figure 3 shows the Aided MAF calculated for the 640AA and the XD-985 microphones. Lest someone conclude from the comparison between the two microphones that we haven't made much progress in the last 40 years, it should be pointed out that the 640AA along with its accompanying preamplifier occupies approximately 50 cm³, while the XD-985 microphone, with its built-in FET preamplifier, occupies less than 0.2 cm³: a 250:1 reduction in microphone size. By paralleling the output of five matched XD-985 microphones, moreover, a microphone with a noise level within 1 to 3 dB of the 640AA can be constructed in less than 1/50 of the volume.

To recapitulate a bit, Fig. 3 shows the pure-tone MAF as a function of frequency, which is determined by the microphone noise, assuming that: (a) the microphone is placed in a quiet free-field environment, (b) the amplifier and earphone contribute no noise of their

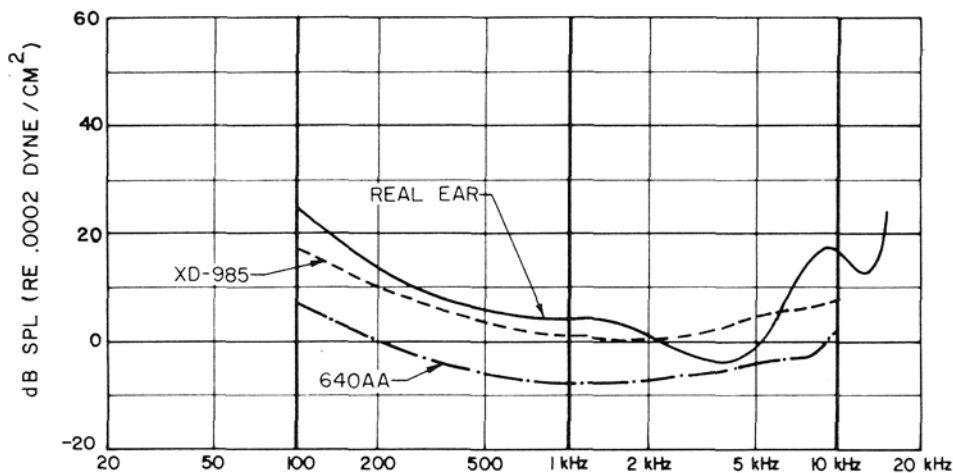


FIG. 3: Minimum audible fields: (a) Real ear per ISO R226-1961 (binaural, 0° incidence free-field); (b) aided MAF calculated for single 640AA microphone (90° incidence); and (c) aided MAF calculated for single XD-985 microphone.

own, and (c) the system has sufficient acoustical gain so that the amplified microphone noise is at least 10 to 20 dB above the listener's own threshold.

C. Unaided MAF for real ears

To compare the noise level of microphones and ears, one needs to know the pure-tone threshold of real ears. The solid line in Fig. 3 shows the commonly accepted binaural MAF for young ears with good hearing, taken from ISO Recommendation R226-1961. Note that this solid curve is typical of "acute young ears." The majority of the population has a threshold which is somewhat higher.⁵

D. Microphones quieter than ears

As can be seen from Fig. 3, a speech amplification system using a single 640AA microphone mounted in free space should allow almost any user to hear sounds which were some 10 dB quieter at most frequencies than those which could be heard by a typical pair of good young ears.⁶ From a practical standpoint, this can be put to good use in verifying that the noise level in a free-field audiometry room is low enough so that it will not contaminate threshold measurements.

Even a single subminiature XD-985 microphone has a calculated Aided MAF lower than that of a pair of good young ears except in the 2-6-kHz region, where head and ear diffraction and resonance effects provide a boost of 15 to 20 dB in eardrum pressure on real ears. As will be seen later, some of this boost can be picked up by mounting the microphone on the head, as it is used in a hearing aid.

II. THE EAR CONSIDERED AS A MICROPHONE

A. The noise spectrum of the ear

To avoid having to replot each microphone's noise spectrum in terms of "aided MAF," it seems reasonable to turn the tables and consider the ear as a microphone, i. e., to plot the equivalent noise level of the ear considered as a microphone. This is not a new thought—the spectrum level of the apparent noise level of the ear was plotted by French and Steinberg (1947). Although

their curve was not labeled as such, they commented later in the paper that the observed effect of low-level masking is "exactly the effect which would be obtained if the threshold in the absence of noise were itself determined by residual noise, which combines on a power basis with other noises which may be present."

To obtain the spectrum level of this "residual noise" of the ear, French and Steinberg simply subtracted the value of the critical band level (dB) from the hearing threshold level (dB SPL) at each frequency. From our viewpoint, this procedure amounts to calculating the noise levels a microphone should have in order to produce an aided MAF exactly equal to the (unaided) real-ear MAF of ISO R-226 shown in Fig. 3. In this sense, the curve shown in Fig. 4 can be considered the equivalent third-octave noise level of the human ear considered as a microphone.⁷ (Figure 4 was obtained from the real-ear MAF curve of Fig. 3 by *subtracting* the corrections in the fourth column of Table I. As before, a third-octave calculation was chosen as more useful than a spectrum level calculation.)

With the apparent one-third octave noise level of a pair of good human ears in hand, it becomes possible to readily compare any microphone—whose one-third octave spectra is known—with the human ear. Unfortunately, the noise level of most microphones is given only as a single number—the "A-weighted noise level." Thus, a similar number for the ear would be desirable.

B. A-weighting the ear

It is possible to calculate an equivalent A-weighted noise level of the ear by simply applying the A-weighting characteristic (ANSI Standard S1.4-1971) to the apparent real-ear noise level shown in Fig. 4. A difficulty arises, however, since the apparent noise level of the ear above 5 kHz is rising virtually without limit. Although this is easily explained (the threshold of hearing rises sharply above 5 kHz), any attempt to integrate the apparent real-ear noise-level curve of Fig. 4 from zero to infinite frequency would result in an absurd number.

Since the intent is to obtain an A-weighted figure which

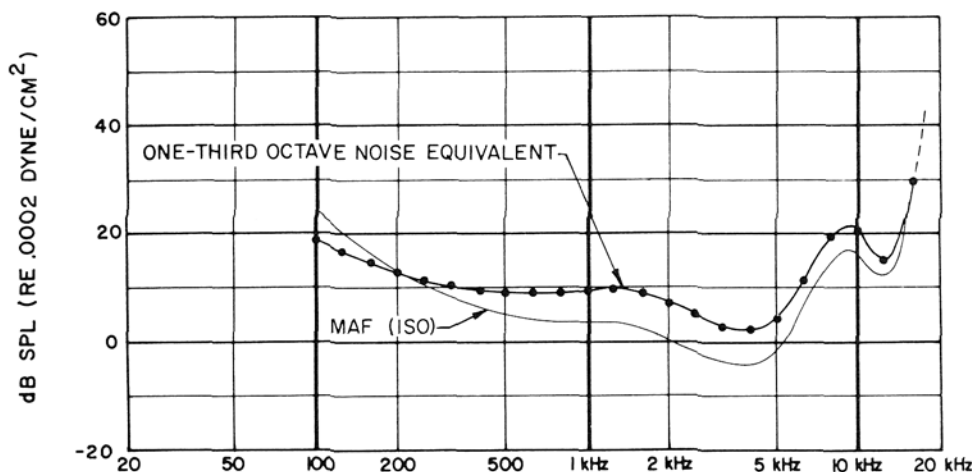


FIG. 4. Apparent one-third-octave noise level of real ears (approximately equal to the 0° incidence free-field threshold of hearing for one-third octave bands of noise).

can be compared to real microphones, two ways of dealing with this problem suggest themselves: One is to completely ignore any contributions to the *A*-weighted noise above 5 kHz; the other is to assume the one-third octave noise continues gradually upward with a slope of 1 to 2 dB octave above 5 kHz, as is typical of many microphones. Integrating the *A*-weighted noise under the first assumption produces an equivalent SPL of 19.3 dB; under the second assumption, one obtains 20.7 dB. Thus, it seems fair to conclude that the threshold levels of a pair of good, young, real ears are limited by an apparent internal noise that is the equivalent of a typical microphone noise of about 20 dB *A*. Probably a better way of saying the same thing is that a microphone whose *A*-weighted noise level is 20 dB can be expected to produce an aided threshold roughly as low as that of a pair of good young ears.

The comparable number for a *single* ear would be 1.5–2 dB higher, or about 22 dB for the better ear. The statement, "An acute young ear has an apparent *A*-weighted noise level of 20 dB SPL," is sufficiently accurate for most purposes.

By way of comparison, the *A*-weighted noise level of the 640AA used with a quiet preamplifier is about 13 dB. (More precisely, one would say, "... is approximately equivalent to a 13 dB SPL *re* 0.0002 dyn/cm².") The *A*-weighted noise level of the XD-985 sub-miniature condenser microphone with its built-in preamplifier is typically 20 dB. Here again, the noise level of the XD-985 indicated that it should be quieter than the human ear. This conclusion was verified experimentally as described in Sec. III.

III. EXPERIMENT 1: THRESHOLD MEASUREMENTS USING THE XD-985

A. Experimental set up—free-field Békésy audiometry

We have a floating anechoic chamber which is built as a box within a box within a box, resulting in an internal noise level well below the threshold of hearing at all frequencies. This was verified during this experiment using a Brüel & Kjaer 4132 microphone (which is slightly quieter on the IRPI preamplifier than the 640AA) and a one-third octave filter set. The data so

obtained is shown in Fig. 9 at the end of this paper. The loudspeaker response was equalized within ± 5 dB with an *RC* network at the input of the power amplifier. The remaining small perturbations in speaker response were compensated for by recording the speaker response on a Grason–Stadler Model E800 Békésy Audiometer and then tracing the inverse of that response with a milling machine into a Grason–Stadler cam blank. With the new cam in place, the output of the audiometer was used to drive the equalized power amplifier, resulting in a sound field which was constant within ± 1 dB—with the exception of a spike at 6.5 kHz—from 100 Hz to 10 kHz. The sound field was measured 4 ft (1.2 m) from the face of the loudspeaker, in the location later to be occupied by the center of the subject's head.

B. Subjects and procedure

Continuous Békésy monaural threshold tracings were obtained on five ears of four subjects (both ears of one subject were used) chosen on the basis of previous ear-phone audiometry data as follows: One subject had an unusually low threshold, one had an approximately "normal" threshold, and two subjects had a roughly 20-dB loss over a good part of the audio band. Figure 5 shows the individual monaural MAF tracings obtained on the five ears (dotted curves). The nontest ear of the subject was carefully sealed with a Flent Ear Stopple. The binaural MAF from ISO R226 is shown as a solid line for comparison.

In order to avoid the low-frequency vibrational artifacts mentioned by Rudmose (1962), the subjects were asked to kneel on a cushion (in an upright position) rather than sit in a chair. Rudmose found that the standard free-field audiometry setup could sometimes produce artificially low thresholds at low frequencies; the summation of the airborne and 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. This may explain why the low-frequency thresholds we observed were generally higher—even for the subject with "acute hearing"—than those given in ISO R226. The small sample size rules out any positive conclu-

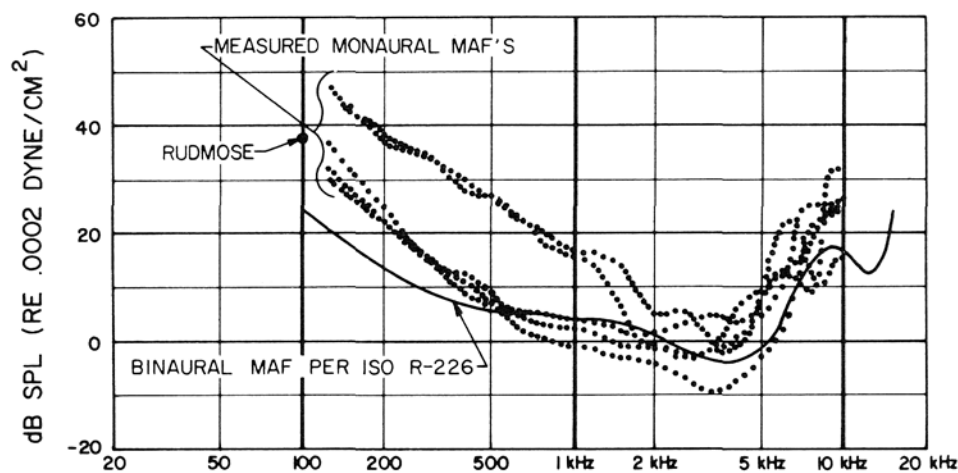


FIG. 5. Free-field Békésy threshold tracings on five unaided test ears.

sion, but our limited data appears consistent with the 100-Hz findings of Rudmose (1962).⁸ The noise levels measured in the anechoic chamber were well below those which would affect the threshold measurements (see Fig. 9).

In order to experimentally verify the Aided MAF calculated for the subminiature XD-985 microphone, an XD-985 microphone was wired into a pre-1970-vintage hearing aid. This aid had the disadvantage that it did not contain one of the newer wide-band receivers,⁹ and thus its output fell off sharply above 3.5 kHz. It had the advantage that it was immediately available and had been previously wired up for an external microphone. The leads between the microphone and hearing aid were left long enough so that the microphone could be attached to the flat surface of the subject's earmold. The microphone thus partook of both head diffraction effects and some pinna diffraction effects, although in most cases the subject's earmold filled nearly all of the concha.

With the subject's nontest ear stopped up as before, the gain of the hearing aid was turned up until the subject described the hiss of the amplified microphone noise as "comfortably loud," insuring that the subject's own threshold would not interfere with the measurements. Continuous Békésy tracings were obtained in the "aided" condition, using the same procedure as before.

C. Results and discussion

The average and range of the aided MAF tracings on the five ears tested is shown in Fig. 6 (solid line), compared to the previously calculated values of the MAF aided by the XD-985 microphone from Fig. 3 (dashed line). As can be seen, the performance is better than calculated at some frequencies and poorer than calculated at others. Most of this discrepancy can be accounted for. Above 3.5 kHz, for example, the response of the hearing aid was falling off at 30 dB/octave; the poorer than calculated performance above 5 kHz is thus easily explained in terms of the upward spread of masking. Similarly, head and pinna diffraction effects provided an increased microphone response within the

1.5–5 kHz region, which readily explains the better than calculated performance in that frequency region. The poorer than calculated performance below 1 kHz may have been due to noise produced in the hearing aid amplifier, which was assumed noiseless in the calculations.

Up until now, we have been considering a single microphone. Based on the results of Hirsh (1948) and Egan (1965), the use of a binaural microphone–amplifier–earphone system should produce a 3-dB reduction due to binarual summation, since the noise out of the two microphones would be uncorrelated. (The MAF for monaural listening, on the other hand, is typically only 1 to 2 dB higher than the binarual MAF. Few people have "matched ears," and a matching of the loudness at each ear is required before perfect binarual summation can occur.) Thus, Fig. 7 shows the aided MAF calculated for a binaural hearing aid based on the experimental results shown in Fig. 6. Note that at all frequencies "binarually aided MAF" is nearly equal to or better than the binarual MAF for good young ears per ISO R226-1961. Thus, it seems reasonable to conclude that the XD-985 microphone is, in fact, quieter than the human ear.

D. Comparison of XD-985 and previous hearing aid microphones

The XD-985 represents an improvement of 6 to 8 dB over previously available wideband subminiature microphones. Interestingly enough, it represents little, if any, improvement over previously available subminiature magnetic microphones in the speech band, assuming the average of the thresholds at 500, 1000, and 2000 Hz is used as the basis for comparison. In actual practice, however, the noise of the hearing aid amplifier used with these magnetic microphones often produced a much higher level, especially in the early days of transistor amplifiers.

Figure 8, which is a modification of a graph shown by Davis and Kranz (1964), helps put the noise level of various microphones in perspective compared to the normal range of hearing. Note that the aided threshold determined by all of the hearing aid microphones

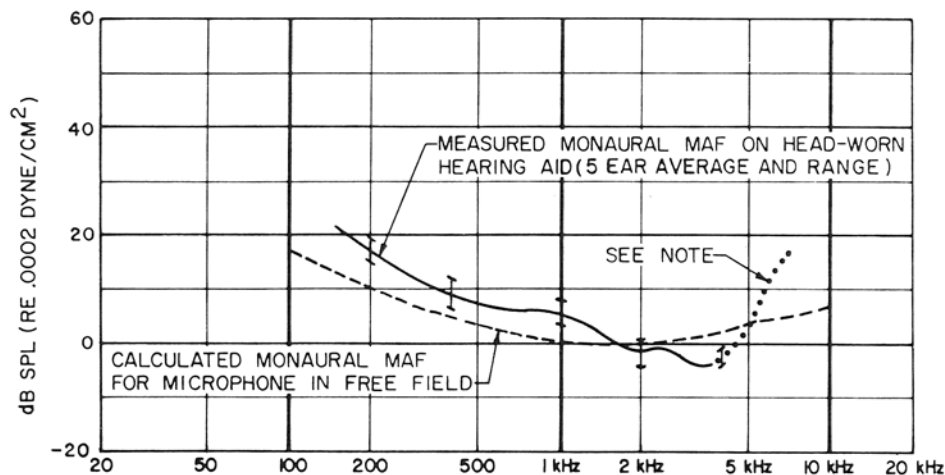


FIG. 6. Comparison of measured and calculated "aided MAF" (monaural) for XD-985 microphone. Note: Response of hearing aid fell off at 30 dB/octave above 3.5 kHz.

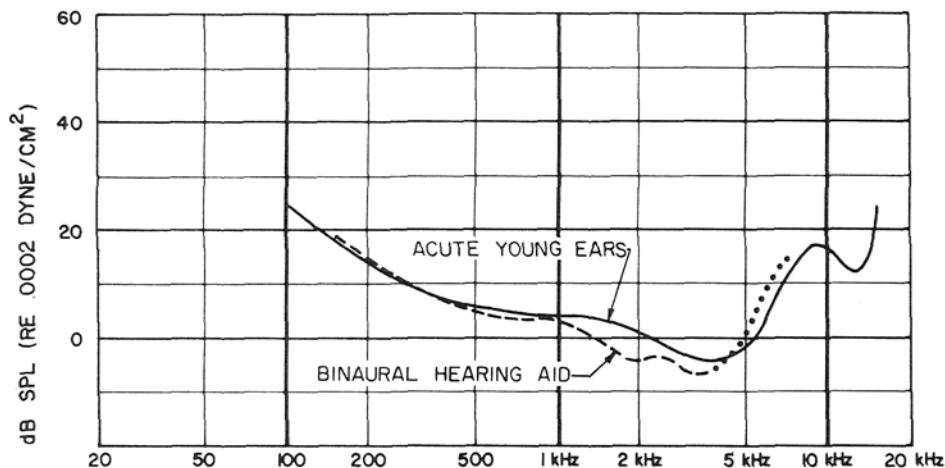


FIG. 7. Comparison between real-ear binaural MAF (per ISO R226-1961) and aided MAF calculated for binaural hearing aid using two XD-985 microphones.

falls in the lower half of what is usually considered the "range of normal thresholds."

Three non-hearing-aid microphones are also shown in Fig. 8. One is the 640AA whose noise level has already been discussed at some length. The other two are larger experimental microphones. One is the special high-sensitivity ribbon-type velocity microphone described by Olson (1972) that has a flat frequency response from 50 to 15000 Hz. The other is the experimental electret-condenser microphone described recently by Sessler and French (1974) that has a flat response from 20 to 4000 Hz. Both microphones

are interesting because they show that it is possible to achieve a noise level some 25 dB better than that of the human ear!

IV. CONCLUSIONS

The internal noise level of most readily available hearing aid microphones is low enough so that it creates no real liability for the hearing aid user.

One hastens to add that this does *not* mean that the average hearing aid wearer will be able to enjoy "normal hearing." As those suffering from sensorineural

HEARING THRESHOLD LEVELS AND HEARING IMPAIRMENT

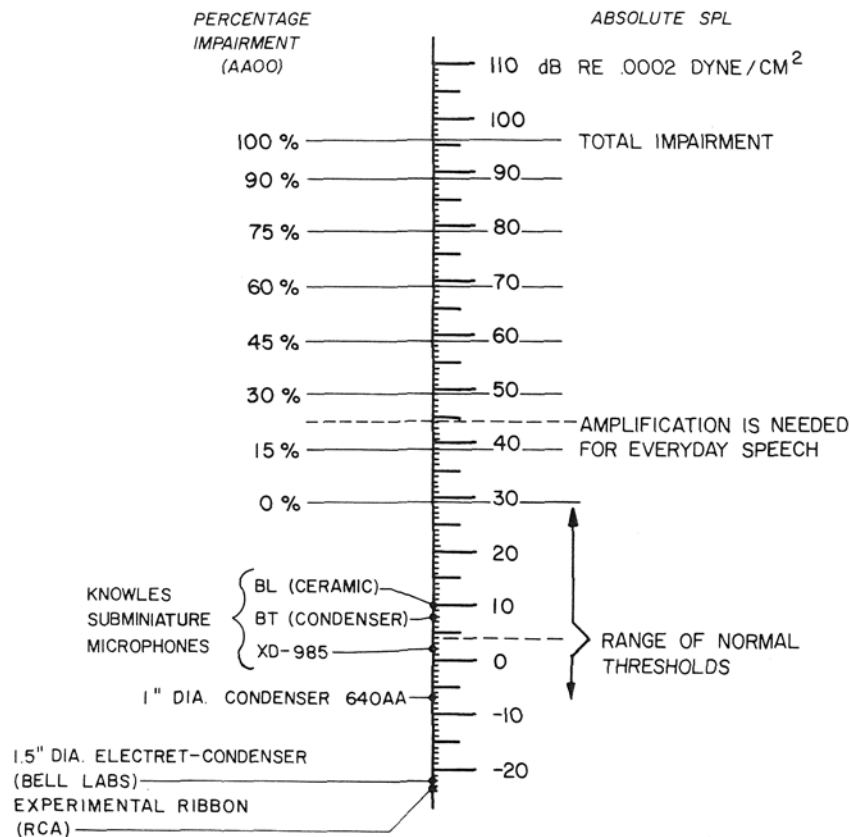


FIG. 8. Comparison between real-ear and microphone-aided hearing levels. Graph shown in terms of the average MAF at 500, 1000, and 2000 Hz. (The average for acute young ears per ISO R226-1961 is +4 dB.)

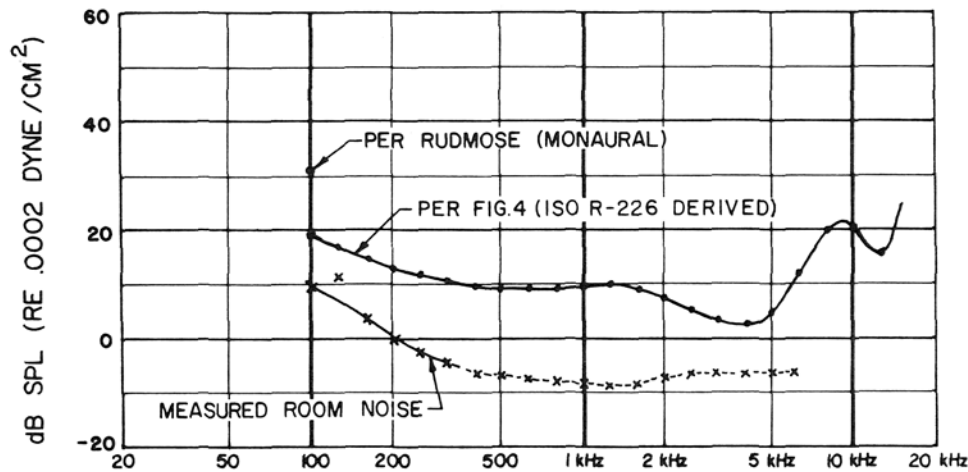


FIG. 9. Measured one-third octave noise in test room and threshold of hearing for one-third octave bands of noise. Note: Above 400 Hz, room noise was below microphone noise. Dashed line indicates upper limit of room noise extrapolated from known microphone noise level.

loss are only too painfully aware, being able to "hear" and being able to understand what one hears can be two totally different things. What it does mean is that with many modern headworn hearing-aids, the wearer who is willing to turn up the gain far enough can detect sounds roughly as quiet as can be detected by good young ears. It has been demonstrated theoretically and confirmed experimentally, moreover, that it is possible to build a hearing aid with which the wearer can achieve an aided threshold *better* than that of good young ears.

V. REMARKS

Two pitfalls in evaluating a hearing aid need to be avoided by the careful experimenter. One is to go into a quiet room, turn up the gain of the hearing aid until the noise of the microphone and/or input amplifier is heard, and conclude that the hissing sound proves the hearing aid is "noisy." It may be noisy, but a more sophisticated test is required to establish that fact. As mentioned in the Introduction, the hissing sound one hears upon turning up the gain of a wide-band hearing aid is not unlike the quiet hissing sound a person with normal hearing will hear due to the "noise" in his own ears after spending 10 or 15 min in an absolutely quiet anechoic chamber.

The other pitfall is to use the difference between aided and unaided threshold as a measure of the gain of the hearing aid, without first determining that the amplified microphone and amplifier noise, reproduced at the output of the hearing aid, is at least 10 dB below the threshold of the test subject for the gain settings employed during the test.

Although the *audibility* of microphone noise was not part of this study, it should be noted that the noise of the XD-985 microphone is audible (to a good ear) when used in a hearing aid set to unity acoustical gain. This is to be expected. We have seen that the noise level of the XD-985 is comparable to the apparent noise level of a good ear, but that the spectral distributions of the two are not precisely matched. Thus, while adding the external noise of the microphone might be expected to increase the overall subjective noise level by only 3 dB, the subjective noise level in some critical bands would

be increased by a greater amount.¹⁰ As alluded to in the Introduction, the audibility of microphone noise is critically dependent on both the overall system gain and the frequency response of the reproducer(s).

[*Note added in proof:* As shown by Fig. 9, it is possible to ascertain by direct measurement that the noise level in a test room is well below the normal threshold of hearing. In the present measurement, no change in noise level was observed in any one-third-octave band above 1 kHz when the measurement microphone (B & K 4132 on IRPI preamplifier) was sealed in a pressure cooker. Above 1 kHz, the dashed line in Fig. 9 was thus drawn 6 dB below the measured system noise level. (This was felt to be a conservative estimate of the maximum level, since such a level should have produced a change of 1 dB when the pressure cooker was sealed.)]

Finally, a rough rule of thumb for estimating the practical importance of a given microphone noise level follows from the results of this paper. As we have seen, a microphone with an *A*-weighted noise of 20 dB (equivalent SPL) will produce an aided threshold (MAF) curve roughly equal to the real-ear MAF curve of a good young ear as given by ISO R-226. Thus, *subtracting 20 dB from the A-weighted microphone noise provides an estimate of the aided-MAF curve (in terms of its displacement from the ISO R-226 curve) the user can expect to achieve with that microphone.* For example, the real-ear MAF curve crosses 0 dB SPL at about 2 kHz (see Fig. 3). A microphone with an *A*-weighted noise of 30 dB SPL could thus be expected to produce an aided threshold of about 10 dB SPL at 2 kHz. (In the case of a complete hearing aid, there is no simple rule because of the strong effect of bandwidth on the measured overall noise. A crude approximation would be to subtract 10 dB from the equivalent noise SPL of a narrow-band hearing aid, and 15–20 dB for a wide-band aid, to obtain an estimate of the aided-MAF curve that aid should provide within its passband.)

ACKNOWLEDGMENTS

The author benefited from discussions with Tom Tillman regarding the proper application of masking data

to the present problem, and from many discussions with Elmer Carlson and Richard Peters over the years on the subject of microphone noise.

APPENDIX

Several attempts to calculate the important sources of microphone noise and the apparent noise level in real ears have been made over the last half-century.

In the case of microphone noise, the important noise sources are reasonably well understood.¹¹ For most practical microphones, they are as follows:

(1). *The random collision of air molecules with the microphone diaphragm.* Generally speaking, the most important component is due to the air molecules in the acoustical "damping resistance" normally used to smooth the microphone frequency response. Becking and Rade-maker (1954) described the first direct measurement of the noise contributed by the damping resistance in the 640AA capacitor microphone. Killion (1967) later verified their results and extended them across the audio band. The noise contributed by the "Brownian movement" of the air outside the microphone (technically speaking, the real part of the microphone's radiation impedance) is usually too small to be measured, although the high-sensitivity ribbon microphone described by Olson (1972) allowed a direct verification of its existence.

(2). *Electrical noise internal to the microphone,* caused by the thermal agitation of the electrons in the conductive and dielectric materials used in the microphone. In the case of magnetic microphones, the dc resistance of the coil (or ribbon), eddy current losses, and Barkhausen noise in the magnetic materials all contribute. In the case of piezoelectric and capacitor microphones, the dissipation factor of the dielectric materials can be important. This is especially true of piezoelectric transducers (Baerwald, 1940).

(3). *Noise in the electronic amplifier following the microphone.* This is the most commonly discussed source of noise, but it is often the least important: With modern amplifiers, it is not uncommon for the amplifier noise to be 5–10 dB below that of the associated microphone over much of the audio band (see Griese, 1966; Killion, 1967; Olson, 1972; Sessler and French, 1974).

In the case of the apparent noise level of real ears, the picture is less clear. Whereas the designer of a low-noise microphone can often calculate all of his important noise sources to within a few per cent accuracy, the absolute values of the anatomical noise sources are not so easily pinned down. By analogy with a microphone, the real-ear noise sources can be grouped as follows:

(1) Brownian movement of air molecules impinging on the eardrum;

(2) Thermal agitation of the molecules in the middle-ear system (technically speaking, the real part of the mechanical impedance of the middle-ear system);

(3) Brownian noise in the inner ear, specifically at hair-cell activation level; and

(4) Noise in the central nervous system.

Several authors have estimated that the Brownian-pressure fluctuations in the air are well below the levels required to effect hearing thresholds (Sivian and White, 1933; deVries, 1952; Harris, 1968). A precise calculation of the Brownian noise spectrum at the eardrum should soon be possible, based on recent refinements in our knowledge of the external auditory system (Shaw, 1975) and thus of the real part of the radiation impedance seen looking out from the eardrum.

Both deVries (1952) and Harris (1968) attempted to calculate the internal noise level of the middle and inner-ear system. Harris concluded that: "Our degree of knowledge of the physical constants of the ear and of the proper dynamical theory of cochlear motion make it impossible to say whether the Brownian noise at the level of the hair cell is the limiting factor or that the limiting factor occurs higher up in the auditory nervous system." At the moment, therefore, the hypothesis that the best hearing thresholds are limited by the thermal agitation noise levels in the auditory system is plausible, but by no means certain.

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¹The spectrum level is the noise level which would be measured using a 1-Hz bandwidth filter.

²A somewhat different approach was taken by Baerwald (1940) who calculated the "absolute deafness" (in phons) produced by the microphone noise, assuming an amplifying system with unity acoustical gain. In contrast, we assume here an amplifying system with enough acoustical gain so that the "self-noise" of the ear is rendered unimportant.

³The 640AA was designed by F. Romanow and later refined by M. Hawley at Bell Labs some 40 years ago as a smaller version of the original condenser microphone design of Wente (1917).

⁴The B & K 4144, which is more readily available now than the WE 640AA, produces similar results, with some improvement at the lower frequencies due to the higher sensitivity of the B & K microphone.

⁵According to the 1939 World's Fair Hearing Tests, only about 1% of the population would qualify as having "acute young ears" from the standpoint of the threshold data of Fig. 3, although recent studies have found the percentage to be much higher. All studies agree, however, that the median threshold for adults is higher than that shown in Fig. 3.

⁶A microphone-ear comparison similar to that shown in Fig. 3 was shown by Soffel (1966) for a one-half inch condenser microphone coupled to an rf preamplifier, resulting in noise level below that of human hearing. Griese (1966) also showed a noise spectrum for a condenser microphone and rf pre-amplifier combination which was below that of human hearing, although he did not make that observation.

⁷Based on the results of Hirsh and Bowman (1953), it is reasonable to conclude that the curve of Fig. 4 is also approximately equal to the 0° incidence free-field threshold of hearing for one-third octave bands of noise. As such, the curve has two additional uses. One is in checking the noise level of free-field audiometry rooms, as mentioned above. The

other is its use as the minimum noise band level in the calculation of articulation index. The curve of Fig. 4 lies within a decibel or two at most frequencies of that shown by Kryter (1962), Fig. 3. See also ANSI standard S3.5-1969, Table I.

- ⁸Assuming a binaural advantage of 2.5 dB at 100 Hz, the 37-dB monaural threshold data of Rudmose (1962) is equivalent to a binaural threshold SPL of approximately 34 dB. The present monaural data (three ears) would be equivalent to a binaural threshold of about 33 dB at 100 Hz. This can be compared to the 100-Hz binaural threshold SPL obtained by various authors: 32.5 dB by Sivian and White (1933); 33 dB by Churcher and King (1937); 32 dB by Yeowart and Evans (1974). In contrast, the NPL observations of Robinson and Dadson (1956) and Anderson and Whittle (1971) are 25 and 27 dB, respectively, which is roughly 7 dB lower.
- ⁹Killion and Carlson (1974b).
- ¹⁰Informal listening tests indicate a similar microphone with an A-weighted noise level of roughly 10 dB (equivalent SPL) would be required in order for its noise to be completely inaudible to a good ear listening at unity acoustical gain (tests conducted in a free-field, using a loudspeaker with a reasonably flat frequency response).
- ¹¹The classic work on microphone noise is that of Baerwald (1940), who discussed the important noise sources for magnetic, condenser and piezoelectric microphones. See also Y. Rocard, *General Dynamics of Vibrations* (Unger, New York 1960), especially pp. 242-245.
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