To the Graduate Council:

I am submitting herewith a thesis written by Laurence Abikoff entitled "The Influence of Harmonics on Pure Tone Threshold Measurements of Subjects with Moderately-Severe to Severe High Frequency Hearing Impairments." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Audiology.

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THE INFLUENCE OF HARMONICS ON PURE TONE THRESHOLD MEASUREMENTS OF SUBJECTS WITH MODERATELY-SEVERE TO SEVERE HIGH FREQUENCY HEARING IMPAIRMENTS

A Thesis

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L. A.

ABSTRACT

Ten moderately-severe to severely hearing impaired adult subjects were selected from The University of Tennessee Hearing and Speech Center client population to participate in a study designed to examine the effect of harmonic distortion level upon high frequency tonal thresholds.

Hearing thresholds were obtained at 4,000 Hz and 8,000 Hz for each subject using two presentation conditions: tones having a standard level of harmonic distortion as per the ANSI - 1969 protocol, and tones having a reduced level of harmonic distortion. The data obtained from a comparison of threshold results were statistically analyzed to determine if there were statistically significant differences in threshold sensitivity related to the level of harmonic distortion in the test stimuli. Subject thresholds were then determined for extra high frequency harmonics of the test tones. This procedure attempted to relate the lack of differences found in the primary test comparison to elevated hearing sensitivity for harmonics of the frequency under test.

Results of the *t*-test for related measures yielded no statistically significant difference between threshold levels for test tones with a standard level of harmonic distortion and test tones with a reduced level of harmonic distortion.

All subjects tested had markedly poorer threshold sensitivity for extra high frequencies than for the audiometric high frequency

fundamentals. Therefore, no data could be obtained for a worst case example.

It was concluded that for a selected hearing impaired population reduction in the level of harmonic distortion does not appear to result in a significant change in threshold sensitivity for a high frequency fundamental tone under test.

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CHAPTER I

INTRODUCTION

The American National Standards Institute "Specifications for Audiometers" (ANSI S3.6 - 1969) and its subsequent revisions represent a general agreement among maker, seller and user groups as to the requirements that need to be met to assure uniformity, validity, and reliability among commercially available audiometers. The scope of the ANSI S3.6 - 1969 standard includes sections on definitions, general requirements for pure tone audiometers and requirements for speech audiometers. The ANSI S3.6 - 1969 standard, as it exists today, is the result of an ongoing process to incorporate state-of-the-art research and technology into these widely accepted guidelines.

There are substantial differences between the ANSI S3.6 - 1969 standard and its predecessor, the American Standards Association's "Audiometers for General Diagnostic Purposes" (ASA Z24.5 - 1951). Specifications in the ASA-51 standard that were considered controversial such as the determination of "standard reference threshold sound pressure levels" for each of the pure tone test frequencies were subsequently the focus of extensive research and revision as reflected in the International Standards Organization (ISO) standard of 1964 and the ANSI standard of 1969. Other items that were considered less controversial such as harmonic distortion levels have received only minor attention and are either essentially intact or only slightly more rigorous than the ASA specifications of thirty years ago.

The need to limit the level of harmonic distortion associated with pure tone audiometric testing is acknowledged by the present American standard (ANSI S3.6 - 1969) as well as its predecessors, the ASA Z24.5 - 1951 standard and the ISO - 1964 standard.

Harmonic distortion, that is, the unwanted introduction of acoustic energy at exact multiples of the fundamental frequency, is recognized by these standards as having a potentially contaminating effect upon the validity of pure tone threshold measurement. This is the case because as the level of harmonic distortion increases the possibility of subject response to the harmonic component similarly increases. The present American standard requires that the sound pressure level of harmonics be at least 30 decibels below the sound pressure level of the fundamental or test frequency.

Harmonic distortion requirements of the present standard appear to be adequate when compiling data on a normally hearing population. This is because the sound pressure level of the harmonics are negligible when the presentational level of the test tone remains within the range of normal hearing sensitivity.

It is not clear, however, that the harmonic distortion levels allowed by the present standard are necessarily adequate for a population of hearing impaired subjects. Consider that a 4-kHz signal presented via TDH-39 earphones at 70 dB HL (80.5 dB SPL) is also delivering up to 41 dB HL (50.5 dB SPL) at 8 kHz; and a signal presented at 90 dB HL (103.0 dB SPL) at 8 kHz is also delivering up to 73.0 dB SPL at 16 kHz. The possibility then exists that these high energy levels at the harmonics may, in some cases, artifically lower threshold responses for high frequency clinical test tones. Furthermore, the method for calculation of harmonic distortion in pure tone audiometers commonly employed in audiometer calibration is to measure the second harmonic of the test frequency up to 4 kHz to assure that it is at least 30 dB below the sound pressure level of the test frequency. For the 6-kHz and 8-kHz test tones no harmonic distortion measures are made. Other harmonics (i.e., third harmonic and total harmonic distortion) are not usually considered in the calibration procedure (Bruel and Kjaer, 1974). Therefore, there is relatively little known about the spectral quality of test tones presented in the clinical setting beyond the level of the second harmonic.

The aforementioned harmonic distortion levels represent possibly detectable stimuli to at least some listeners who exhibit severely impaired hearing sensitivity at audiometric high frequencies yet who do not evidence similar hearing impairments at harmonics of the test signal. This point is also true for listeners with low and/or mid frequency hearing loss, and although it is not an object of this study, it bears mention.

One observation which may be made to support the presently accepted levels of harmonic distortion is the typical configuration of the pure tone audiogram. It might be argued that in order for harmonic distortion to become a contaminating factor in pure tone testing, the subject's hearing threshold would have to be greater than 30 dB SPL more sensitive at the second or higher harmonic to be of consequence in the test procedure. Since this degree of sensitivity difference is an extremely rare occurrence, it should be noted as an important rationale for maintaining harmonic distortion requirements at their existing levels. Yet in order to verify this observation, it is necessary to compare the threshold sensitivity of hearing impaired subjects for tones with different levels of harmonic distortion. By reducing the level of harmonic distortion it can be determined whether subject thresholds were influenced by the level of harmonic distortion in the test signal.

The harmonics of high frequency audiometric test tones extend beyond the frequency range typically examined in audiometric testing and calibration. The second harmonic of the 8 kHz stimulus is 16 kHz, and the third harmonic of the 4 kHz stimulus is 12 kHz. Measurement of auditory function and calibration of the instrumentation used in the extra high frequency range (i.e., 10 kHz to 20 kHz) requires special consideration. There is not, at the present time, any definitive standard relating to procedures, calibration, or instrumentation for ascertaining thresholds in this frequency range. Thus, measurements utilized in investigation of contaminating influences of harmonics must be developed and related to the procedures and findings of previous researchers rather than a standardized protocol.

Purpose

The present study was designed to examine whether acceptable harmonic distortion according to the ANSI-1969 protocol contaminates high frequency pure tone thresholds (i.e., 4 kHz and 8 kHz) of subjects having moderately-severe to severe high frequency hearing impairments.

Problem: In order to assure the validity of pure tone threshold responses of moderately-severe and severely hearing impaired listeners, it is necessary to control the level of harmonic distortion of the generated signal. Only by filtering the audiometric signal so that harmonic distortion levels are significantly reduced can it be determined whether the subject is responding to the test stimulus and not to a harmonic or some other combination of complex auditory stimuli.

Hypothesis

The hypothesis stated in null form is: there are no significant differences in hearing thresholds for tones of 4,000 Hz and 8,000 Hz in moderately-severe and severely hearing impaired listeners tested using two presentation conditions: clinical tones and experimental tones (refer to definitions in the following section).

The criterion measures will be the difference in applied voltage and the analogous difference in the sound pressure level at which thresholds were obtained for the two test conditions.

Definition of Terms

The following are definitions of the technical terms used in the body of this report. The terms are defined specifically in relation to and for the purpose of this study.

Bilateral sensory hearing impairment. A loss of hearing sensitivity of between 60 dB HL and 90 dB HL at frequencies of 4 kHz and/or 8 kHz. The clinically obtained thresholds at the nontest ear are not more than 25 dB HL more sensitive than the hearing threshold of the corresponding test frequency for the ear under test. This condition shows no indication of conductive pathology.

Clinical tones. Audiometric test tones with harmonic distortion not exceeding 3.2% (-30 dB) (American National Standards Institute, S3.6 - 1969).

Experimental tones. Tones with harmonic distortion not exceeding 1.0% (-40 dB) are designated as experimental tones in this study.

Extra high acoustic frequencies. The frequency range above 8,000 Hz to 20,000 Hz (Lipscomb & Cutts, 1970).

Harmonic distortion. A comparison of the sound pressure level of the second harmonic with the sound pressure level of the fundamental frequency under test yielding a percentage relationship between the two components (Stevens & Davis, 1939, p. 7).

High frequencies. 4,000 Hz and 8,000 Hz are designated as high frequency in this study.

Moderately-severe to severe hearing loss. For the purpose of this study, this degree of hearing impairment was defined as being in the range of 60 dB HL to 90 dB HL based upon the average of audiometric pure tone thresholds at 500 Hz, 1,000 Hz and 2,000 Hz.

CHAPTER II

REVIEW OF LITERATURE

Harmonic Distortion and the American Standard

The development of an American standard for audiometers began in 1932, when,

> Following a proposal by the Acoustical Society of America, the American Standards Association initiated a standardization project on acoustical measurement and terminology (ASA Z24.5 - 1951, inside cover).

In 1945 the Council on Physical Medicine for the American Medical Association issued "Minimum Requirements for Acceptable Audiometers." This document proceeded the American Standards Association publication of requirements for audiometers and is, in fact, the first American standard for audiometer performance.

The American Medical Association publication and the 1935-1936 National Health Survey Hearing Study provided an information base for the more widely recognized ASA standard, "Audiometers for General Diagnostic Purposes," ASA Z24.5 - 1951, which in section 3.6, "Harmonics in the Output of Air-Conduction Earphones," specifies that "the sound pressure of the fundamental signal shall be at least 25 dB above the sound pressure of any harmonic" (p. 9). The present American National Standards Institute "Specifications for Audiometers" (ANSI S3.6 - 1969) in section 4.1.3, "Purity of Tones," requires that, "The sound pressure level of any harmonic of the fundamental shall be at least 30 dB below the sound pressure level of the fundamental" (p. 10).

The 30 dB reduction in the level of harmonics (3.2% harmonic distortion) is only slightly more rigorous than the requirements specified eighteen years earlier in ASA Z24.5 - 1951, section 3.6, "Harmonics in the Output of Air-Conduction Earphones."

Neither the ASA - 1951 nor the ANSI - 1969 committees which formulated the American standards revealed research findings to support any specific harmonic distortion levels. There was a notable absence of literature relating to harmonic distortion relevant to audiometry and audiometer calibration (Beranek, 1981; Grason, 1981).

Harmonic Distortion and Related Phenomena

Stevens and Davis (1938) downplayed the importance of harmonic distortion in the generation of pure tones. They concluded that when compared to aural harmonics (harmonics generated in the ear as a result of nonlinearity and asymmetry in the auditory transducer) the distortion introduced by the pure tone generator can be considered negligible, while the effect of the aural harmonic may be so substantial that, "for certain low frequencies the aural harmonic of an originally pure tone may have a greater sensation level than the fundamental itself" (p. 69).

While this observation tends to support maintaining the present limit of harmonic distortion, it is equally important to note research that questions the status quo.

In 1968, Bredberg reported data which compared pure tone audiometric results to histologic examination of the cochlea. He found that the area of the cochlea assumed responsible for the demonstrated hearing sensitivity of his subject had no sensory cells capable of producing such a response. He therefore concluded that some other sensory factors must be involved.

In general, Bredberg found good agreement between the loss of a given number of outer hair cells in the basal coil of the cochlea and the elevation of pure tone threshold in the analogous frequency range. A notable exception was found at the area of the basilar membrane presumed related to the audition of a 4,000 Hz tone,

> where a given loss of hair cells was associated with a lesser hearing loss than that produced by equal cell loss either at 17 mm (2,000 cps-270°) or 7 mm (8,000 cps-60°) . . . it is possible that neighboring regions, showing less damage, were stimulated rather than the actual regions normally reacting to a tone of 4,000 cps at threshold (Bredberg, 1969, p. 117).

He also observed that,

> the two ears of one subject are interesting in relation to the sensitivity of the inner hair cells. One ear showed a complete degeneration of the Organ of Corti and associated nerves in the osseous spiral lamina in one sector, whereas the other ear showed a loss only of outer hair cells in the corresponding region. Still the hearing loss was essentially the same for both ears, 55-70 dB for the frequencies involved (2,000-4,000 Hz) (p. 118).

While he notes the possibility of these responses being due to greater sensitivity of neighboring regions which may have been stimulated, he tempers this observation by stating that,

> Although parallels might be drawn between the mechanical stimulation pattern in the cochlea, the tuning curves of

> single auditory units, and the present observations on the relation of hair cell loss to threshold sensitivity for pure tones, a further analysis at present would necessarily be based more on speculation than on definitive evidence. Crucial information is lacking on the crucial link between mechanical stimulation of hair cells and discharge patterns in the auditory nerve . . . Information on the pathologically altered human cochlea is even more sparse in this respect (p. 119).

Orchik and Mosher (1975) compared threshold sensitivity for narrow band noise with varying filter slopes to standard audiometric pure tones of frequencies of 250 Hz, 500 Hz, 1 kHz, and 2 kHz for hearing impaired children with sharply sloping audiometric configurations. The attenuation of the narrow band noise signal in the area of the second harmonic was adjusted to 10 dB, 15 dB, and 20 dB. They found that "as the filter slope was decreased, threshold sensitivity improved . . . The most dramatic differences are evident at 1,000 Hz and 2,000 Hz" (p. 52). Mean thresholds at 1,000 Hz were 71.4 dB SPL for pure tone stimuli, 52.4 dB SPL for narrow band noise with a 10 dB/octave filter slope, and 63.9 dB SPL for narrow band noise with a 20 dB/octave filter slope. At 2,000 Hz the pure tone threshold was 95.4 dB SPL, threshold for narrow band noise with a 10 dB/octave filter slope was 64.4 dB SPL, and threshold for narrow band noise with a 20 dB/octave filter slope was 77.2 dB SPL. They concluded that "a threshold difference as great as 20-30 dB could not be explained as a response to a frequency within the bandwidth of the noise" (p. 52). Stephens and Rintelmann (1978) found similar threshold differences between narrow band noise thresholds and pure tone thresholds for frequencies up to 4,000 Hz in adult subjects.

While these findings do not directly bear on the influence of harmonic distortion on threshold sensitivity, they do direct our attention to an investigation of the part played by adjuncts to the test stimulus which may contribute to threshold responses of hearing impaired subjects.

Hearing Sensitivity at Frequencies Above 8,000 Hz

Cullen et al. (1980) examined the hearing sensitivity in extra high frequencies (i.e., 10 kHz to 20 kHz) of hearing impaired subjects. They demonstrated that for some hearing impaired subjects hearing threshold levels for the frequency range between 10 kHz and 16 kHz required significantly less sound pressure than was needed to attain threshold responses for audiometric high frequencies (i.e., 4 kHz and 8 kHz). It should also be noted that extra high frequency threshold sensitivity is not routinely examined in clinical audiometric testing.

Several researchers (Berlin, 1981; Fausti et al., 1979; Harris and Myers, 1971; Harris and Ward, 1967; Lipscomb and Cutts, 1971; Rosen et al., 1964; Zislis and Fletcher, 1966) have developed normative data for threshold sensitivity for extra high frequencies. While there is a good deal of interstudy variability, the majority of the investigators have determined thresholds for extra high frequency tones to be within the following ranges: at 10 kHz—5 dB SPL to 26 dB SPL, at 12 kHz—10 dB SPL to 20 dB SPL, at 14 kHz—5 dB SPL to 30 dB SPL, and at 16 kHz—20 dB SPL to 50 dB SPL (Northern et al., 1972). It should be noted that the minimum sound pressure levels required to attain threshold at these frequencies is not substantially different than the sound pressure level requirements for attaining thresholds of audiometric high frequencies. Furthermore, Berlin (1977) notes that some subjects with severe to profound sensory hearing losses in the audiometric high frequencies do not necessarily evidence similar losses in their extra high frequency hearing sensitivity.

Measurement Apparatus for Extra High Frequencies

The National Bureau of Standards NBS-9A coupler is the device specified by the ANSI - 1969 standard for use in the measurement of acoustic output of audiometers. This coupler is designed to be most useful in the 125 Hz to 8 kHz frequency range (Weissler et al., 1965). However, in the frequency range above 8 kHz to 20 kHz this coupler may produce divergent results, and, at this time, no standard exists for calibration of this frequency range (Gauz, 1981). It has, therefore, been deemed necessary by numerous researchers to develop alternative calibration procedures for instrumentation utilized in extra high frequency studies.

Myers and Harris (1970) compared two methods for the calibration of soundfield extra high frequencies. One set of measures was obtained by placing a 1/4-inch microphone at a location which simulated the virtual center of a space in which the subject's head would be positioned for testing. A second measure was obtained using a 1/4-inch microphone positioned at the eardrum of a Shilling artificial head. Results of the two procedures were found to be in generally good agreement.

Fausti et al. (1979) utilized a 6 cc flat-plate coupler designed by the Koss Company for assessing high frequency response characteristics of their commercial earphones. The acoustic output of the earphone was channelled into a 1/2-inch measuring microphone set into this coupler, read on a voltmeter, and converted into dB SPL. The authors acknowledge the relative nature of this procedure and conclude that:

> We are aware that other couplers and calibration techniques exist. We contend, however, that the primary goal of a plan for calibration should be a means of monitoring the transducer output in a repeatable fashion, and, secondarily, have a direct relationship to the sound pressure level at the eardrum (Fausti et al., 1979, p. 1715).

Berlin (1981) suggested that the same technique for calibration of extra high frequency output as used by Fausti et al. (1979). He further described a procedure by which a clinical audiometer could be adapted to measure thresholds in the extra high frequency range in a clinical setting and proposed threshold norms for young adults of about 20 dB SPL in the frequency range from 9 kHz to 15 kHz.

Lipscomb and Cutts (1971) used a calibration system composed of "a mold of an actual external auditory meatus mated to a standard 2 cc coupler" (p. 34).

Stelmachowitz et al. (1981) used measurements obtained on a 6 cc flat-plate custom designed coupler for which correction factors were obtained via a comparison with levels recorded from a Knowles probe microphone which was positioned to within 0.5 centimeters of the eardrum. Thus, the corrected flat-plate coupler measurements were presumed to be analogous to the probe microphone measurements, and, therefore, relatively close to a real ear calibration.

Most recently Kruger et al. (1982) evaluated a new coupling device, the Headset Ear Simulator Frame (HESF) to calibrate extra high frequency response of both supraaural and circumaural earphones. This device incorporated the Zwislocki Occluded Ear Simulator into a U-shaped housing which afforded excellent stability of placement, and reportedly simulated the pressure of the earphone on the external ear in a more realistic fashion than the traditional method of applied weight.

Numerous other extra high frequency studies (Dadson and King, 1954; Harris and Myers, 1971; Harris and Ward, 1967; Rosen, 1964; Sivian and White, 1933; Zislis and Fletcher, 1966) presented a variety of calibration procedures. It is therefore important to note the problematic nature of relating studies which would at first appear to be directly comparable. Further confounding any such comparison between these studies are differences in signal sources, transducers, measurement procedures, and the subject samples (Northern et al., 1972).

Gauz (1981) notes that clinical use of extra high frequency measurements may have been further precluded due to such potentially contaminating factors as the interaction of head movement, and ear canal volume and configuration as they relate to standing waves, the exclusion of the nontest ear, and the absence of a suitable transducer durable and inexpensive enough for clinical use.

In particular reference to the present study, no apparatus has been suggested in the literature for the controlled generation of extra high frequency harmonics as they relate to the high frequency fundamental under test.

CHAPTER III

PROCEDURES

The present study was designed to examine the effect of harmonic distortion on the high frequency tonal thresholds of subjects with moderately-severe to severe high frequency hearing impairments. A comparison was undertaken of threshold test results for tones having a standard level of harmonic distortion with tones having a substantially reduced level of harmonic distortion. The study also examined subject hearing sensitivity for harmonics of the test frequencies that occurred in the extra high frequency range (i.e., 12 kHz and 16 kHz). These measurements were obtained in order to determine if differences in hearing sensitivity for extra high frequency harmonics were a significant factor in the relationship between the two test conditions.

Subjects

The adult subjects were selected from the client population of The University of Tennessee Hearing and Speech Center, Knoxville, Tennessee. In order to obtain an adequate number of subjects who met the criteria for participation in this study, it was necessary to review all audiologic test records for a full year period. Subjects were required to meet the following criteria for participation in this study:

1. Moderately-severe to severe hearing loss (as previously defined.
2. Clinically determined sensory hearing impairment of between 60 dB HL and 90 dB HL for 4 kHz and/or 8 kHz.
3. Threshold at the nontest ear not more than 25 dB HL more sensitive than the threshold of the ear under test for the corresponding test frequency (i.e., 4 kHz and/or 8 kHz).

The threshold criterion for the nontest ear was selected to preclude the possibility of cross hearing. A level of 25 dB HL was selected as a conservative requirement, and is, in fact, 15 dB HL more stringent than the level utilized in audiometric threshold testing to assure for the exclusion of the nontest ear. Excluded from this study were subjects with histories of retrocochlear or middle ear pathologies as well as subjects judged as either inconsistent or difficult to test in clinical testing reports. In order to assure for better response accuracy, children under the age of eighteen years and geriatrics over the age of sixty-five were also excluded from the study.

Both left and right ears were tested on subjects who met the criteria requirements bilaterally. Unilateral testing was performed upon the remainder of the sample. A total of 14 ears met the criteria requirements for 4,000 Hz, and 11 ears met the criteria requirements for 8,000 Hz.

The mean age of subjects was 46.2 years with a range of 25.2 to 61.9 years of age.

Stimuli

The test stimuli consisted of (1) clinical tones (as previously defined) of 4 kHz and/or 8 kHz, (2) experimental tones (as previously defined) of 4 kHz and/or 8 kHz, and (3) extra high frequency test tones of 12 kHz and 16 kHz. All stimuli were presented as pulsed signals with a 50% duty cycle, 500 millisecond period, and 50 millisecond rise-decay time.

Test Procedure

Subjects were seated in a Suttle model SE228 soundproof audiologic test booth. Test tones were presented utilizing a psychophysical Method of Limits. The examiner slowly increased the presentation level from an initial signal off value by adjusting the sliding output control of a TEAC MB-20 model 2 Audio Mixer. Subject response was noted by the illumination of the response light. The signal intensity was then slowly decreased until it reached the off position. A second ascent was then begun. The voltage value at which the subject first responded to the second ascending presentation of a test stimulus was recorded as the threshold level.

Stimuli were presented in the following order:

1. 4 kHz clinical tone,
2. 4 kHz experimental tone,
3. 8 kHz clinical tone,
4. 8 kHz experimental tone,
5. 12 kHz tone, and

6. 16 kHz tone.

For those subjects who were tested for both ears, this protocol was recycled for the second ear.

Subjects were instructed to push the response button as soon as they heard the tone. Both written and oral instructions were provided to each subject as well as an opportunity to ask questions (Appendix A).

It should be noted that one deficiency in the design of the test procedure was the omission of a reliability test. However, the closeness of scores between the clinical and experimental test conditions, as reported in the results section of this study, proved to be a measure of reliability. These results suggest a very high degree of test-retest reliability.

Instrumentation

Apparatus developed for stimulus presentation and threshold measurement utilized in this study is shown in Figure 1.

Subjects were seated in a Suttle Model SE228 soundproof test booth. A one volt signal generated from a Wavetek Model 159 waveform generator was fed through two output channels of the generator. This single signal source was adjusted to generate a square wave through one channel and a sinusoidal wave through the second channel. The square wave signal from the first channel was fed into s flip-flop circuit resulting in a square wave one-half the frequency originally generated by the signal source and in phase with the

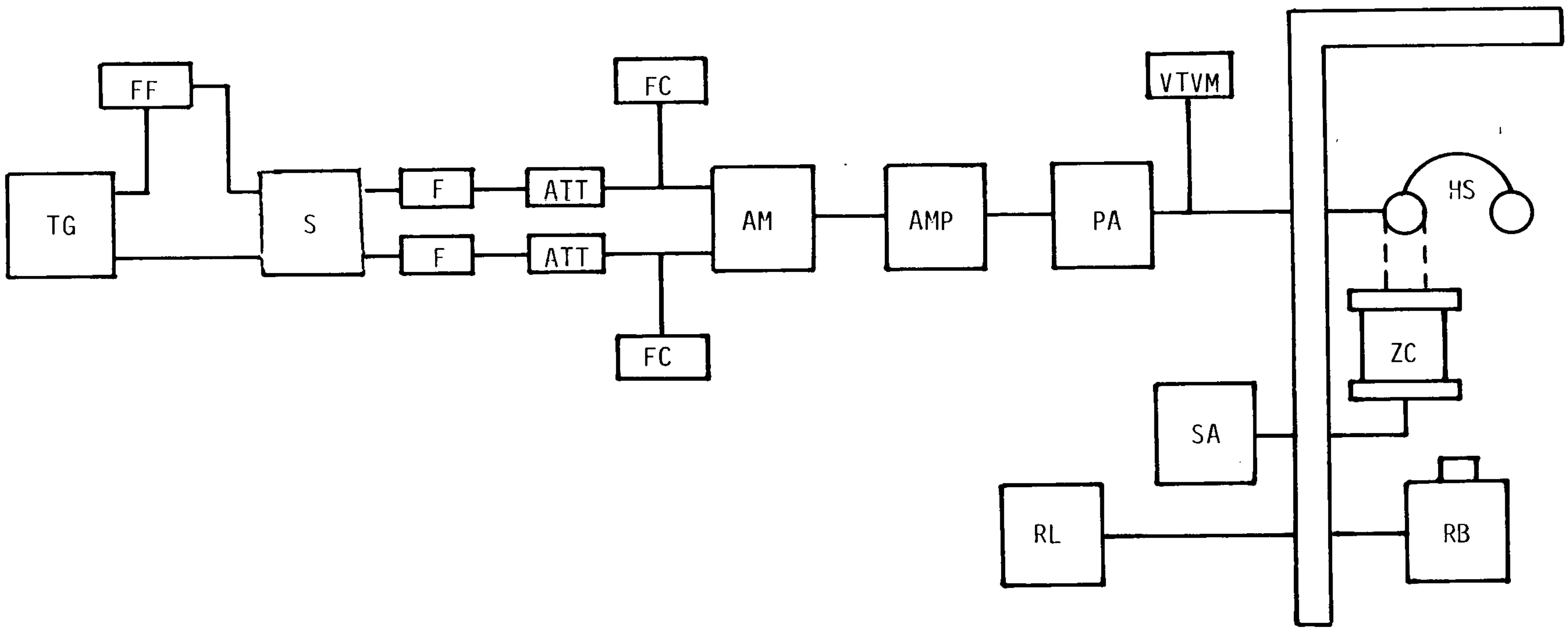

Figure 1. Instrumentation for threshold measurement and calibration of harmonic distortion levels in test signals.

TG—Wavetek Model 159 waveform generator; FF—custom designed flip-flop circuit; S—Grason-Stadler Model 829E electronic switch; F—Rockland Model 852 dual hi/lo filter; ATT—Hewlet-Packard Model 3500 attenuator; FC—Data Precision Model 5740 frequency counter; AM—TEAC MB-20 Model 2 audio mixer; AMP—SAE Model 2200 power amplifier; PA—Altair Model PW-5 power attenuator; VTVM—Hewlett-Packard 400H Model 1051 vacuum tube voltmeter; HS—Sennheisser Model 414 headset; ZC—Zwislock Occluded Ear Simulator; SA—Bruel and Kjaer Model 2107 spectrum analyzer; RB—custom designed response button; RL—custom designed response light.

signal generated through the second channel. The signals were then delivered to two channels of a Grason-Stadler Model 829E electronic switch for gating and shaping, thus producing pulse tones of 500 millisecond period, 50% duty cycle, and 50 millisecond rise and decay times. Each signal was then passed through two cascaded channels of a Rockland Model 852 dual hi/lo filter. In each case the first filter channel was adjusted to a high pass setting allowing passage of only that part of the signal above -10% of the center frequency. Similarly, the second filter channel was set to its low pass function to allow signal passage of below +10% of the center frequency. This filtering arrangement was utilized to control the level of distortion from the generated signal. The resulting output from the filters was two sinusoidal signals with a center frequency ratio of 1:2. These signals were then routed to Hewlett-Packard Model 350D attenuators to regulate signal intensity. Data Precision Model 5740 frequency counters were connected in parallel from the output of the attenuator in each channel in order to provide ongoing monitoring of frequency accuracy. The signals were then fed into a TEAC MB-20 Model 2 audio mixer which consolidated the two inputs into one continuously variable output maintaining a constant yet adjustable intensity relationship between the two inputs. To control the output intensity from the audio mixer, the signal was first passed through an SAE Model 2200 power amplifier, and then through an Altair Model PW-5 power attenuator. A Hewlett-Packard 400H Model 1051 vacuum tube voltmeter was connected in parallel to the output of the attenuator so that the voltage applied to the earphone at threshold levels might be measured and recorded. Finally, the signal was delivered into the right earphone of a Sennheisser Model 414 headset. The right earphone served as the output transducer for all testing. Thus, this earphone was always coupled to the ear under test, while the left earphone received no signal.

Calibration

Two separate procedures were required to calibrate the instrumentation in this study due to both the complexity of the test stimuli and the special problems related to extra high frequency audiometry.

1. Frequency Response of the Earphone

In order to select an appropriate earphone for use in this investigation, a pilot study was undertaken. The criteria utilized for selection of an earphone were as follows:

1. Smoothness of the frequency response in the 4-kHz to 16-kHz range.
2. Consistency of the frequency response over repeated trials and placements.
3. Linearity of the frequency response at varied input voltages.

The three earphones tested for possible utilization in this study were the Telephonics Model TDH-39, the Koss Model 6A and the Sennheisser Model HD-414.

The earphone chosen, the Sennheisser Model HD-414, provided the smoothest frequency response as well as the most consistent results in terms of repeated trials and placements in the calibration procedure.

The possibility of some interaction of the test results with the hearing sensitivity of subjects for harmonics of the test frequencies necessitated making threshold measurements at these harmonic frequencies. In order to more accurately assess these thresholds, it was necessary to determine the sensitivity of the Sennheisser Model 414 earphone in this study. The results of this calibration procedure when referenced to test results was intended to yield a relative rather than absolute assessment of subject threshold.

The instrumentation utilized to obtain frequency response curves for the earphones in the pilot study is shown in Figure 2. The output of a Bruel and Kjaer Model 1022 Beat Frequency Oscillator was connected to the earphone which was then coupled to a flat plate housing a Zwislocki Occluded Ear Simulator. The voltage corresponding to the acoustic input applied to the 1/2-inch microphone housed in this coupler was fed into a Bruel and Kjaer Model 2607 measuring amplifier, and then to a Bruel and Kjaer Model 2307 graphic level recorder. Another Bruel and Kjaer Model 2607 measuring amplifier was connected in parallel to the output of the beat frequency oscillator to measure voltage applied to the earphone. Figures 3, 4, and 5 show the frequency response charted for the Sennheisser Model 414 earphone used in this study, the Telephonics Model TDH-39 earphone, and the Koss Model 6A earphone.

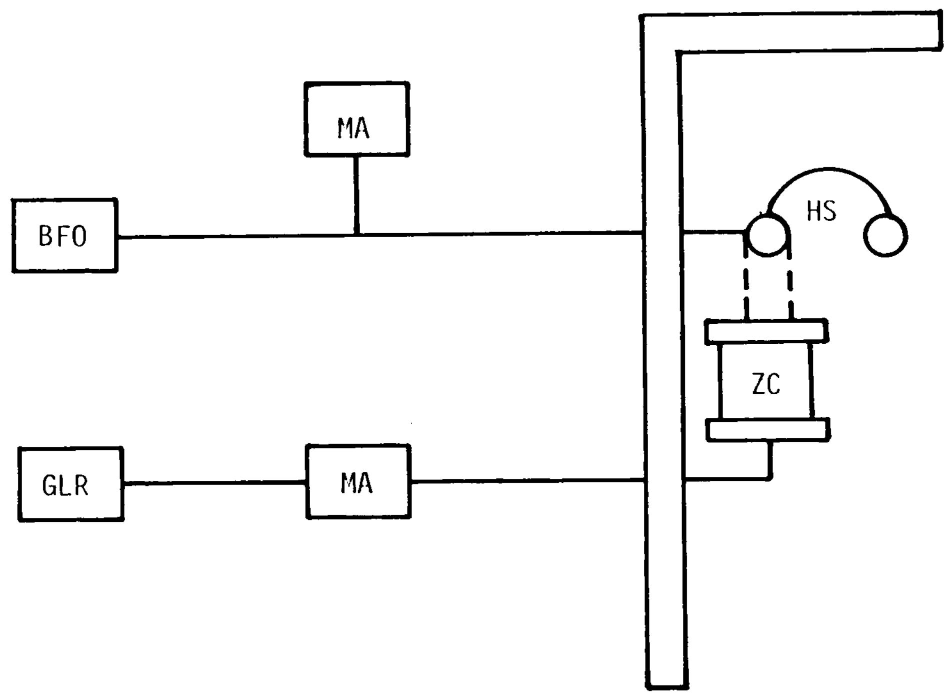

Figure 2. Instrumentation for frequency response measures of earphones in the pilot study.

BFO—Bruel and Kjaer Model 1022 Beat Frequency Oscillator; MA—Bruel and Kjaer Model 2607 measuring amplifier; HS—headset under test; ZC—Zwislocki Occluded Ear Simulator; GLR—Bruel and Kjaer Model 2307 graphic level recorder.

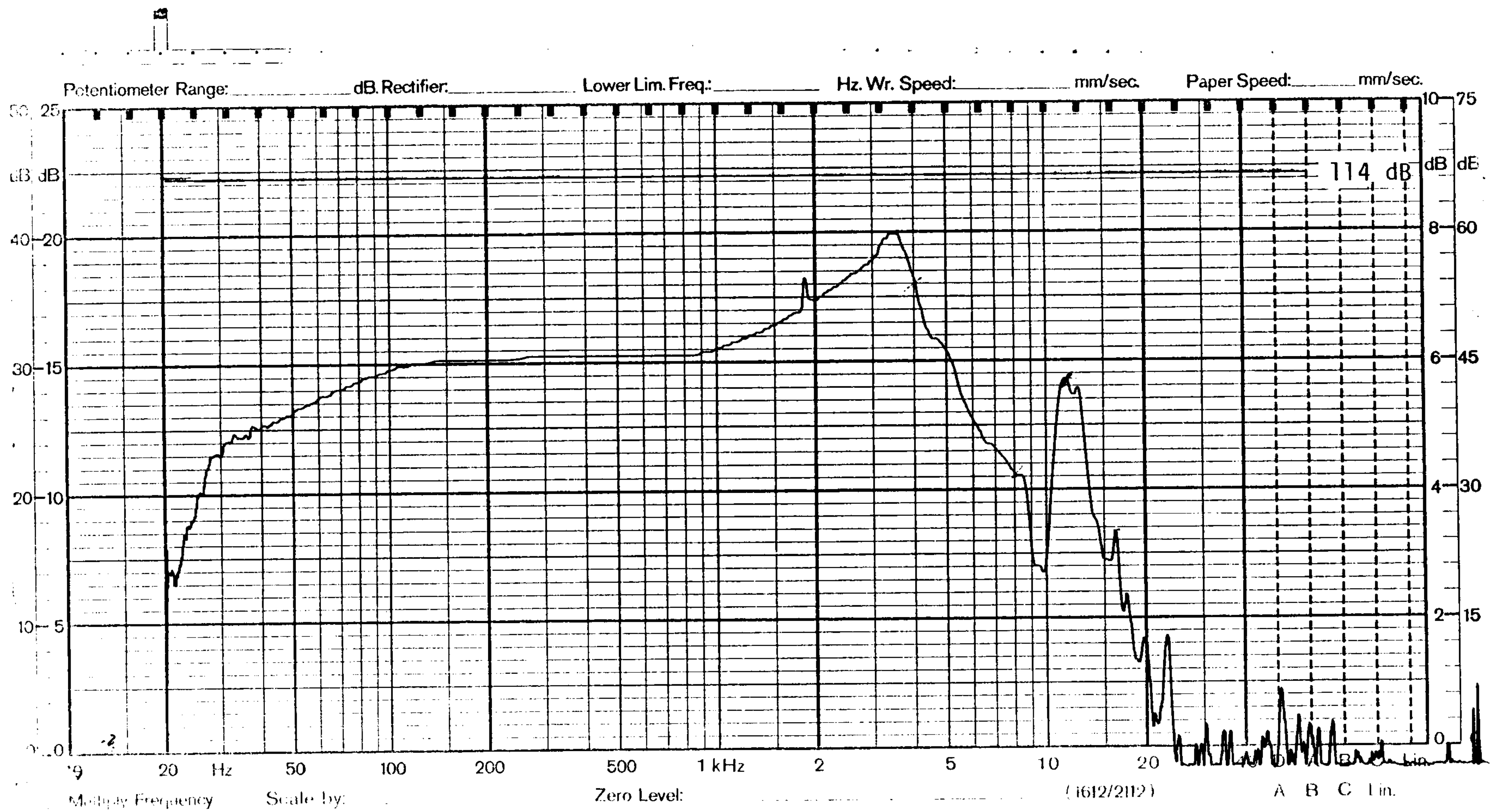

Figure 3. Frequency response of Sennheisser Model 414 right earphone with superimposed 114 dB reference point.

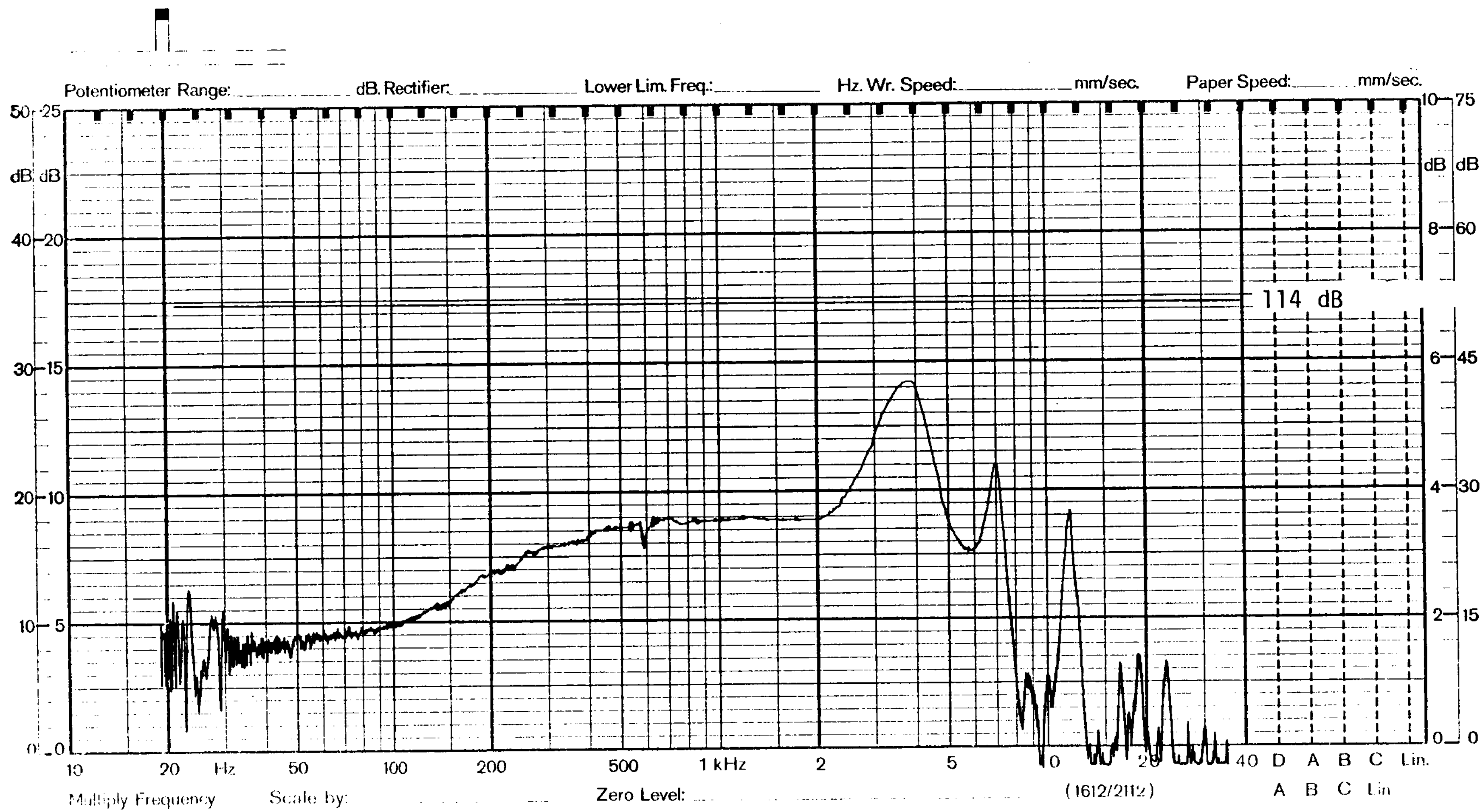

Figure 4. Frequency response of Telephonics Model TDH-39 earphone with superimposed 114 dB reference point.

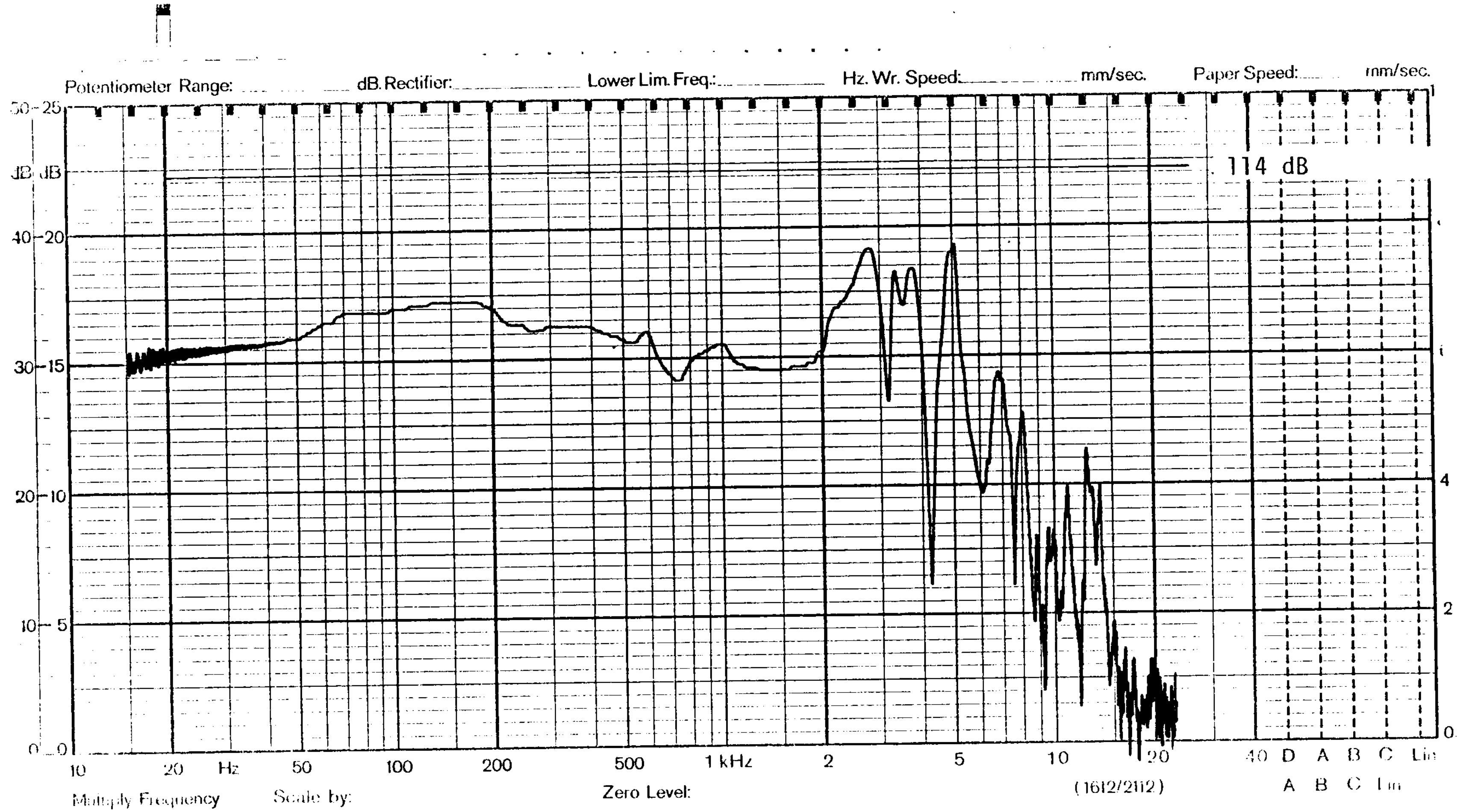

Figure 5. Frequency response of Koss Model 6A earphone with superimposed 114 dB reference point.

The signal output level (in dB) as measured by this procedure was referenced to a precalibrated pistonphone signal source producing a 124 decibel, 220 Hz signal. When coupled to the Zwislocki Occluded Ear Simulator and fed into the graphic level recorder, a 124 decibel reference point was established. The input attenuator of the graphic level recorder was then adjusted to 10 dB allowing the reference signal from the pistonphone to be charted at 114 decibels and, thereby, the reference point could be superimposed upon the graphics of the earphone frequency response curves.

2. Harmonic Distortion Levels

The following calibration procedure was employed to produce the 3.2% (-30 dB) level of harmonic distortion required for the first test condition.

The right earphone of a Sennheisser Model 414 headset was coupled to a flat plate housing a Zwislocki Occluded Ear Simulator. The Bruel and Kjaer Model 4134 1/2-inch microphone with a Bruel and Kjaer Model 2619 cathode follower incorporated into this coupler was connected to a Bruel and Kjaer Model 2107 spectrum analyzer (Figure 1). A continuous 4-kHz signal at a one volt amplitude was generated from a Wavetek Model 159 waveform generator and reshaped by the instrumentation so that into channel A of the TEAC MB-20 Model 2 audio mixer was fed a 4 kHz sinusoidal wave, and into channel B was fed an 8 kHz sinusoidal wave. The output voltage through the earphone for the 4 kHz test frequency (f_0) and the superimposed 8-kHz second harmonic (f_1) was measured by the spectrum analyzer. The channel A and channel B attenuators of the audio mixer were then adjusted so that the intensity of the second harmonic was measured at 30 dB below the intensity of the fundamental frequency. The position of the channel attenuators were then marked. With the channel attenuators fixed at the aforementioned settings, the output attenuator of the audio mixer was varied and measurements were made at the spectrum analyzer to assure for the linearity of this relationship at various intensity levels. This linear relationship was further checked by varying the output from the waveform generator. These measures were repeated after removing the earphone from the coupling system and then replacing it. The same sequence of procedures was followed to calibrate the 8 kHz test tone (f_0) and its 16 kHz second harmonic (f_1).

The second test condition required that the second harmonic of the test frequency not exceed the 1.0% (-40 dB) harmonic distortion level. To this end, channel B of the audio mixer which superimposed the added level of harmonic distortion (f_1) necessary in the first test condition was switched off. In this mode, harmonic distortion levels were measured using the previously stated paradigm and proved to be, as required, below the 1.0% harmonic distortion level for both the 4-kHz and 8-kHz fundamentals.

For the purpose of comparison, calibrations were also made using both a Bruel and Kjaer Model 4152 Artificial Ear, and a Wojcik Ear set into the Zwislocki Occluded Ear Simulator. The coupling system chosen, the flat plate housing a Zwislocki Occluded Ear Simulator, provided the most consistent results.

Treatment of Data

The data were analyzed to determine whether there were statistically significant differences between the two test conditions. Difference scores (DS) were then obtained by subtracting the appropriate threshold readings of the 4 kHz test condition utilizing a standard level of harmonic distortion from the 4 kHz threshold reading utilizing the reduced level of harmonic distortion. This procedure was repeated to obtain a DS for the 8 kHz threshold measurements.

A positive DS represented a poorer threshold for the stimulus having a standard level harmonic distortion as compared to the stimulus having a reduced level of harmonic distortion; a negative DS represented the reverse finding; and, a DS of 0 represented the same response for both test conditions.

Difference scores were calculated and analyzed for subject thresholds at 4 kHz in the two test conditions; a separate set of difference scores were calculated and analyzed for subject thresholds at 8 kHz in the two test conditions. From these sets of difference scores, the mean difference score was determined for the two conditions in the 4 kHz set and for the two conditions in the 8 kHz set.

The *t* Test for Related Measures was utilized to test the statistical significance of differences between test conditions. The following formula for the *t* scores was used (Bruning and Kintz, 1977, p. 14):

$$\underline{t} = \frac{\overline{X} - \overline{Y}}{\sqrt{\dfrac{\Sigma D^2 - \dfrac{(\Sigma D)^2}{N}}{N(N - 1)}}}$$

in which $\overline{X}$ = the mean of the threshold responses in the first test condition, $\overline{Y}$ = the mean of the threshold responses in the second test condition, $\underline{\Sigma}$ = "sum of," $\underline{D}$ = the mean threshold difference between the test conditions, and $\underline{N}$ = the number of ears.

CHAPTER IV

RESULTS AND DISCUSSION

It was the purpose of this study to determine if a reduction in the harmonic distortion level of audiometric high frequency test tones would result in a threshold change in subjects having moderately-severe to severe high frequency sensory hearing losses.

The study was also designed to investigate the interaction of hearing sensitivity for extra high frequency harmonics of the test tones with threshold differences noted between the two test conditions.

Results

The results as presented in Tables 1 and 2 offer a comparison of threshold responses for the two test conditions at both 4 kHz and 8 kHz. Raw data provided in these tables reveal that differences in subject thresholds between the two test conditions were very small in all cases. This is most clearly evident in Table 2 which offers the extrapolated decibel equivalent of the threshold voltage measures. The decibel differences for the two test conditions did not exceed 1.6 dB for any of the ears under test. Tables 3 and 4 list subject threshold responses for the 12 kHz and 16 kHz harmonics of the test frequencies. Data in these tables reveal that hearing sensitivity for extra high frequency harmonics of the test tones was substantially poorer than for the fundamental high frequency tones.

Table 1

Comparison of Threshold Results Obtained at the Two Test Conditions for Both 4 kHz and 8 kHz Stimuli (in Voltage)*

		Threshold Value (mV)*			
Subject	Ear	4 kHz Condition 1**	4 kHz Condition 2***	8 kHz Condition 1**	8 kHz Condition 2***
1	1	520	550	280	300
2	2	900	870	NR(10V)	NR(10V)
3	3	950	1100	NR(10V)	NR(10V)
3	4	260	300	4700	4600
4	5	360	370	550	525
5	6	380	400	1350	1100
6	7	485	520	550	565
6	8	440	440	710	720
7	9	125	105	4200	5050
8	10	155	160	950	900
8	11	140	135	540	600
9	12	210	195	NR(10V)	NR(10V)
10	13	310	280	1400	1500
10	14	90	95	135	145
$\overline{X}$		380.4	394.3	1396.4	1455.0

*Voltage applied to the earphone at threshold levels.

**Test stimuli with standard level of harmonic distortion (ANSI - 1969).

***Test stimuli with reduced level of harmonic distortion (H.D. $\leq$ 1.0%).

Table 2

Comparison of Threshold Results Obtained at the Two Test Conditions for Both 4 kHz and 8 kHz Stimuli (in Decibels)*

		Threshold Value (dB)*			
Subject	Ear	4 kHz Condition 1**	4 kHz Condition 2***	8 kHz Condition 1**	8 kHz Condition 2***
1	1	99.8	100.3	79.4	80.0
2	2	104.6	104.3	NR****	NR
3	3	105.1	106.3	NR	NR
3	4	93.8	95.0	103.9	103.8
4	5	96.6	96.9	85.3	84.9
5	6	97.1	97.5	93.1	91.3
6	7	99.2	99.8	85.3	85.5
6	8	98.4	98.4	87.5	87.6
7	9	87.4	85.9	103.0	104.6
8	10	89.3	89.6	90.1	89.6
8	11	88.4	88.1	85.1	86.1
9	12	91.9	91.3	NR	NR
10	13	95.3	94.4	93.4	94.0
10	14	84.6	85.1	73.1	73.7
$\overline{X}$		95.1	95.2	89.0	89.2

*Decibels re: sound pressure level from the frequency response curve of the earphone referenced to a 114 dB SPL calibration tone.

**Test stimuli with standard level of harmonic distortion (ANSI - 1969).

***Test stimuli with reduced level of harmonic distortion (H.D. $\leq$ 1.0%).

****No response at maximum value of the signal (10 volts).

Table 3

Threshold Responses for the 12 kHz and 16 kHz Harmonics of the Test Frequencies (in Voltage)*

Subject	Ear	Threshold Value (mV)* 12 kHz	16 kHz
1	1	NR(10V)**	NR(10V)
2	2	NR(10V)	NR(10V)
3	3	NR(10V)	NR(10V)
3	4	4800	NR(10V)
4	5	3100	2900
5	6	NR(10V)	NR(10V)
6	7	3400	NR(10V)
6	8	2550	NR(10V)
7	9	NR(10V)	NR(10V)
8	10	NR(10V)	NR(10V)
8	11	NR(10V)	NR(10V)
9	12	NR(10V)	NR(10V)
10	13	1950	NR(10V)
10	14	590	3900

*Voltage applied to earphone at threshold level.

**No response at 10 volts.

Table 4

Threshold Responses for the 12 kHz and 16 kHz Harmonics
of the Test Frequencies
(in Decibels)*

Subject	Ear	Threshold Value (dB)*	
		12 kHz	16 kHz
1	1	NR**	NR
2	2	NR	NR
3	3	NR	NR
3	4	111.6	NR
4	5	107.8	95.2
5	6	NR	NR
6	7	108.6	NR
6	8	106.1	NR
7	9	NR	NR
8	10	NR	NR
8	11	NR	NR
9	12	NR	NR
10	13	103.8	NR
10	14	93.6	97.8

*Decibels re: sound pressure level from the frequency response curve of the earphone referenced to a 114 dB SPL calibration tone.

**No response at maximum output of instrumentation (10 volts).

In no case was the threshold for an extra high frequency harmonic equal to or better than the threshold for the fundamental frequency. The measures in Tables 1 and 3 are presented as output voltages which is the method by which results were recorded in this study. From these voltage values, analogous decibel levels were calculated and are presented in Tables 2 and 4.

A _t_ test was utilized to determine if there were statistically significant differences between the thresholds for the test tones with standard level of harmonic distortion and test tones with reduced level of harmonic distortion. The results of the _t_ test for the combined ears tested are shown in Table 5. Differences in the mean threshold comparisons were not statistically significant for either the 4 kHz or 8 kHz stimuli at a .05 level of confidence. Similarly these results when referenced to threshold levels in decibels (Table 6) were not statistically significant at the .05 level of confidence.

Thus, the null hypothesis as stated:

> There are no differences in hearing thresholds for tones of 4,000 Hz and 8,000 Hz in moderately-severe and severely hearing impaired listeners tested using two presentation conditions: clinical and experimental tones

cannot be rejected.

Discussion

Because no statistically significant differences were found between test conditions at either test frequency, high frequency

Table 5

Results of Analysis of Threshold Differences Obtained for Test Tones with Standard Level of Harmonic Distortion and Test Tones with Reduced Level of Harmonic Distortion (in Voltage)

Frequency	Mean Threshold with Standard Level of H.D. (mV)	Mean Threshold with Reduced Level of H.D. (mV)	Difference (mV)	*t*
4 kHz	380.4	394.3	13.9	1.1542*
8 kHz	1396.8	1455.0	58.2	0.6935**

*All values of *t* less than 2.16 (df = 13, α = .05) are not significant.

**All values of *t* less than 2.23 (df = 10, α = .05) are not significant.

Table 6

Results of Analysis of Threshold Differences Obtained for Test Tones with Standard Level of Harmonic Distortion and Test Tones with Reduced Level of Harmonic Distortion (in Decibels)*

Frequency	Mean Threshold with Standard Level of H.D. (dB)	Mean Threshold with Reduced Level of H.D. (dB)	Difference (dB)	*t*
4 kHz	95.1	95.2	0.1	0.4569**
8 kHz	89.0	89.2	0.2	0.6289***

*Decibels re: sound pressure level from the frequency response curve of the earphone referenced to a 114 dB SPL calibration tone.

**All values of *t* less than 2.16 (df = 13, α = .05) are not significant.

***All values of *t* less than 2.23 (df = 10, α = .05) are not significant.

audiometric test tones utilizing the presently allowable level of harmonic distortion based on this investigation might be considered a valid determinor of high frequency audiometric thresholds for a selected clinical population. The need to further attenuate levels of harmonic distortion beyond the present ANSI-1969 protocol as a routine course is not apparently justified. Threshold measures obtained for the 12 kHz and 16 kHz harmonics of the test tones failed to identify any subject with hearing sensitivity for extra high frequency harmonics of greater than 30 dB better than hearing sensitivity for the high frequency fundamental. A more definitive relationship between harmonic distortion and high frequency audiometric testing might have been obtained if such a subject was found.

It is an important consideration for this study that subject thresholds for extra high frequency harmonics were relatively poor in comparison to thresholds recorded for the same subjects for the fundamental frequencies utilized in the primary test comparison. Results such as reported by Cullen et al. (1980) wherein subject thresholds for extra high frequencies were substantially better than were thresholds for audiometric high frequencies were not found in these data. It is clear that such a sensitivity difference would have been an important factor to analyze in respect to the present findings. However, in light of the results of this study, such a sensitivity difference would not appear to be a typical finding and of questionable value in regard to a broad view of the effect of harmonic distortion on the determination of high frequency audiometric thresholds. It is important to note, however, that while determinations of audiometric high frequency thresholds were not significantly affected by the level of harmonic distortion in the test signal, these results cannot be generalized to a population in which extra high frequency threshold sensitivity is substantially better than audiometric high frequency threshold sensitivity. For such a population the level of harmonic distortion in the test signal would appear to be directly related to the level at which threshold responses are obtained.

Intrasubject threshold difference for the two test conditions were smaller than anticipated. These differences ranged from 0.0 dB to 1.5 dB for the 4 kHz comparison, and 0.1 dB to 1.6 dB for the 8 kHz comparison, well below the standard 5 dB step utilized in traditional audiometric testing. It should be noted that no formal procedure was used to verify the reliability of subject responses. However, the closeness of scores between the clinical and experimental tones is in itself a measure of reliability. While subjects with sensory hearing losses are normally able to detect smaller intensity differences than a normal hearing population, this range remains remarkably small and, yet, the author cannot conceive of factors in the protocol that would result in these data being contaminated.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Ten moderately-severe to severely hearing impaired adult subjects, ages 25 to 61 years, were selected from the client population of The University of Tennessee Hearing and Speech Center to participate in a study designed to examine the effect of harmonic distortion level upon high frequency tonal thresholds.

Hearing thresholds were obtained for 4-kHz and 8-kHz tones for each subject using two presentation conditions: tones having a standard level of harmonic distortion as per the ANSI - 1969 protocol, and tones having a reduced level of harmonic distortion. The data obtained from a comparison of threshold results between the two test conditions were analyzed to determine if there were statistically significant differences in hearing thresholds related to the level of harmonic distortion in the test stimuli. The results of these comparisons yielded no significant differences in hearing thresholds between test condition for either of the test frequencies (4 kHz and 8 kHz). Subject thresholds were then determined for extra high frequency harmonics of the test tones. This procedure was meant to relate any differences found in the primary test comparison to subject hearing sensitivity for harmonics of the frequency under test. The results of this procedure revealed that threshold sensitivity for extra high frequency harmonics of the test tones was substantially poorer than threshold sensitivity for the fundamental high frequency tones. Within the scope of this relationship, hearing sensitivity for extra high frequency harmonics had no significant effect upon threshold sensitivity for high frequency test tones in either of the presentation conditions.

Conclusions

Based upon the obtained results and within the limitations of this study, the following conclusions relative to the interaction of presently accepted harmonic distortion levels with clinically obtained high frequency hearing thresholds are drawn:

1. In general, it appears that for moderately-severe to severely hearing impaired subjects threshold sensitivity for extra high frequency harmonics of high frequency audiometric test tones is significantly poorer than threshold sensitivity for the audiometric high frequency fundamentals.

2. For a selected hearing impaired population as represented by the subjects in this study a reduction in the level of harmonic distortion beyond the presently allowable level set forth by the ANSI - 1969 standard does not result in a significant change in threshold sensitivity for the high frequency fundamental under test. It should be noted that subject selection attempted to uncover a worst case example. That is, a subject with hearing sensitivity for extra high frequency harmonics at least 30 dB better than hearing sensitivity for the high frequency fundamental. No such subject was

found for inclusion in the sample selected for participation in this study.

3. For the population selected and within the limitations of this study, hearing sensitivity for extra high frequency harmonics had no significant effect upon threshold sensitivity for high frequency audiometric test tones in either of the presentation conditions (i.e., standard level of harmonic distortion, and reduced level of harmonic distortion).

4. The inclusion of extra high frequency threshold testing into the audiometric testing regimen on a routine basis might well serve to identify those subjects whose hearing sensitivity for extra-high frequency harmonics could potentially influence the threshold level at which audiometric high frequency measures were obtained. Hence, for those subjects a reduction in the level of harmonic distortion in the test signal might yield more accurate threshold measures.

Suggestions for Further Study

There are a number of limitations and shortcomings in the present study which might well be addressed by future researchers so that the results herein reported might be further tested and generalized.

It is suggested that:

1. A replication of this study for audiometric low frequency and middle frequency test tones might well be initiated to determine

whether the findings of the present investigation can be generalized to the entire range of audiometric test frequencies.

2. Replication of this study for subjects with conductive hearing impairments and for subjects with severe "U" shaped audiograms could further test the degree to which the conclusions of this study can be generalized.

BIBLIOGRAPHY

BIBLIOGRAPHY

American National Standards Institute, "Specifications for Audiometers," ANSI S3.6-1969. New York, American National Standards Institute (1970).

American Standards Association, "Audiometers for General Diagnostic Purposes," No. 2245. New York, The Association (1951).

Beiter, R. C., and Rupp, R. R., "Standard Audiometric Procedures for Thresholds Above 8 kc/s: A Normative Study." Journal of Auditory Research 12:199-202 (1972).

Beranek, L. L., telephone conversation, November 3, 1981.

Berlin, C. I., "Ultra-Audiometric Hearing in the Hearing Impaired and the Use of Upward-Shifting Translating Hearing Aids." Studies in the Use of Amplification for the Hearing Impaired. Excerpta Medica (1980).

Berlin, C., "Residual Ultra-Audiometric Hearing in the Hearing Impaired." In Friends of KAM's Fund Newsletter (1981).

Berlin, C. I., Wexler, K. F., Jerger, J. F., Halperin, H. R., and Smith, S., "Superior Ultra-Audiometric Hearing: A New Type of Hearing Loss which Correlates Highly with Unusually Good Speech in the 'Profoundly Deaf.'" Otolaryngology 86:111-116 (1978).

Bredberg, G., "Cellular Pattern and Nerve Supply of the Human Organ of Corti." Acta Oto-Laryngologica Supplement 236 (1968).

Bruel and Kjaer Instruments, "Revised Instruction Manual for Model 159 Audiometer Calibration." Copenhagen, Denmark.

Bruning, J. L., and Kintz, B. L., Computational Handbook of Statistics. Glenview, Illinois, Scott, Foresman and Company (1977).

Collins, M. J., Cullen, J. K., and Berlin, C. I., "Auditory Signal Processing in a Hearing-Impaired Subject with Residual Ultra-Audiometric Hearing." Audiology 20:347-361 (1981).

Cullen, J. K., Collins, M. J., Berlin, C. I., "Auditory Processing at Ultra-Audiometric Frequencies," Kresge Hearing Research Laboratory of the South, New Orleans, La. Paper presented at the 1980 meeting, American Speech-Language-Hearing Association, Detroit, 1980.

Fausti, S. A., Frey, R. H., Erickson, D. A., Rappaport, B. Z., and Cleary, E. J., "A System for Evaluating Auditory Function from 8000-20000 Hz." Journal of Acoustical Society of America 66: 1713-1718 (1979).

Fausti, S. A., Frey, R. H., Erickson, D. A., and Rappaport, B. Z., "2 AFC versus Standard Clinical Measurement of High Frequency Auditory Sensitivity (8-20 kc/s)." Journal of Auditory Research 19:151-157 (1979b).

Fletcher, J. L., "Reliability of High-Frequency Thresholds." Journal of Auditory Research 5:133-137 (1965).

Gauz, M. T., "High Frequency Thresholds: Reliability, Validity and Normative Aspects." Unpublished Dissertation, Wayne State University (1981).

Grason, R. L., telephone conversation, October 27, 1981.

Harris, J. D., and Ward, M. D., "High-Frequency Audiometry to 20 kc/s in Children of Age 10-12 Years." Journal of Auditory Research 7:241-252 (1967).

Harris, J. D., and Myers, C. K., "Tentative Audiometric Threshold-Level Standards from 8 through 18 k Hz." Journal of Acoustical Society of America, in Letters to the Editor 49:600-601 (1971).

Hsiao, H. S., "Breaking New Ground: The Extended High-Frequency Audiometer." Hearing Aid Journal, April 7-10 (1982).

International Electrotechnical Commission (affiliated to the International Organization for Standardization (ISO)), "Pure Tone Audiometers for General Diagnostic Purposes," Publication 177, First Edition. Geneva, Switzerland, 1965.

Kruger, B., Kaplan, S., Karp, A., and Joscelyn, E., "Evaluation of a New Headset Ear Simulator Frame for Circumaural and Supraaural Earphone Calibration," Audiology Research Laboratory of the Albert Einstein College of Medicine, Report No. 1004. Bronx, New York, 1082.

Lipscomb, D. M., and Cutts, B., "A Proposed System for Testing 'Extra-High' Frequencies." Journal of Auditory Research 11:360-364 (1971).

Myers, C. K., and Harris, J. D., "Comparison of Seven Systems for High-Frequency Air-Conduction Audiometry." Journal of Speech and Hearing Research 13:254-270 (1970).

Northern, J. L., Downs, M. P., Rudmose, W., Glorig, A., and Fletcher, J. L., "Recommended High-Frequency Audiometric Threshold Levels (8000-18000 Hz)." Journal of Acoustical Society of America 52:585-595 (1972).

Orchik, D. J., and Mosher, N. L., "Narrow Band Noise Audiometer: The Effect of Filter Slope." Journal of the American Audiology Society, Vol. 1, No. 2, pp. 50-53 (1975).

Report of Council on Physical Medicine, "Minimum Requirements for Acceptable Audiometers." Journal of the American Medical Association, Vol. 127, No. 9, pp. 520-521 (1945).

Rosen, S., Plester, D., El-Mofty, A., and Rosen, H. V., "High Frequency Audiometry in Presbycusis." Archives of Otolaryngology 79:18-32 (1964a).

Rosen, S., and Rosen, H. V., "High Frequency Studies in School Children in Nine Countries." Laryngoscope 81:1007-1013 (1971).

Stelmachowicz, P. G., Gorga, M. P., and Cullen, J. K., "A Calibration Procedure for the Assessment of Thresholds Above 8000 Hz." Kresge Hearing Research Laboratory of the South, New Orleans, La. (1981).

Stephens, M. M., and Rintelmann, "The Influence of Audiometric Configuration on Pure-Tone, Warble-Tone and Narrow-Band Noise Thresholds of Adults with Sensorineural Hearing Losses." Journal of the American Audiology Society, Vol. 3, No. 5, pp. 221-226 (1978).

Stevens, S. S., and Davis, H., Hearing, Its Psychology and Physiology. New York, John Wiley & Sons, Inc., 1938.

Vassallo, L., Sataloff, and Menduke, H., "Air Conduction Thresholds for High Frequencies." Journal of Occupational Medicine 9:353-357 (1967).

Vassallo, L., Sataloff, J., and Menduke, H., "Very High Frequency Audiometric Technique." Archives of Otolaryngology 88:251-253 (1968).

Weissler, P. G., Smith, E. L., and Cook, R. K., "Description of National Bureau of Standards 9-A Coupler." NBS Report 8658 (1968).

Zislis, T., and Fletcher, J. L., "Relation of High Frequency Threshold to Age and Sex." Journal of Auditory Research 6:189-198 (1966).

Zwislocki, J. J., "An Acoustic Coupler for Earphone Calibration," Report LSC-S-7. Laboratory Sensory Communication, Syracuse University (1970).

Zwislocki, J. J., "An Ear-Like Coupler for Earphone Calibration," Report LSC-S-9. Laboratory Sensory Communication, Syracuse University (1971).

APPENDIXES

APPENDIX A

INSTRUCTIONS TO SUBJECTS

You are going to hear a series of pulsing high pitch tones, all in one ear. Some of these tones may be best described as "squeaky" sounding. When you hear the pulsing tone, no matter how loud or soft and no matter how high or low in pitch, signal that you have heard the tone by pressing the button on the switch. Press the button as soon as you hear the tone. Keep it pressed as long as you hear it. Release the button whenever the tone ceases. Remember to press the button everytime and as soon as you hear the tone. Any questions?

APPENDIX B

WRITTEN INFORMED CONSENT DOCUMENT

You are asked to participate in a study to assess the effect of signal distortion (harmonics) on hearing tests. You will participate in one experimental session, not to exceed one-half hour in length, which will consist of two brief tests of high frequency hearing sensitivity.

I understand and agree to the following:

1. Individual identities will be kept confidential, as will all data obtained.
2. All test results will be available to me upon request.
3. All testing will take place in a sound treated test booth.
4. Tests will be conducted by qualified individuals.
5. I am free to withdraw consent and discontinue participation in the study at any time.
6. Refusal to participate will not affect any future contacts I may have with The University of Tennessee Hearing and Speech Center.
7. This project has been approved by The University of Tennessee Committee on Research participation and potential subjects are not at risk.
8. I understand that although this study may not benefit me, it may provide useful information for future hearing evaluations.
9. Any further questions concerning these procedures will be answered by contacting:

David M. Lipscomb, Ph.D.
Phone: 974-4123

Signature ______________________________

Date ______________________________

VITA

Laurence Abikoff was born in New York City, New York, on October 21, 1948. He received a Bachelor of Arts degree in Speech and Hearing from the City College of New York in January, 1971. In the fall of 1972 he accepted a position as Speech Therapist with the Springfield Department of Schools, Springfield, Massachusetts, and remained in this position until the summer of 1977.

Mr. Abikoff then moved to Portland, Oregon, where he was employed as a counselor for the Urban League. He remained at this position until his entrance into the Master of Arts program in Audiology at The University of Tennessee, Knoxville, Tennessee, in the fall of 1980.

Mr. Abikoff received his Master's degree in December, 1983. He is presently employed as an audiologist in New Hampshire.