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Recommended High-Frequency Audiometric Threshold Levels (8000–18 000 Hz)

JERRY L. NORTHERN AND MARION P. DOWNS

University of Colorado Medical Center, Denver, Colorado 80220

WAYNE RUDMOSE

TRACOR, Incorporated, Austin, Texas 78721

ARAM GLORIG

Callier Hearing and Speech Center, Dallas, Texas 75235

JOHN L. FLETCHER

Memphis University, Memphis, Tennessee 38111

The normal range of auditory sensitivity for pure-tone signals (8000 to 18 000 Hz) has been well bracketed in laboratory studies, generally with experienced listeners. This study reports results obtained during a field survey of high-frequency hearing conducted with 237 subjects at the 1968 Denver ASHA Convention. These results agree quite closely with data from the laboratory studies. The purposes of this study are threefold: (1) to report high-frequency field survey audiometric thresholds as a function of age and sex; (2) to review and compare results of all previous reports of high-frequency hearing threshold studies, with particular attention to differences in calibration techniques; and (3) to recommend the Zislis and Fletcher [J. Aud. Res. **6**, 189–198 (1966)] threshold results obtained from sixth through 12th grade girls, with smoothing and minor modifications at 16 and 18 kHz, as the best representation of the "most sensitive hearing" for frequencies from 8000 to 18 000 Hz. It is recommended that these values be used as an interim standard until such time as official standard values are promulgated.

INTRODUCTION

Investigators have recently shown increased interest in the auditory sensitivity levels of the human organism for auditory signals, 8000 to 18 000 Hz. For many years, researchers who were interested in studying high-frequency hearing were beset by instrumentation and calibration problems. Dr. Harvey Fletcher's original published reports on high-frequency normative studies in 1929 indicated that for the frequencies above 10 000 Hz, "the data are very uncertain and vary greatly with various individuals." He stated that "at the high frequencies it is difficult to distinguish the hearing sensation from pain." This effect has not been reported in studies since. Instrumentation problems undoubtedly account for the fact that in the years since 1929 high-frequency audiometry was reported only in research investigations. Until recently, no clinical applications were suggested.

In the early 1960s, Rudmose developed a clinical suprahigh-frequency audiometer which featured a Békésy–type, fixed frequency, tracking procedure. This audiometer uses a polarized Brüel & Kjær microphone as a transducer, enclosed within a special conical plastic tip, which the patient holds in his ear canal. Development and calibration of the audiometer has been described previously by Fletcher (1965). In a comparison of seven systems used to measure suprahigh-frequency thresholds, Harris and Myers (1969) reported the TRACOR technique as the preferable system.

The clinical usefulness of high-frequency measurements with this type of audiometer is becoming evident. Jacobsen *et al.* (1969) reported that ototoxicity from kanamycin could be identified two months earlier

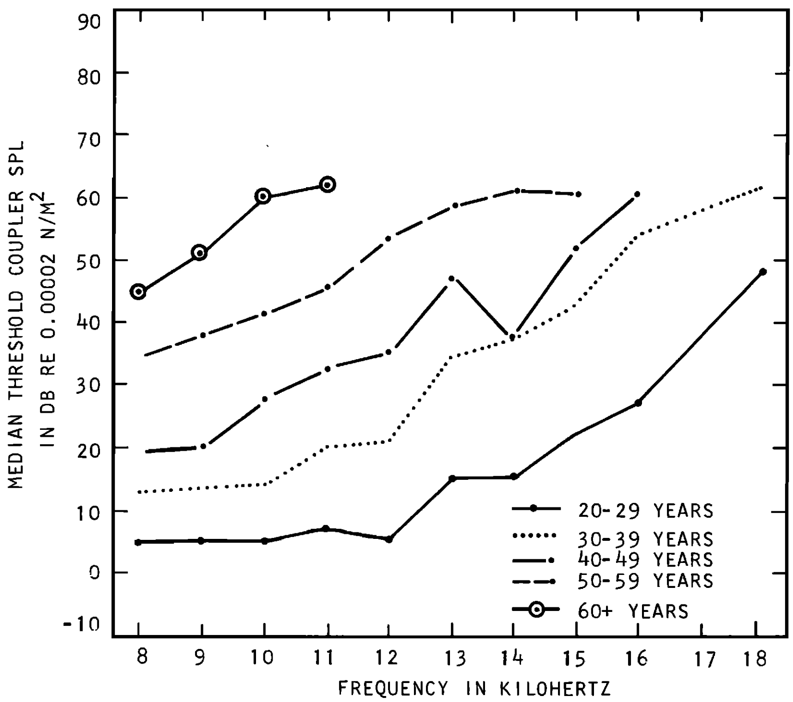

FIG. 1. Field study median high-frequency audiometric survey thresholds by age decade- Threshold values are recorded as SPLs measured on the high-frequency reference coupler.

through high-frequency threshold monitoring than with standard audiometric monitoring. Corliss *et al.* (1969) suggested that noise-induced hearing loss, in some instances, becomes evident in the high frequencies sooner than in the standard test frequencies. Fletcher *et al.* (1967) reported on the significance of high-frequency hearing in patients with meningitis. High-frequency hearing thresholds have been established by investigators interested in clinical applications for such hearing measurements (Vassallo, Sataloff, and Menduke, 1967; Vassallo and Sataloff, 1968). Relationships between high-frequency audiometry and noise-induced hearing loss have been reported by Sataloff, Vassallo, and Menduke (1967) and Downs, Hemenway, and Doster (1969). Rosen and Olin (1968) related high-frequency hearing loss through 14 000 kHz with coronary heart disease.

With these demonstrations of the clinical utility of high-frequency audiometry, it seems pertinent that two questions be answered concerning high frequency audiometry: (1) What are normal threshold values for various age levels? and (2) What sound-pressure level (SPL) values should be recommended for 0-dB hearing threshold level (HTL) for frequencies 10 000–18 000 Hz?

The purpose of this paper is to report a field study of high-frequency thresholds for individuals of various age decades, to compare field study thresholds with previous evaluations of high-frequency hearing, and to recommend standard reference level values for 0-dB HTL for test frequencies of 10 000 to 18 000 Hz.

TABLE I. Information concerning subjects utilized in the ASHA field survey of high-frequency audiometric thresholds.

Age group	Number of subjects		
	Female	Male	Total
20+ years old Mean age 24.5 Range 20–29 years	73	44	117
30+ years old Mean age 34.0 Range 30–39 years	21	42	63
40+ years old Mean age 44.1 Range 20–49 years	12	25	37
50+ years old Mean age 53.0 Range 50–58 years	8	8	16
60+ years old Mean age 65.0 Range 62–68 years	2	1	3
70+ years old	0	1	1
Total	116	121	237

TABLE II. Ambient noise levels of test environment (in dB *re* 0.00002 N/m²).

Frequency (in Hz)	Sound level in general exhibit area (in dB)	Sound level inside booth (in dB)
31.5	66.5	59.0
63.0	59.5	47.0
125.0	65.5	48.0
250.0	65.0	36.0
500.0	66.0	30.0
1000.0	61.0	17.5
2000.0	59.5	15.0
4000.0	49.0	21.0
8000.0	34.0	20.0
16000.0	24.5	20.0

TABLE III. Threshold coupler SPL values for all subjects including mean, standard deviation, standard error of the mean, and median scores.

Age group		Frequency in kilohertz 8	9	10	11	12	13	14	15	16	18
20–29 years	Mean	8.5	6.2	7.6	10.2	13.3	19.1	24.4	32.6	41.9	59.3
	S.D.	14.3	15.1	15.8	16.8	18.1	16.8	18.6	20.0	20.7	17.0
	SE_m	1.3	1.4	1.5	1.6	1.7	1.6	1.8	1.9	2.0	1.9
	Median	5.0	5.0	5.0	7.0	5.5	15.0	15.0	22.0	27.5	48.0
30–39 years	Mean	16.2	14.2	17.5	24.3	35.3	35.1	40.4	48.0	57.4	74.0
	S.D.	17.5	18.5	18.4	19.5	19.0	19.3	19.2	18.3	16.2	9.0
	SE_m	2.2	2.3	2.3	2.5	2.6	2.6	2.7	2.8	2.8	2.3
	Median	13.0	14.0	14.0	20.0	21.0	34.0	37.0	43.0	54.0	61.0
40–49 years	Mean	20.0	21.6	26.6	32.0	38.3	45.7	46.5	57.4	69.9	78.6
	S.D.	17.5	18.5	17.8	14.8	19.0	18.8	17.9	10.0	2.8	1.7
	SE_m	2.5	3.0	3.0	2.6	3.5	3.6	4.0	2.8	1.0	0.9
	Median	19.5	20.0	27.5	32.5	35.0	47.0	37.5	52.0	60.0	
50–59 years	Mean	35.4	35.1	38.0	44.6	48.2	49.6	60.7	66.8	72.0	
	S.D.	19.0	19.8	20.3	18.7	19.1	18.0	12.0	3.6	2.2	
	SE_m	4.7	5.0	5.0	4.7	5.5	6.8	4.9	1.8	1.2	
	Median	34.5	38.0	41.5	45.5	53.5	58.5	61.0	60.5		
60+ years	Mean	40.8	45.5	54.3	57.7	64.0					
	S.D.	11.6	11.3	10.2	8.3	2.0					
	SE_m	5.8	5.7	5.9	4.8	1.4					
	Median	45.0	51.0	60.0	62.0						

I. FIELD SURVEY OF HIGH-FREQUENCY AUDITORY THRESHOLDS

A scientific exhibit featuring suprahigh-frequency audiometry was presented for four days at the November 1968 Convention of the American Speech and Hearing Association in Denver, Colorado (Northern *et al.*, 1968). As part of the exhibit, conventioneers were encouraged to take a suprahigh-frequency hearing test in one of two IAC 400 A sound rooms equipped with TRACOR ARJ4-HF audiometers. Subjects answered questionnaires adapted from the 1954 Wisconsin State Fair Hearing Survey (Glorig *et al.*, 1957) concerning their auditory history. In addition, otoscopic examinations were given to each subject by experienced otolaryngologists. All audiometric testing was conducted by clinically certified audiologists.

During the 28 h of the exhibit, 237 individuals were given suprahigh-frequency hearing tests. Data concerning age and sex of the subjects are shown in Table I. Most subjects were members of the American Speech and Hearing Association and should not be considered inexperienced. On the other hand, few subjects, if any, had participated in previous suprahigh-frequency hearing tests. Since one-half of this sample was composed of subjects less than 30 years old, the incidence of prolonged noise exposure was limited. To maintain field conditions of the survey, results from subjects with noise exposure were included in the data analysis. Mean threshold values of subjects with history of noise exposure were not substantially different from thresholds of non-noise exposed subjects.

The audiometers were calibrated daily by measuring voltage at each test frequency and matching the results with the audiometer manufacturer's specifications. Test environment ambient noise levels are shown in Table II.

A. Procedure

Each subject tracked his threshold at 8, 9, 10, 11, 12, 13, 14, 15, 16, and 18 kHz. One ear per subject was randomly selected and tested. Subjects tracked at each test frequency long enough to provide a stabilized threshold. Each test (all ten frequencies) took approximately seven minutes. Thresholds were recorded to the nearest 1.0 dB. To facilitate analysis of the data, biological HTL values recorded on the audiometer were converted to SPL in decibels as measured using the special calibration coupler (see Appendix A).

B. Results

Median high-frequency hearing thresholds for all subjects, presented by age decades are shown in Fig. 1. It should be noted that suprahigh-frequency threshold sensitivity decreases with advancing age, and further, that the rate decreases more rapidly at the higher test frequencies. High-frequency hearing threshold levels for the 20- and 30-year decade groups remain relatively stable between 8 and 12 kHz, but rapidly decrease for frequencies above 13 kHz. The 60- to 70-year decade age group includes data from only four subjects, and accordingly these results should be interpreted with caution. Table III presents the mean values, the standard deviation for each mean, the corresponding standard error of the mean, and the median values of the survey data as a function of age.

As test frequency increased, the number of subjects able to respond in each age group decreased. These

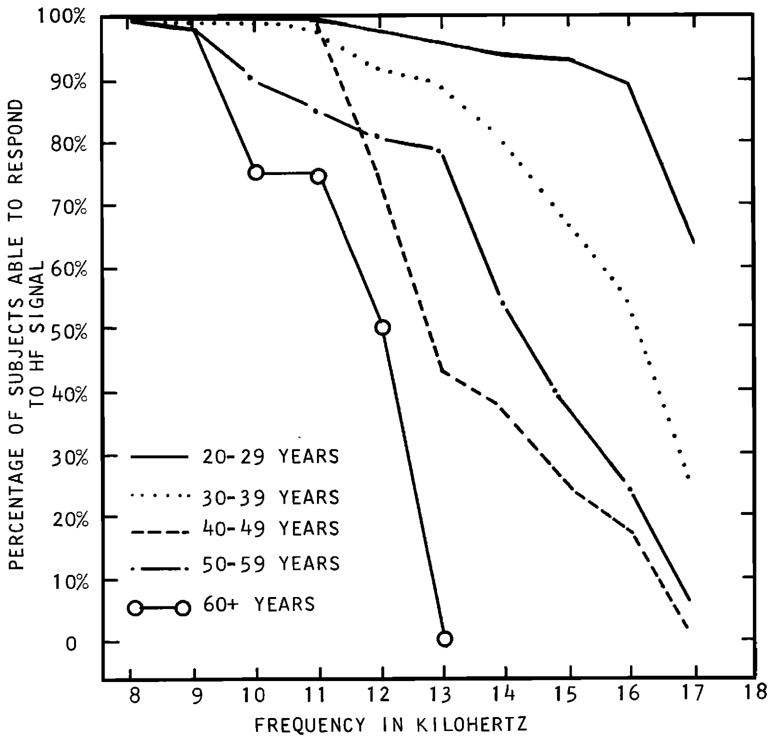

FIG. 2. Percentage of total subjects (by age decade group) able to respond to field study high-frequency audiometric survey.

data are presented in Fig. 2. The number of 20+ year-old subjects who are unable to hear the high-frequency test signals does not decrease substantially until 18 000 Hz. Only 66% of the 30+ year-old group were able to respond to frequencies above 14 000 Hz. A similar trend for fewer subjects to respond at higher test frequencies may also be seen for the 40+ and 50+ year groups, (Fig. 4).

Mean high-frequency hearing threshold levels for male and female subjects are reported by age decades in Figs. 3 and 4. The male subjects show a more orderly progression of hearing loss than that demonstrated by the females. Mean high-frequency thresholds, standard deviations, and standard error of the mean scores for male and female subjects, by age decade, are presented in Tables IV and V.

II. RATIONALE FOR PROPOSED REFERENCE LEVELS

It is difficult, and sometimes confusing, to compare results of high-frequency threshold studies. For example, Harris and Ward (1967) illustrate the results of

TABLE IV. High-frequency threshold values for female subjects including mean, standard deviation, standard error of the mean, and median ($N=116$).

Age group		8	9	10	11	12	13	14	15	16	18
		Frequency in kilohertz									
20–29 years	Mean	8.3	4.2	3.0	5.2	8.7	15.6	21.7	31.0	39.4	58.8
	S.D.	13.0	14.4	11.0	11.8	15.4	13.9	17.6	20.0	20.1	17.5
	SE_m	1.6	1.7	1.3	1.4	1.9	1.7	2.2	2.4	2.5	2.3
	Median	10.0	4.0	4.0	5.0	5.0	14.0	16.0	24.0	34.0	55.0
30–39 years	Mean	14.9	11.0	12.1	20.1	24.3	31.2	39.6	47.1	60.0	72.0
	S.D.	15.8	16.7	18.3	17.8	16.9	18.4	17.9	18.0	15.9	5.1
	SE_m	3.6	3.6	4.0	3.9	3.7	4.2	4.2	4.5	4.3	2.1
	Median	11.0	10.0	10.0	18.0	20.0	30.0	34.0	43.0	56.0	60.0
40–49 years	Mean	12.8	10.8	20.6	28.8	42.0	50.2	44.0	56.0	61.0	62.0
	S.D.	9.5	12.8	17.0	15.0	17.8	19.3	19.4	13.2		
	SE_m	2.7	3.7	5.1	4.5	5.3	5.8	8.0	6.0		
	Median	15.0	7.0	18.0	27.0	42.0	59.0	34.0	50.0	61.0	62.0
50–59 years	Mean	29.2	32.0	21.4	42.3	39.4	46.0	57.0	68.7	71.7	
	S.D.	18.8	22.1	24.2	21.4	20.7	17.6	15.0	1.7	1.7	
	SE_m	6.6	7.8	8.6	7.5	9.2	8.8	8.7	0.9	0.9	
	Median	24.5	32.5	35.5	47.0	37.0	51.0	60.0	61.0	61.0	

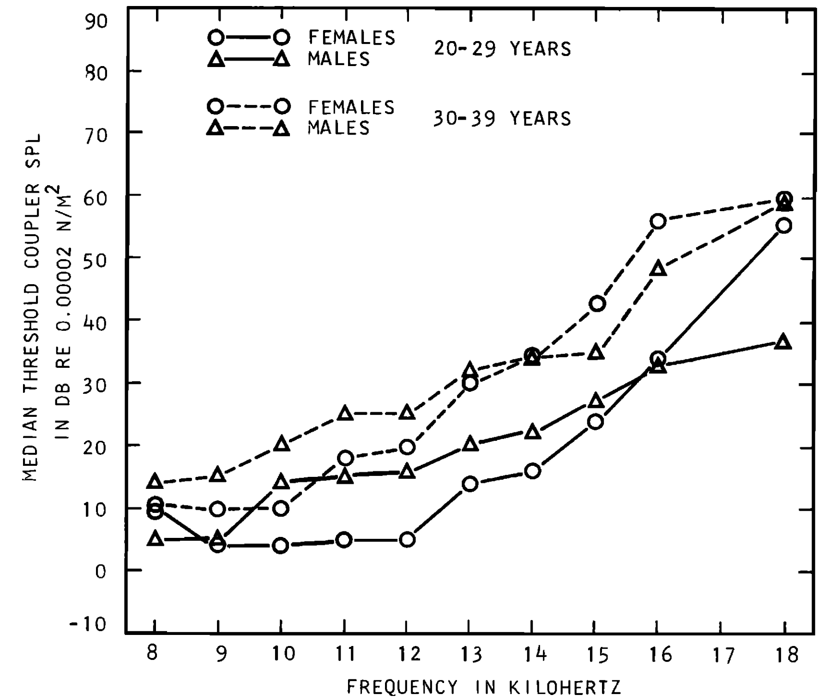

FIG. 3. Field study median high-frequency audiometric survey thresholds for males and females from 20 to 29 years and 30- to 39-year age decade groups. Threshold values are recorded as sound pressure levels measures on the high-frequency reference coupler.

four different studies which appear to be directly comparable, but this is not strictly true. The SPL values for the Zislis and Fletcher (1966), and the Rudmose threshold reference, are coupler SPL values for threshold where the coupler is the one described in this paper. The Harris and Ward values were measured with a 1-in.-diam condenser microphone mounted at the eardrum position in the Schilling artificial head, and the Rosen (1964) values were obtained using a $\frac{1}{8}$-in. condenser microphone placed at the entrance to the ear canal and at the eardrum of the Schilling artificial head. Furthermore, different sound sources were used for calibration except for the Zislis and Fletcher and Rudmose study. This calibration information is in the text of the Harris and Ward article, but the comparative threshold figure ordinate is only labeled, "SPL in dB."

In another study, Harris and Myers (1971) compare high-frequency thresholds with two previous studies. The Harris and Myers data are comparable to the Zislis and Fletcher data, with one possible exception. Both studies report "coupler SLP" for threshold; however, the couplers are slightly different and the earphones are also different. The Harris coupler was a $\frac{1}{4}$-in. condenser microphone used in the same manner as the $\frac{1}{2}$-in. con-

TABLE V. High-frequency threshold values for male subjects including mean, standard deviation, standard error ot the mean, and median ($N=121$).

Age group		8	9	10	11	12	13	14	15	16	18
		Frequency in kilohertz									
20–29 years	Mean	9.0	7.4	14.3	19.5	20.5	24.1	28.1	35.6	36.5	60.5
	S.D.	16.3	15.8	19.6	19.6	19.8	20.0	19.9	19.7	20.0	15.8
	SE_m	2.4	2.4	3.0	3.0	3.0	3.1	3.1	3.2	3.4	3.9
	Median	5.0	4.5	14.0	15.0	15.5	20.0	22.0	25.0	33.0	37.0
30–39 years	Mean	16.6	16.6	20.1	26.4	27.1	36.7	40.9	48.2	55.0	75.1
	S.D.	17.6	18.7	17.8	20.0	19.2	20.0	19.8	18.5	16.7	10.5
	SE_m	2.7	2.9	2.8	3.1	3.2	3.3	3.5	3.6	3.7	3.3
	Median	14.0	15.0	20.0	25.0	25.0	32.0	34.0	35.0	48.0	59.0
40–49 years	Mean	23.7	26.8	29.9	33.7	36.2	42.9	47.9	58.1	69.5	79.5
	S.D.	18.2	17.3	17.0	14.0	19.3	18.0	17.0	7.7	3.1	1.5
	SE_m	3.6	3.4	3.5	3.1	4.4	4.3	4.5	2.4	1.3	1.0
	Median	21.0	26.0	28.0	30.0	34.0	37.0	38.0	52.0	60.0	62.0
50–59 years	Mean	43.6	38.3	44.6	46.8	54.7	54.3	64.3			
	S.D.	15.2	16.6	12.2	15.2	15.4	17.3	6.0			
	SE_m	5.4	5.9	4.3	5.4	5.8	10.0	3.4			
	Median	42.0	45.0	45.0	46.0	57.0	62.0	62.0			

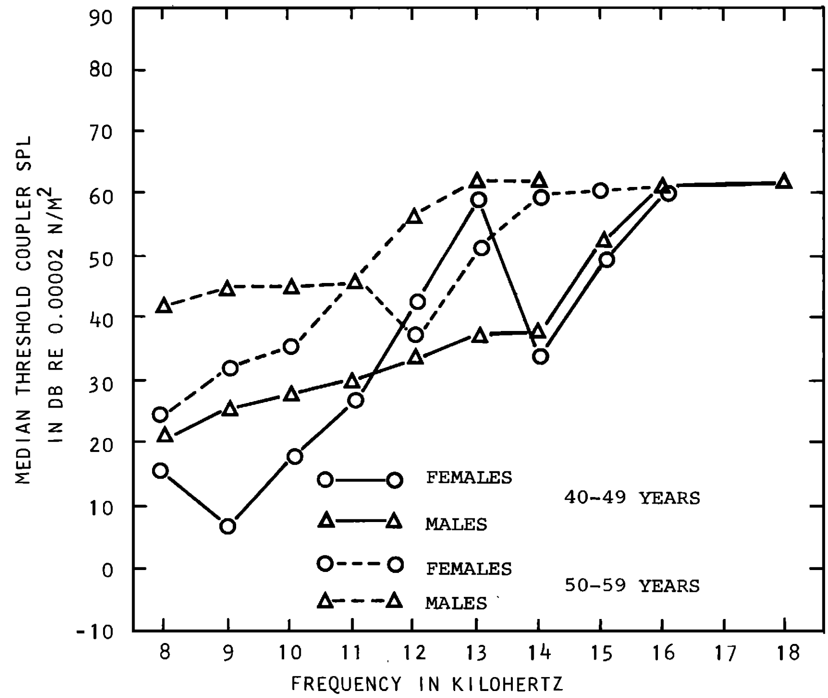

FIG. 4. Field study median high-frequency audiometric survey thresholds for males and females from 40 to 49 years and 50- to 59-year age decade groups. Threshold values are recorded as sound-pressure levels measured on the high-frequency reference coupler.

denser microphone used in the Fletcher study. It is reasonable to believe that these two "couplers" may give different results even for the same transducer. The Harris transducer used a 1-in. condenser microphone coupled to a 30-mm conical horn fitted with a plastic olive. The Fletcher transducer used a 1-in. condenser microphone coupled to a $\frac{1}{8}$-in. brass tube loosely filled with steel wool with a Teflon cone around the brass tube (the cone is not connected acoustically with the tube). Since different transducers react differently on the same coupler (as shown in Table A-I of Appendix A), it seems reasonable that different transducers on different couplers might be even more different in terms of their results. It is not anticipated, however, that these differences would be more than a decibel or so at any particular frequency, yet a comparison study should be made to eliminate this question. Harris and Myers (1971) also compare their results with the British Standard MAP (Dadson and King, 1954). Dadson and King clearly state that their data are in terms of SPL values measured at the entrance to the ear canal. The work of Teranishi and Shaw (1968), for example, shows that for frequencies in the range of interest, significant differences exist between the SPL at the eardrum and at the entrance of the ear canal.

TABLE VI. Median eardrum SPL in decibels for zero threshold (data rounded to nearest decibel).

Frequency (in kHz)	Sivian and White[a]	Dadson and King[b]	Rudmose (TRACOR)[c]	Zislis and Fletcher[d]	Harris and Myers[e]	Northern *et al.*[f]
8	20	17	16	14	13	21
9			18	16	23	23
10	29	24	21	18	23	26
11			18	18	18	25
12	35	29	14	18	16	20
13			15	19	26	28
14	46	37	17	22	30	27
15	50	41	17	22	35	32
16			18	38	37	36
18			27	64	85	60

[a] 1933—Weighted data based on a sample of both young and older subjects.
[b] 1952—Smoothed curve based on two studies—one study 45 males and 54 females (198 ears) except for 15 kHz where 17 subjects failed to hear tone; 18–25 years—other study based on 512 males (1024 ears); same age group.
[c] 1961—12th grade; 8 females, 4 males for frequencies through 14 kHz; 2 females, 1 male for 15, 16, and 18 kHz—best ear each subject.
[d] 1966—6–12 grade females; left ear; most sensitive (60 ears).
[e] 1971—17–23 year males; right and left ear combined (200 ears).
[f] 1971—20–29 year; 73 females, 44 males; one ear per subject—randomly chosen.

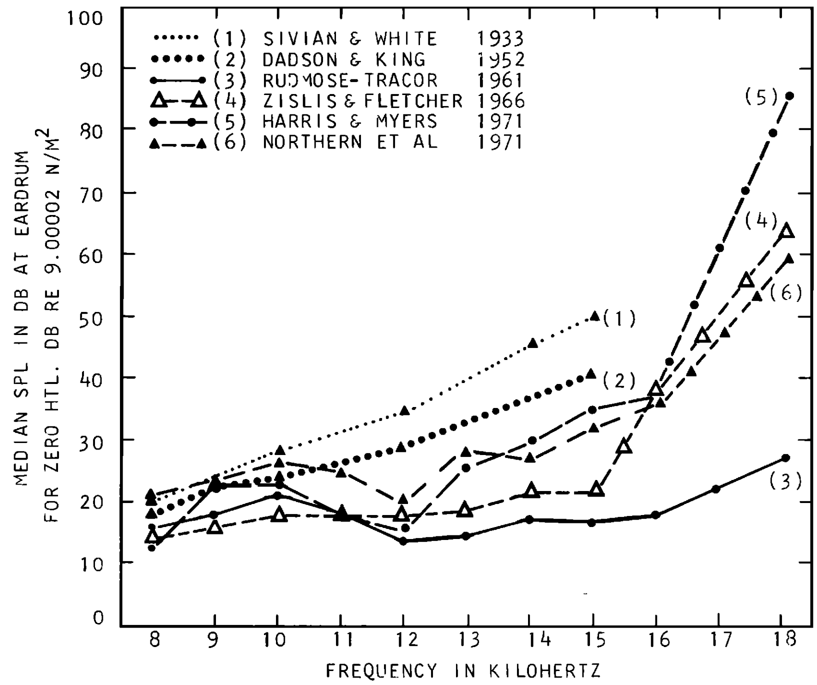

FIG. 5. Summary of median values obtained in six different high-frequency audiometric threshold studies. Threshold values are recorded as sound pressure levels measured at the eardrum.

In this paper an attempt has been made to bring together as much data as possible and compare all data on the basis of some common point of reference. For this comparison, eardrum SPL for zero HTL has been chosen as this reference point. The data of Zislis and Fletcher, as well as those in this paper, can be converted by means of the conversion factors in Table A-I of the Appendix. The Dadson and King data can also be converted by using information reported in the Teranishi and Shaw paper to obtain the conversion factor from entrance of ear canal to eardrum SPL. These factors are 0, 3, 4, 7, and 6 dB for frequencies 8, 10, 12, 14, and 15 kHz, respectively, based on the published curves. The classic Sivian and White (1933) study presents data for MAP obtained by a probe tube approximately 1 to 1.5 cm from the eardrum. Most likely this point is a little nearer the eardrum than was the Dadson and King probe; however, the same conversion factors will be used since 1.5 cm is not near enough to the eardrum to measure eardrum SPL (Sivian and White estimate their probe measured eardrum pressure accurately only up to about 4000 to 4500 Hz). The Harris and Myers data are also converted to eardrum SPL values based on the factors of Table A-I of Appendix A. The results of these various threshold conversions are shown in Fig. 5 and Table VI.

The results of the six studies summarized in Table VI should be compared in light of the different studies, equipment, and procedures. Sivian and White actually utilized a probe tube in the ear canal; however, the probe was used to calibrate a loudspeaker source and then the earphone was adjusted to be equally loud as the loudspeaker (the probe being removed before the earphone was placed in the ear). The earphone was then used to obtain the actual thresholds at these higher frequencies. Furthermore, their data were weighted with other studies (calibration techniques still different) to derive the values shown. The Dadson and King data were derived using a closed coupler to store the data obtained on the large number of subjects and used a smaller number of subjects to obtain the factors which related coupler SPL to entrance to ear canal SPL. Both their data and Sivian and White's data have now been corrected still further by factors relating entrance to ear canal SPL to eardrum SPL. The remaining four studies used essentially the same equipment with the same calibration techniques. Thus, although the six studies are similar, the equipment and calibration are somewhat different.

Possibly the greatest differences between the six reviewed studies are in the subjects used. Sivian and White's data were based on subjects whose age ranged from 18 to at least 40 years. The Dadson and King subjects ranged from 18 to 25 years in age, yet 17 of the 99 subjects failed to hear the 15-kHz tone. For the Rudmose–TRACOR data, young 11th grade (16–17 years) students were used and there were more girls than boys. All subjects obtained thresholds for all frequencies; however, for frequencies 15, 16, and 18 kHz only three subjects were used as these last three frequencies were measured several months later (see Appendix A). The Zislis and Fletcher study had both boys and girls from grades six through 12. The Harris and Myers' students used male subjects only in the 17- to 23-year age range, whereas the Northern *et al.* curve is from 20- to 29-year-old subjects. All of the studies, except the Northern *et al.* field study, can be classified as laboratory-type studies where some degree of practice was permitted.

TABLE VII. Recommended high-frequency threshold values.

Frequency (in kHz)	8	9	10	11	12	13	14	15	16	18
Eardrum SPL (in dB) re 0.00002 N/m²	14	15	17	18	19	20	21	23	30	56
Coupler SPL (in dB) *re* 0.00002 N/m² 1-in. condenser microphone driver	−2	−3	−4	0	5	7	9	13	22	44
Coupler SPL (in dB) Coupler SPL (in dB) *re* 0.00002 N/m² 1-in. dynamic microphone driver	5	4	4	9	15	15	15	17	24	51

III. RECOMMENDED REFERENCE LEVELS

Considering the basis on which the ISO (1964) thresholds were derived, it might be said that the Zislis–Fletcher and Rudmose–TRACOR studies represent possibly the "best hearing" in this frequency range. These two studies are in good agreement except for the two highest frequencies (16 and 18 kHz). The Harris–Myers and Northern *et al.* studies used comparable subjects and the results are in good agreement for all frequencies except the very highest, 18 kHz. Perhaps the all male set of subjects used by Harris and Myers influences the 18-kHz thresholds more than the thresholds at other frequencies.

It appears as if the normal range of hearing in this high-frequency range has been well bracketed by several studies. If the experiences of the past in establishing biological baseline data for zero HTL are to guide us in extending the zero HTL values to 18 kHz, it seems only appropriate to give substantial weight to the data based on young, most sensitive, ears in the range above 12 000 Hz. The four studies since 1961 are in reasonable agreement for frequencies 8000 through 12 000 Hz. The Zislis and Fletcher data represent a good arbitrary compromise "most sensitive hearing" for frequencies 8000 through 18 000 Hz. The Rudmose data are suspect for 16 and 18 kHz due to the small number of subjects used, yet it is hard to understand why the Zislis and Fletcher data rise quite so suddenly to approximate the 20- to 29-year-old group of Northern *et al.* study for these two highest frequencies.

Based on the studies cited, it is recommended that the Zislis and Fletcher sixth to 12th grade girls left-ear data, with general smoothing, be used as reference levels through 15 kHz. Reference values for 16 and 18 kHz are recommended to be 30 and 56 dB in terms of eardrum SPL. Coupler SPL values for two different types of earphones are calculated utilizing Table A-I of Appendix A. These recommended values are given in Table VII.

IV. SUMMARY

A field survey of high-frequency hearing thresholds (8 to 18 kHz) was conducted at the 1968 convention of the American Speech and Hearing Association in Denver, Colorado. Thresholds were obtained from 237 subjects who were tested in IAC test suites with TRACOR–Rudmose ARJ-4HF audiometers. All subjects were otoscopically normal and completed questionnaires concerning auditory history and noise-exposure backgrounds. Median and mean high-frequency thresholds are reported in SPL and in decibels measured with the special high-frequency coupler for age decades and by sex. The ear's sensitivity to high-frequency pure tones is shown to decrease with an increase in test frequency. Further, human sensitivity for high-frequency signals decreases inexorably as a function of age. Comparative analysis of six different high-frequency audiometric studies is presented, and recommendation is made for 0-dB HTL sound-pressure levels for test frequencies from 10 000 to 18 000 Hz which can be used as an interim standard.

APPENDIX A. HIGH-FREQUENCY AUDIOMETER CALIBRATION

At the time the Rudmose ARJ-4HF high-frequency audiometer was developed, a calibration technique also had to be established.[A1] Concomitant research (Rudmose 1964) indicated that the use of an open condenser microphone without any associated volume enclosure serves as an acceptable high frequency "coupler" for calibration purposes. The original calibration data were obtained from a small group of high school students by determining the ac driving voltage on the condenser microphone earphone for the median threshold level of the group at each frequency. Keeping this voltage and frequency fixed, the earphone tip was placed so that it almost touched the top edge of a Brüel & Kjær ½-in. microphone (grid on) with the sound from the earphone going "parallel to and across" the microphone diaphragm (see Fig. A-1). The sound-pressure level produced by the earphone as measured by the calibrating microphone was designated as the "threshold calibration SPL" or "threshold coupler SPL."

The original calibration study was not intended to be definitive, but was truly a "quick and dirty" measurement to enable the early instruments to be calibrated so that the device could be evaluated by researchers in the field. Only 12 high school students, eight females and four males, who were in between their junior and senior years were used. They were naive subjects and because of their commitment to a special, short-term course they were attending at S.M.U. in the summer 1961, they were not able to practice for any period of time nor were they able to return for repeat tests.

Thresholds were measured from 4 through 14 kHz using this group. The prototype audiometer did not extend in frequency beyond 14 kHz; however, it quickly became evident that the range should be extended to at least 18 kHz. At the time this was done the original group of subjects had returned to their home schools and were no longer available. Three subjects, whose average thresholds through 14 kHz agreed closely with the thresholds of the original group were used to extend the baseline data to 18 kHz. Users of all TRACOR high-frequency audiometers were advised of the questionable nature of the zero levels, yet now so much time has passed that "age" has evidently given an aura to the original data which they do not deserve. The results of this paper, and those of Harris *et al.* (1971), Zislis and Fletcher (1966), and others indicate that the limited number of subjects used in the original TRACOR calibration study were hyperacoustic for frequencies above 15 kHz.

The need for establishing a better set of biological threshold values and for recording these in terms of eardrum SPL is obvious; and because of its desire to contribute to the knowledge of the field, TRACOR supported the research (performed in 1968) which led to the ability to relate threshold calibration levels to eardrum sound pressure levels.

The concept of the experiment was simple: (1) Use a loudspeaker and measure the subject's threshold SPL at his eardrum; (2) measure his "audiometric threshold" with the ARJ-4HF audiometer; and (3) keep the audiometer set on the "audiometric threshold" and measure the corresponding "coupler threshold SPL." Assuming that the subject's ear and responses remained constant during the time between the loudspeaker threshold determination and the audiometer threshold determination, then the same SPL was produced at the eardrum by the audiometer as was produced by the loudspeaker, the latter being measured by the microphone probe. Hence, the difference between the "eardrum SPL" and the "coupler SPL" is the correction factor that converts the "calibration threshold SPL" or "coupler threshold SPL" value to the "eardrum threshold SPL" value. For this experiment it is not necessary that the subjects be young and have normal hearing in this frequency range. The subject truly is serving as a "transfer device," and the only requirement is that he can determine his pure-tone threshold in this frequency range.

As is always the case the theory is simple and the experiment is another matter. The difficult part is to measure eardrum SPL values at frequencies in the range between 8 and 18 kHz. Probes are difficult to

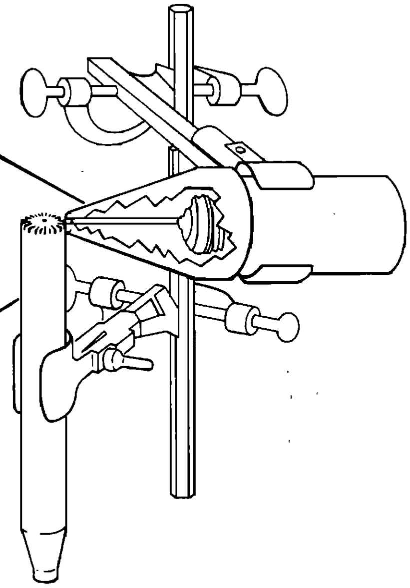

FIG. A-1. The HF reference coupler used to store high-frequency threshold data and to calibrate high-frequency audiometers.

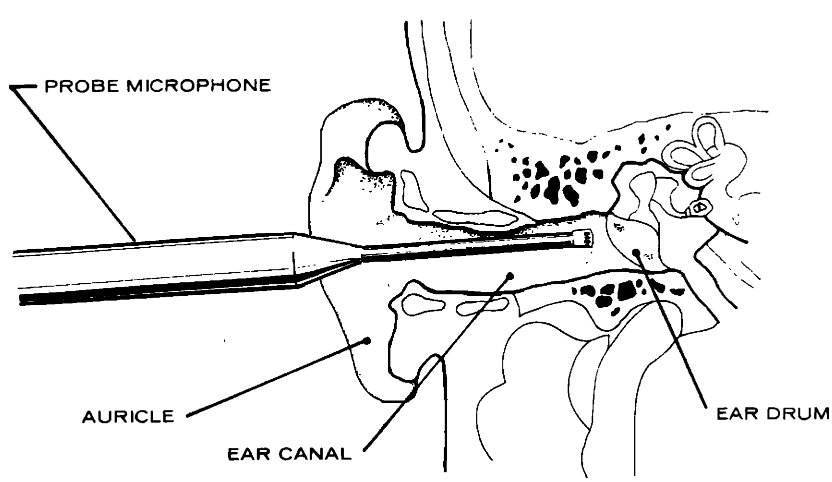

FIG. A-2. Cross-section diagram of the ⅛-in. microphone as it was placed in the ear canal to measure the sound pressure level at the eardrum.

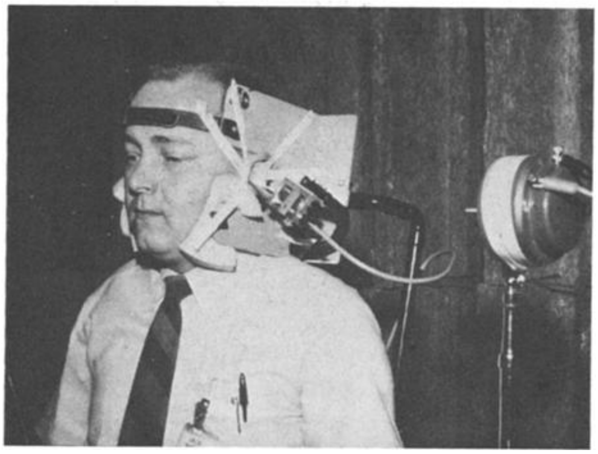

FIG. A-3. Subject in position for obtaining eardrum sound-pressure threshold levels.

make and calibrate for such a range; so a $\frac{1}{8}$-in. Brüel & Kjær condenser microphone was used instead of a probe. The subject was seated in a chair, located in an anechoic chamber, with his head clamped firmly with respect to his chair. It was difficult to straighten the ear canal with a conventional speculum; so the simple technique of "pulling the pinna" was used. For each subject the pinna was pulled in various dirctions using different locations for "pulling." Once the canal was forced into a "straight position" by this type of pulling, the pinna was held in this position while it was taped (with adhesive tape) to the head. Once the canal was straight, the microphone (with its preamplifier and mounting) was carefully positioned within $\frac{1}{16}$ in. of the eardrum (see Fig. A-2). The microphone and mounting were fixed in a micrometer screw arrangement which was rigid with respect to the chair and head clamp (see Fig. A-3). Once the microphone was properly positioned, the subject obtained his threshold using the same Békésy technique as utilized with the ARJ-4HF audiometer; however, the source was an Altec high-frequency driver unit. This driver units, or loudspeaker, was about 18 in. from the subject's head and was pointed toward the ear under test. The eardrum SPL, as measured by the $\frac{1}{8}$-in. condenser microphone, was related directly in terms of the Békésy recording to the corresponding Békésy recording using the ARJ-4HF audiometer.

The subject obtained his "eardrum SPL threshold" values for all of the frequencies by the procedure described above. He then obtained his "audiometric threshold" values using the ARJ-4HF and the RA-114HF audiometers. This entire procedure was repeated once each day on three different days for each of the ten subjects. For a few of the subjects it was not possible to obtain thresholds at 16 and 18 kHz.

It should be mentioned that for the loudspeaker measurements the fact that the pinna was taped in an unnatural position and the fact that the microphone, attachments, and preamplifier obstructed the canal somewhat does not influence the data. The measurements were not true "free field" measurements, and it is not important that the ear canal was pulled so that it was unusually straight or that the pinna was flat against the head—the only measure of importance is the actual SPL on the eardrum for threshold hearing. The ear is a

TABLE A-I. Calibration data for TRACOR ARJ-4HF and RA-114HF audiometers. *Note*: The "coupler" in this case is a $\frac{1}{2}$-in. diameter Brüel & Kjær microphone with protective grid on. The earphone is placed close ($\frac{1}{32}$ in.) to the grid in such a way that the $\frac{1}{8}$-in. tube is parallel to the grid face. The sound is therefore at grazing (or parallel) incidence to the grid (and microphone diaphragm). Figures enclosed by ( ) are interpolations. Standard deviations and standard errors for the RA-114HF conversion are similar to those for the ARJ-4HF conversion factors. "Zero HTL" is zero hearing threshold level, and the corresponding decibel values are re 0.0002 microbar.

	ARJ-4HF					RA-114HF	
Frequency (in kHz)	I[a] Coupler SPL (in dB) for zero HTL	I Coupler to eardrum conversion factor (in dB)	I Standard error of conversion factor	I Standard deviations of conversion factor	TRACOR eardrum SPL for zero HTL	II[b] Coupler SPL (in dB) for zero HTL	II Coupler to eardrum conversion factor (in dB)
8	0	16	1.2	6.3	16	7	9
9	0	(18)			(18)		
10	0	21	0.7	3.8	21	8	13
11	0	(18)			(18)		
12	0	14	0.7	4.1	14	10	4
13	2	(13)			(15)		
14	5	12	1.4	7.8	17	11	6
15	7	(10)			(17)		
16	10	8	1.6	7.8	18	12	6
18	15	12	1.7	7.7	27	22	5

[a] These values apply to the TRACOR ARJ-4HF audiometer using a 1-in. condenser microphone driving a $\frac{1}{8}$-in. tube (acoustically damped) as the earphone.
[b] These values apply to the TRACOR RA-114HF audiometer using a 1-in. dynamic microphone driving a $\frac{1}{8}$-in. tube as the earphone.

pressure operated device and except for experimental fluctuations (and possibly the statistical nature of hearing) the same SPL exists on the eardrum at threshold independently of how the sound is generated and how it is delivered to the eardrum.

The results indicate that the impedance of the audiometer source (the earphone unit used with the audiometer) influences the transfer factors which convert "calibration SPL values" to "eardrum SPL values." The conversion factors are different for the TRACOR ARJ-4HF audiometer and the TRACOR RA-114HF audiometer since the ARJ-4HF uses a condenser microphone and the RA-114HF uses a dynamic microphone. Since either audiometer should produce the same threshold values on a given subject, and since the conversion factors are different, the "calibration threshold" values are different for these two audiometers. This phenomenon is no different from the case of conventional frequency audiometers using different types of earphones. The trouble lies in the fact that the "calibration coupler" does not represent truly the acoustic impedance of the ear over the frequency range being used. This is not surprising for it was not intended to do so but was intended to serve only as a means of storing threshold data.[A2]

Based on the data obtained, the results are shown in Table A-I.

[A1] Although this appendix is written by Rudmose, the credit for the work belongs to Jack Rawls and Tom Evans. Although no longer with TRACOR, Mr. Rawls and Mr. Evans conducted the measurements reported in this Appendix. Portions of this material were presented at the Convention of the American Speech and Hearing Association, Denver, Colorado, 1968.

[A2] If constant voltage is maintained on each of the two types of driver units the acoustic response on the "calibration coupler" is significantly different when damping is not present in the $\frac{1}{8}$-in. tubes. Even after acoustical damping is added to the $\frac{1}{8}$-in. tube on the condenser microphone driver, there are still differences. Equal sound-pressure levels measured on the coupler should not necessarily produce equal eardrum sound-pressure levels under the same electrical driving conditions.

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