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INTENSITY CALIBRATION OF AUDITORY EVOKED BRAINSTEM POTENTIAL STIMULI THROUGH BEHAVIORAL AND ELECTROACOUSTICAL STRATEGIES

By

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ABSTRACT

INTENSITY CALIBRATION OF AUDITORY EVOKED BRAINSTEM POTENTIAL STIMULI THROUGH BEHAVIORAL AND ELECTROACOUSTICAL STRATEGIES

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Auditory evoked brainstem potentials (AEBPs) are used extensively by the neurological and audiological communities to assess central nervous system function and auditory sensitivity from an electrophysiological approach. The AEBP waveform parameters are influenced by aberrant end-organ and/or neural function and can be profoundly altered by changes in the acoustical properties of the AEBP eliciting stimulus. The click-like stimulus is produced by driving an earphone transducer with a rapid rise-time, brief duration electrical impulse. To make a valid interpretation of test data, the clinician must be confident that deviations from the expected norm in terms of waveform parameters are truly a reflection of physiological abnormality and not the electrophysiological manifestation of stimulus parameter alteration. Therefore, the calibration of AEBP stimuli is paramount to the precise evaluation of auditory sensitivity

and/or central auditory nervous system integrity. Unfortunately, there is no generally recognized standard for the electroacoustical calibration of transients.

The purpose of this study was to suggest a plan to examine the reliability and validity of several electroacoustical calibration procedures relative to estimates of auditory sensitivity obtained from normal hearing subjects. Calibration variables included earphone system, coupler, cushion and the method by which instrumentally measured stimuli are quantified. Additionally, the symmetry of the stimulus waveforms was systematically varied in an effort to identify that calibration method which yielded the most consistent prediction of threshold as measured by behavioral means.

The statistical analyses of the behavioral threshold data revealed not only significant main effects but also interactions among Coupler, Intensity Designation, Earphone Cushion and Stimulus on mean threshold sound levels for AEBP stimuli. Through consideration of these analyses and theoretical and practical issues, it was concluded that for the calibration of supraaural earphones, alone, the NBS-9A/peak equivalent (pe) SPL-rms coupler/intensity specification is best suited to the clinical calibration of these transients. For the calibration of these stimuli presented through a transducer mounted alternately in either a supraaural or circumaural cushion, the Penn State flat plate/peSPL-rms combination is the most reliable for the electroacoustical calibration of 0 dB nHL. These results and recommendations will undoubtedly serve the neurological and oto-audiological communities as a guide toward the standardization of AEBP transient stimuli.

To John, Dan, Tom, Mary Beth and Charlie whose support and coaching mean more to me than you'll ever know.

To Margaret M. and John D. Connelly without whom none of me would have been possible.

I love you all very much. Thanks for everything.

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CHAPTER 1

DEVELOPMENT OF RESEARCH STRATEGIES

Introduction

Auditory evoked brainstem potentials (AEBPs) are extensively used to evaluate neurological site-of-lesion, to aid in the determination of sensorineural hearing loss etiology and to assess auditory sensitivity from an electrophysiological approach. These sub-microvolt waveforms are elicited by click or click-like transients which are generated by driving an earphone with a rapid rise-time, brief duration electrical pulse. The determination of peripheral and central auditory functional normality is made from the AEBP waveform parameters, and any deviations from the established laboratory norms should be regarded as a reflection of central auditoy nervous system dysfunction.

The AEBP wave morphology and its defining parameters are influenced not only by aberrant auditory end-organ and/or neural functioning, but they are profoundly altered by changes in stimulus parameters and by changes in the acoustical properties of the AEBP eliciting stimulus. The acoustical properties of clicks produced by different transducers vary with the type of earphone and its response characteristics and with the type of earphone coupling to the ear. In addition, inter-individual differences in the properties of the outer ear influence click characteristics which introduce another source of stimulus variability.

It is for the determination of auditory sensitivity or of the site of auditory system lesion that the AEBP procedure is performed. The clinician must be confident that deviations from the expected norm in terms of waveform parameters are truly a reflection of physiological abnormality and not an electrophysiological manifestation of stimulus parameter alteration. Therefore, every possible confounding or influencing variable must be controlled and defined for the most precise evaluation of auditory acuity and/or central auditory nervous system integrity.

All sources of variability must be accounted for with regard to AEBP testing. Inter-individual differences in the anatomical configuration of the outer ear cannot be controlled for on a testee to testee basis. However, a complete exploraton of the effects of changes in stimulus parameters and of the influence of the click's acoustical properties on these brainstem potentials is paramount to the precise electrophysiological assessment of auditory function. Unfortunately, there is no standard procedure for the acoustic calibration of transients, and the specification of click stimuli has been essentially ignored for this clinical endeavor.

The intensity, spectrum and temporal characteristics of click stimuli produced by different transducers have been ignored by those performing AEBP evaluations, in part because of the lack of a calibration protocol for such stimuli, and in part because of difficulties associated with the electroacoustic descriptions of click signals. Notwithstanding the problems of calibrating transients, audiologists are primarily concerned with the determination of auditory sensitivity. The accuracy of statements regarding auditory thresholds is limited by the experimenter's or clinician's knowledge of the stability of the electroacoustic properties of the stimulus and his awareness of how these factors influence threshold. The acoustical properties of the stimulus can be known only through careful calibration procedures.

The precise measurement and specification of the acoustical attributes of a signal are essential for clinical electrophysiological as well as for experimental pursuits. Even the most subtle change in the physical dimensions of the acoustical stimulus can result in altered mechanical, hydrodynamic and electrochemical responses of the auditory system. The stimuli must be exactly specified, monitored and replicated to minimize the impact of stimulus artifact and to differentiate between stimulus effects and subject effects. Changes in physiological functioning caused by alterations in the physical dimensions of the acoustical signal can be studied and predicted, but only if the stimulus is precisely described.

In the experimental realm, the goal of electro-acoustical calibration is the description of the exact dimensions of the stimulus in terms of its intensity, duration, frequency or spectrum, phase and waveform. Given sufficient detail in the description of equipment and procedures, other experimenters can replicate stimuli within defined limits of precision. Finally, equipment checks and stimulus verifications can be performed regularly without serious interruptions of equipment usage if calibration procedures are standardized and made an integral part of the stimulus generation system.

This study was undertaken to develop a calibration protocol for the intensity specification of AEBP stimuli. Without such a protocol and its resultant quantification and specification of that transient stimulus used in AEBP studies, clinicians in the audiological community can not make scientifically based interpretations of AEBP data as they relate to measurements of auditory sensitivity. Without an intensity reference and a description of stimulus parameters the neurological clinicians can be misled by AEBP waveform characteristics which, for example, change over time -- do these changes truly reflect an alteration in the central nervous system function, or are they simply the reflection of altered earphone dynamics over time? Certainly, a reliable procedure for the intensity and waveform calibration of the transient signals used in AEBP evaluations is needed to forge a standardized approach to testing and interpreting these data.

To illustrate the widespread and growing use of auditory evoked potentials in audiology and neurology, the following section is presented.

Auditory Evoked Brainstem Potentials

History

In 1970 Jewett recorded electrical potentials from brainstem auditory structures of the cat using computer averaging techniques. This signal averaging method was then applied to humans (Jewett, Romano & Williston, 1970), and it was reported that distinct electrical potentials -- probably generated by brainstem structures -- with peak latencies of 7 milliseconds (msec) or less could be recorded in a non-invasive manner. Finally, Jewett and Williston (1971) presented an extensive study that revealed remarkable waveform consistency within and between subjects with excellent repeatability over a period of several months. The component peaks of the waveform were labeled I through VII. Jewett and Williston strongly suggested that wave I was identical to the N1 potential of the eighth nerve and that waves II through VII represented neural activity from progressively rostral brainstem centers. An illustration of the auditory evoked potential is provided below. (Figure 1)

Subsequent experimental and clinico-pathological studies offered convincing evidence that these potentials of less than 1.0 microvolt (uV) were the far-field reflection of electrical activity generated by the auditory nerve (wave I), pontine auditory nuclei and tracts (waves II, III and IV) and the auditory centers and pathways of the mid-brain (wave V) (Jewett, 1970; Buchwald & Huang, 1975; Starr & Hamilton, 1976; Stockard & Rossiter, 1977; Starr, 1978). The generators of waves VI and VII have not yet been confirmed.

Clinical Applications

Neurology. AEBPs have been used extensively in neurology to aid in the identification of acoustic and cerebellopontine angle tumors (Clemis & Mitchell, 1977; Eggermont, Don & Brackmann, 1980); palatal myoclonus (Epstein, Stappenback & Karp, 1980); locked-in syndrome due to bascular insult (Gilroy, Lynn, Ristow & Pellerin, 1977; Seales, Torkelson, Shuman, Rossiter & Spencer, 1981); coma (Starr & Achor, 1975; Uziel & Benezech, 1978; Hari, Sulkawa & Haltia, 1982); postconcussion dizziness (Rowe & Carlson, 1980); Noseworthy, Miller, Murray & Regan, 1981); leukodystrophies (Ochs, Markand & DeMyer, 1979); demyelinating disease (Starr & Achor, 1975; Robinson & rudge, 1977; Shanon, Himelfarb & Gold, 1981); neurological disease entities without obvious clinical manifestations (Stockard, Stockard & Sharbrough, 1977); and brain death (Starr, 1976; Greenberg, Becker, Miller & Mayer, 1977).

For neurological site-of-lesion testing the AEBPs are typically evoked using a click stimulus presented at a high intensity level. This high stimulus intensity is necessary for the clear definition and identification of the first five components. Level of lesion is determined by evaluating the latency relationships among selected positive components of the response waveform and stimulus onset, and by measuring relative (inter-peak) latency values among positive peaks. The individual's absolute and relative latency data are then evaluated against the laboratory norms for that stimulus.

A latency can be judged as abnormal by several methods: if it exceeds a specific number of standard deviations from the mean (Gilroy, et al., 1977; Maurer, Leitner & Schafer, 1980); if its value exceeds the one-tailed 95% or 99% confidence limit for normals (Rowe, 1978; Stockard, Stockard & Sharbrough, 1978); or if the intra-individual, inter-aural latency comparison of a particular response parameter exceeds a prescribed number of msec (Selters & Brackmann, 1977; Rowe, 1978; Bauch, Rose & Harner, 1982).

The inter-peak latencies of waves I, III and V are especially important for the localization of neurological lesions in the brainstem. Inter-peak latencies (IPLs) represent an operational definition of transmission time through the auditory pathways of the brainstem based on absolute latency differences. The I-III IPL represents transmission time in the pontomedullary region of the brainstem, the III-V latency indicates the central conduction time through the pons and caudal mid-brain region, and the I-V latency quantifies caudal pons to mid-brain transmission time (Stockard, et al., 1977; Rowe, 1978; Shanon, et al., 1981). An abnormally prolonged IPL indicates a dysfunction of the auditory system at the level associated with that inter-peak comparison.

Audiology. The applications of AEBPs to audiological concerns have included sensorineural hearing level prediction from AEBP thresholds (Jerger & Mauldin, 1978); the evaluation of pseudohypacusis (Kavanaugh & Beardsley, 1979); AEBP as an adjunct to traditional auditory measures in children with otitis media (Mendelson, Salamy, Lenoir & McKean, 1979); as an auditory screening procedure for newborns (Schulman-Galambos & Galambos, 1979; Frye-Osier, Hirsch, Goldstein & Weber, 1982); a predictor of site of sensorineural hearing loss lesion (House & Brackmann, 1979); the assessment of the severity and nature of auditory dysfunction (Hecox & Galambos, 1974; Schulman-Galambos & Galambos, 1975; Picton, Woods, Baribeau-Braun & Healey, 1977); and the re-construction of audiogram shape by the AEBP technique (Don, Eggermont & Brackmann, 1979).

The administration of AEBPs for audiometric information requires that a latency-intensity function (LIF) be generated by plottng the changes in wave V latency with systematic variations in stimulus intensity (Hecox & Galambos, 1974; Picton, et al., 1977), and a "reasonably accurate estimate of threshold can be obtained" (Hecox & Galambos, 1974, p. 35).

Clinical Concern

Concern about the lack of standardization of AEBP stimuli and its effect on inter-laboratory comparisons of data has been repeatedly expressed in the literature. Ornitz and Walter remarked about the difficulty as early as 1975:

> Little attention has been paid to the physical parameters of the stimulus (usually click) and their effects on the waveform of the response. Most reports simply specify the width of the pulse used as input to the audio amplifying system, without regard to polarity or waveform of the output or of the resulting sound wave. (p. 492)

Rowe's recognition of the problem was expressed in 1978 when he stated:

> Published studies with normal values for peak latencies and for interpeak conduction times are often not comparable because of variations in stimulus technique. (p. 459)

Evidently, the difficulties had not been resolved as of 1981.

> If experimental stimuli were more fully measured and described in scientific reports, some of the confusing and apparently conflicting findings might begin to disappear. (Weber, Seitz & McCutcheon, 1981, p. 19)

Coats and Martin (1977) expressed an appreciation of the click calibration predicament. Their results -- generated with meticulously measured and rigorously controlled stimuli -- nonetheless "understate the accuracy that could be obtained with more rigidly standardized methodology." (p. 622) This opinion was echoed by Stockard,

Stockard, Westmoreland and Corfits (1979) in reporting that the result of their study

> indicates that more rigorous control of these stimulus ... variables is required than has been previously applied to BAER (brainstem auditory evoked potentials) studies including our own. (p. 831)

The difficulties associated with calibrating a click stimulus and the fact that brainstem potentials can be evoked only by transients are appreciated by both the neurological and audiological communities in spite of the fact that the methodologies used by each discipline are different (high intensity stimulus delivery versus LIFs). The neurological concern is stated:

> In neurology ... up to now little attention has been paid to stimulus generation and electro-mechanical transduction and their effects on the waveform responses. (Maurer, et al. 1980, p. 130)

From the audiological community came the following comment:

> For clinical application of AP (action potential) and ABP (auditory brainstem potentials) latency-intensity function, the stimulus values known to influence AP and ABP latencies must be controlled carefully. (Coats & Kidder, 1980, p. 339)

Summary

Auditory evoked brainstem potentials testing has far-reaching applications for neurology, otology and audiology. The accuracy of interpretive statements based on the results of this evaluation critically depends on the tester's understanding of the influences on waveform of stimulus parameters and the most subtle variations in the acoustical properties of the transient. Clearly, the determination of auditory sensitivity and/or the site--of-lesion predictability depends on a rigorously generated, monitored and controlled stimulus. Meticulous calibration procedures are unquestionably a part of the AEBP testing routine. This fact is recognized in both neurology and audiology, but little has been done to include it as an indispensible adjunct to clinical testing.

To illustrate the profound influence of stimulus delivery and subject related issues on the AEBP waveform, the following section will review investigations performed to study these effects.

Stimulus Delivery and Subject Related Issues

The earphone transducer, the cushion and the headband must be considered as one system, hereafter referred to as "headset". Different transducers with different cushions can generate vastly different acoustical signals with an equivalent electrical input. In addition, the application force of the headset to the head (Burkhard & Corliss, 1954; Erber, 1968), the pinna-to-ear seal and repositioning of the headset to the ear (Atherley & Lord, 1965) can have a profound effect on the threshold and the sound pressure in the external ear produced by the earphone. Another source of variability is the inter-individual diversity in the anatomical attributes of the persons under test. The following sections detail these stimulus delivery and subject related issues.

Headset Components

Transducer Effects. A survey of the audiological and neurological literature revealed that a variety of earphones have been used to deliver click stimuli. Telephonics TDH-39's (Schulman-Galambos & Galambos, 1975; Picton, *et al.*, 1977; Stockard, *et al.*, 1977, 1978; Jerger & Mauldin, 1978; Stockard & Westmoreland, 1981) and TDH-49's (Don, *et al.*, 1979; Eggermont, *et al.*, 1980); Telex 1470's (Stockard, *et al.*, 1977; Coats & Kidder, 1980); Sharp HA-600's (Starr, 1976); Realistic phones (Hecox & Galambos, 1974; Salamy & McKean, 1976); Beyer DT 502S phones (Terkildsen, Osterhammel & Huis in't veld, 1973); Yamaha 11-P headsets (Mitchell & Clemis, 1977); and unspecified earphones and headsets (Schulman-Galambos & Galambos, 1979; House & Brackmann, 1979; Kavanaugh & Beardsley, 1979; Mendelson, *et al.*, 1979) represent the assortment of transducers that have been reported. Picton, Stapells and Campbell (1981) commented on the use of such a variety of earphones:

> The acoustic properties of clicks produced by different transducers are different and this can cause significant changes in the recorded response particularly at lower intensities. (p. 18)

This issue of transducer difference is certainly a factor contributing to the difficulties associated with making inter-laboratory comparisons of AEBP data.

Weber, et al. (1981) examined just the contribution of earphone to the brainstem auditory evoked responses. He and his co-authors stated, "An earphone's damping and resonant characteristics will ... contribute greatly to the acoustical properties of the click stimulus" (p. 15). They also cautioned that changes in the earphone's diaphragm from the use of high intensity levels and from dropping or mis-handling, for example, may significantly alter the diaphragm excusions and change damping characteristics. These changes can be manifested by the transducer's ability to evoked a brainstem response and an alteration in the AEBP latencies due to changes in click acoustics.

The effect of structurally different transducers on AEBPs was investigated by Hughes and Fino (1980). Electromagnetic (EM) TDH-39 driver was compared to a piezoelectric (PZ) earphone using the same electrical input to the phones for click generation and evocation of the brain stem response. There was a spectral difference between the earphones; both had a maximum resonance at 4k Hz, but the PZ earphone had resonance peaks at 1k, 2k and 5k Hz, as well. In the AEBP recordings, click artifact measured at 1.1 msec post-stimulus onset was reduced by 75% of the maximum for the PZ phone but only 10% of maximum for the EM transducer. Waves IV and VII appeared in the PZ generated recordings significantly more often than in the EM recordings. The major finding in this study was the discovery of a small vertex-positive deflection, I', at tenths of a msec earlier than wave I. This repeatable, stable wave had not been evident with any EM recordings due to the marked click artifact produced by those transducers which completely oblitereated that early component. Hughes and Fino (1981) only speculated as to the origin of I'.

Cushion Effects. The general function of the earphone cushion is to couple the earphone transducer unit to the ear. The cushion may be of either the circumaural (CA) type which actually circles the pinna and contacts the head, or of the supraaural (SA) type in which the contact area is almost totally pressing on the pinna.

The primary objection to using CA ear cushions for experimental and clinical endeavors is that coupler calibrations of earphones mounted in CA cushions are highly variable. Due to the increased volume between the transducer diaphragm and the tympanic membrane and the resultant changes in sound presure relative to the MX41/AR cushion, threshold sensitivity with the CA is modified as compared to the ANSI S3.6-1973 standard.

Earphone cushion type has not been reported in the AEBP literature as often as other technical factors, but the following transducer/cushion assemblies have been reported: TDH-39's mounted in CZW-6 cushions (Jerger & Mauldin, 1978); TDH-49's with MX41/AR cushions (Eggermont, et al., 1980) TDH-39's taped to the ears of infants (Schulman-Galambos, 1975); and TDH-39's "fitted with a soft foam circumaural cushion cut to fit the size of the newborn pinna" (Stockard & Westmoreland, 1981, p. 33).

The differential effects of earphone cushions on AEBP parameters have been essentially ignored by all except Coats and Kidder (1980) who provide the singular report on cushion effects on AEBPs. They state their experimental rationale as follows:

> Since acoustical coupling affects the frequency spectrum of the delivered sound stimulus, and since click frequency spectrum is known to have a profound effect on AE (auditory evoked) and ABR (auditory brainstem response) latencies and amplitudes, one might expect input-output functions to differ under different coupling conditions. (p. 339-340)

Click stimuli were generated by driving a Telex 1470 earphone capsule with 24 usec rectangular electrical pulses. The earphone was coupled to the ear by an MX41/AR cushion and an unspecified CA cushion. Click intensity was calibrated in peak equivalent SPL with appropriate acoustic couplers and sound measurement equipment. Behavioral click thresholds were 33.0 ± 1.9 dB peSPL for the CA cushion and 34.2 ± 1.8 dB for the SA.

Results of the spectral analyses revealed that clicks delivered by the SA cushion had greater concentration of acoustic energy above 6k Hz than did the CA cushion. A comparison of wave I (designated N1 by the authors) latencies evoked by the different earphone cushions revealed a significant mean latency difference between the CA and SA cushions of 0.287 msec. The mean wave V latency differencce of 0.123 msec was also statistically significant. For both

AEBP components the CA-generated latencies were longer than the SA. The I-V IPL mean difference was 0.18 msec with the SA values longer than the CA.

Coats and Kidder (1980) reported that these effects of ear speaker coupling on latencies were predictable from the cushion effects on stimulus spectrum. Since an increase in high frequency click energy tends to decrease wave I latency more than wave V, and the SA cushion showed more acoustical energy above 6k Hz than did the CA, then the I-V IPL should predictably be longer for the SA condition, and, indeed, it was.

The Coats and Kidder (1980) study clearly demonstrated the influence of cushion and concomitant spectral considerations on the brainstem response paramaters. Such a critical variable cannot be overlooked in the experimental and clinical studies of peripheral and central auditory function using the AEBP technique.

Behavioral and electrophysiological changes observed from the use of different cushions with an equivalent electrical input are caused by the cushion's effects on the frequency response of the earphone. Therefore, earphone transducers and cushions must be considered and evaluated as one assembly (Dirks, Morgan & Wilson, 1976).

Anatomical Effects

Inter-subject variation in aural geometries has been studied and was found to have an effect on the sound pressures generated in the ear by the standard transducer/cushion. Burkhard and Corliss (1954) found no effect on external ear sound presures for the same subject but did find a statistically significant effect between subjects due to subjects' individual anatomical differences. These anatomical variations influence acoustical load and sound pressure. Erber (1968) found that with identical electrical signals delivered into the same transducer/-cushion system, adult males had lower mean sound levels than adult females and male and female children. These differences were most evident at frequencies about 3150 Hz, and, acording to Erber, could at least partly be explained by the structural differences in the subjects' ears.

Sex Effects

Inter-subject variability in AEBP response parameters and behavioral click thresholds has been studied with particular emphasis on gender differences in the response. Both wave V peak latency and the I-V IPL are shorter in females than in males (Beagley & Sheldrake, 1978; Stockard, et al., 1978; Stockard, et al., 1979; Jerger & Hall, 1980; Michalewski, Thompson, Patterson, Bowman & Litzelman, 1980). These differences in electrophysiological data are interesting vis-a-vis the results of several studies that evaluated behavioral click thresholds. Michalewski, et al. (1980) found no statistically significant difference in the pre-AEBP audiograms of the male and female subjects used in their study, and there was no significant gender effect on behavioral click thrshold. Stapells, Picton and Campbell

(1982) also found no statistically significant influence of the subject's gender on click threshold; collapsed across ear and click polarity, the mean click threshold for males was 36.4 dB peak SPL and 36.3 dB peak SPL for females. Stockard, et al. (1978), Stockard, et al. (1979) and Michalewski, et al. (1980) believe that these sex effects on AEBPs are probably due to the anatomical variations in head and brainstem size and/or to differences in the length of the external auditory canals and auditory nerve dimensions between males and females.

Summary

This section detailed the stimulus delivery and subject variables that influence AEBP response parameters used to assess peripheral and central auditory system normalcy. Obviously, rigorous control of these variables is necessary to elimate or at least significantly reduce these stimulus effects so that deviations from the norm can be attributed to the subject and not to imprecise AEBP technique. Such control of stimulus variables can be realized only through careful calibration procedures. The following section will present procedures that have been used for click calibration.

Intensity Calibration Procedures

Hearing losses of specific etiologies have characteristic LIFs, and a critical determinant in evaluating AEBP response thresholds is stimulus intensity. Unfortunately, there is neither a generally recognized standard which specifies the acoustic calibration of click intensity, nor is there a clinical standard which designates transducer or driver/cushion configuration. Intensity calibrations have been performed using real ear (behavioral) procedures and artifical ear (acoustical) procedures. Each of these real and artificial ear methods provides several designations that can be used for the description of stimulus intensity. These methods and designations are precise for slow rise time, long duration stimuli, however, neither a calibration procedure nor an intensity specification for impulsive acoustic stimuli has been standardized.

Real Ear Calibration

The real ear intensity calibration of any signal involves several general steps. An average behavioral threshold for the stimulus is determined using a homogeneous group of otologically and audiometrically normal subjects. The average electrical voltage measured at the earphone terminals which corresponds to the average behavioral threshold is then used to drive the same transducer/cushion configuration in an artificial ear for the measurements of sound pressure produced at that driving voltage. The resultant coupler sound pressure level (SPL) is taken as the acoustical threshold reference for that stimulus and earphone system. Sensation Level and Normal Hearing Level are two real ear methods used in the calibration of auditory signals.

Sensation Level. Sensation level (SL) is defined by ANSI S3.20-1973 as

> the pressure level of the sound in decibels above its threshold of audibility for the individual subject or for a specific group of subjects. (p. 45)

The calibration of a signal in terms of SL simply involves the determination of an individual's threshold with that stimulus or the average threshold of a defined homogeneous group. Whether SL refers to an individual or group should be reported so that it is evident whether the intensity calibration reflects a singular value or a statistical entity. It should be noted that the dB SL method and intensity specification most often refer to an individual rather than a group (Dirks, et al., 1976; Durrant & Lovrinic, 1977; Davis, 1978; Price, 1978; Dobie, 1980). A report was found in the literature in which it was stated that AEBP stimuli were presented at SLs of 20, 40 and 60 dB. However, it was not specified whether SL referred to each subject's threshold or to a group threshold (Cobb, Skinner & Burns, 1978).

The advantages of the SL intensity method and designation are: it is quckly performed; periodic calibration checks are quite rapidly effected if SL refers to an individual; it provides a well-defined behavioral reference for each subject; and SL has an audiological precedent.

The disadvantages of the SL designation and procedure are: it is an equivocal reference since it relates only to what an individual (in most applications) judges as barely audible, and thresholds obtained even in quiet vary among subjects (Dirks, et al., 1976); although the ANSI S3.20-1973 standard clearly specifies a sound pressure as part of the definition, SL is seldom related to an acoustical or physical reference in its application to AEBP testing; SL varies with the subject's ability to accurately respond; and, most importantly, it is determined by the degree of the subject's hearing loss (Stapells, 1982). Subjects with hearing losses may provide very similar click thresholds, yet they may have widely varying pure tone audiograms (Dirks et al., 1976).

The major disadvantage to using SL as an intensity reference and for generating AEBP normative data is that the SL method inflates the standard deviation of the control group, thus building variability into the norms. Since normal hearing is audiometrically defined as a range of thresholds from 0 dB HL to approximately 20 dB HL, then the norms for a particular SL could actually have been collected using intensities that span about a 20 dB range. Using the Picton, et al. (1981) LIF slope based on a normal Hearing Level (nHL) procedure, this 20 dB range could result in a wave V latency difference between that normal threshold range of 0.76 msec. This procedural influence on the normative data would serve to increase the inter-subject variability (inflated standard deviation) and, therefore, increase the number of false negatives on response interpretation. With the SL procedure, the experimenter or clinician has done no more than to "calibrate" his procedure in that the response-evoking signal will be presented at the same number of decibels above stimulus threshold for each individual tested. Patients with a hearing loss of a fluctuating or deteriorating nature would not be evaluated at an equal intensity at subsequent examinations. Because the SL calibration does not relate the stimulus to an external reference at the time of a particular measurement, no determination of auditory sensitivity is possible.

In the application of the SL specification to AEBPs, not only has each subject's threshold been used as a stimulus reference (Wolfe, Skinner & Burns, 1978; Noseworth *et al*., 1981), but subjects have even been tested at stimulus levels relative to the experimenter's SL (Salamy & McKean, 1976).

Normal Hearing Level. The normal Hearing Level (nHL) calibration method is procedurally equivalent to a group SL. Stimulus thresholds are obtained on about 10 otologically and audiometrically normal young adults. The mean threshold established for the group is designated 0 dB nHL, and supra-threshold stimulus levels are referred to this average. This method and specification were first reported by Picton, *et al.* (1977).

The advantage of the nHL calibration procedures is that it results in an intensity specification as a statistical entity, and, thus, it better describes threshold, itself defined in statistical terms. One disadvantage is the same as for the SL calibration in that there is no acoustical reference for 0 dB nHL. There is also a disadvantage to this method in terms of the periodic re-calibration of click intensity (Weber, et al., 1981; Stapells, et al., 1982). Whenever an intensity check is necessary a normal jury must be convened and re-tested. This is a tedious and laborious task, not at all economical in terms of tester time and equipment usage.

The use of the 0 dB nHL reference to generate LIFs results in normative data that have been collected at the same stimulus intensity for each normal subject. Subsequently, each subject is evaluated at the same physical intensity level regardless of his click threshold or audiogram. Because the tester is relatively certain of the intensity of the stimulus being delivered to the ear, the response of the peripheral or central auditory system to that signal can be evaluated by inspection of the AEBP waveform, latency and amplitude deviations from normal.

A serious disadvantage of the nHL calibration (true also for SL) is that stimulus waveform and spectral differences are not evident from behavioral calibration procedures. It has been shown that reversing click polarity has no effect on group threshold (Stapells, et al., 1982), yet it has a marked influence on AEBP latency measurements (Ornitz & Walter, 1975; Stockard, et al., 1978).

Stapells, et al. (1982) studied the effects of spectrum on click thresholds of normals and found a statistically significant difference in the group threshold using stimuli of different spectra. The stimuli were a 2k Hz single cycle sine wave and a 2k Hz single cycle offset cosine wave. The cosine wave had a flat spectrum to about 6kHz; the sine signal had less acoustic energy in the low frequencies (2k Hz and lower). With data collapsed across stimulus polarity, the average threshold for the cosine stimulus was 32.4 dB peak SPL and 24.3 dB peak equivalent SPL (peSPL). The sine thresholds were 29.9 dB peak SPL and 27.05 peSPL. This is evidence not only of a marked effect of stimulus spectrum on threshold but also of an interaction between spectrum and intensity designation at threshold.

Hecox and Galambos (1974), Starr and Achor (1975), Starr (1976), Gilroy, et al. (1977), Picton et al. (1977), Stockard, et al. (1977, 1978), Mendelson, et al. (1979), Rowe and Carlson (1980) and Stockard and Westmoreland (1981) have used the nHL calibration and intensity designation method, yet none of these reports provided acoustical data regarding the physical levels of the click at 0 dB nHL.

Disadvantages of Real Ear Calibration. For relatively slow rise time, long duration signals such as those used in audiometry, the SL and nHL procedures yield comparable resuls. The click, however, is impulsive and has a Complex waveform and a broad spectrum. Not only are the acoustical calibration problems associated with this type of stimulus evident, but threshold data determined from a group norm could be meaningless when applied to patients or subjects with peripheral hearing losses. The interaction between click spectrum and audiometric configuration could result in equivalent behavioral thresholds for clicks, yet could produce disparate AEBP responses and different interpretations concerning peripheral and central auditory functions.

Another disadvantage to these methods is that they provide no method for the evaluation of attenuator linearity or signal spectrum.

Artificial Ear Calibration

Acoustic couplers and ear simulators have been designed to overcome the difficulties associated with real ear calibration methods and to provide laboratories with standardized acoustical loads for the specification of signal parameters. The function of an earphone coupler is to interface an ear cushion assembly to acoustical measurement devices. The type of cusion, CA or SA, is a determinant of which type of coupler should be used. The coupler's specific shapes and cavity sizes serve to present the headset with an acoustical load similar to that of an average human ear. These cavity dimensions have been specified in detail, thereby facilitating the manufacture of the couplers within defined limits of precision. This design and manufacturing feature aid in providing uniform and repeatable measurements among facilities that use such a coupling device. Three coupler configurations are presented which can be used with varying degrees of success to measure the acoustical parameters of an earphone.

NBS-9A Coupler. The National Bureau of Standards (NBS) 9A coupler is manufactured from a solid block of non-magnetic, non-porous, hard and stable material. Designed in consideration of a sound pressure-in-the-canal criterion, the NBS-9A coupler cavity is approximately cylindrical in shape and has the acoustic reactance of a volume of air of approximately 5.6 cubic centimeters. The base of this cavity is terminated by a microphone which measures the sound pressure developed in the cavity by a signal from the earphone seated at the other end of the coupler. The earphone/cushion assembly is situated on the coupler lip with an application force of 400 to 500 grams introduced either by weight or spring force.

The NBS-9A is the standard reference coupler specified in ANSI S3.6-1974, "Specifications for Audiometers". Although this coupler has been the standard for about 30 years, it has a serious shortcoming -- the typical ear and the 9A differ significantly in their acoustical impedances. Consequently, the sound pressure generated by an earphone in the coupler do not match the earphone response in the ear (Zwislocki, 1970). Pressures in the ear below 500 Hz are generally lower than NBS-9A coupler presure due to the acoustical leakage between the SA cushion and the pinna. There is good correspondence between coupler and ear pressures from 500 to 1.5k Hz; from 1.5k to 8k Hz there is only fair agreement between the coupler pressures and the pressures measured in the external auditory canal. These differences are unpredictable because of the uncertain influences of aural geometries and acoustic loads on the earphone's response in the ear (ANSI S3.7-1973). An additional problem with the NBS-9A is that it can not be configured for use with a CA earphone cushion.

Zwislocki Coupler. Zwislocki (1970) designed a coupler that better reproduced the acoustical impedances of the median human ear and provided coupler pressure measurements that replicated the earphone's response as measured at the eardrum. The Zwislocki coupler was designed in consideratoin of an acoustic impedance-at-the-tympanic membrane criterion. In addition, the simple cavity shapes and external configuration of the Zwislocki coupler are accurately specified, and the device could be easily duplicated in a small machine shop.

The Zwislocki coupler is modular in design and simulates the acoustical analogs of the ear's four main anatomical parts. The eardrum part of the coupler is the most important in that it replicates "the proximal part of the ear canal and the impedance at the eardrum." (Zwislocki, 1971; p. 5) The ear canal segment is screwed into the top of the eardrum assembly and serves to hold insert receivers. The third section mimics the acoustical properties of the outer ear and has the approximate dimensions of the concha, hence, its name is the concha part. The fourth section of the coupler is the head part which is a plate that simulates the side of the head.

One advantage to this coupler is that resonances can be adjusted to allow the tester to measure sound pressure at different canal points by simulating the acoustical impedances analogous to those different canal positions. Another advantage is that both SA and CA cushions can be evaluated with this one coupling device.

Zwislocki's (1970, 1971) data on the comparison of this coupler with real ear responses indicated very good agreement between the artificial and the real ear (probe tube microphone method) calibrations for CA and SA cushions.

Penn State Flat Plate Coupler. Michael and Bienvenue (1976) developed a flat plate coupler at Pennsylvania State University for the calibration of CA earphones. The coupler is constructed of 1.2 inch-thick metal and is elliptical in shape. The 6 cubic centimeter cavity was eliminated from the design to minimize the effects of coupler resonances and earphone position on the measured pressure. The sound pressure measuring microphone is positioned within a centrally located shaft with the diaphragm of the microphone nearly flush with the surface of the plate.

The results of the Michael and Bienvenue (1976) study indicated that this one-piece flat plate coupler measured CA earphone/cushion assembly threshold pressures with consistency comparable to data generated with the standard

SA MX41/AR evaluated with the NBS-9A standard coupler for audiometric measurements.

The pressure generated in a coupler at threshold driving voltage is measured and must be specified regardless of which type of coupler configuration is used. The following section specifies the intensity designations available for acoustical calibrations.

Intensity Specifications

The intensity references below developed from the actual procedures used to measure the sound pressure. These references have been used as click intensity references.

Peak SPL. Peak SPL designates the intensity in terms of sound pressure at the maximum (or peak) pressure of the acoustical event (Picton, et al., 1981; Stapells, et al., 1982). Limitations in the meter ballistics of conventional analog sound level meters preclude their use for measuring click sound pressure (Weber, et al., 1981).

Peak Equivalent SPL. Another intensity designation is peak equivalent SPL (peSPL) which is a relative specification in which click intensity is expressed in terms of peak-to-peak (p-p) pressure of a steady state pure tone (Dirks, et al., 1976). The peSPL procedures according to Dirks is as follows:

1) A high intensity click is displayed on the oscilloscope; the peak amplitude of the initial rarefaction is measured.

2) The peak amplitude of the initial rarefaction is doubled for the p-p value of click amplitude.

3) A pure tone is delivered to the second channel of the oscilloscope, and its amplitude is adjusted so that tonal p-p amplitude is equal to the doubled peak click value.

4) The intensity of the pure tone at that peak equivalent amplitude is then determined in an acoustical coupler calibration system. Click intensity can then be expressed in coupler peak equivalent SPL in dB relative to the pure tone used.

Arlinger (1981) found that for AEBP stimuli, 0 dB nHL was generally in the range of 20 to 40 dB peSPL.

Summary. These methods of click intensity specification and calibration are available, though none is recognized as a standard procedure for the acoustical definition of 0 dB nHL. As early as 1976 Davis urged for the acoustical specification of auditory evoked potential stimuli. Evidently, his suggestion has not been followed on a routine basis in either the audiological or the neurological communities.

Summary

Auditory evoked brainstem potential testing is performed to evaluate auditory sensitivity and/or hearing loss site-of-lesion for audiometric purposes and to assess the functional integrity of the brainstem as reflected by afferent auditory pathway activity for neurological pursuits. Latency-intensity funtions are generated for the audiometric application of this technique, and, typically, high intensity stimuli are used to generate the AEBPs for neurological purposes. It is clear that the intensity of the response-evoking stimulus is a critical determinant of the defining parameters of the AEBP whether for audiological or neurological evaluations.

Calibration of click intensity must be performed to provide an external physical reference for the transient stimulus which elicits an internal electrophysiological or behavioral response. Real ear calibration procedures such as SL or nHL provide neither a physical referent for threshold nor can they specify waveform, spectral or temporal features. It has been demonstrated that with marked variations in stimulus parameters the behavioral threshold for the transient can remain unchanged, yet there can be a profound influence on the electrophysiological response. Only the electraoacoustical calibration of signal intensity can precisely define stimulus features. Unfortunately, there is no generally recognized standard for the electroacoustical calibration of transients. This study addressed the issue of intensity specification through behavioral and electroacoustical strategies.

Statement of Research Goals

The purpose of this study was to suggest a plan to examine the reliability and validity of several electro-acoustic calibration procedures relative to estimates of auditory sensitivity obtained from normal hearing subjects. Calibration variables included earphone system, coupler system and the method by which instrumentally measured stimuli are quantified. Additionally, the symmetry of the stimulus waveforms was systematically varied in an effort to identify that calibration method which yields the most consistent prediction of threshold as measured by behavioral means.

These goals are stated as follows:

1. the determination of which intensity specification and acoustic coupler yields the most reliable electroacoustic index of stimulus level;
2. the determination of which intensity specification and acoustic coupler yields the most reliable description of behavioral threshold when:
    a. stimulus symmetry (waveform) is varied, and,
    b. headset is varied.

The specific methods and procedures by which these goals were realized are detailed in Chapter 2.

CHAPTER 2

RESEARCH METHODS AND PROCEDURES

This study employed behavioral and electroacoustical strategies to determine the intensity specification and coupler configuration which yielded the most accurate and reliable description of AEBP stimuli. This investigation was conducted in four parts listed below:

1. Initial electroacoustical calibration of headsets and stimulus delivery system;
2. Behavioral intensity calibration procedure for the determination of threshold driving voltages for the experimental stimuli;
3. Electroacoustical quantification and description of 0 dB nHL for the experimental stimuli under several coupler configurations and intensity specifications;
4. Final electroacoustical calibration of headsets and stimulus delivery system (replication of Part 1).

The sections which follow detail each of these methodological parts.

Parts 1 and 4

Initial and Final Electroacoustical Calibration

The frequency response characteristics of the transducer and each cushion and the linearity of the stimulus attenuator were determined at the outset of the experimental investigation and after the data collection

procedures to ensure that the system had been stable in function during the course of the experiment. These electroacoustical calibrations were performed using each headset interfaced to the sound measurement apparatus and employed a single coupler configuration. The sections which follow specify the methods and procedures used for the initial and final stimulus delivery system response specification.

Frequency Response Measurements

System Measured. Two transducer/cushion configurations were evaluated: 1) a TDH-39P 300 Ohm earphone transducer (Serial Number 812185) mounted in an MX41/AR SA cushion, and 2) the same TDH-39P driver mounted in an Auraldome CA cushion. These headset arrangements were used for Parts 2 through 4 of this study as well.

The stimulus generator and attenuator were hard-wired components of the Madsen 2250 Electrical Response Averaging System (ERA 2250).

Coupler. Headset frequency response measurements were made using the Zwislocki coupler with the ear simulator, concha section and flat plate. Only one coupler was used for Parts 1 and 4 since these measurements were used to assess stimulus delivery system stability from the beginning to the end of the experiment. It was reasonable to assume that a single coupler would reflect any stimulus changes with time.

Procedure. The Bruel and Kjaer (B & K) 4143 half-inch pressure microphone was coupled to the measurement apparatus, and the system was calibrated using a General Radio 1986 Omnical Sound Level Calibrator. The frequency response characteristics of each headset were determined using the ANSI recommended procedure for "Continuous-Response-Versus-Frequency" measurements (ANSI S3.7-1973, p. 29). A diagram of the electroacoustical measurement system is found in Figure 2.

(Figure 2)

Attenuator Linearity

The linearity of the ERA 2250 right attenuator was determined electrically using the equipment configuration specified in Figure 3.

(Figure 3)

The peak-to-peak voltage of a 2k Hz signal was measured in 10 dB nominal steps from the maximum attenuator setting to the limits of the electrical measurement system.

The use of the right attenuator only for the experimental procedures ensured that any significant experimental effects were not caused by the use of different attenuators.

Part 2

Behavioral Intensity Calibration

The purpose of the behavioral intensity calibration procedure was to determine the average threshold driving voltage for a group of ormal young adults using the headsets and the stimuli which could be employed in clinical AEBP procedures.

Subjects

Twenty subjects (10 male, 10 female) were used to determine the individual and average threshold driving voltages for the two stimuli and the two headset configuratios under test. Each subject was between 18 and 30 years of age and met the following criteria:

Informed Consent. Each subject read and signed the informed consent form found in Appendix A.

Audiological History. Each subject reported a negative history for hearing loss, tinnitus, dizziness, noise exposure and familial hearing loss. None had an active upper respiratory infection.

Otoscopic Screening. The otoscopic screening was negative for excessive cerumen and tympanic membrane retraction and/or bulging for each subject.

Audiometric Test Requirements. Each subject was required to have pure tone air conduction thresholds of 10 dB or better for each ear at the audiometric octaves 250 through 8k Hz. These tests were performed using an audiometer calibrated to ANSI S3.6-1973 in a double-walled sound suite that met the ANSI standard for acceptable background noise in an audiometric testing facility (ANSI S3.1-1977).

Tympanometric measurements must have resulted in a Type A tympanogram with the point of maximum compliance between ± 50 mm $H_{2}O$.

Crossed and uncrossed acoustic reflex thresholds in each ear must have been 95 dB HTL or better at the octave frequencies 250 through 4k Hz. The subject must not have demonstrated acoustic reflex decay at 1k Hz in either ear. The impedance measurements were performed on a Grason Stadler 1723 Middle Ear Analyzer.

Stimuli

Two single cycle signals as employed by Stapells, *et al*. (1982) were used for both the behavioral and the electroacoustical intensity calibration procedures.

One signal known as "symmetrical" (SYM) was produced by driving the earphone with one cycle of a 2k Hz sine wave. The second signal, called "asymmetrical" (ASYM), was generated with one-half cycle of a 2k Hz sine wave. The initial deflection for both the SYM and ASYM electrical signals was in the positive direction as viewed on an oscilloscope. These electrical signals were produced by the ERA 2250 stimulus generator.

The stimuli were presented at a rate of 20 per second (sec). The listening period for each stimulus train was approximately 1 to 2 sec as controlled by the experimenter.

Stimulus Delivery System

Headset. The same two headsets specified in Part 1 were used in this study. The TDH-39P (300 Ohm, Serial Number 812185) was mounted in the MX41/AR SA and the Auraldome CA cushions.

Equipment. The ERA 2250 stimulus generator and right attenuator were used to drive the transducer for the experimental stimuli. Figure 4 presents a diagram of the experimental configuration for the behavioral intensity calibration procedure.

(Figure 4)

Auditory Threshold Determination Procedure

The right and the left ear of each subject were tested for stimulus threshold. Two trials per stimulus for each headset were evaluated for each ear for the assessment of intra-trial reliability. Presentation order of the stimuli, headset and ear were counter-balanced across subjects. The audiometric evaluation served as a training session for the determination of the SYM and ASYM stimulus thresholds.

Threshold was defined as the lowest stimulus intensity at which the subject responded to at least half of the stimuli presented on ascending threshold searches with a minimum of three responses at a single intensity.

Threshold was manually determined using the American Speech-Language-Hearing Association guidelines for pure tone threshold determination (ASHA, 1978). Stimulus attenuation was controlled in 5 dB steps.

Each subject responded with a button that activated a small light outside the test chamber. The instructions were read to each subject as follows:

> You are going to hear brief presentations of a clicking or tapping sound. The sounds will start out easy to hear, but they'll get softer and

> harder to hear as the test continues. Every time you hear one of the clicking sounds, you are to press the button as soon as you hear it, and keep the button pressed for as long as you hear the sound; release the button when the sound goes away. You are to press the button no matter how soft the tapping is -- even if you only think you hear it. Listen very carefully. Do you understand?

Threshold was recorded as the nominal value indicated by the ERA 2250 attenuator. The subject was dismissed after all thresholds had been determined.

Threshold Voltage Determination Procedure

It was necessary to convert the nominal threshold values as indicated on the ERA 2250 right attenuator to earphone driving voltages because it was those voltages that would be used as reference values for the electroacoustical specification of 0 dB nHL signal intensity to be performed in Part 3. The ERA 2250 nominal attenuator readings did not accurately reflect threshold levels of the SYM and ASYM stimuli, so voltage conversions were necessary. These voltage measurements were made using the procedure and equipment diagrammed in Figure 5.

(Figure 5)

Part 3

Electroacoustical Intensity Specification

The intensity calibration of the acoustic signal that resulted from the threshold driving voltages for each subject under each headset and stimulus condition was performed using several acoustic coupler configurations and intensity specifications. The goal of experimental Part 3 was the determination of which coupler/intensity combination yielded the most valid and reliable electroacoustic index of stimulus level. In addition to the intensive characteristics, the temporal and spectral features of each signal produced by the different headsets in each coupler were described.

Headset and Coupler Configurations

The TDH-39/SA and the TDH-39/CA headsets were each linked to the measurement apparatus using a Zwislocki coupler with ear simulator, concha section and flat plate and using the PSFP coupler. In addition, the NBS-9A coupler was used with the SA headset to replicate the work of Stapells, et al. (1982).

The Zwislocki coupler was fit with a B & K 4134 half-inch pressure microphone (S/N 296714) and B & K 2615 pre-amplifier (S/N 166238). The PSFP and the NBS-9A both used the same B & K 4144 one-inch pressure microphone (S/N 406584).

Intensity Measurements

Peak SPL and peSPL intensity designations were used to quantify each subject's threshold experience for the stimulus produced by each headset under evaluation with the couplers specified.

Peak SPL. The equipment for the peak SPL measurement consisted of the appropriate coupler and microphone,

pre-amplifier and sound level meter. The equipment used in this study is specified in Figure 6.

(Figure 6)

The peak SPL measurement procedure was performed in the sound suite used in Part 2 of this study. The procedure was as follows:

1. The sound level meter was set to the linear frequency weighting scale.
2. The ERA 2250 right attenuator was then adjusted to the threshold driving voltage for each subject's responses (generated in Part 2) to activate the headset under test. The right attenuator was then adjusted to a nominal 70 dB intensity to raise the acoustical signal well above the noise floor of the room and test equipment.
3. The peak coupler pressure produced by that driving voltage plus 70 dB was measured. The 70 dB introduced in step 2 was then subtracted from this reading.
4. The resulting peak SPL then replaced the threshold driving voltages for all of the data generated by each subject in Part 2.

This procedure was repeated for each headset/coupler combination and for each stimulus.

<u>peSPL.</u> The peSPL measurements were made using each coupler and microphone, the sound level meter, the oscilloscope and a tone generator. The equipment configuration is depicted in Figure 7.

(Figure 7)

Two peSPL designations were used as intensity specifications. First, the equivalent pure tone was measured in terms of its peak SPL (hereafter referred to as "peSPL-peak"). Second, the pure tone was measured as root-mean-squared (rms) SPL (hereafter referred to as "peSPL-rms").

The peSPL procedures was as follows:

1. The ERA 2250 right attenuator was set to the threshold driving voltage for ech subject's responses (as generated in Part 2) to activate the headset under test. The attenuator was then adjusted to a 70 dB nominal intensity to raise the acoustical signal well above the noise floor of the room and equipment.

2. The acoustical signal produced in the coupler was then displayed on the oscilloscope; this signal's peak-to-peak voltage was measured from the oscilloscope.

3. A 2k Hz pure tone produced by a function generator was delivered to channel 2 of the oscilloscope. Tonal amplitude was adjusted so that its voltage equaled the peak-to-peak voltage of the experimental stimulus.

4. Tonal intensity at that peak-to-peak voltage was then determined in each acoustic coupler by driving the earphone with that tonal voltage.

5. The peSPL-peak and the peSPL-rms of the voltage-equivalent pure tone plus the 70 dB added in step 1 were measured on the sound level meter. The 70 dB was then subtracted from this reading.

6. The resulting peSPL-peak and peSPL-rms then replaced the threshold driving voltage for all of the data generated by each subject in Part 2.

Stimulus intensity was expressed in peSPL-peak and peSPL-rms in db(A) relative to the 2k Hz pure tone used. These intensity specifications were performed on both headsets and coupler configurations using the SYM and ASYM stimuli.

Data Analyses. The threshold driving voltges measured for each subject under each experimental condition (2 headset x 2 stmuli x 2 ears x 2 trials) were converted to peak SPL, peSPL-peak and peSPL-rms intensities as a result of this experimental effort.

To evaluate any differences in threshold between the right and left ears and between trial 1 and trial 2 threshold determinations, a two-way (Ear x Tral) analyses of variance (ANOVA) with repeated measures was performed separately for females and males for each combination of coupler, headset, stimulus and intensity specification. The F statistic was considered statistically significant if it exceeded the probabilty level, p = .01. A total of 60 separate ANOVAs were performed (2 sexes x 3 intensity specifications x 2 couplers x 2 headsets (SA and CA) x 2 stimuli = ANOVAs plus 2 sexes x 3 intensities x 1 coupler (NBS-9A) x 1 headset x 2 stimuli = 12 ANOVAs).

If the Ear x Trial ANOVAs indicated the absence of any statistically significant main effects for either variable, then these data would be averaged into a single value for each subject under each experimental condition. Further statistical analyses of the data would be contingent upon the results of the Ear x Trial analysis.

Intensity Reliability Measurement

A reliability study was performed to determine which coupler configuration and intensity specification yielded the most consistent stimulus intensity levels.

Equipment and Procedures. The equipment and measurement procedures were identical to those specified to the peak SPL, peSPL-peak and peSPL-rms measurements. This reliability investigation was performed for each coupler and headset combination using each stimulus.

Driving Voltages. The driving voltages used were the mean driving voltages for each stimulus condition. These mean threshold driving voltages were calculated by collapsing all ear and trial threshold voltages across all subjects (2 ears x 2 trials x 10 subjects/sex x 2 sexes = 80 data per mean). These data had been generated in Part 2.

Reliability Measurement. Reliability measurements were made by repeating each intensity measurement ten times. The earphone and coupling mass were physically removed from the coupler and replaced for each of the observations. All combinations of headset, stimulus, coupler and intensity designation were evaluated.

Data Analyses. The means and standard deviations of all thresholds generated under each experimental condition were calculated. These descriptive statistics were scrutinized to determine which coupler/intensity specification combination yielded the most consistent repeated intensity measurements.

To quantify the associations between the SYM and ASYM stimulus thresholds and those thresholds obtained using the different cushions as measured by the various couplers and intensity combinations, Pearson product moment correlation coefficients (r's) were calculated. These data were analyzed in three ways: 1) different stimuli - SA cushion; 2) different stimuli - CA cushion; and 3) same stimuli - different cushions. The coefficient of determination (r^2) was calculated for all statistically significant r's to determine the strength of the relationship between the two threshold measurements under consideration.

Stimulus Spectrum

The spectrum of each stimulus/headset combination (10 total) was generated using each coupler with the appropriate microphone and B & K 2112 Spectrometer linked to a B & K 2305 Graphic Level Recorder. Each spectrum was automatically recorded by the B & K system. The equipment configuration is shown in Figure 8.

(Figure 8)

A third-octave filter analysis was performed by the spectrometer. The input to the measurement system from the earphone was a 50 dB re: mean threshold driving voltage signal presented at a rate of 20 stimuli per second.

Stimulus Waveforms

The acoustical signal waveform was evaluated in order to depict its pressure changes as a function of time. Each stimulus/cushion combination was evaluated using each coupler with the appropriate microphone, the B & K Microphone Power Supply and the oscilloscope. The equipment is diagrammed in Figure 9.

(Figure 9)

The acoustical signal was evaluated at an intensity of 80 dB re: mean threshold driving voltage presented at 30 stimuli per second. The oscilloscope voltage and time scales were set at 0.2 volts/division and 0.5 msec/division, respectively, for all of the signals evaluated. A Polaroid photograph was taken of each stimulus, and the stimulus waveforms presented were photocopied directly from these photographs.

Chapter 3 details the statistical analyses performed on all data and specifies the results of each analysis.

CHAPTER 3

RESULTS

This study was conducted to determine the coupler configuration and intensity specification that yielded the most accurate and reliable description of AEBP stimuli. The probability level used throughout the data analyses for statistical significance was $\underline{p} = <.01$. The results of each of the four experimental steps are detailed in the sections that follow.

Parts 1 and 4

Initial and Final Electroacoustical Calibration

Frequency Response Characteristics

The frequency response curves of the TDH-39/SA headset generated in Parts 1 and 4 of this experiment are shown in Figures 10 and 11, respectively.

(Figures 10 and 11)

These curves show an 8 dB SPL rise in earphone output from 20 through 2k Hz with major resonance peaks at 3.3k, 6.1k and 10.5k Hz. These initial and final response characteristics are virtually identical indicating no appreciable change in the earphone transducer dynamics during the course of this experiment.

The frequency response curves of the TDH-39/CA headset are presented in Figure 12 (initial, pre-test curve) and Figure 13 (final, post-test curve).

(Figure 12 and 13)

These frequency response curves show a flat response from 20 through 150 Hz, a 13 dB SPL increase in signal level from 150 to 300 Hz, and a 4 dB SPL decrease in signal intensity from 300 to 3k Hz. This headset displayed a dual-peaked resonance with the trough centered at approximately 5k Hz. There was another resonance at 10k Hz. These initial and final response characteristics are virtually identical indicating that there was little, if any, change in earphone dynamics during the course of this experiment.

Attenuator Linearity

The peak-to-peak voltage measurements of the 2k Hz signal used to assess right attenuator linearity were converted to $\log_{10}$ values to facilitate the graphic representation of these data. Figure 14 depicts the right attenuator output voltage as a function of nominal attenuator setting.

(Figure 14)

The values were identical for the initial and final system calibration procedures indicating no change in attenuator linearity during the course of the experiment.

Part 2

Behavioral Intensity Calibration

Subject Data

Age. The ages of the female subjects ranged from 22.0 to 29.9 years (X = 24.2 ± 2.88 years). The males ranged in age from 22.5 to 28.5 years (X = 25.2 ± 1.94 years). A one-way ANOVA performed on the age data revealed no statistically significant difference between the female and male subjects' ages (F (1,18) = 4.80 $p > .01$).

Pure Tone Thresholds. A two-way (Sex x Ear) ANOVA with repeated measures was performed on the pure tone thresholds measured in Part 2. The results of the ANOVA indicated no statistically significant effect of subject sex or ear on the rsults of the pure tone threshold testing. For females the mean pure tone threshold across the six octave frequencies tested was 2.25 ± 4.45 dB HTL (Hearing Threshold Level) for the right and left ears combined and was 4.04 ± 4.65 dB HTL for the males (F(1,118) = 6.32 $p > .01$). The right ear mean threshold collapsed across frequency and subject sex was 3.12 ± 4.59 dB HTL and 3.16 ± 4.34 dB HTL for the left ear (F(1,118) = 0.009, $p > .01$). There was no statistically significant Sex x Ear interaction (F(1,118) = .76 $p > .01$).

Threshold Driving Voltages

The threshold driving voltages for each subject's right and left ear trial 1 and 2 for each headset/stimulus combination are listed in Appendix B. No statistical analyses were performed on these data since they served only as voltage references for the acoustical intensity level measured in Part 3. The means and standard deviations were calculated and used as reference voltages for the intensity reliability measurements.

Part 3

Electroacoustical Intensity Specification

Three couplers and three intensity designations were used to specify the acoustical threshold intensity level that was measured electrically in Part 2. Each subject's threshold driving voltages for right and left ears, trial 1 and trial 2 were converted to acoustical intensity levels using the equivalents in Appendix C.

Preliminary Data Reduction

The results of the 30 Ear x Trial ANOVAs with repeated measures performed on the female subjects for each combination of coupler, headset and stimulus intensity revealed no statistically significant main effects for either Ear or Trial or for the interaction between these independent variables. These data are summarized in Table 1.

(Table 1)

The 30 Ear x Trial ANOVAs with repeated measures performed on the male subjects also failed to reveal any statistically significant main effects or interactions at the $\underline{p}$ =>.01 level. These ANOVA results are summarized in Table 2.

(Table 2)

The absence of any main effects or interactions for all subjects' Ear and Trial data permitted the reduction of each subject's four data entries for each experimental condition into a single value. The right ear/trial 1, right ear/trial 2, left ear/trial 1 and left ear/trial 2 thresholds for each subject under each condition were averaged. This mean threshold value replaced the four other values as each subject's data entry for further analyses. These reduced data for each subject under each experimental condition are listed in Appendix D.

Three Coupler Analysis

In order to simultaneously evaluate the effects of the NBS-9A, the PSFP and the Zwislocki couplers, only the threshold data for the SA cushion could be used since the NBS-9A could not be configured for use with CA cushions.

A four-way (Sex x Coupler x Stimulus x Intensity) ANOVA with repeated measures was performed to assess the influence of each independent variable and possible interactions on threshold data. The ANOVA results revealed no statistically significant main effect for Sex ($F(1,18) = 1.73$, $\underline{p} > .01$). In addition, there was no statistically significant interaction between Sex and any other independent variable. The results from the other three independent variables were all statistically significant, as well as were the interactions among these variables.

To simplify the reporting and interpretations of this three coupler analysis, the data for males and females were pooled since they were not statistically different. A three-way (Coupler x Stimulus x Intensity) ANOVA with repeated measures was then re-calculated with these pooled data. The results of the three-way ANOVA are summarized in Table 3.

(Table 3)

This analysis revealed statistically significant main effects for all three independent variables, as well as for all interactions among these variables. The eta squared for Intensity was 0.30, 0.36 for Coupler and 0.03 for Stimulus.

The means and standard deviations for these pooled threshold data for each experimental condition are listed in Table 4. The graphic representations of the ANOVA results are found in Figure 15 for the SYM-SA and ASYM-SA stimulus/ cushion combinations.

(Table 4) (Figure 5)

Stimulus Effects. Inspection of Table 4 and Figure 15 reveals that the thresholds for the SYM stimulus (X= 27.6 ± 1.74 dB) were consistently higher than for the ASYM stimulus (X = 25.9 ± 1.85 dB) collapsed across all levels of intensity specification and coupler. The difference between these means was statistically significant (F(1,19) = 10.3 *p*<.01). The eta squared was calculated to be 0.03 indicating a very weak relationship between stimulus and threshold in that only 3% of the variance in the data could be attributed to the influence of stimulus. For the NBS-9A, peakSPL combination, however, the mean SYM threshold was 29.6 ± 1.17 dB and the ASYM mean was 31.2 ± 3.04 dB.

Coupler Effects. Comparison of the coupler means averaged over all stimulus and intensity combinations showed the highest threshold values for the NBS-9A (X = 29.1 ± 1.72 dB). The PSFP mean threshold was 28.3 ± 1.88 dB and 24. ± 1.89 dB for the Zwislocki coupler. The differences between these means were statistically significant (F(2,38) = 342.4 *p*<.01). The eta squared was 0.36 which indicated that 36% of the variability in these threshold data could be attributed to the influence of acoustic coupler used to make the intensity measurements. The Newman-Kuels specific comparison test showed that the three means differed from each other, and these differences were statistically significant at the .01 level.

Intensity Effects. The peakSPL mean threshold was 29.3 ± 1.93 dB. The mean threshold intensity for the peSPL-peak was 27.8 ± 1.85 dB and 24.4 ± 1.71 dB for the peSPL-rms designation. The ANOVA revealed that these means were statistically different (F(2,38) = 9334.5 *p*<.01). The eta squared measure indicted that 30% of the variance in the threshold data could be due to the effect of the intensity designation used to measure the acoustical level of the signal. Newman-Kuels specific comparison test results showed that the mean threshold levels for all three intensity specifications differed significantly. (*p*<.01).

Two Coupler - Two Cushion Analysis

The SA and CA cushion effects could be analyzed using data for the PSFP and Zwislocki couplers, only, since the NBS-9A could not be configured for use with CA earphone cushions.

A five-way (Sex x Coupler x Cushion x Stimulus x Intensity) ANOVA with repeated measures was performed to assess the effect of each independent variable and any possible interactions among these variables on threshold data. The ANOVA results revealed no statistically significant main effect for Sex ($F(1,18) = 3.46$, p .01). In addition, there were no statistically significant interactions between Sex and any other variable. The results from the other independent variables were all statistically significant, as were the interactions among these variables.

To simplify the reporting and interpretations of this anlaysis, the data for females and for males were pooled to eliminate subject sex as an independent variable since this variable did not significantly influence threshold. A four-way (Intensity x Coupler x Cushion x Stimulus) ANOVA with repeated measures was then performed on these pooled data. The results of the four-way ANOVA are summarized in Table 5.

(Table 5)

This analysis revealed statistically significant main effects for Intensity Specification, Coupler, Cushion and

Stimulus, as well as for most of the interactions among these variables. The eta squared for Intensity was 0.28, for Coupler was 0.31, 0.13 for Cushion and 0.04 for Stimulus.

The means and standard deviations for these threshold data for each experimental condition are listed in Table 6. The graphic representations of the ANOVA results are found in Figure 16.

(Table 6) (Figure 16)

Stimulus Effects. Inspection of Table 6 and Figure 16 reveal that the mean thresholds for the SYM stimulus for both the SA cushion (X = 27.1 ± 1.94 dB) and the CA cushion (X = 23.9 ± 1.69 dB) were greater than for the ASYM stimulus thresholds in the same SA cushion (X = 25.2 ± 1.86 dB) and the CA cushion (X = 22.6 ± 1.89 dB). These data were collapsed across both couplers and all three intensity specifications. The eta squared was calculated to be 0.04 which indicated that although the relationship between stimulus and threshold might be very real, it is a very weak association.

Cushion Effects. Threshold levels with the SA cushion collapsed across both stimuli and both couplers (X = 26.2 ± 1.88 dB) were consistently higher than for the corresponding CA thresholds (X = 23.2 ± 1.76 dB). According to the ANOVA results, these means were statistically different (F(1,19) = 339.9 $p<.01$). The eta squared of 0.13 indicated that 13% of the variability in threshold data was caused by the influence of the different ear cushions used.

Coupler Effects. The mean threshold for the PSFP (X = 27.0 ± 1.61 dB) was statistically significantly greater than the mean threshold measured in the Zwislocki coupler (X = 22.5 ± 2.04 dB) (F(1,19) = 6.71, _p_<.01). These data were averaged across all stimulus/cushion combinations and intensity designations. The eta squared value was calculated from the ANOVA results to be 0.31. This value indicated a very strong relationship between acoustic coupler used for the intensity measurement of these stimuli and the resultant intensity level. Thirty-one percent of the variability in the threshold data could be attributed to the effects of the independent variable, Coupler. For the peSPL-peak and peSPL-rms designations, the PSFP thresholds were higher than the Zwislocki for all stimulus/cushion comparisons, except the SYM-SA/Zwislocki versus the ASYM-CA/PSFP where the Zwislocki values were greater.

Intensity Effects. The results of the analysis were inspected for Intensity designation effects. On the average, the peakSPL threshold designations were highest (X = 27.2 ± 1.84 dB). The peSPL-peak mean was 24.9 ± 1.78 dB. The ANOVA indicated that these means were significantly different (F(1,38) = 9913.6 _p_<.01). The Newman-Kuels specific comparison test indicated that the three mean intensities all differed significantly from each other. Eta squared was calculated to be 0.28. This strength-of-association measure indicated that 28% of the variability in the dependent variable could be accounted for by the influence of the independent variable, Intensity Designation.

Pure Tone/Click Threshold Correlational Analysis

Each subject's mean pure tone threshold was calculated by averaging the right and left ear audiometric thresholds at each of the six octave frequencies tested. A Pearson product moment correlation coefficient (r) was then calculated for each subject's mean pure tone threshold and the threshold for the experimental stimulus under each earphone, coupler and intensity designation combination. These correlation coefficients are presented in Table 7.

(Table 7)

An inspection of Table 7 reveals that none of the mean pure tone threshold/experimental stimulus threshold r's reached statistical significance at the .01 level. These analyses revealed little relationship between each subject's mean pure tone threshold and his threshold intensity level for the SYM and ASYM stimuli presented with the SA and CA cushions as measured in the three different couplers using three intensity specifications.

Intensity Reliability Analysis

The reliability data for the ten intensity measurements made for each of the experimental conditions are listed in

Appendix E. The means and standard deviations for these measurements are listed in Table 8.

(Table 8)

Coupler Effects. An inspection of the standard deviations for the three couplers indicates that the Zwislocki coupler demonstrated the smallest spread of intensity levels around the mean on the repeated measures for all experimental conditions. The average standard deviation for the Zwislocki coupler was 0.43 ± 0.15 dB. The NBS-9A mean standard deviation for all conditions was 0.52 ± 0.40 dB and was 0.72 ± 0.53 dB for the PSFP. This informal analysis indicated that the Zwislocki coupler provided the most consistent threshold sound level measurements of the three couplers tested across all combination of stimulus, cushion and intensity designation.

Intensity Effects. The mean standard deviation for the peSPL-peak designation was 0.50 ± 0.39 dB. The peakSPL mean standard deviation was 0.56 ± 0.37 dB and was 0.63 ± 0.45 dB for the peSPL-rms specification. The peSPL-peak sound level designation provided the most consistent measurement of sound level of the three intensity designations studied.

Cushion Effects. The mean standard deviation for the reliability data generated with the transducer mounted in the CA cushion was 0.53 ± 0.73 dB and was 0.58 ± 0.49 dB for the SA mounted transducer. Although the average spread of repeated measurements around the means was smaller for the

CA than the SA cushion, there was more variability associated with this smaller spread than with the SA.

Stimulus Effects. Averaged across coupler, intensity designation and cushion, the repeated sound level measurements for the SYM stimulus had a mean standard deviation of 0.44 ± 0.05 dB and for the ASYM stimulus it was 0.68 ± 0.08 dB. The mean SYM stimulus repeated sound level measurements were not only less variable than the ASYM, but the variability associated with all of these average measurements was less.

To evaluate the strength of the relationship between intensity measurements made by varying either the stimulus or the cushion and the coupler/intensity designation to quantify those sound levels, Pearson r's were calculated for each combination of independent variable.

Different Stimuli - SA Cushion. The Pearson r's and coefficients of determination (r^2) for the SYM-SA/ASYM-SA threshold relationships as measured in all coupler/intensity combinations are listed in Table 9.

(Table 9)

Only the r's for the NBS-9A coupler were statistically significant at the .01 level. The significant correlation coefficients indicated that only for the signals measured in the NBS-9A coupler was there a relationship between the thresholds obtained for the SYM-SA and the ASYM-SA stimuli. The mean difference between the SYM and the ASYM threshold sound levels for the NBS-9A coupler was 1.23 ± 1.01 dB. The mean difference for the PSFP was 1.73 ± 0.21 dB and was 1.67 ± 0.76 dB for the Zwislocki coupler.

There was little difference in the SYM-ASYM threshold relationship among the three intensity specifications. The r^2 values indicated that the threshold association was moderately strong in that approximately 32% of the total variance in these data could be accounted for by the strength of the relationship between the thresholds for these different stimuli.

Different Stimuli - CA Cushion. The Pearson r's and the coefficients of determination for the SYM-CA and ASYM-CA threshold relationships as measured in the PSFP and the Zwislocki couplers using the three intensity specifications are listed in Table 10.

(Table 10)

The r's for the Zwislocki/peakSPL (.63) and the Zwislocki peSPL-rms (.61) combinations were statistically significant at the .01 level. None of the evaluations for the PSFP coupler reached statistical significance. The mean difference between the SYM and the ASYM threshold sound levels for th CA cushion were 0.73 ± 0.25 for the PSFP and 0.50 ± 0.20 dB for the Zwislocki coupler. The r^2 for the peakSPL intensity designation (0.40) indicated a slightly stronger association between SYM-CA and ASYM-CA thresholds as measured with this specification than with the peakSPL-rms intensity (r^2 = 0.34). The mean difference between the thresholds for these two stimuli were 0.60 ± 0.14 dB for the peakSPL measurement, 0.60 ± 0.14 dB for the peSPL-peak and 0.65 ± 0.49 dB peak SPL-rms.

Same Stimuli - Different Cushions. The Pearson r's and r^2 values for the SYM-SA/SYM-CA and the ASYM-SA/ASYM-CA correlational analyses as measured using the PSFP and the Zwislocki couplers and specified by the various intensities are listed in Table 11.

(Table 11)

The r's calculated for both stimuli comparing the SA and the CA thresholds under the three stimulus specifications for the PSFP coupler were all statistically significant at the .01 level. It was remarkable that all six r's were .93 or higher for this coupler. The mean difference between the same stimulus - different cushions was 2.67 ± 0.51 dB for the ASYM stimulus for the PSFP. The r^2 values were 0.87 or higher which points to a powerful association between the thresholds obtained using the same stimulus with the SA and CA cushions under all coupler/intensity combinations.

The correlations for the stimuli measured in the Zwislocki coupler showed a different pattern than for the PSFP. None of the r's for the SYM stimulus was statistically significant, however all of the r's for the ASYM stimulus were significant at the .01 level. The correlation coefficients were .78 for the peakSPL, .75 for the peSPL-peak and .78 for the peSPL-rms. The mean differences for the Zwislocki coupler were 3.43 ± 0.72 dB for the SYM stimulus and 1.73 ± 0.67 dB for the ASYM. The r^2 values ranged from 0.57 to 0.62 indicating a strong relationship between the ASYM-SA and ASYM-CA thresholds as measured with the Zwislocki coupler.

Stimulus Spectrum

The spectra of each stimulus generated under each cushion with each acoustic coupler are presented in Figures 17 through 26, inclusive.

(Figures 17 - 26)

Inspection of the spectra measured with the PSFP revealed a remarkable similarity between the spectra for the two stimuli with the SA cushion. The same was also true for the two stimuli with the CA cushion. This trend was also apparent for the stimuli evaluated using the Zwislocki coupler -- overall, the spectra for the two stimuli generated with the same cushion were of very similar morphology. With both the PSFP and the Zwislocki couplers, the spectra for the SYM stimulus reflected enhanced intensity levels centered at 2k Hz. This is especially evident for the Zwislocki-generated spectrum.

The NBS-9A spectra demonstrated considerable differences between the SYM and ASYM stimuli. The ASYM spectrum showed a flat response from 100 Hz to 3k Hz. The SYM stimulus spectrum shows approximately a 7 dB per octave increase in intensity from 300 to 1.7k Hz, then a 4 dB intensity decrease from 2k to 4k Hz and a 17 dB decrease from 4k to 8k.

Stimulus Waveform

The acoustical waveforms of each stimulus generated under each cushion with each acoustic coupler are presented in Figures 27 through 36, inclusive.

(Figures 27 - 36)

Coupler Effects. Inspection of these waveforms reveals a marked difference in amplitude of signals as a function of acoustic coupler. The stimuli produced the NBS-9A are of much higher voltage than the acoustical signals in the PSFP and the Zwislocki couplers with identical driving voltages for the SA cushion.

In addition, the NBS-9A and the PSFP couplers maintained very similar wave morphologies for the SYM and the ASYM driving voltage functions. This waveform preservation held for the CA as well as the SA cushion. Such waveform consistency is not seen in the Zwislocki coupler waveforms where both the primary stimulus shape and the ringing chracteristics are much altered relative to the waveforms generated in the other coupling devices.

Cushion Effects. The most outstanding cushion effect seen was a greater signal amplitude produced with the SA cushion than with the CA cushion. This relationship was evident for the PSFP and Zwislocki couplers with both the SYM and ASYM driving voltage functions.

Another readily seen cushion effect is the increased post-stimulus ringing of the CA headset as compared to the SA cushion.

Stimulus Effects. It is difficult to assess any differences in acoustic waveform that could be attributed solely to the driving voltage function into the transducer. The SYM and ASYM electrical functions are inherently different, and the acoustical waveforms produced by these input functions would be expected to differ. It is interesting to note, however, the remarkable similarity in acoustical waveform of the two electrically dissimilar driving functions in the Zwislocki coupler with the SA cushion.

Chapter 4 will present the discussion of these data and the statistical analyses as they relate to the experimental goals of determining the most reliable and accurate coupler and intensity designation for the description of AEBP stimuli.

CHAPTER 4

DISCUSSION

The purpose of this study was to investigate the effects of variables relevant to the calibration of transient stimuli, especially those used in clinical AEBP evaluations. Both the results of the statistical analyses of the data collected in this study and the careful consideration of some theoretical and practical issues related to the sound level specification of very brief duration signals contributed significantly to the formulation of an appropriate coupler/intensity designation for the calibration of AEBP stimuli.

The sections to follow discuss further some of the statistical results and offer possible explanations for the findings.

Sex Effects

The results of the analysis of the pre-experiment pure tone audiograms revealed no statistically significant difference in pure tone thresholds for female and male subjects. Subject gender also proved to have little appreciable influence on the mean thresholds for the AEBP stimuli. The ANOVA results revealed no statistically significant sex effect on threshold across all levels of the other independent variables. The mean thresholds, for example for the NBS-9A coupler-SYM stimulus, were for females 30.2 ± 1.05 dB peak SPL, 31.5 ± 1.07 dB peSPL-peak and 27. 8 ± 1.08 dB peSPL-rms. The mean thresholds for male subjects were 28.9 ± 0.94 dB peakSPL, 31.2 ± 3.15 dB peSPL-peak and 26.5 ± 0.86 dB peSPL-rms.

These results are supported by the findings of two other studies reported in the literature. Michalewski, et al. (1980) found no statistically significant difference in the pre-AEBP audiograms of the female and male subjects in their study nor was there a significant gender effect on behavioral click thresholds. Stapells, et al. (1982) also found no statistically significant influence of the subject's gender on click threshold; collapsed across ear and click polarity, the mean threshold for females was 36.3 dB peakSPL and 36.4 dB peakSPL for males.

The lack of difference reported here and elsewhere with regard to pretest audiograms and behavioral AEBP stimulus threshold is interesting vis-a-vis the profound differences in the latencies and amplitudes of the brainstem potentials evoked by these same stimuli for the two sexes. Evidently, the precision with which these behavioral and electrophysiological techniques can reflect structural variations within the central auditory nervous system is remarkably different. The effects of the subject's sex on the AEBP waveform parameters are so pronounced that separate latency and amplitude norms for females and males have been suggested to decrease the probability of false positives on AEBP data interpretation (Stockard, et al., 1978, 1979; Michalewski, et al, 1980).

Stockard, et al. (1978, 1979) and Michalewski, et al. (1980) believe that these sex effects on the AEBP are probably due to the anatomical variations in head and brainstem size and/or to differences in the length of the external auditory canals and auditory nerve dimensions between females and males. Such structural differences can certainly have a marked influence on the AEBP latency measurements. It is apparent that the anatomical factors have little measureable influence on the sound pressure generated by the AEBP stimuli at the tympanic membrane of both sexes. It is this sound pressure that is a critical acoustical determinant of stimulus threshold.

Separate normative data for each sex may be quite necessary for the interpretation of AEBP waveform parameters, but there is considerable evidence to indicate that such is not the case for the behavioral thresholds of these stimuli.

Coupler Effects

Statistical Analyses

The results of the three-coupler ANOVA for the SA cushion and the four-way ANOVA for the SA/CA cushion comparision revealed a statistically significant difference among the mean thresholds measured on the different couplers. The mean thresholds for the SA cushion were

29.1 ± 1.72 dB for the NBS-9A, 28.3 ± 1.88 dB for the PSFP and 24.0 ± 1.89 dB for the Zwislocki. For the CA cushion the mean thresholds were 27.0 ± 1.61 dB for the PSFP and 22.5 ± 20.04 dB for the Zwislocki. All of these mean thresholds were averaged across stimuli and intensity specifications.

The eta squared for coupler effect for the SA analysis was 0.36 and was 0.31 for the CA analysis. These values indicate a strong relationship between the threshold pressure level measured with an equivalent electrical input to the transducer and the coupler used to make those measurements. Approximately one-third of the variance in the data from this experiment can be attributed to the influence of acoustic coupler on the threshold measurements.

The relationship between coupler and threshold -- although statistically significant and a strong association -- must be interpeted with qualifications. For both the SA and the CA analyses, there were statistically significant two-, three- and four-way interactions among the independent variables. There were, in addition to all of the statistically significant two-way interactions, Intensity x Coupler x Stimulus interactions for both the SA ($F(4,76)=70.4$, $\underline{p}<.01$) and the CA ($F(2,38)=78.5$, $\underline{p}<.01$) cushions. The strength of these relationships was weak in that the eta squared values indicated that only 0.8% (SA) and 0.2% (CA) of the data variance was caused by these interactive effects. Although a very weak effect, the relationship among these variables is, nonetheless, real. These triple interactions can be interpreted as showing that the measurement of AEBP stimulus threshold is different for the three couplers used and for the three intensities used, but the association of these variables and threshold is different for the two stimuli used in the experiment.

The two-way Coupler x Stimulus interactions were also statistically significant (SA - $F(2,38)=11.5$ $\underline{p}<.01$; CA - $F(1,19)=11.9$ $\underline{p}<.01$). The SA eta squared was 0.02 and 0.0003 for the CA cushion. These strength-of-association measures indicate that only 2% or less of the variability in mean threshold data can be accounted for by the effects of the Coupler x Stimulus interactions. However, the statistically significant interactions do qualify the statements that can be made with regard to the significant main effects.

In consideration of the results of these statistical analyses, a recommendation as to the coupler of choice for use in the calibration of AEBP stimuli cannot be made without a careful inspection of and an understanding of how the coupler effects vary with the intensity designation and with the stimulus used. These issues will be detailed in their respective sections of this report. A final recommendation for the coupler and intensity specification combination which best describes the sound level of the AEBP stimuli will be made following a detailed accounting of those intensity and stimulus effects and some theoretical and practical considerations outlined in a later section.

Spectral Comparisons

The PSFP and the Zwislocki couplers yielded click stimulus spectra that were remarkably similar for the 10 stimulus/cushion combinations. These spectra were very different compared to those generated using the NBS-9A coupler for both stimuli. The spectra measured with the NBS-9A showed considerably more low frequency energy than either the PSFP or the Zwislocki couplers.

Waveform Comparisons

The acoustic coupler has a strong effect on the pressure changes as a function of time waveforms. The NBS-9A coupler produced stimuli with waveforms of higher voltage than the other two couplers with an equivalent driving voltage and voltage function into the transducer.

The Zwislocki coupler resulted in SYM and ASYM waveforms that were grossly different from the voltage driving functions that produced these stimuli. The NBS-9A and the PSFP couplers, however, preserved the electrical driving function in the acoustical waveform for both stimuli and cushions.

Discussion

The most striking overall effect of coupler on mean AEBP stimulus thresholds is the intensity effect: the highest mean sound levels are generated in the NBS-9A coupler, the second highest in the PSFP and the lowest in the Zwislocki coupler. Zwislocki (1971) compared the SPLs obtained by measuring the frequency response characteristics of a transducer in an MX41/AR cushion using an NBS-9A coupler to the SPLs measured using a Zwislocki coupler. He found that from 3.5k Hz and higher, there was a 4 dB SPL higher output for the NBS-9A than for the Zwislocki coupler using the same earphone. The results of this study indicated that there was approximately a 5 dB difference in mean thresholds of AEBP stimuli using these two acoustic couplers with the NBS-9A than for the Zwislocki coupler using the same earphone. The results of this study indicated that there was approximately a 5 dB difference in mean thresholds of AEBP stimuli using these two acoustic couplers with the NBS-9A yielding the higher mean thresholds.

The frequency response curves of the headsets used in this study were evaluated for a pre-and post-experiment stimulus delivery system response verification using a single coupler. It would have been interesting to compare the frequency response characteristics of the same earphone/cushion in the different couplers under a standard input/output measurement technique to determine how much of the mean thresholds produced in each coupler could be accounted for by the SPL enhancements of each coupler due to its resonance characteristics.

The NBS-9A coupler was designed to mimic the acoustical load that the average human ear presents to an earphone transducer mounted in a SA cushion. This acoustical load results in coupler resonances which will increase the SPL of sound input at the coupler's resonant frequencies. The PSFP, however, was designed without that acoustical load specifically to minimize the influences on SPL of high frequency coupler resonances. Some of the differences in mean threshold sound levels between the NBS-9A and the PSFP can therefore be explained on the basis of the differences in the geometries of the two couplers. The NBS-9A has resonance characteristics which enhance certain frequencies, thereby increasing the sound level measured in the coupler, whereas the PSFP design leads to lower SPLs by virtue of the absence of such resonance effects.

The microphones used in these measurements could have some effect on the sound levels measured in each coupler. The NBS-9A and PSFP both used the same B & K 4144 one-inch pressure microphone. The Zwislocki coupler, however, used a B & K 4145 half-inch pressure microphone. Any differences in the frequency response characteristics or in the calibration of these microphones could have contributed to the differences seen among the three couplers used in this study.

Intensity Effects

The ANOVA results for both the SA and the CA cushions indicated a statistically significant difference among the mean threshold sound levels designated by the three intensity specifications. For the SA cushions, the mean threshold was 29.3 ± 1.93 dB peakSPL, 27.8 ± 1.85 dB peSPL-peak and 24.4 ± 1.71 dB peSPL-rms. The mean thresholds for the CA cushion were 25.8 ± 1.83 dB peakSPL, 23.3 ± 1.71 dB peSPL-peak and 20.7 ± 1.74 dB peSPL-rms. These means were calculated by averaging threshold values across stimulus and coupler.

The strength of the relationship between threshold measurement and the intensity designation, calculated as the eta squared, indicated that 30% of the variability with the SA cushion and 28% of the variance in the CA generated data can be attributed to the intensity designation effect. This effect is very strong. However, as with the coupler effect, the interpretatins of these results must be tempered by recognition of the influence of the statistically significant interactions among intensity and the other independent variables.

The ANOVA performed on the SA data which evaluated all three couplers revealed a statistically significant intensity x Coupler interaction ($F(4,76) = 192.7$, $p<.01$). The eta squared was calculated to be 0.02 indicating a very weak influence of the interactive effects on mean threshold sound levels. Nonetheless, this interaction has a direct impact on the interpretation of the main effects of the independent variables, Intensity and Coupler. The peakSPL intensity designation yielded, on the average, the highest mean threshold with the peSPL-peak the next highest and peSPL-rms the lowest. The statistically significant effect of Coupler indicated that, on the average, the NBS-9A coupler resulted in the highest sound level and the PSFP and Zwislocki coupler resulted in lower sound levels. The Intensity x Coupler interaction indicates that the relationship between intensity designation and mean threshold sound level was different for the different couplers and did not strictly follow a pattern.

A similar Intensity x Coupler interaction was seen for the two-coupler analysis which included results from both the SA and CA cushions ($F(2,38)=471.5$, $p<.01$). In addition to this Intensity x Coupler interaction, the two-coupler analysis revealed an Intensity x Stimulus interaction, as did the three-coupler analysis. These interactions can be interpreted to mean that the three intensities used to specify sound level hold different relative positions in terms of highest to lowest sound level depending on the stimulus waveform.

In consideration of the ANOVA results presented, it is clear that a recommendation for a preferred intensity designation cannot be made without first scrutinizing any intensity interactions with the remaining independent variables, Stimulus and Cushion, as well as an analysis of the reliability data. In addition, the discussion that follows in a later section concerning some theoretical and methodological issues will help to formulate the recommendation for a preferred intensity designation for AEBP stimuli.

Cushion Effects

Statistical Analyses

The statistical analysis that evaluated the SA and CA thresholds revealed a statistically significant difference between mean thresholds produced by these two cushions with the same transducer. The SA mean threshold was 26.2 ± 1.88 dB and was 23.2 ± 1.76 dB for the CA cushion averaged across the PSFP and Zwislocki couplers and across the three intensity specifications and both stimuli. The eta squared of 0.13 indicated a moderate relationship between cushion and mean threshold. However, this main effect for cushion must be cautiously interpreted in view of several statistically significant interactions.

The ANOVA revealed a statistically significant Intensity x Cushion interaction ($F(2,38) = 51.6$, $\underline{p}<.01$). The eta squared was calculated to be .002. Although the influence of these interactive effects of intensity designation and cushion on mean threshold sound levels is significant, the effect is extremely weak; less than 1% of the variance in the threshold data can be attributed to the effects of the interaction. Although only very weakly related, at best, this interaction does limit the interpretation of the main effects for both Cushion and Intensity. The relationship between cushion and threshold was different for the three different intensity designations, and there was no pattern to the association.

The test for significance for the Coupler x Cushion interaction indicated no statistical differences among mean threshold sound levels for all coupler/cushion combination (F(1,19)=1.89 $\underline{p}<.01$).

The triple interaction among Intensity x Coupler x Cushion also limits the interpretations of the main effects of these variables (F(2,38)=117.8, $\underline{p}<.01$). The eta squared value indicated that only 0.4% of the threshold variance could be attributed to the effects of this interaction.

Spectral Comparisons

A comparison of the spectra for the same stimulus produced with different cushions revealed that the SA cushion with both the SYM and ASYM stimuli for the PSFP and the Zwislocki couplers produced a double-peaked resonance in the low frequencies, whereas the CA cushions produced a single resonance in the same frequency area. The SA cushion showed a spectral peak at 60-80 Hz and a second peak at 90-150 Hz. The CA cushion produced a singular peak at approximately 75 Hz.

The high frequency effects of cushion on spectrum were coupler-dependent. For the PSFP, there was a 500 Hz resonance and a more pronounced broad peak centered at about 2k Hz for the SA cushion than for the CA. The cushion/coupler spectral effects for the Zwislocki coupler were different for the two different stimuli.

Waveform Comparisons

The most pronounced effect of cushion on stimulus waveform was caused by a sound level effect. Waveforms were of lower voltage for the CA than for the SA cushion. In addition, there was markedly increased post-stimulus ringing with the CA cushion, whereas this lack of damping was not evident in the SA waveforms.

Discussion

The sound level at threshold effect caused by the different cushions has been reported elsewhere. Jerger and Tillman (1959) compared pure tone thresholds obtained using an NAF CA cushion to those obtained with an MX41/AR SA cushion. The mean difference in threshold sensitivity between the SA and the CA cushions was 7.90 ± 4.63 dB, the SA thresholds being lower. Stein and Zerlin (1963) investigated pure tone thresholds using the MX41/AR SA and the Sharpe HA-10-A CA headset. They found a mean threshold difference between these cushions of 5.68 ± 6.6 dB, again, the SA cushion yielded lower (better) mean thresholds. The cushion effect in this study amounted to approximately 3 dB averaged across couplers, intensity specifications and stimuli.

Burkhard and Corliss (1954) and Stein and Zerlin (1963) attributed the threshold difference between the SA and CA earphone cushions to the difference in the volume of air under each cushion. The greater the volume of air under the cushion, the lower the sound pressure level produced with an equivalent electrical input to the earphone terminals.

The Jerger and Tillman (1959) and Stein and Zerlin (1963) studies used pure tones as the stimulus to evaluate the SA/CA differences. In 1980 Coats and Kidder reported on the results of a similar comparison using a 24 microsecond rectangular electrical pulse as the transducer input. They found that the maximum output of the CA cushion was 2 dB less than that of the MX41/AR. In addition, mean behavioral click threshold was 33.0 ± 1.9 dB peSPL for the CA cushion and 34.2 ± 1.8 dB peSPL for the SA.

Shaw (1966) reported the response curves across frequency of a SA and CA cushion as measured in the human ear canal by a probe tube microphone technique. He found a strong resonance-anti-resonance pattern from 2k to 7k Hz across ten subjects for the CA earphone. This high frequency response pattern was not present for the SA cushion.

Coats and Kidder (1980) found high frequency spectral differences between SA and CA cushions with a click input to the earphone terminals. The SA cushion showed more spectral energy above 6k Hz than the CA cushion. The results of this study did not show these same spectral differences, but the input voltage functions to the transducer were very different from that used by Coats and Kidder (1980).

Stimulus Effects

Statistical Analyses

The mean threshold sound level for the SYM stimulus was 26.3 ± 1.68 dB and was 24.9 ± 1.92 dB for the ASYM stimulus. The difference between these means was statistically different as evidenced by the three-coupler ANOVA as well as by the two-coupler ANOVA ($F(1,19)=10.8$, $p<.01$ and $F(1,19)=16.5$, $p<.01$, respectively). The eta squared values were 0.03 and 0.04 for these two analyses indicating a very weak relationship between Stimulus and mean threshold sound level. Due to the presence of statistically significant interactions, however, this main effect for Stimulus must be interpreted cautiously.

There was no statistically significant Cushion x Stimulus interaction ($F(1,19)=3.35$ $p>.01$) nor was there a triple effect among Coupler x Cushion x Stimulus ($F(1,19)=1.18$, $p>.01$). However, two other triple interactions were significant. There was a statistically significant inter-relationship among Intensity x Coupler x Stimulus ($F(2,38)=78.5$, $p<.01$, eta squared = 0.002 for the two-coupler analysis and $F(4,76)=70.4$, $p<.01$, eta squared = 0.008 for the three-coupler analysis). Among the variables Intensity x Cushion x Stimulus there was also a significant interaction ($F(2,38)=8.95$, $p<.01$, eta squared = 0.0003). Indeed, the relationship among these independent variables is different with the various levels of the third variable. Although the influence of these interactive effects on threshold is quite weak (less than 1% of the variance in threshold can be attributed to the interactions). The interpretations of the main effects due to Stimulus (or to any of the other variables) must be qualified and stated separately for each level of the other two variables.

Confounding the results further is the presence of a quadruple interaction among Intensity x Coupler x Cushion x Stimulus ($F(2,38)=95.9$, p,<.01, eta squared = 0.003). Although the relationship between all combinations of these variables and mean threshold sound level is statistically significant, the eta squared value indicates an extremely weak association. This four-way interaction severely limits the statements that can be made concerning the pattern of main effects for all independent variables studied.

Spectra and Waveform Comparisons

By virtue of the fact that the driving voltage function into the transducer is different, the spectra and wave morphologies produced by the two stimuli are different. Generalizations are difficult to make concerning the unadulterated effects of stimulus on spectrum and waveform due to the stimulus alterations introduced as a function of coupler, especially, and of cushion.

Discussion

The stimulus effects on mean threshold sound level seen in this study are comparable to those of Stapells, et al. (1982). Stapells and his colleagues measured the NBS-9A coupler sound levels of the SYM and ASYM stimuli produced by a TDH-49 transducer mounted in an MX41/AR cushion. The mean thresholds for the SYM stimulus were 30.1 dB peakSPL and 27.2 dB peSPL-rms. The ASYM mean threshold sound levels were 32.2 dB peakSPL and 24.1 dB peSPL-rms. Under identical measurement conditions in this study (except for the use of a TDH-39 transducer) the SYM stimulus had mean thresholds of 29.6 ± 1.17 dB peakSPL and 27.2 ± 1.17 dB peSPL-rms. The ASYM mean threshold sound levels were 31.2 ± 3.04 dB peakSPL and 26.3 ± 1.81 dB peSPL-rms. The spectra of the Stapells, et al. (1982) stimuli bore a striking similarity to those of Figures 17 and 18, and the differences in these curves could certainly be due to the different frequency response characteristics of the TDH-39 and TDH-49 transducers.

Reliability Measurements

An inspection of the standard deviations for the ten repeated measurements made with each combination of the independent variables revealed that the Zwislocki coupler with a mean standard deviation across experimental conditions of 0.43 ± 0.15 dB and the peSPL-peak intensity designation with a mean standard deviation of 0.50 ± 0.39 dB yielded the most consistent sound level measurements compared to the other couplers and sound levels evaluated. However, these data can only be used as a guide to formulating the most reliable coupler/intensity combination for the calibration of transients used in AEBP evaluations due to the statistically significant interactions among all of the independent variables studied. Theoretical and methodological considerations will be outlined that will aid in the formulation of an acoustically appropriate coupler/ intensity combination for the measurement and calibration of auditory evoked potential stimuli.

Clinical Recommendations

Several very practical issues must be addressed before a calibration protocol for the specification of AEBP stimulus sound levels can be formulated. These practical issues deal with 1) the type of calibration instrumentation already available in the clinical setting; 2) the method of stimulus delivery to the ear; and 3) the type(s) of acoustical signal(s) to be presented to the clinical population. Each issue will be considered in the following discussions.

Coupler Recommendation

Coupler-less Facility. The calibration instrumentation already available in a clinical setting or the budgetary flexibility necessary to procure such equipment must be given first priority in the formulation of a calibration protocol for AEBP stimulus sound levels in a facility that does not have such instrumentation.

A clinical facility that already has the NBS-9A coupler would use it as the standard coupler for the calibration of audiometers, and would find that it also provided a reliable acoustic coupling device for the measurement of transients' sound levels produced by SA cushions. The mean threshold sound pressures produced in the NBS-9A were the highest of the three couplers evaluated (29.1 dB) across the three intensity specifications, but it also had the smallest variability across all subjects tested (1.72 dB). Using this coupler, the spectra and waveforms of the AEBP stimuli are well maintained relative to the input voltage function. There are few, if any, interactive effects between the acoustical signal produced by the transducer and the frequency-dependent pressure response of this coupler.

Repeated sound level measurements using the NBS-9A coupler demonstrated only a 0.52 dB spread of measurements around the means of all experimental conditions tested. Although there was no statistically significant correlation between pure tone thresholds and AEBP stimulus thresholds for any of the coupler/intensity combinations evaluated, the NBS-9A was the only one of the three that demonstrated a statistically significant correlation between the thresholds for the two different stimuli used. The mean difference between these thresholds was only 1.23 dB averaged across the three sound level designations used.

Based on a comparison of the mean threshold sound levels measured, on spectral and waveform considerations and on the results of reliability of measurement analyses, the clinician performing AEBP examinations can be confident that the NBS-9A coupler will lead to calibration data which are a reliable reflection of AEBP stimulus parameters.

In a clinical setting where calibration instrumentation, including an acoustic coupler, were to be procured, the NBS-9A remains the coupler of choice. From the point of view of a cost benefit analysis and in consideration of the problems associated with the calibration of even sustained pure tones through CA cushions under any conditions, this standard coupler is recommended. In terms of cost, the NBS-9A is commercially manufactured and readily available to the consumer, thus keeping its cost low compared to a specially tooled and machined device like most of the flat plate designs. This one acoustic coupling device would serve in the calibration of pure tone and speech audiometers and for generating the frequency response curves of any clinically used transducers mounted in the MX41/AR or other SA cushion. In a clinical setting where one coupler is to be purchased, it would clearly be unwise to buy one that could be used with CA as well as SA assemblies since there is no standard coupler for the calibration of CA cushions. To sacrifice a standard coupler that is used with the standard audiometric cushion for a non-standard coupling device which could be used with both SA and CA headsets would be a foolish purchase, indeed.

In consideratoin of the findings of this study and of the issues detailed above, the NBS-9A is the recommended acoustic coupling device to be procured by a coupler-less clinical facility that is in pursuit of an appropriate coupler for the calibration of AEBP stimuli. This NBS-9A will also reliably serve centers that have this coupler and wish to calibrate stimuli for AEBP evaluations.

Facility Desiring Coupler for CA Calibrations. A clinical facility that owns an NBS-9A coupler and wishes to procure a coupler specifically for the calibraton of CA earphones could select from either the PSFP or the Zwislocki coupler. Another alternative would be to have designed and machined a custom flat plate for use with the NBS-9A to configure it for use with a CA cushion. This third possibility was not investigated in this study. Perhaps the calibration issue should not focus on what coupler or intensity specification to use, but rather the issue may be that calibration of AEBP stimuli must be performed even if CA earphones are being used regardless of which coupler/ intensity combination yields the most reliable results.

The PSFP yielded mean threshold sound levels that were higher and had a lower standard deviation than the Zwislocki coupler measurements (27.0 ± 1.61 dB versus 22.5 ± 2.04 dB). The mean difference between SYM-SA and ASYM-SA thresholds for the PSFP was 1.73 ± 0.21 dB and was 1.67 ± 0.76 dB for the Zwislocki. The SYM-CA and ASYM-CA mean threshold difference was 0.73 ± 0.25 dB for the PSFP and 0.50 ± 0.20 dB for the Zwislocki. Neither coupler produced a statistically significant correlation between the SYM and ASYM thresholds for any of the intensity specifications evaluated for the SA cushion. For the correlation of the CA thresholds for the SYM and ASYM stimuli, the Zwislocki coupler combined with the peakSPL and peSPL-rms sound level designations were statistically significant.

More important in deciding which coupler would be better suited for the calibration of AEBP stimuli delivered through CA phones is the issue of how thresholds for the same stimuli compare when delivered through the same transducer mounted in the different cushions. For both the SYM and ASYM stimuli each delivered through the different headsets, the performance of the PSFP coupler is far better than that of the Zwislocki coupler. The correlations between threshold sound levels produced in the PSFP for the cushion comparisons ranged from a remarkable .93 to .99. None of the correlation coefficients was statistically significant for the SYM-SA/SYM-CA comparison for the Zwislocki coupler, and the ASYM-SA/ASYM-CA correlatiosn ranged from .75 to .78. Michael and Bienvenue (1976) studied the differences between the NBS-9A with a custom flat plate and the PSFP in the calibration of pure tones. They found that the CA cushion resulted in a power loss of 2 dB relative to the SA cushion, but that the CA cushion could be calibrated on the PSFP with a consistency of measurement comparable to that of a standard SA cushion on the standard NBS-9A coupler.

In terms of coupler influences on stimulus waveform, the PSFP coupler preserved the electrical driving voltage function in the acoustical attributes of the stimulus, however the Zwislocki coupler introduced marked variations in the acoustical signal. In the Zwislocki coupler, the primary stimulus morphology was grossly altered relative to that in the PSFP, and the ringing characteristics in the Zwislocki were much sustained as compared to the PSFP.

Besides the statistical issues, one might consider cost of the coupler. The PSFP is not commercially available and its manufacture would need to be privately contracted. This could prove to be a rather expensive capital outlay. A Zwislocki-type coupler is a production item made by Industrial Research Products called the DB-100. However, the Zwislocki coupler uses a half-inch microphone, the purchase of which would add appreciably to the cost of this coupler as would the cost of a calibrator for this smaller microphone. The PSFP uses a one-inch pressure microphone. Any clinical facility that already uses an NBS-9A has a one-inch microphone and calibrator that could be used with the PSFP.

Based both on the results of this study and cost-related issues, the PSFP coupler is the recommended acoustical device for the calibration of signal parameters used in AEBP evaluations.

Intensity Specification Recommendation

The recommendation for a suitable intensity specification for the calibration of 0 dB nHL for AEBP stimuli must be made in careful consideration of two methodological issues. First, is the sound level specification of a transient best represented by a quantification of its maximum acoustical pressure, or is it best to describe it in terms of the sound pressure of a pure tone of equivalent driving voltage? Second, if the sound level description is best represented by the peSPL specification, then is it better to match the tonal voltage amplitude to the transient's peak or peak-to-peak voltage, and is it better to measure the sound level of the equivalent tone in terms of its peak or rms sound pressure? The answers to these questions will undoubtedly provide a better basis for the recommendation of an intensity specification than the limited interpretations of the statistical results of this study.

PeakSPL or peSPL? PeakSPL readings indicate the pressure value for the maximum excursion of the stimulus from the zero baseline. Specifically related to sound measurements, the peak sound pressure is "the maximum absolute value for the instantaneous sound pressure" (ANSI S3.20-1973).

The peakSPL measurement of a transient reflects the maximum pressure value of the signal. The sound level instruments used in this study could be adjusted to measure peakSPL. The B & K manual for these measurement devices cautions the user that the peak measurements made actually reflect the half peak-to-peak value of the signal. If the signal has unequal pressure variations on either side of zero, the peak value read on the meter may not truly be the peak or maximum SPL.

In addition to this problem is the difficulty of the sound measurement instrument's meter to reflect or record the peak pressure of transient stimuli. Meter ballistics are such that the sound level indicator cannot possibly reach the maximum pressure value as fast as the stimulus reaches it and immediately decays. This very rapid stimulus decay will cause the needle to fall even before it reaches the maximum. To steady the meter for a peak reading, the stimulus rate can be increased, however the sound level reading would then be a reflection of some sort of average or steady-state pressure of the continuous clicks.

The problems related to the direct measurement of a transient's sound level can be overcome by substituting an easily measured sustained pure tone for that transient. The voltage of the pure tone would be equivalent to the driving voltage at threshold of the transient. This method is the peak equivalent SPL, referred to herein as peSPL.

A criticism of the peSPL specification is that the threshold sound level of a very brief auditory signal is being referred to that of a sustained tone. Due to the psychoacoustical phenomenon known as temporal integration, the thresholds and perceived loudness of two such disparate signals are radically different.

Briefly stated, temporal integration in the auditory system is the process by which the intensity of a sound needed to reach threshold increases as stimulus duration decreases. In other words, the briefer the sound, the more acoustically intense it must be to elicit a threshold response.

In the calibration of the sustained pure tones used in clinical audiometry, the goal of the task is to equate average psychophysical threshold, called 0 dB HL, to physically meaningful acoustical units in dB SPL. The durations of the tonal stimuli used in clinical audiometry far exceed the time constants of temporal integration (Arlinger, 1981), and this loudness phenomenon does not confound the calibration results.

The AEBP stimuli, however, present two issues related to temporal integration's effects on threshold sound level calibration of these stimuli and the inter-laboratory comparison of normative data. Psychophysical threshold is affected by not only the stimulus presentation rate of these transients but also by the duration of the listening period used to measure threshold for these repetative stimuli. Stapells, <u>et al</u>. (1982) studied both phenomena and found a statistically significant 4.53 dB decrease in mean threshold with every tenfold increase in click rate. In addition, the effect of listening period on stimulus threshold was statistically significant. There was a 2.5 dB threshold improvement as listening duration increased from 100 to 300 msec.

It should be clear from these data that the sound levels that result from the electroacoustical calibration of AEBP stimuli will depend on both the click rate and listening duration used to establish the mean threshold for that particular stimulus. Of course, the same click rate must be used for the acoustical calibration as was used for the behavioral calibration of 0 dB nHL.

This temporal integration argument against peSPL is certainly justified if the goal of sound level calibrations were considered to be the measurement and quantification of an acoustic stimulus in terms of its human, psychoacoustical threshold perception. In this case, peSPL would certainly be an erroneous and mis-leding sound level specification.

However, "the purpose of coupler calibration of earphones is to provide a simple, convenient, and reproducible means of determining their acoustical output." (ANSI S3.7-1973, p. 7) Without doubt, the peSPL sound level specification provides such a means by eliminating, or at least by minimizing, the problems associated with the direct measurement of the acoustical characteristics of transient stimuli.

The first methodological consideration associated with the intensity specification of a transient has been elucidated. The peSPL measurement and specification is the choice over the peakSPL procedure and sound level designation. The second methodological issue will be discussed in the section to follow.

Tonal Voltage Match. For peSPL measurements, the voltage of the surrogate tone can be matched to either the peak or the peak-to-peak voltage of the transient. The peak measurement of the transient is simply the voltage of the transient at the maximum excursion of the waveform. The peak-to-peak measurement is the absolute value of the difference between the maximum positive and negative excursions of the waveform. Each of these methods of measuring peSPL has a precedence in the AEBP literature.

Davis (1976) and Arlinger (1981) adjusted the amplitude of the substitute tone to the peak amplitude of the transient. It was that peak voltage of the tonal stimulus that served as the input to the earphone terminals, and the coupler sound level of this sustained tone at that equivalent voltage was measured. Zerlin and Naunton (1975), Dirks, et al. (1976), Vernon, et al. (1976) and Stapells, et al. (1982) measured the peak-to-peak voltage of the transient and based tonal voltage adjustment on this value.

In order that the sound level specified in the peSPL designation for a transient incorporates as much of the acoustical energy information related to that transient as possible, the peak-to-peak voltage measurement and match should be performed. The matching of the substitute tone's peak-to-peak voltage to the peak-to-peak voltage of the transient at 0 dB nHL driving voltage is recommended by Durrant (1983) as the method of choice for AEBP stimulus intensity specification.

Tonal SPL Measurement. The equivalent threshold driving voltage (peak-to-peak threshold voltage of transient matched to peak-to-peak voltage of surrogate tone) of the tonal signal can be measured by the acoustical calibration instruments as either peak or rms SPL. The peak SPL reading has been explained in a previous section. The rms (root-mean-squared) specification means that the waveform was rectified, the amplitude of the signal was measured at every point in time, these values were squared and averaged, and, finally, the square root of this quantity was calculated to be the rms measurement.

For a periodic oscillatory function such as a sine wave or pure tone, the relationship among these three designations can be stated mathematically: peak = peak-to-peak/2; peak = 1.414 x rms; rms = 0.708 x peak; rms = 0.35 x peak-to-peak; and peak-to-peak = 2.83 x rms. It is clearly seen that with a signal that is symmetrical about the zero crossing, a single measurement could be easily converted to another.

Both tonal peak SPL and rms SPL have been reported in the AEBP literature in regard to peSPL measurements. Arlinger (1981) measured the tonal sound level as peakSPL. Alternatively, Zerlin and Naunton (1975), Vernon, _et al_. (1976) and Stapells, _et al_. (1982) specified peSPL in terms of the rms SPL of the surrogate pure tone.

The American National Standard Specifications for Audiometers (ANSI S3.6-1973) defines the SPL produced by an audiometer as "the rms sound pressure level developed by the audiometer earphone in a coupler" (ANSI S3.6-1973, p. 8). Since the pure tone output of an audiometer at 0 dB HL is specified in dB rms SPL, then it follows logically that the substitute pure tone used for peSPL measurements of 0 dB nHL for transient stimuli should also be measured as rms rather than peakSPL.

Chapter 5 will present a summary of the results of this study and will present the conclusions which form the bases for the recommendation of a coupler and intensity specification for the clinical calibration of AEBP stimuli.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Since 1977 auditory evoked brainstem potentials (AEBPs) have been used extensively by both the neurological community to evaluate site of central nervous system dysfunction and by audiologists and otologists to assess auditory sensitivity from an electrophysiological approach. The AEBP waveform parameters are influenced not only by aberrant end-organ and/or neural functioning, but they are profoundly altered by changes in the acoustical properties of the AEBP eliciting stimulus. The stimulus is called a click and is produced by driving an earphone with a rapid rise-time, brief duration electrical impulse. In order to make a valid interpretation of test data, the clinician must be confident that deviation from the expected norm in terms of waveform parameters are truly a reflection of physiological abnormality and not an electrophysiological manifestation of stimulus parameter alteration. Therefore, every possible variable must be controlled and defined for the most precise evaluation of auditory acuity and/or central auditory nervous system integrity.

The purpose of this study was to suggest a plan to examine the reliability of several electroacoustical calibration procedures relative to estimates of auditory

sensitivity obtained from normal hearing subjects. Calibration variables included earphone system, coupler system, cushion and the method by which instrumentally measured stimuli are quantified. Additionally, the symmetry of the stimulus waveforms was systematically varied in an effort to identify that calibration method which yields the most consistent prediction of threshold as measured by behavioral means.

The results of the statistical analyses of the threshold data generated by twenty otologically and audiometrically normal young adults revealed statistically significant effects of coupler used, sound level measurement made, type of earphone cushion and stimulus on the mean threshold sound levels of the AEBP stimuli. In addition, there were statistically significant two-, three- and four-way interactions among these independent variables. The presence of these interactive effects on mean threshold sound level measurements severely restricted the recommendations for an acoustically appropriate coupler/intensity combination for the clinical calibration of AEBP stimuli based solely on these results.

Through the consideration of theoretical and practical methodological issues and the results of this investigation -- limited by the interactions as they were -- research conclusions have been drawn and recommendations have been formulated. They are as follows:

1. The most reliable electroacoustical index of AEBP stimulus sound level will result from the use of the NBS-9A coupler/peSPL-rms intensity specification in clinical facilities where AEBP stimuli are to be presented through earphone transducers mounted in SA cushions, only. In facilities where both SA and CA cushions are used for AEBP evaluations, the PSFP coupler/peSPL-rms combination is recommended.
2. The NBS-9A/peSPL-rms and PSFP/peSPL-rms coupler/intensity specification combinations yield the most reliable descriptions of mean behavioral threshold (0 dB nHL) when both stimulus symmetry and earphone cushion are varied.

It is intended that these conclusions and recommendations provide the clinician performing electrophysiological examinations of auditory function of the brainstem with an appropriate acoustical calibration method for AEBP stimuli. Through the use of such a recommended calibration procedure, the enormous variability associated with the inter-laboratory comparison of data should decrease markedly. In addition, through the complete reporting of the electroacoustic index of stimulus sound level and spectral and waveform parameters, clinicians can replicate the investigations or clinical techniques of others within defined limits of precision. The results and recommendations of this study will undoubtedly serve both the neurological an the oto-audiological communities as a guide toward the standardization of AEBP stimulus calibration.

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APPENDICES

APPENDIX A

INFORMED CONSENT
RELEASE FORM

I, ______________________________________, freely and voluntarily consent to serve as a subject in a scientifically conducted study of auditory sensitivity for click-like stimuli conducted by Dr. Oscar I. Tosi and Miss Patricia E. Connelly of the Department of Audiology and Speech Sciences.

I understand that the purpose of the study is to determine the reliability and validity of several calibration procedures for the specification of click-like stimuli used in auditory evoked potentials endeavors.

I fully understand that I will not be exposed to any experimental conditions that threaten my hearing or my physical or psychological well-being. I understand that in the unlikely event of physical injury resulting from research procedures, Michigan State University, its agents, and employees will assume that responsibility as required by law. Emergency medical treatment for injuries or illness is available where the injury or illness is incurred in the course of an experiment. I have been advised that I should look toward my own health insurance program for payment of said medical expenses.

I understand that data gathered from me for this experiment are confidential, that no information uniquely identified with me will be made available to other persons or agencies and that the publication of the results of this investigation will maintain my anonymity. I engage in this study freely, without payment to me or from me, and without implication of personal benefit. I understand that I may cease participation in this study at any time.

I understand that I may ask questions about the nature of and the procedures followed in this study. I have been provided with a copy of this consent form. Upon the study's completion I may request additional explanation about the investigation.

Date________________ Signed ____________________________________

Appendix B

Driving Voltages in Millivolts (mv) for Subjects' Right (R) and Left (L) Ear

Trial 1 and Trial 2 Thresholds for Each Cushion/Stimulus Combination

	Cushion			
	SA		CA	
	Stimulus			
Subject	SYM	ASYM	SYM	ASYM
		Females		
#1				
R1	.34 mv	.30 mv	.59 mv	.54 mv
R2	.34	.30	1.1	.54
L1	.34	.30	.59	.54
L2	.34	.30	.59	.54
#2				
R1	.34	.18	.59	.54
R2	.34	.30	.59	.54
L1	.34	.30	.59	.30
L2	.34	.30	.34	.30
#3				
R1	.34	.18	.34	.30
R2	.20	.18	.34	.30
L1	.34	.18	.34	.54
L2	.20	.18	.34	.54
#4				
R1	.34	.30	1.1	.54
R2	.34	.30	.59	.30
L1	.20	.18	.34	.18
L2	.34	.18	.34	.18
#5				
R1	.34	.30	.59	.54
R2	.20	.18	.34	.30
L1	.34	.18	.34	.18
L2	.20	.18	.34	.18
#6				
R1	.34	.18	.59	.30
R2	.34	.18	.59	.30
L1	.34	.30	.59	.30
L2	.34	.30	.59	.30
#7				
R1	.20	.18	.34	.18
R2	.20	.18	.34	.18
L1	.20	.18	.34	.30
L2	.20	.18	.34	.30

Appendix B continued

	Cushion			
	SA		CA	
	Stimulus			
Subject	SYM	ASYM	SYM	ASYM
#8				
R1	.34 mv	.18 mv	.59 mv	.30 mv
R2	.34	.18	.34	.30
L1	.34	.30	.34	.30
L2	.34	.30	.34	.30
#9				
R1	.20	.18	.34	.18
R2	.20	.18	.34	.18
L1	.20	.18	.34	.18
L2	.20	.18	.34	.18
#10				
R1	.34	.30	.59	.30
R2	.34	.30	.34	.30
L1	.34	.18	.59	.30
L2	.34	.18	.59	.30
		Males		
#1				
R1	.20 mv	.18 mv	.59 mv	.30 mv
R2	.20	.18	.34	.54
L1	.34	.30	.34	.30
L2	.34	.18	.34	.30
#2				
R1	.20	.18	.34	.30
R2	.20	.18	.34	.30
L1	.34	.30	.34	.30
L2	.34	.30	.34	.30
#3				
R1	.34	.10	.34	.18
R2	.34	.10	.34	.18
L1	.34	.18	.34	.18
L2	.34	.18	.34	.18
#4				
R1	.20	.18	.20	.30
R2	.20	.18	.20	.18
L1	.34	.18	.34	.18
L2	.34	.18	.34	.18
#5				
R1	.34	.30	.34	.30
R2	.34	.30	.34	.30
L1	.20	.18	.59	.30
L2	.20	.18	.34	.18

Appendix B continued

	Cushion			
	SA		CA	
	Stimulus			
Subject	SYM	ASYM	SYM	ASYM
#6				
R1	.34	.18	.59	.18
R2	.34	.18	.59	.18
L1	.34	.10	.20	.18
L2	.34	.10	.20	.18
#7				
R1	.20 mv	.18 mv	.34 mv	.30 mv
R2	.20	.18	.34	.30
L1	.20	.18	.34	.30
L2	.20	.18	.34	.30
#8				
R1	.20	.18	.34	.54
R2	.20	.18	.34	.30
L1	.34	.18	.20	.18
L2	.34	.18	.20	.18
#9				
R1	.20	.30	.34	.30
R2	.20	.18	.59	.30
L1	.20	.18	.34	.30
L2	.20	.18	.34	.30
#10				
R1	.34	.30	.34	.54
R2	.34	.30	.59	.54
L1	.34	.30	.34	.30
L2	.34	.30	.34	.30

Appendix C

Threshold Driving Voltage-to-Acoustical Intensity Level Conversion Values

		Acoustical Intensity		
	Voltage	Peak SPL	peSPL-peak	peSPL-rms
NBS-9A Coupler-SA Cushion				
SYM	.34 mv	30.9 dB	28.1 dB	24.5 dB
	.20	27.2	24.4	20.8
ASYM	.30	30.5	26.8	23.7
	.18	27.4	23.7	20.7
	.10	24.1	20.8	17.9
Zwislocki Coupler-SA Cushion				
SYM	.34 mv	34.0 dB	32.3 dB	29.1 dB
	.20	28.2	26.5	23.4
ASYM	.30	33.2	28.9	25.9
	.18	30.3	26.0	23.0
	.10	24.3	20.0	17.0
Zwislocki Coupler-CA Cushion				
SYM	.59 mv	31.5 dB	32.8 dB	29.1 dB
	1.1	33.3	34.6	30.9
	.34	29.1	30.4	26.7
	.20	25.7	27.0	23.3
ASYM	.54	38.9	34.3	30.7
	.30	31.0	29.7	26.3
	.18	27.0	26.7	23.7
PSFP Coupler-SA Cushion				
SYM	.34 mv	28.6 dB	27.2 dB	23.3 dB
	.20	24.0	23.0	19.1
ASYM	.30	28.3	29.0	24.2
	.18	24.1	22.1	19.4
	.10	19.0	17.6	15.0
PSFP Coupler-CA Cushion				
SYM	.59 mv	26.3 dB	24.4 dB	23.4 dB
	1.1	30.2	29.2	27.1
	.34	21.5	20.4	19.1
	.20	17.3	16.5	15.0
ASYM	.54	27.5	24.3	21.4
	.30	23.0	21.6	19.2
	.18	18.3	16.5	14.4

Appendix D

Mean Thresholds for Each Subject (Females #1-10; Males #11-20) under Each Experimental Condition

	Intensity					
	peakSPL		peSPL-peak		peSPL-rms	
	Stimulus					
Subject	SYM	ASYM	SYM	ASYM	SYM	ASYM
			NBS-9A Coupler-SA Cushion			
1	32.0	38.9	33.2	34.2	29.8	30.7
2	30.8	35.0	32.2	32.0	28.5	28.5
3	29.1	35.0	30.3	32.0	26.7	28.5
4	30.7	31.0	31.8	29.3	28.3	26.1
5	29.7	31.0	31.0	29.3	27.2	26.1
6	31.5	31.0	32.7	29.7	29.1	26.2
7	29.1	29.0	30.3	28.2	26.7	25.0
8	29.7	31.0	31.0	29.7	27.2	26.2
9	29.1	27.0	30.3	26.7	26.7	23.7
10	30.8	31.0	32.2	29.7	28.5	26.2
11	29.7	33.0	31.0	30.7	27.2	27.7
12	29.1	31.0	30.3	29.7	26.7	26.2
13	29.1	27.0	30.3	26.7	26.7	23.7
14	27.3	28.0	28.7	27.3	25.0	24.3
15	29.7	30.0	31.0	29.0	27.2	25.6
16	28.6	27.0	29.8	26.7	26.2	23.7
17	29.1	31.0	30.3	29.7	26.7	26.2
18	27.3	31.0	28.7	29.3	25.0	26.1
19	29.7	31.0	31.0	29.7	27.2	26.2
20	29.7	35.0	31.0	32.0	27.2	28.5
			PSFP Coupler-SA Cushion			
1	34.0	33.2	32.2	28.8	29.1	25.8
2	34.0	32.5	32.2	28.2	29.1	25.2
3	31.1	30.2	29.3	26.0	26.2	23.0
4	32.5	31.7	31.0	27.3	27.7	24.3
5	31.1	31.0	29.3	26.7	26.2	23.7
6	34.0	31.7	32.2	27.3	29.1	24.3
7	28.2	30.2	26.5	26.0	23.3	23.0
8	34.0	31.7	32.2	27.3	29.1	24.3
9	28.2	30.2	26.5	26.0	23.3	23.0
10	34.0	31.7	32.2	27.3	29.1	24.3
11	31.1	31.0	29.3	26.7	26.2	23.7
12	31.1	31.7	29.3	27.3	26.2	24.3
13	34.0	27.2	32.2	23.0	29.1	20.0
14	31.1	30.2	29.3	26.0	26.2	23.0
15	31.1	31.7	29.3	27.3	26.2	24.3
16	34.0	27.2	32.2	23.0	29.1	20.0
17	28.2	30.2	26.5	26.0	23.3	23.0
18	31.1	30.2	29.3	26.0	26.2	23.0
19	28.2	31.0	26.5	26.7	23.3	23.7
20	34.0	33.2	32.2	28.8	29.1	25.8

Appendix D continued

			Intensity			
	peakSPL		peSPL-peak		peSPL-rms	
			Stimulus			
Subject	SYM	ASYM	SYM	ASYM	SYM	ASYM
			PSFP Coupler-CA Cushion			
1	30.8	30.5	28.1	26.7	24.5	23.7
2	30.8	29.7	28.1	26.0	24.5	23.0
3	29.0	27.3	26.2	23.7	22.6	20.7
4	30.0	29.0	27.2	25.2	23.6	22.2
5	29.0	28.2	27.6	24.5	22.6	21.3
6	30.8	29.0	28.1	25.2	24.5	22.2
7	27.2	27.3	24.3	23.7	20.7	20.7
8	30.8	29.0	28.1	25.2	24.5	20.7
9	27.2	27.3	24.3	23.7	20.7	20.7
10	30.8	29.0	28.1	25.2	24.5	22.2
11	29.1	28.2	26.2	24.5	22.6	21.3
12	29.1	29.0	26.2	25.2	22.6	22.2
13	30.8	25.7	28.1	22.2	24.5	19.2
14	29.1	27.3	26.2	23.7	22.6	20.7
15	30.8	29.0	26.2	25.2	22.6	22.2
16	30.8	25.7	28.1	22.2	24.5	19.2
17	27.2	27.3	24.3	23.7	20.7	20.7
18	29.1	27.3	26.2	23.7	22.6	20.7
19	27.2	28.2	24.3	24.5	20.7	21.3
20	30.8	30.5	28.1	26.7	24.5	23.7
			Zwislocki Coupler-SA Cushion			
1	28.6	28.2	27.2	29.0	23.2	24.2
2	28.6	27.2	27.2	27.2	23.2	23.0
3	26.2	24.1	25.1	22.1	21.2	19.3
4	27.3	26.2	26.2	25.6	22.2	21.7
5	26.2	25.2	25.1	23.7	21.2	20.6
6	28.6	26.2	27.2	25.6	23.2	21.7
7	24.0	24.1	23.0	22.1	19.1	19.3
8	28.6	26.2	27.2	25.6	23.2	21.7
9	24.0	24.1	23.0	22.1	19.1	19.3
10	28.6	26.2	27.2	25.6	23.2	21.7
11	26.2	25.2	25.1	23.7	21.2	20.6
12	26.2	26.2	25.1	25.6	21.2	21.7
13	28.6	21.6	27.2	19.7	23.2	17.2
14	26.2	24.1	25.1	22.1	21.2	19.3
15	26.2	26.2	25.1	25.6	21.2	21.7
16	28.6	21.6	27.2	19.8	23.2	17.2
17	24.0	24.1	23.0	22.1	19.1	19.3
18	26.2	24.1	25.1	22.1	21.2	19.3
19	24.0	25.2	23.0	23.7	19.1	20.6
20	28.6	28.2	27.2	29.0	23.2	24.2

Appendix D continued

			Intensity			
	peakSPL		peSPL-peak		peSPL-rms	
			Stimulus			
Subject	SYM	ASYM	SYM	ASYM	SYM	ASYM
			Zwislocki Coupler-CA Cushion			
1	27.2	27.5	25.6	24.2	24.2	24.3
2	25.1	25.2	23.3	23.0	22.2	20.2
3	25.1	25.2	20.3	23.0	19.1	20.2
4	24.8	21.7	23.6	19.7	22.2	17.3
5	22.7	21.7	21.3	19.7	20.2	17.3
6	26.2	23.0	24.3	21.6	23.3	19.2
7	21.5	20.6	20.3	19.1	19.1	16.7
8	22.7	23.0	21.3	21.6	20.2	19.2
9	21.5	18.2	20.3	16.5	19.1	14.3
10	21.5	23.0	23.3	21.6	22.2	19.2
11	22.7	24.1	20.8	22.2	20.2	19.7
12	21.5	23.0	20.3	21.6	19.1	19.2
13	21.5	18.2	20.3	16.5	19.1	14.3
14	19.3	19.5	18.3	17.7	17.1	15.6
15	22.7	21.7	20.8	20.2	20.2	18.0
16	21.7	18.2	20.3	16.5	19.2	14.3
17	21.5	23.0	20.3	21.6	19.1	19.2
18	19.0	21.7	18.3	19.7	17.1	17.3
19	22.7	23.0	21.3	21.6	20.2	19.2
20	22.7	25.2	21.3	23.0	20.2	20.2

Appendix E

Reliability Measurement Data

			Intensity			
	peakSPL		peSPL-peak		peSPL-rms	
			Stimulus			
Observation	SYM	ASYM	SYM	ASYM	SYM	ASYM
			NBS-9A Coupler-SA Cushion			
1	36.0	35.0	31.8	30.7	28.0	29.2
2	36.5	35.0	31.8	30.8	28.0	26.5
3	37.0	33.5	31.5	31.0	27.6	26.8
4	36.4	34.7	31.8	30.7	28.0	29.2
5	37.0	34.4	31.5	30.2	27.6	26.0
6	37.2	34.5	32.0	30.8	27.5	26.5
7	36.9	34.4	31.3	31.2	26.6	27.2
8	36.9	34.2	31.8	30.5	28.0	26.3
9	37.2	34.9	31.7	30.7	27.8	29.2
10	37.0	35.0	32.0	30.5	27.5	26.3
			PSFP Coupler-SA Cushion			
1	32.0	32.0	28.6	28.3	25.6	25.3
2	32.2	32.0	28.7	28.2	25.5	25.2
3	32.0	32.2	28.5	28.6	25.3	25.6
4	32.0	32.2	28.7	28.5	25.5	25.5
5	32.0	29.7	28.0	25.5	24.7	22.5
6	32.5	29.0	28.2	24.7	25.2	21.7
7	32.5	29.7	28.2	25.5	25.2	22.5
8	32.0	29.7	29.2	25.5	26.1	22.5
9	32.2	29.8	28.2	25.6	25.2	22.6
10	32.2	29.8	28.2	25.6	25.2	22.6
			PSFP Coupler-CA Cushion			
1	29.7	28.8	25.3	24.5	22.3	21.3
2	29.6	29.3	25.6	24.7	22.6	21.2
3	29.6	28.7	25.0	24.2	22.0	21.2
4	29.6	30.2	25.7	25.2	22.7	22.0
5	29.5	31.5	25.1	24.5	22.1	21.3
6	31.2	29.2	25.5	24.5	22.5	21.3
7	31.7	28.7	25.1	25.0	22.1	21.6
8	29.6	31.2	26.3	25.2	23.3	22.0
9	30.3	28.8	25.7	25.0	22.7	21.6
10	30.2	28.6	25.1	24.7	22.1	21.2

Appendix E continued

	Intensity					
	peakSPL		peSPL-peak		peSPL-rms	
	Stimulus					
Observation	SYM	ASYM	SYM	ASYM	SYM	ASYM
	Zwislocki Coupler-SA Cushion					
1	26.5	25.8	24.6	22.6	21.6	19.6
2	26.5	25.8	24.6	22.6	21.6	19.6
3	26.6	25.7	24.7	22.3	22.2	19.3
4	26.7	26.1	25.0	22.3	22.3	20.1
5	27.2	25.6	25.7	22.6	23.1	19.5
6	26.3	25.6	24.2	22.6	21.3	19.5
7	26.3	25.7	24.2	22.2	21.3	19.3
8	26.6	25.6	24.7	22.6	22.2	19.5
9	26.5	26.0	24.6	23.2	21.6	19.8
10	26.3	26.1	24.2	23.3	21.3	20.1
	Zwislocki Coupler-CA Cushion					
1	23.7	24.1	20.6	22.2	17.7	19.2
2	23.3	23.8	20.3	21.5	17.6	18.6
3	24.3	23.1	21.0	21.2	18.6	18.2
4	25.0	23.0	22.0	20.8	19.2	18.0
5	23.5	23.2	20.6	21.1	17.3	18.3
6	24.1	23.0	20.8	20.8	18.3	18.0
7	24.0	23.7	20.7	21.8	18.2	18.8
8	23.3	23.0	20.3	20.8	17.6	18.0
9	25.0	23.0	21.2	20.8	19.2	18.0
10	23.5	23.1	20.2	21.2	17.3	18.2

TABLES

Table 1

Summary of Ear x Trial ANOVAs for Females
for Each Experimental Condition

		Statistic		
Condition	$\bar{X}$	SD	F*	p
NBS-9A SYM-SA peakSPL				
R ear	30.6 dB	1.48 dB	2.99	.12
L ear	29.9	1.19		
Trial 1	30.5	1.31	4.08	.07
Trial 2	30.0	1.36		
Ear x Trial			.76	.00
NBS-9A ASYM-SA peak SPL				
R ear	32.6 dB	4.55 dB	.50	.00
L ear	31.4	4.36		
Trial 1	32.4	4.68	2.25	.16
Trial 2	31.6	4.22		
Ear x Trial			2.25	.16
NBS-9A SYM-SA peSPL-peak				
R ear	31.9 dB	1.48 dB	2.99	.12
L ear	31.2	1.19		
Trial 1	31.8	1.31	4.08	.07
Trial 2	31.2	1.36		
Ear x Trial			0.76	.00
NBS-9A ASYM-SA peSPL-peak				
R ear	30.5 dB	2.84 dB	0.51	.00
L ear	29.7	2.77		
Trial 1	30.3	2.94	2.25	.16
Trial 2	29.9	2.66		
Ear x Trial			2.25	.16
NBS-9A SYM-SA peSPL-rms				
R ear	28.2 dB	1.48 dB	2.99	.12
L ear	27.5	1.19		
Trial 1	28.1	1.31	4.08	.07
Trial 2	27.6	2.14		
Ear x Trial			0.76	.00

Table 1 continued

	Statistic			
Condition	$\bar{X}$	SD	F*	p
NBS-9A ASYM-SA peSPL-rms				
R ear	27.1 dB	2.63 dB	0.51	.00
L ear	26.4	2.55		
Trial 1	27.0	2.72	2.25	.16
Trial 2	26.5	2.46		
Ear x Trial			2.25	.16
PSFP SYM-SA peakSPL				
R ear	32.3 dB	2.72 dB	1.00	.34
L ear	32.0	2.90		
Trial 1	32.6	2.62	1.00	.34
Trial 2	31.7	2.99		
Ear x Trial			0.99	
PSFP ASYM-SA peakSPL				
R ear	31.5 dB	1.49 dB	0	
L ear	31.4	1.49		
Trial 1	31.5	1.49	0	
Trial 2	31.5	1.49		
Ear x Trial			0	
PSFP SYM-CA peakSPL				
R ear	29.8 dB	1.74 dB	1.00	.34
L ear	29.6	1.84		
Trial 1	30.0	1.67	1.00	.34
Trial 2	29.4	1.91		
Ear x Trial			0.99	
PSFP ASYM-CA peakSPL				
R ear	28.6 dB	1.60 dB	0	
L ear	28.6	1.60		
Trial 1	28.6	1.60	0	
Trial 2	28.6	1.60		
Ear x Trial			0	
PSFP SYM-SA peSPL-peak				
R ear	30.3 dB	2.74 dB	0.99	
L ear	30.6	2.72		
Trial 1	31.1	2.44	3.46	.09
Trial 2	29.7	3.03		
Ear x Trial			1.00	.35

Table 1 continued

	Statistic			
Condition	$\bar{X}$	SD	F*	p
PSFP ASYM-SA peSPL-peak				
R ear	27.2 dB	1.49 dB	0	
L ear	27.2	1.49		
Trial 1	27.2	1.49	0	
Trial 2	27.2	1.49		
Ear x Trial			0	
PSFP SYM-CA peSPL-peak				
R ear	27.1 dB	1.65 dB	0.10	.00
L ear	27.0	1.78		
Trial 1	27.2	1.67	1.54	.25
Trial 2	26.9	1.76		
Ear x Trial			1.54	.25
PSFP ASYM-CA peSPL-peak				
R ear	24.9 dB	1.60 dB	0	
L ear	24.9	1.60		
Trial 1	24.9	1.60	0	
Trial 2	24.9	1.60		
Ear x Trial			0	
PSFP SYM-SA peSPL-rms				
R ear	27.4 dB	2.67 dB	0.99	
L ear	27.1	2.84		
Trial 1	27.7	2.58	0.99	
Trial 2	26.8	2.94		
Ear x Trial			1.00	.34
PSFP ASYM-SA peSPL-rms				
R ear	24.2 dB	1.49 dB	0	
L ear	24.2	1.49		
Trial 1	24.2	1.49	0	
Trial 2	24.2	1.49		
Ear x Trial			0	
PSFP SYM-CA peSPL-rms				
R ear	23.4 dB	1.74 dB	1.00	.34
L ear	23.2	1.84		
Trial 1	23.6	2.24	0.99	
Trial 2	23.0	1.91		
Ear x Trial			0.99	

Table 1 continued

	Statistic			
Condition	$\bar{X}$	SD	F*	p
PSFP ASYM-CA peSPL-rms				
R ear	21.9 dB	1.54 dB	0	
L ear	21.9	1.54		
Trial 1	21.9	1.54	0	
Trial 2	21.9	1.54		
Ear x Trial			0	
Zwislocki SYM-SA peakSPL				
R ear	27.2 dB	2.15 dB	1.00	.34
L ear	27.0	2.30		
Trial 1	27.4	2.08	0.99	
Trial 2	26.8	2.37		
Ear x Trial			1.00	.34
Zwislocki ASYM-SA peakSPL				
R ear	25.8 dB	2.16 dB	0	
L ear	25.8	2.16		
Trial 1	25.8	2.16	0	
Trial 2	25.8	2.16		
Ear x Trial			0	
Zwislocki SYM-CA peakSPL				
R ear	24.5 dB	3.02 dB	3.03	.11
L ear	23.2	2.39		
Trial 1	24.3	2.66	3.87	.08
Trial 2	23.4	2.74		
Ear x Trial			0.73	
Zwislocki ASYM-CA peakSPL				
R ear	23.4 dB	3.34 dB	0.51	
L ear	22.5	3.40		
Trial 1	23.2	3.51	2.25	.16
Trial 2	22.7	3.23		
Ear x Trial			2.25	.16
Zwislocki SYM-SA peSPL-peak				
R ear	25.9 dB	1.96 dB	0.99	
L ear	25.7	2.09		
Trial 1	26.1	1.90	0.99	
Trial 2	25.5	2.16		
Ear x Trial			1.00	.34

Table 1 continued

Condition	Statistic $\bar{X}$	SD	F*	p
Zwislocki ASYM-SA peSPL-peak				
R ear	24.9 dB	3.56 dB	0	
L ear	24.9	3.56		
Trial 1	24.9	3.56	0	
Trial 2	24.9	3.56		
Ear x Trial			0	
Zwislocki SYM-CA peSPL-peak				
R ear	23.0 dB	2.88	3.14	.11
L ear	21.8	2.00		
Trial 1	22.8	2.12	2.64	.14
Trial 2	22.0	2.48		
Ear x Trial			0.53	
Zwislocki ASYM-CA peSPL-peak				
R ear	21.4 dB	2.84 dB	0.46	
L ear	20.6	3.03		
Trial 1	21.1	3.02	2.25	.16
Trial 2	20.9	2.85		
Ear x Trial			2.25	.16
Zwislocki SYM-SA peSPL-rms				
R ear	22.0 dB	1.96 dB	0.99	
L ear	21.8	2.09		
Trial 1	22.2	1.90	0.99	
Trial 2	21.6	2.16		
Ear x Trial			1.00	.34
Zwislocki ASYM-SA peSPL-rms				
R ear	21.3 dB	2.47 dB	0	
L ear	21.3	2.47		
Trial 1	21.3	2.47	0	
Trial 2	21.3	2.47		
Ear x Trial			0	
Zwislocki SYM-CA peSPL-rms				
R ear	21.8 dB	2.74 dB	3.03	.11
L ear	20.6	2.14		
Trial 1	21.6	2.39	3.50	.09
Trial 2	20.8	2.48		
Ear x Trial			0.68	

Table 1 continued

Condition	Statistic $\overline{X}$	SD	F*	p
Zwislocki ASYM-CA peSPL-rms				
R ear	18.9 dB	2.56 dB	0.45	
L ear	18.2	2.76		
Trial 1	18.7	2.72	2.25	.16
Trial 2	18.4	2.59		
Ear x Trial			2.25	.16

*F (1,9) = 10.56, p = .01

Table 2

Summary of Ear x Trial ANOVAs for Males for Each Experimental Condition

	Statistic			
Condition	$\overline{X}$	SD	F*	p
NBS-9A SYM-SA peakSPL				
R ear	29.4 dB	1.66 dB	1.08	.33
L ear	28.5	1.58		
Trial 1	29.0	1.66	0	
Trial 2	29.0	1.58		
Ear x Trial			1.00	.34
NBS-9A ASYM-SA peakSPL				
R ear	31.6 dB	4.22 dB	5.51	.04
L ear	29.2	2.08		
Trial 1	30.6	3.08	0.38	
Trial 2	30.2	3.23		
Ear x Trial			0	
NBS-9A SYM-SA peSPL-peak				
R ear	30.6 dB	1.66 dB	1.08	.33
L ear	29.8	1.58		
Trial 1	30.2	1.66	0	
Trial 2	30.2	1.58		
Ear x Trial			0.99	
NBS-9A ASYM-SA peSPL-peak				
R ear	29.9 dB	2.66 dB	5.79	.04
L ear	28.4	1.56		
Trial 1	29.3	2.05	0.57	
Trial 2	29.0	2.18		
Ear x Trial			0	
NBS-9A SYM-SA peSPL-rms				
R ear	27.0 dB	1.66 dB	1.08	.33
L ear	26.1	1.58		
Trial 1	26.6	1.66	0	
Trial 2	26.6	1.58		
Ear x Trial			1.00	.34
NBS-9A ASYM-SA peSPL-rms				
R ear	26.5 dB	2.46 dB	5.69	.04
L ear	25.1	1.36		
Trial 1	26.0	1.86	0.49	
Trial 2	25.7	1.96		
Ear x Trial			0	

Table 2 continued

	Statistic			
Condition	$\bar{X}$	SD	F*	p
PSFP SYM-SA peakSPL				
R ear	30.5 dB	2.99 dB	1.98	.19
L ear	32.3	2.80		
Trial 1	31.4	2.90	2.81	.12
Trial 2	31.4	2.90		
Ear x Trial			0	
PSFP ASYM-SA peakSPL				
R ear	30.4 dB	2.51 dB	0	
L ear	30.4	2.51		
Trial 1	30.6	2.59	2.25	.16
Trial 2	30.3	2.42		
Ear x Trial			0	
PSFP SYM-CA peakSPL				
R ear	28.7 dB	1.91 dB	1.98	.19
L ear	29.8	1.78		
Trial 1	29.2	1.84	0	
Trial 2	29.2	1.84		
Ear x Trial			0	
PSFP ASYM-CA peakSPL				
R ear	27.8 dB	1.90 dB	0	
L ear	27.8	1.90		
Trial 1	28.0	2.00	2.25	.16
Trial 2	27.7	1.80		
Ear x Trial				
PSFP SYM-SA peSPL-peak				
R ear	28.8 dB	2.99 dB	1.98	.19
L ear	30.6	2.80		
Trial 1	29.7	2.90	0	
Trial 2	29.7	2.90		
Ear x Trial			0	
PSFP ASYM-SA peSPL-peak				
R ear	26.1 dB	2.51 dB	0	
L ear	26.1	2.51		
Trial 1	26.3	2.59	2.25	.16
Trial 2	26.0	2.42		
Ear x Trial			0	

Table 2 continued

Condition	Statistic			
	$\overline{X}$	SD	F*	p
PSFP SYM-CA peSPL-peak				
R ear	25.9 dB	1.91 dB	1.98	.19
L ear	27.0	1.78		
Trial 1	26.4	1.84	0	
Trial 2	26.4	1.84		
Ear x Trial			0	
PSFP ASYM-CA peSPL-peak				
R ear	24.2 dB	1.81 dB	0	
L ear	24.2	1.81		
Trial 1	24.3	1.91	2.25	.16
Trial 2	24.0	1.71		
Ear x Trial			0	
PSFP SYM-SA peSPL-rms				
R ear	25.7 dB	2.95 dB	1.95	.19
L ear	27.4	2.75		
Trial 1	26.5	2.84	1.00	.34
Trial 2	26.5	2.86		
Ear x Trial			1.01	.34
PSFP ASYM-SA peSPL-rms				
R ear	23.1 dB	2.51 dB	0	
L ear	23.1	2.51		
Trial 1	23.3	2.59	2.25	.16
Trial 2	23.0	2.42		
Ear x Trial			0	
PSFP SYM-CA peSPL-rms				
R ear	22.3 dB	1.91 dB	1.98	.19
L ear	23.4	1.78		
Trial 1	22.8	1.84	5.62	.04
Trial 2	22.8	1.84		
Ear x Trial			3.75	.08
PSFP ASYM-CA peSPL-rms				
R ear	21.2 dB	1.76 dB	0	
L ear	21.2	1.76		
Trial 1	21.3	1.85	2.25	.16
Trial 2	21.0	1.66		
Ear x Trial			0	

Table 2 continued

	Statistic			
Condition	$\bar{X}$	SD	F*	p
Zwislocki SYM-SA peakSPL				
R ear	25.8 dB	2.37 dB	1.98	.19
L ear	27.2	2.22		
Trial 1	26.5	2.29	0	
Trial 2	26.5	2.29		
Ear x Trial			0	
Zwislocki ASYM-SA peakSPL				
R ear	24.6 dB	2.72 dB	0	
L ear	24.6	2.72		
Trial 1	24.8	2.85	2.25	.16
Trial 2	24.4	2.58		
Ear x Trial			0	
Zwislocki SYM-CA peakSPL				
R ear	22.3 dB	2.75 dB	1.42	.26
L ear	20.9	2.14		
Trial 1	21.6	2.55	0	
Trial 2	21.6	2.34		
Ear x Trial			0.99	
Zwislocki ASYM-CA peakSPL				
R ear	22.7 dB	3.23 dB	6.00	.04
L ear	20.9	2.44		
Trial 1	22.0	2.74	1.05	.33
Trial 2	21.6	2.94		
Ear x Trial			0	
Zwislocki SYM-SA peSPL-peak				
R ear	24.7 dB	2.16 dB	1.98	.19
L ear	25.9	2.02		
Trial 1	25.3	2.09	0	
Trial 2	25.3	2.09		
Ear x Trial			0	
Zwislocki ASYM-SA peSPL-peak				
R ear	23.4 dB	3.66 dB	0	
L ear	23.4	3.66		
Trial 1	23.4	3.88	2.29	.16
Trial 2	23.0	3.44		
Ear x Trial			0	

Table 2 continued

	Statistic			
Condition	$\bar{X}$	SD	F*	p
Zwislocki SYM-CA peSPL-peak				
R ear	21.0 dB	2.37 dB	1.35	.28
L ear	19.8	1.94		
Trial 1	20.4	2.23	0	
Trial 2	20.4	2.07		
Ear x Trial			1.00	.34
Zwislocki ASYM-CA peSPL-peak				
R ear	20.9 dB	2.85 dB	5.56	.04
L ear	19.3	2.66		
Trial 1	20.3	2.65	1.67	.23
Trial 2	19.8	2.86		
Ear x Trial			0	
Zwislocki SYM-SA peSPL-rms				
R ear	20.8 dB	2.16 dB	1.98	.19
L ear	22.0	2.02		
Trial 1	21.4	2.09	0	
Trial 2	21.4	2.09		
Ear x Trial			0	
Zwislocki ASYM-SA peSPL-rms				
R ear	20.2 dB	2.80 dB	0	
L ear	20.2	2.80		
Trial 1	20.4	2.95	2.25	.16
Trial 2	19.9	2.64		
Ear x Trial			0	
Zwislocki SYM-CA peSPL-rms				
R ear	19.8 dB	2.53 dB	1.36	.27
L ear	18.5	2.04		
Trial 1	19.1	2.38	0	
Trial 2	19.1	2.20		
Ear x Trial			0.99	
Zwislocki ASYM-CA peSPL-rms				
R ear	18.4 dB	2.59 dB	5.32	.04
L ear	17.0	2.50		
Trial 1	18.0	2.44	1.74	.22
Trial 2	17.5	2.64		
Ear x Trial			0	

*F (1,9) = 10.56, p = .01

Table 3

Summary of Intensity x Coupler x Stimulus ANOVA for AEBP Stimulus Thresholds

SOURCE	SS	DF	MS	F	P	ETA SQUARED
Blocks/Subjects	690.673	19				
Intensity	1490.777	2	745.388	9334.480	<001	.300
Error	3.034	38	.079			
Coupler	1810.545	2	905.272	342.379	<001	.364
Error	100.474	38	2.644			
Int x Coupler	98.812	4	24.703	192.716	<001	.020
Error	9.741	76	.128			
Stimulus	161.871	1	161.871	10.831	.004	.033
Error	283.933	19	14.943			
Int x Stim	53.429	2	26.714	348.524	<001	.011
Error	2.912	38	.076			
Coupler x Stimulus	78.675	2	39.337	11.498	<001	.016
Error	129.997	38	3.420			
Int x Cplr x Stim	40.805	4	10.201	70.394	<001	.008
Error	11.013	76	.144			
TOTAL	4966.699	359				

Table 4

Means ($\overline{X}$) and Standard Deviations (SD) for Threshold Data Across Couplers and Intensity Designations

	Intensity					
	peakSPL		peSPL-peak		peSPL-rms	
Condition	$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD
NBS-9A Coupler						
SYM-SA	29.6 dB	1.17 dB	30.9 dB	1.15 dB	27.2 dB	1.17 dB
ASYM-SA	31.2	3.04	29.6	1.96	26.3	1.81
PSFP Coupler						
SYM-SA	31.8	2.23	30.1	2.23	26.9	2.19
ASYM-SA	31.0	1.55	26.6	1.54	23.6	1.54
Zwislocki Coupler						
SYM-SA	26.8	1.76	25.6	1.61	21.7	1.61
ASYM-SA	25.2	1.81	24.1	2.63	20.7	1.94

Table 5

Summary of Intensity x Coupler x Cushion x Stimulus ANOVA
for AEBP Stimulus Thresholds

Source	SS	DF	MS	F	P	eta squared
Blocks/Subjects	905.583	19				
Intensity	2191.348	2	1095.674	9913.638	<001	0.280
Error	4.199	38	.110			
Coupler	2417.416	1	2417.416	671.744	<001	0.309
Error	68.375	19	3.598			
Int x CPL	118.637	2	59.318	471.485	<001	0.015
Error	4.780	38	.125			
Cushion	1018.500	1	1018.500	339.941	<001	0.130
Error	56.926	19	2.996			
Int x Cushion	13.661	2	6.830	51.639	<001	0.002
Error	5.026	38	.132			
CPL x Cushion	4.680	1	4.680	1.892	.182	
Error	46.995	19	2.473			
Int x CPL x Cushion	30.882	2	15.441	117.789	<001	0.004
Error	4.981	38	.131			
Stimulus	318.827	1	318.827	16.534	<001	0.041
Error	366.379	19	19.283			
Int x Stim	23.311	2	11.655	120.448	<001	0.003
Error	3.677	38	.096			
CPL x Stim	25.668	1	25.668	11.947	.002	0.003
Error	40.819	19	2.148			

Table 5 continued

Source	SS	DF	MS	F	P	eta squared
Int x CPL x Stim	12.728	2	6.364	78.492	< 001	0.002
Error	3.081	38	.081			
Cushion x Stimulus	9.352	1	9.352	3.349	.079	
Error	53.051	19	2.792			
Int x Cushion x Stim	2.216	2	1.108	8.953	< 001	0.0003
Error	4.703	38	.123			
CPL x Cushion x Stim	1.824	1	1.824	1.178	.291	
Error	29.417	19	1.548			
Int x CPL x Cushion x Stim	23.892	2	11.946	95.867	< 001	0.003
Error	4.735	38	.124			
Total	7815.688	479				

Table 6

Means ($\bar{X}$) and Standard Deviations (SD) for Thresholds Across Intensities, Couplers, Stimuli and Cushions

	Intensity					
	peakSPL		peSPL-peak		peSPL-rms	
Condition	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
			PSFP Coupler			
SYM-SA	31.8 dB	2.23 dB	30.1 dB	2.23 dB	26.9 dB	2.19 dB
ASYM-SA	31.0	1.55	26.6	1.54	23.6	1.54
SYM-CA	29.6	1.45	26.7	1.43	23.0	1.42
ASYM-CA	28.3	1.29	24.5	1.25	21.4	1.22
			Zwislocki Coupler			
SYM-SA	26.8	1.76	25.6	1.61	21.7	1.61
ASYM-SA	25.2	1.81	24.1	2.63	20.7	1.94
SYM-CA	22.7	2.10	21.4	1.84	20.2	1.88
ASYM-CA	22.4	2.49	20.6	2.32	18.3	2.44

Table 7

Pearson Product Moment Correlation Coefficients (r*) for Mean Pure Tone - Experimental Stimulus Threshold Correlations

		Intensity	
Condition	peakSPL	peSPL-peak	peSPL-rms
		NBS-9A Coupler	
SYM-SA	r=.085	r=.079	r=.085
ASYM-SA	.533	.537	.550
		PSFP Coupler	
SYM-SA	.148	.149	.145
ASYM-SA	.314	.321	.321
SYM-CA	.153	.146	.143
ASYM-CA	.335	.345	.281
		Zwislocki Coupler	
SYM-SA	.147	.148	.147
ASYM-SA	.339	.333	.337
SYM-CA	.206	.083	.108
ASYM-CA	.535	.510	.492

*$r_{critical}$=.56, df=18, *p*=.01

Table 8

Means ($\overline{X}$) and Standard Deviations (SD) for Ten Intensity Measurements under Identical Experimental Conditions for Intensity Reliability Assessment

Mean Threshold Driving Voltage	Condition	Intensity					
		peakSPL		peSPL-peak		peSPL-rms	
		$\overline{X}$	SD	$\overline{X}$	SD	$\overline{X}$	SD
				NBS-9A Coupler			
.29 mv	SYM-SA	36.9 dB	0.39 dB	31.8 dB	0.22 dB	27.7 dB	0.43 dB
.22	ASYM-SA	34.6	0.44	30.7	0.30	27.4	1.31
				PSFP Coupler			
.29	SYM-SA	32.2	0.21	28.5	0.34	25.4	0.34
.22	ASYM-SA	30.7	1.29	26.6	1.59	23.6	1.59
.42	SYM-CA	30.1	0.78	25.5	0.42	22.5	0.42
.31	ASYM-CA	29.6	1.04	24.8	0.31	21.5	0.28
				Zwislocki Coupler			
.29	SYM-SA	26.6	0.23	24.7	0.45	21.9	0.58
.22	ASYM-SA	25.8	0.20	22.7	0.35	19.7	0.27
.42	SYM-CA	24.0	0.61	20.8	0.51	18.1	0.69
.31	ASYM-CA	23.3	0.43	21.3	0.45	18.4	0.42

Table 9

Pearson r's and Coefficients of Determination (r^2) for Correlation of SYM and ASYM Thresholds with SA cushion

	Intensity					
	peakSPL		peSPL-peak		peSPL-rms	
Coupler	r*	r^2	r	r^2	r	r^2
NBS-9A	.56	.31	.57	.33	.56	.32
PSFP	.16	-	.15	-	.15	-
Zwislocki	.29	-	.41	-	.35	-

*$r_{critical}$=.56, df=18, p=.01

Table 10

Pearson r's and Coefficients of Determination (r^2) for Correlation of SYM and ASYM Thresholds with CA Cushion

	Intensity					
	peakSPL		peSPL-peak		peSPL-rms	
Coupler	r*	r^2	r	r^2	r	r^2
PSFP	.36	-	.33	-	.29	-
Zwislocki	.63	.40	.53	-	.61	.34

*$r_{critical}$=.56, df-18, p=.01

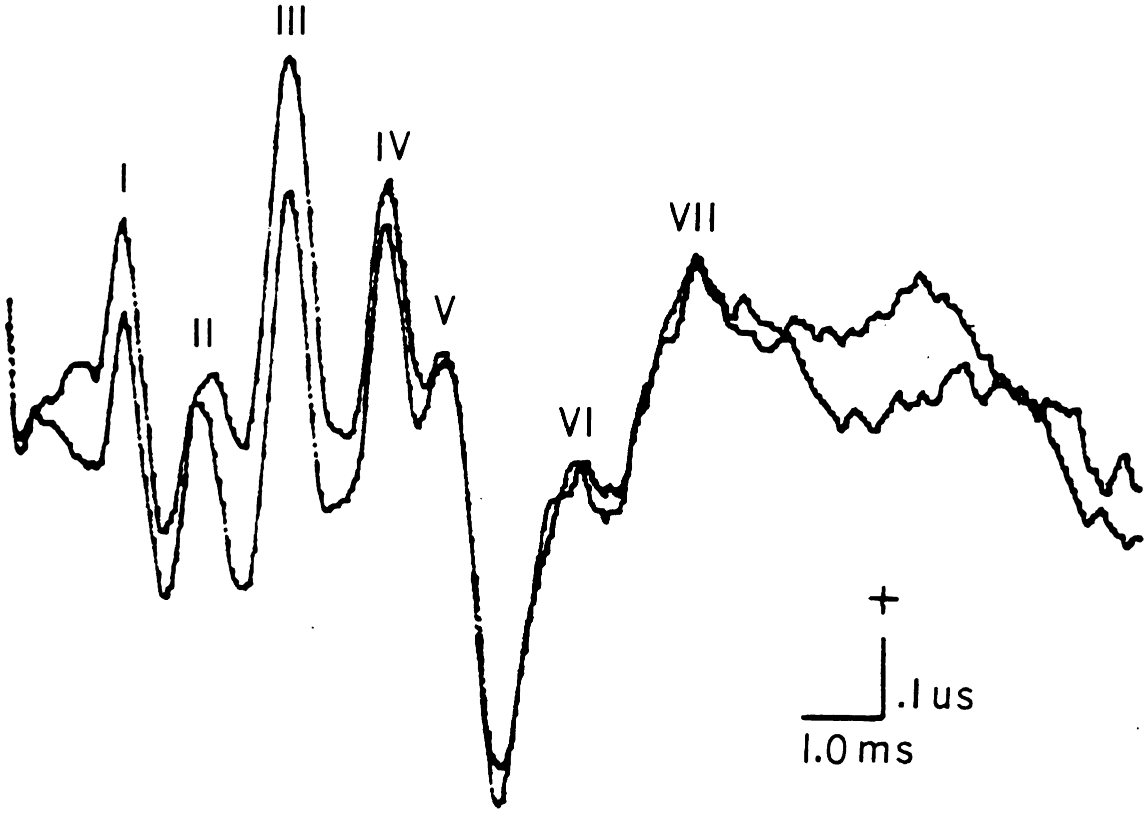
Table 11

Pearson r's and Coefficients of Determination for Correlation of Same Stimuli in Different Headsets

	Intensity					
	peakSPL		peSPL-peak		peSPL-rms	
Coupler	r*	r^2	r	r^2	r	r^2
			SYM Stimuli			
PSFP	.96	.92	.98	.95	.99	.99
Zwislocki	.39	-	.50	-	.50	-
			ASYM Stimuli			
PSFP	.97	.95	.97	.94	.93	.87
Zwislocki	.78	.62	.75	.57	.78	.61

*$r_{critical}$=.56, df=18, p=.01

FIGURES



Right Ear stimulation at 85 dB nHL (click stimulus)
C_z - A_2 montage

Figure 1. Auditory evoked brainstem potential waveform recorded from audiometrically, otologically and neurologically normal young adult.

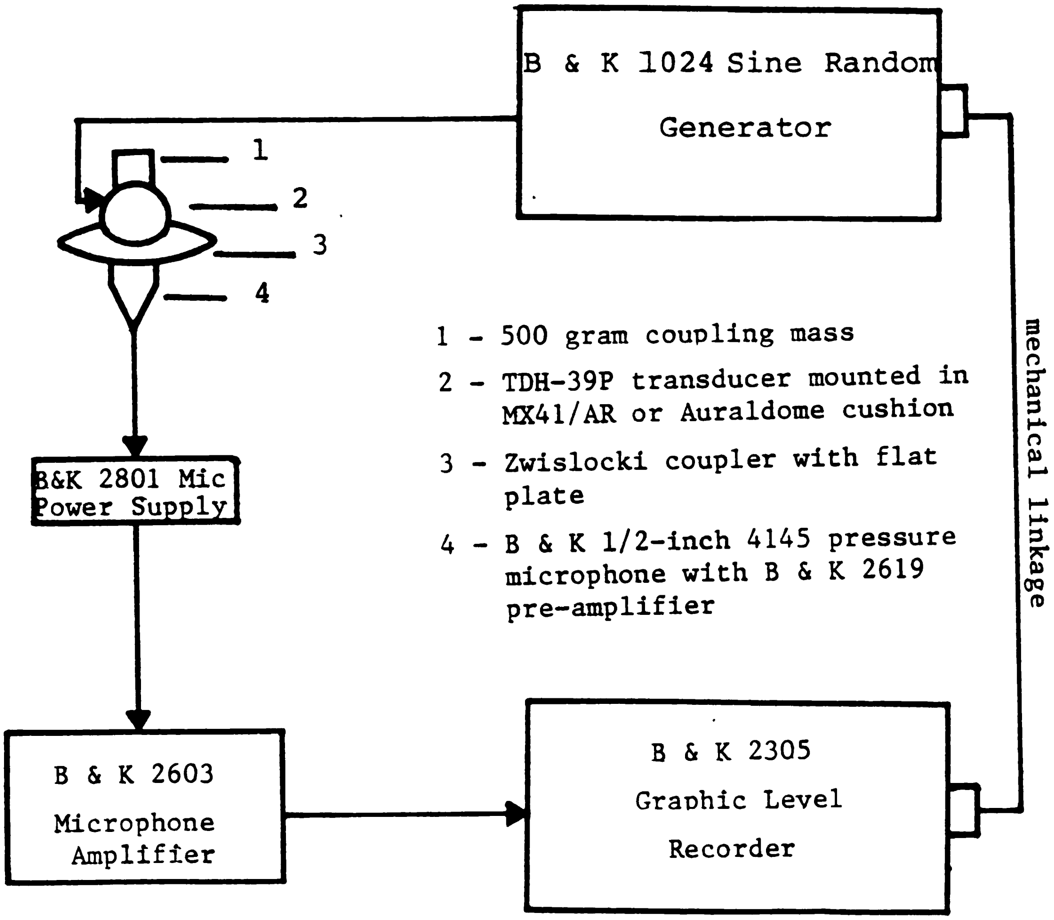


Figure 2. Diagram of test equipment for frequency response curves for pre- and post-test electroacoustical calibration of headsets.

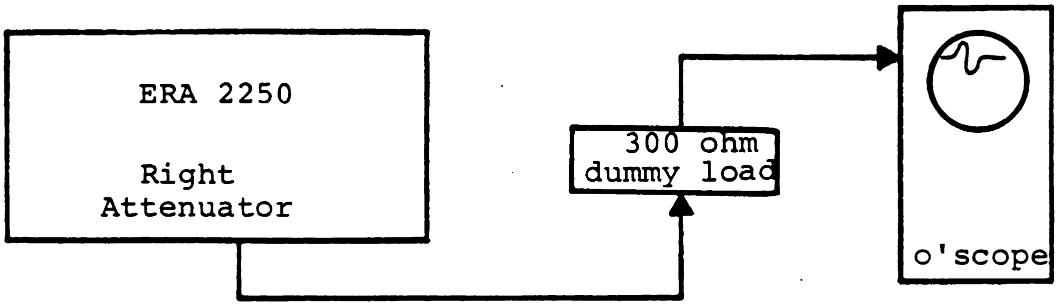


Figure 3. Diagram of test equipment for electronic confirmation of right attenuator linearity.

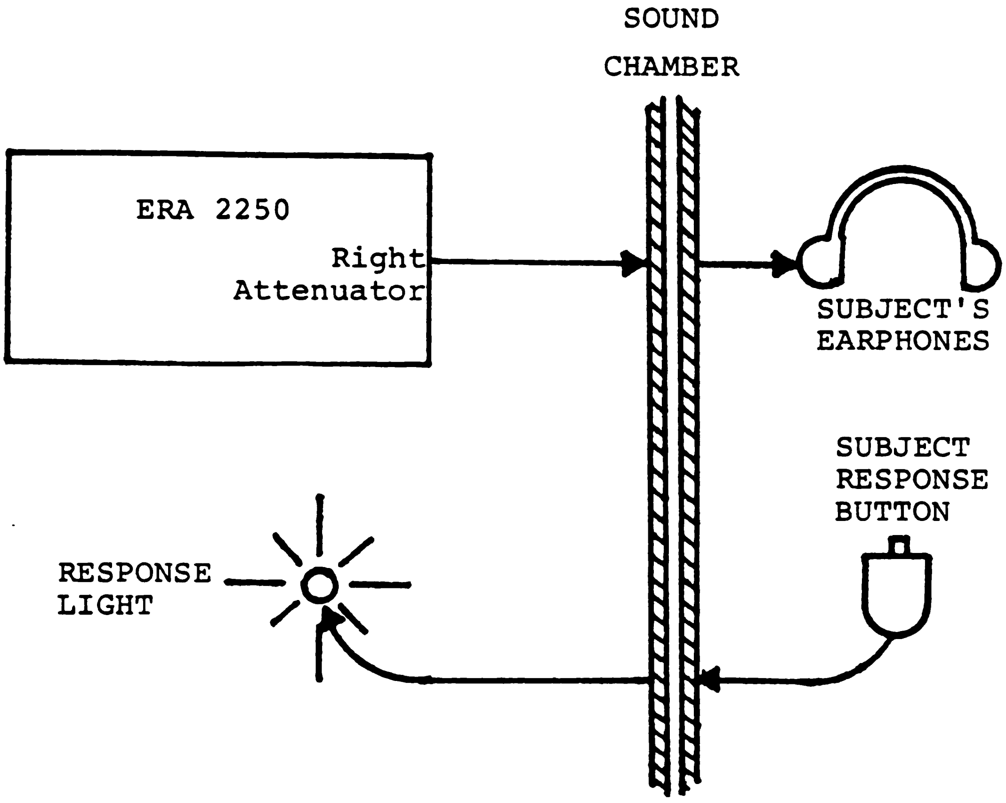


Figure 4. Diagram of experimental apparatus for behavioral calibration of stimulus intensity.

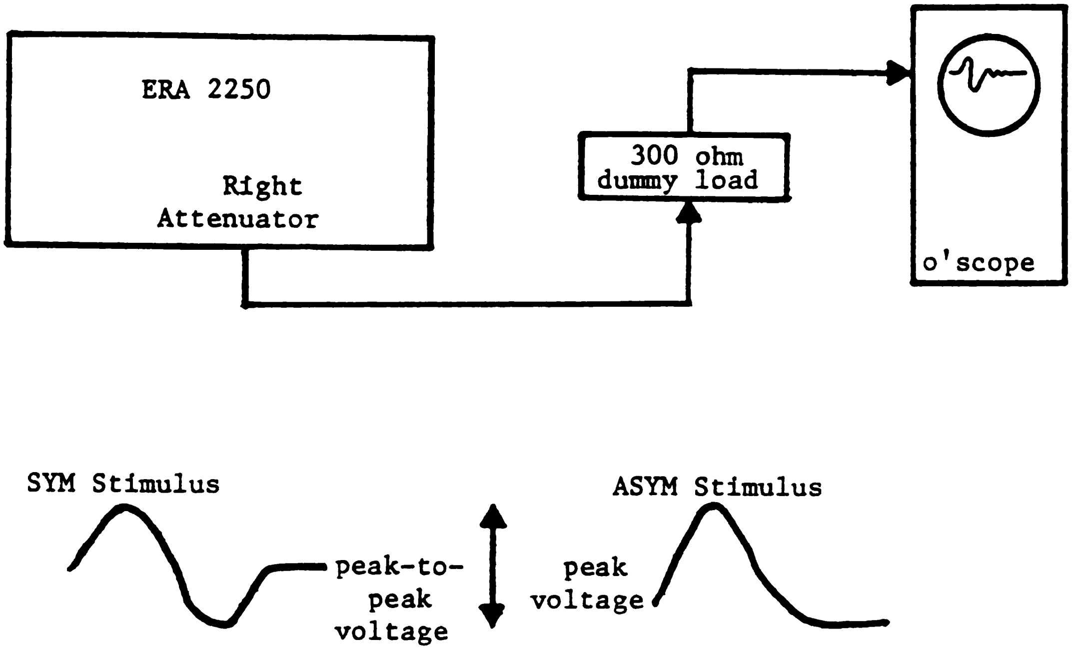
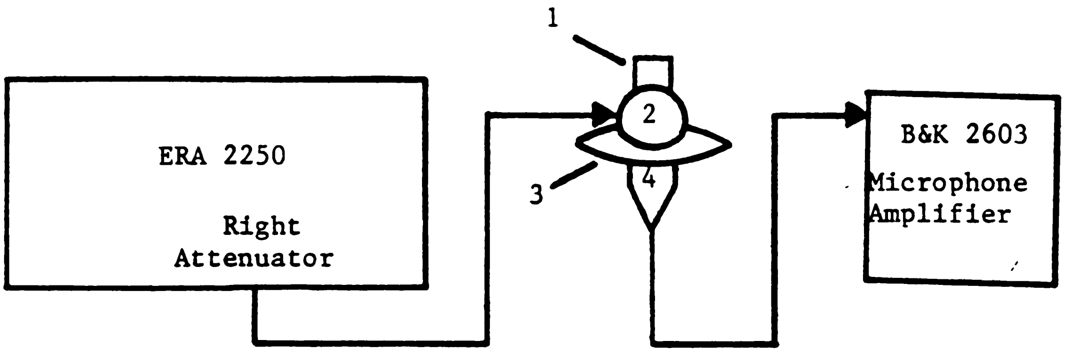


Figure 5. Diagram of equipment and method for determination of threshold driving voltages.



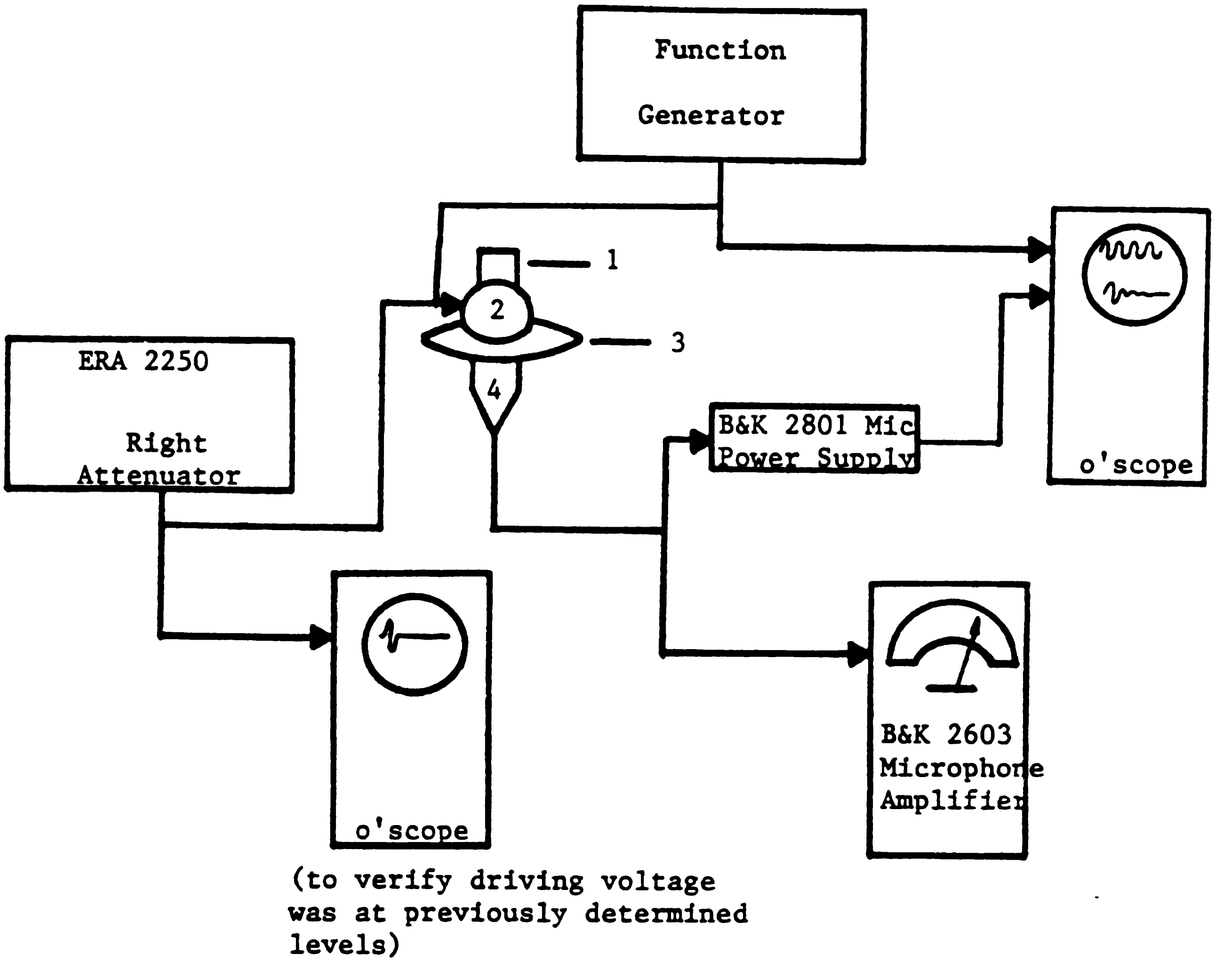
1 - 500 gram coupling mass

2 - TDH-39P transducer mounted in MX41/AR or Auraldome cushion

3 - Coupler (NBS-9A, PSFP, Zwislocki)

4 - B & K microphone and pre-amplifier

Figure 6. Diagram of test equipment for peakSPL sound level measurements.



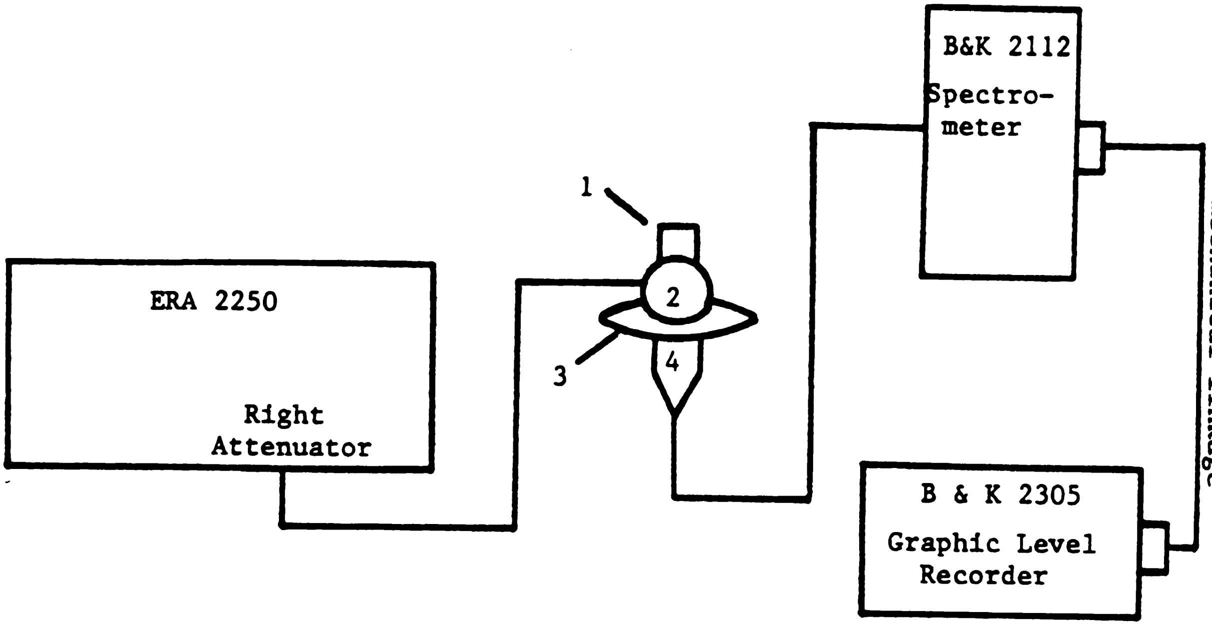
1 - 500 gram coupling mass

2 - TDH-39P transducer mounted in MX41/AR or Auraldome cushion

3 - Coupler (NBS-9A, PSFP, Zwislocki)

4 - B & K microphone and pre-amplifier

Figure 7. Diagram of test equipment for peak equivalent SPL measurements.



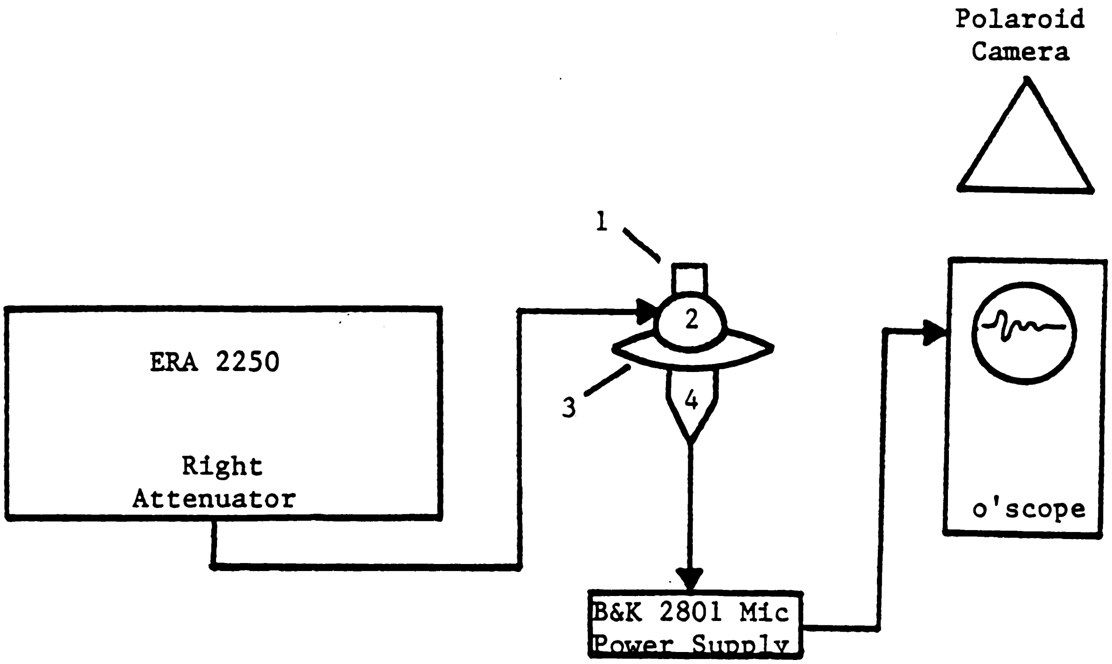
1 - 500 gram coupling mass

2 - TDH-39P transducer mounted in MX41/AR or Auraldome cushion

3 - Coupler (NBS-9A, PSFP, Zwislocki)

4 - B & K microphone and pre-amplifier

Figure 8. Diagram of equipment for spectral recordings of AEBP stimuli.



1 - 500 gram coupling mass

2 - TDH-39P transducer mounted in MX41/AR or Auraldome cushion

3 - Coupler (NBS-9A, PSFP, Zwislocki)

4 - B & K microphone and pre-amplifier

Figure 9. Diagram of equipment for photocopying AEBP stimulus acoustical waveforms from oscilloscope.

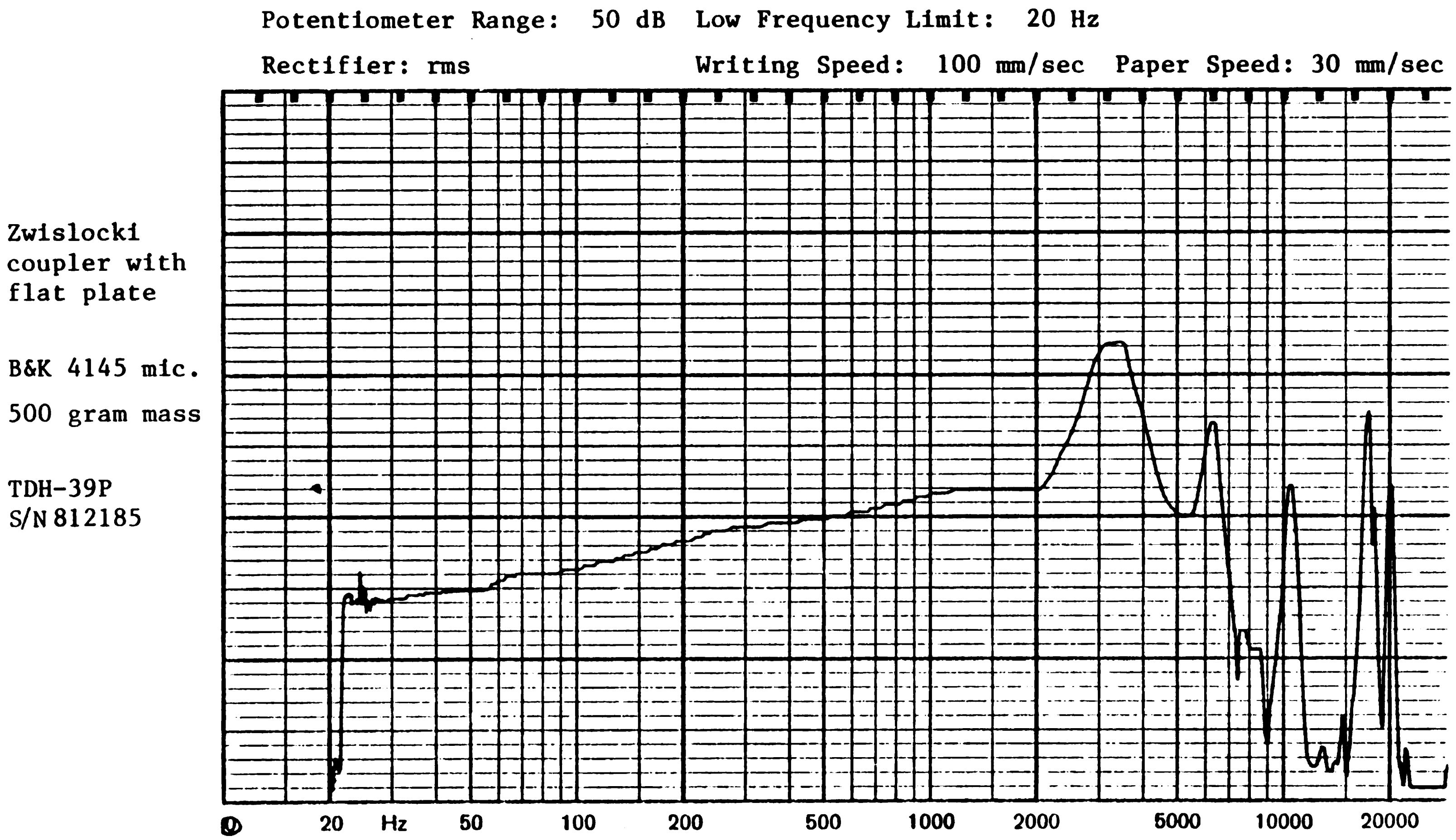


Figure 10. Pre-test frequency response curve of TDH-39P transducer mounted in MX41/AR SA cushion.

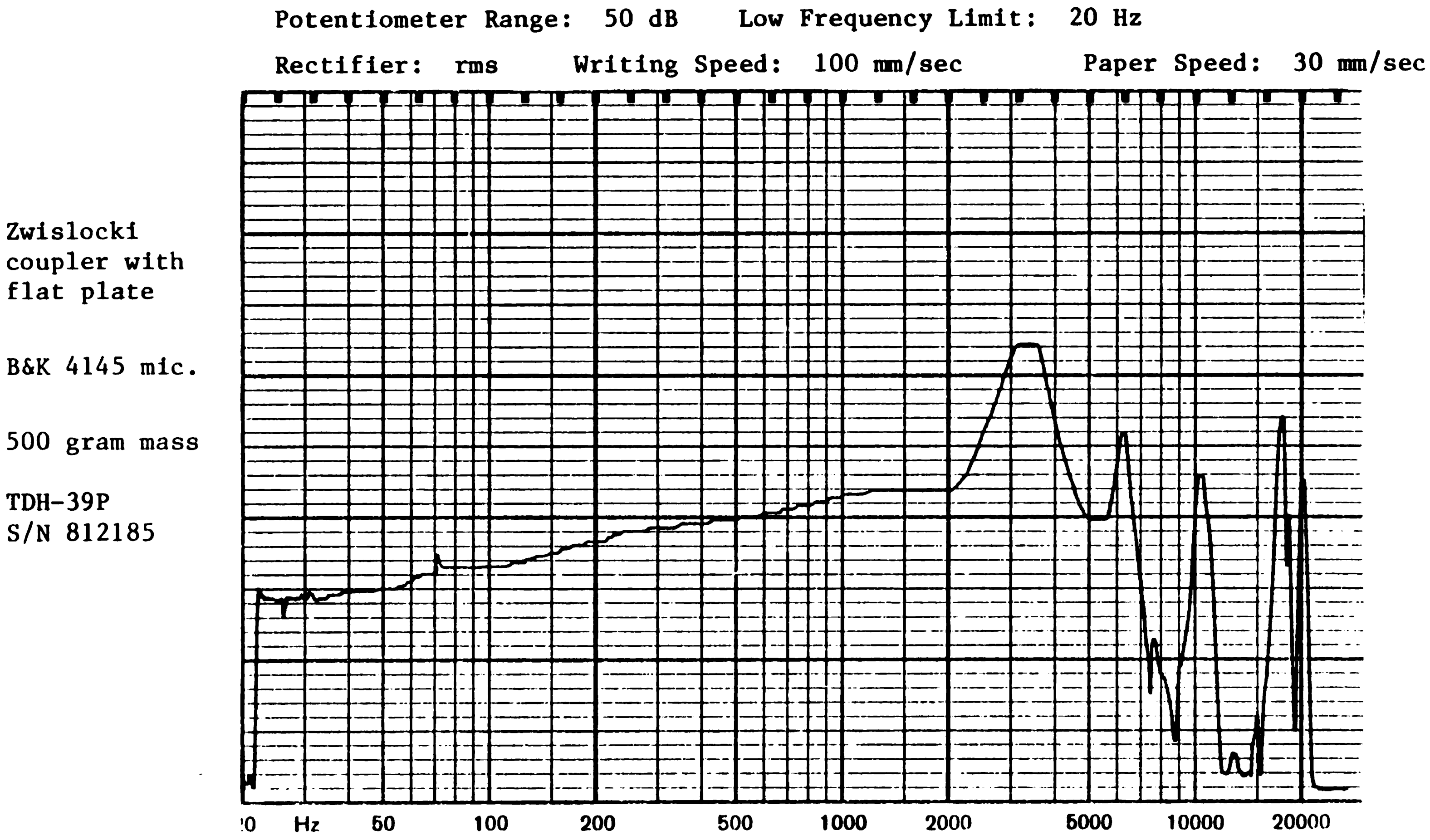


Figure 11. Post-test frequency response curve of TDH-39P transducer mounted in MX41/AR SA cushion.

Zwislocki
coupler with
flat plate

B&K 4145 mic.

500 gram mass

TDH-39P
S/N 812185

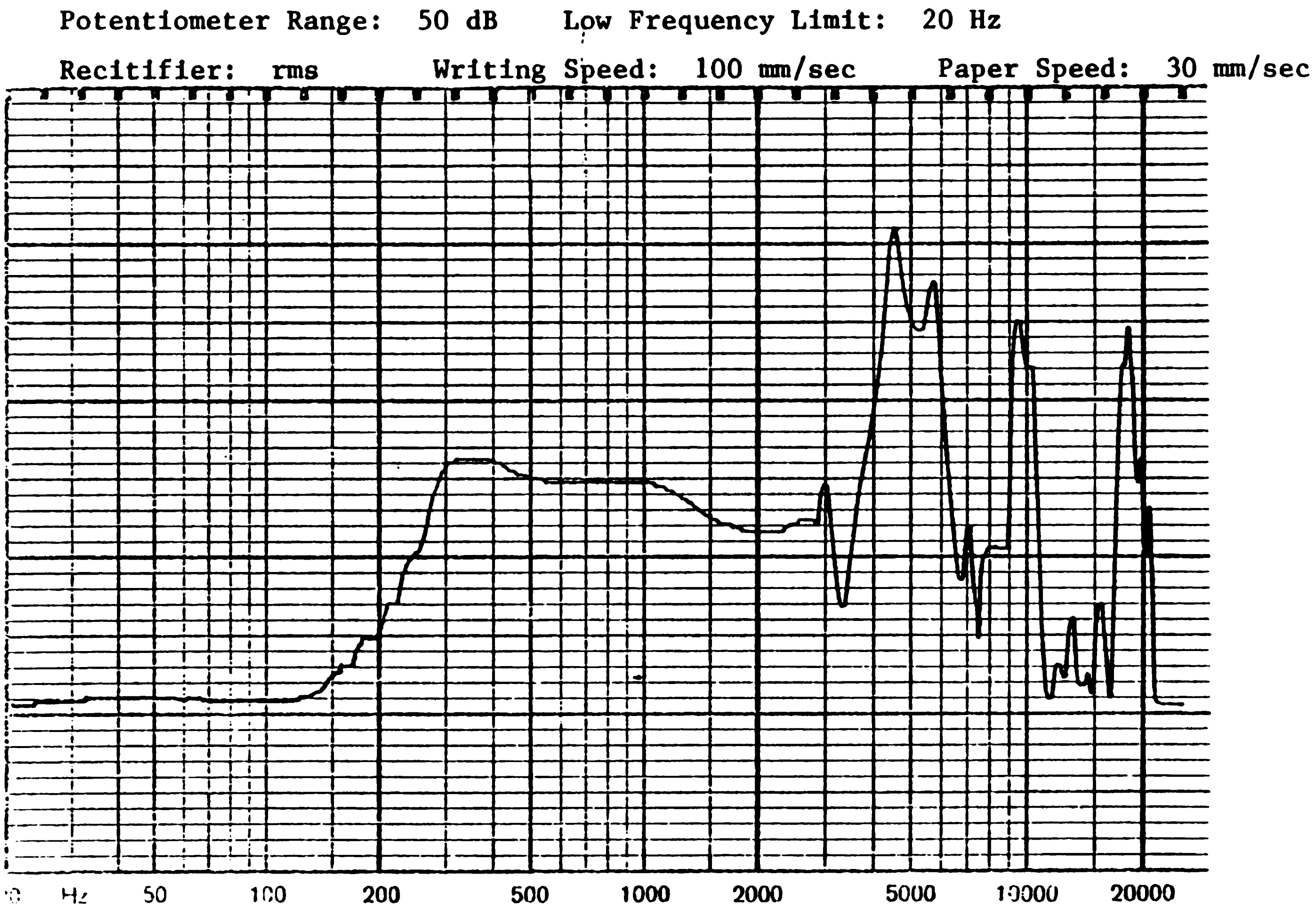


Figure 12. Pre-test frequency response curve of TDH-39P transducer mounted in CA Auraldome cushion.

Potentiometer Range: 50 dB Low Frequency Limit: 20 Hz

Recitifier: rms Writing Speed: 100 mm/sec Paper Speed: 30 mm/sec

Zwislocki
coupler with
flat plate

B&K 4145 mic.

500 gram mass

TDH-39P
S/N 812185

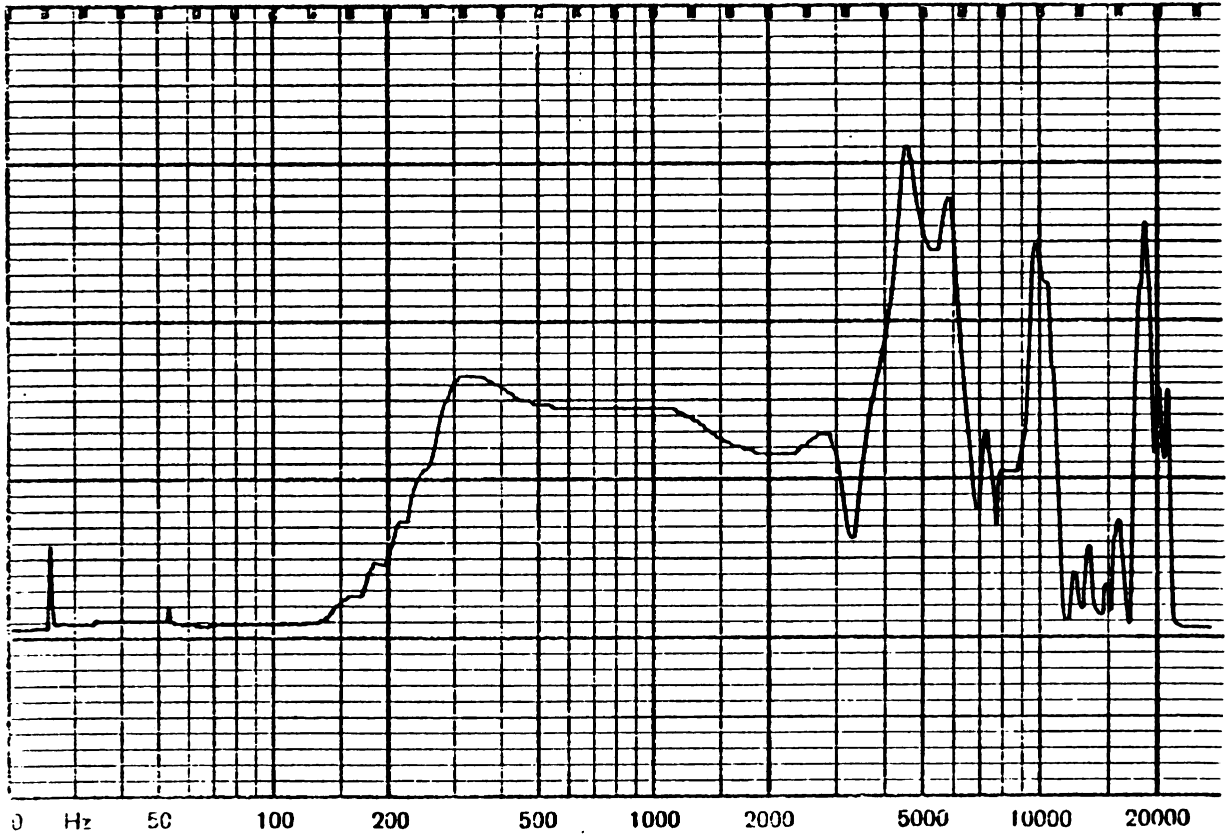


Figure 13. Post-test frequency response curve of TDH-39P transducer mounted in CA Auraldome cushion.

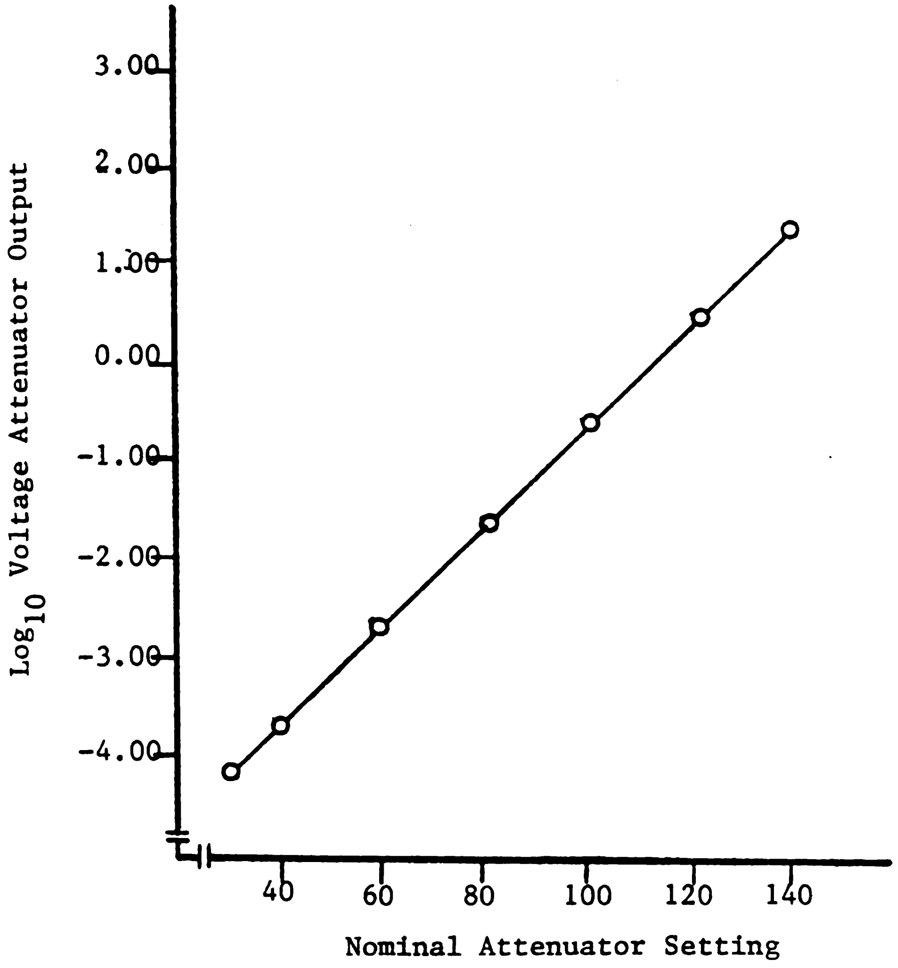
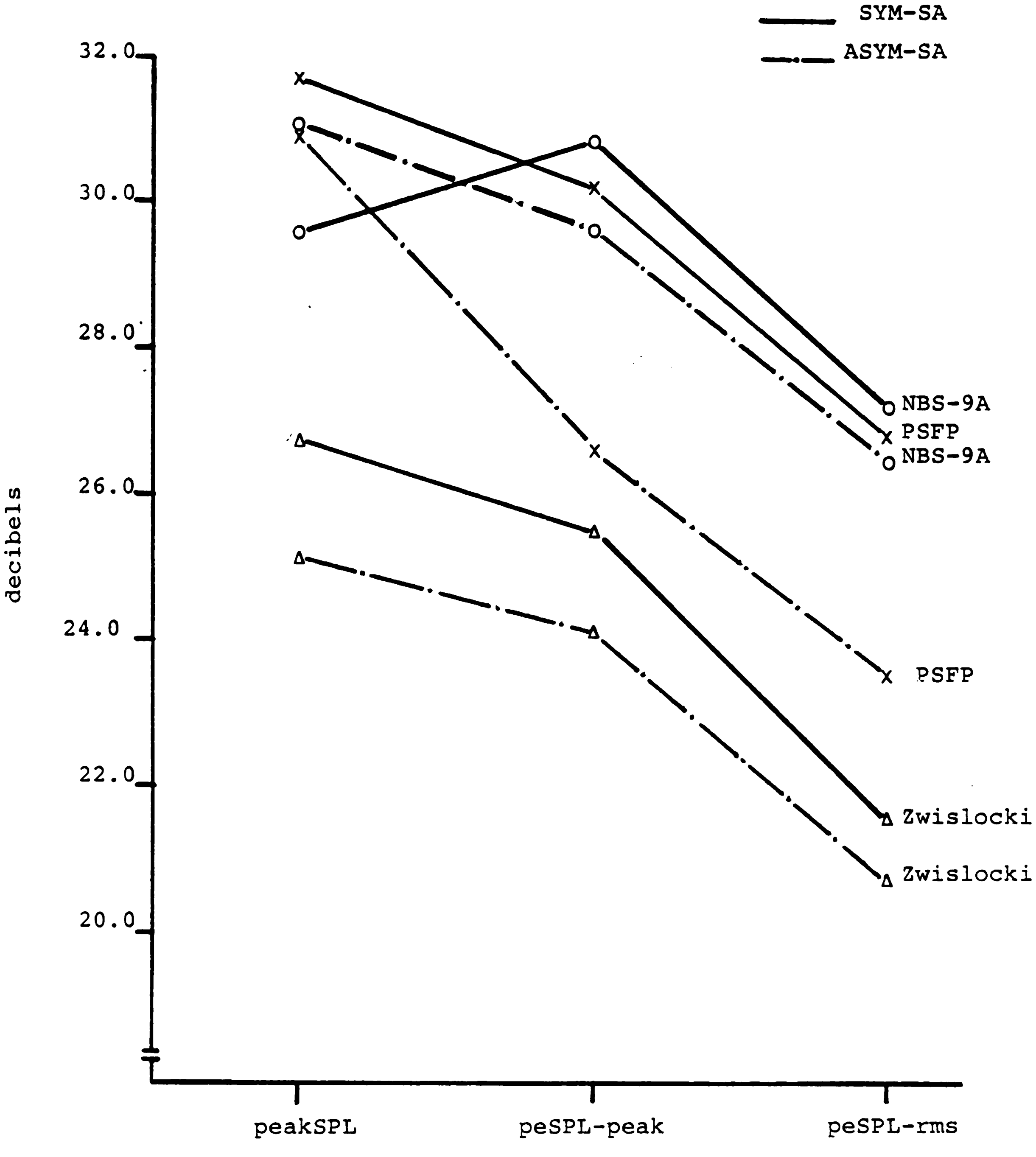


Figure 14. Attenuator linearity as represented by a graph of $\log_{10}$ voltage attenuator output as a function of nominal attenuator setting.



INTENSITY CALIBRATION

Figure 15. Graphic representation of three-coupler ANOVA results.

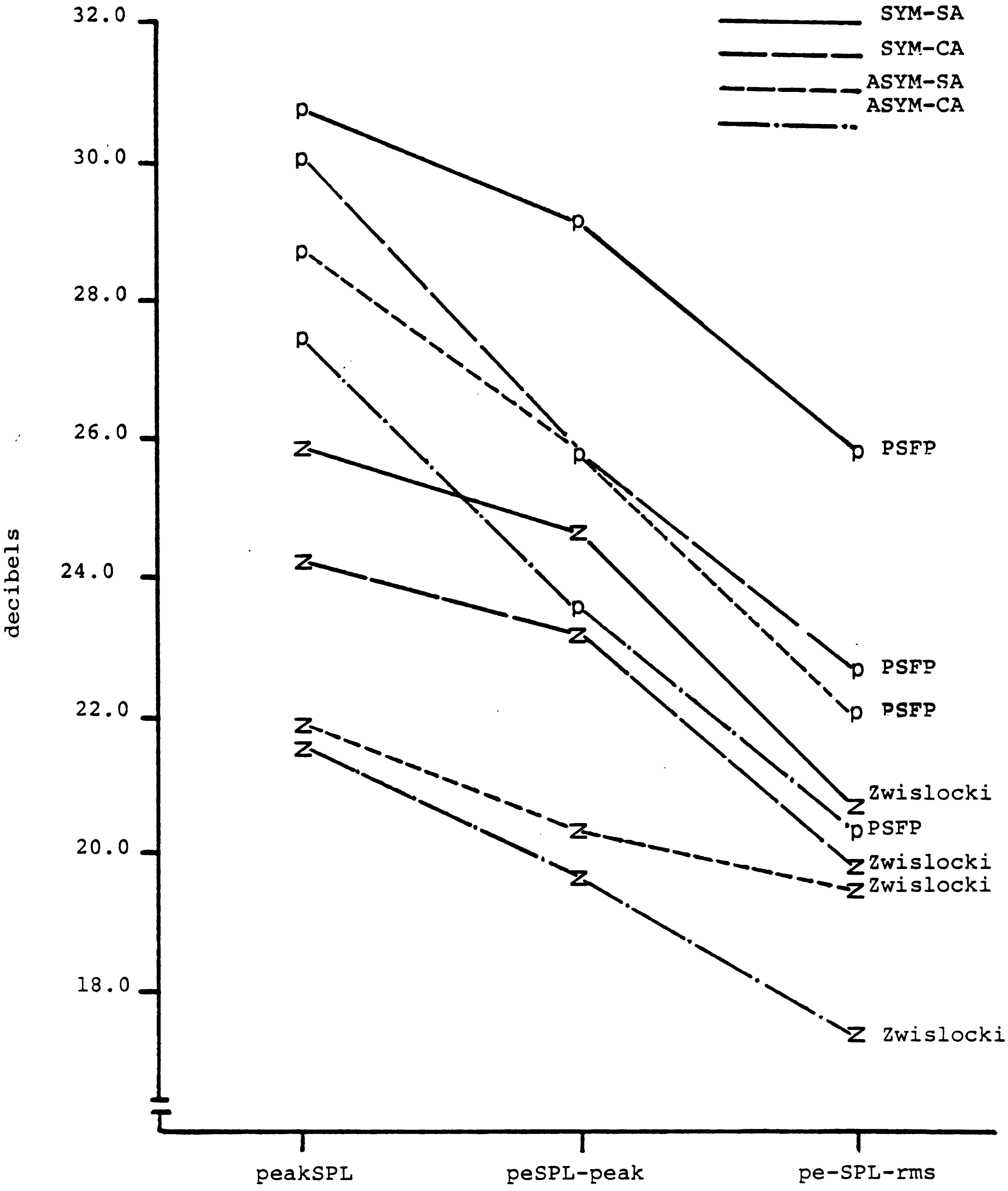


Figure 16. Graphic representation of two-coupler ANOVA results.

Input: 50 dB

Meter Range:
60 dB SL

Range Multi-
plier:
-20 dB

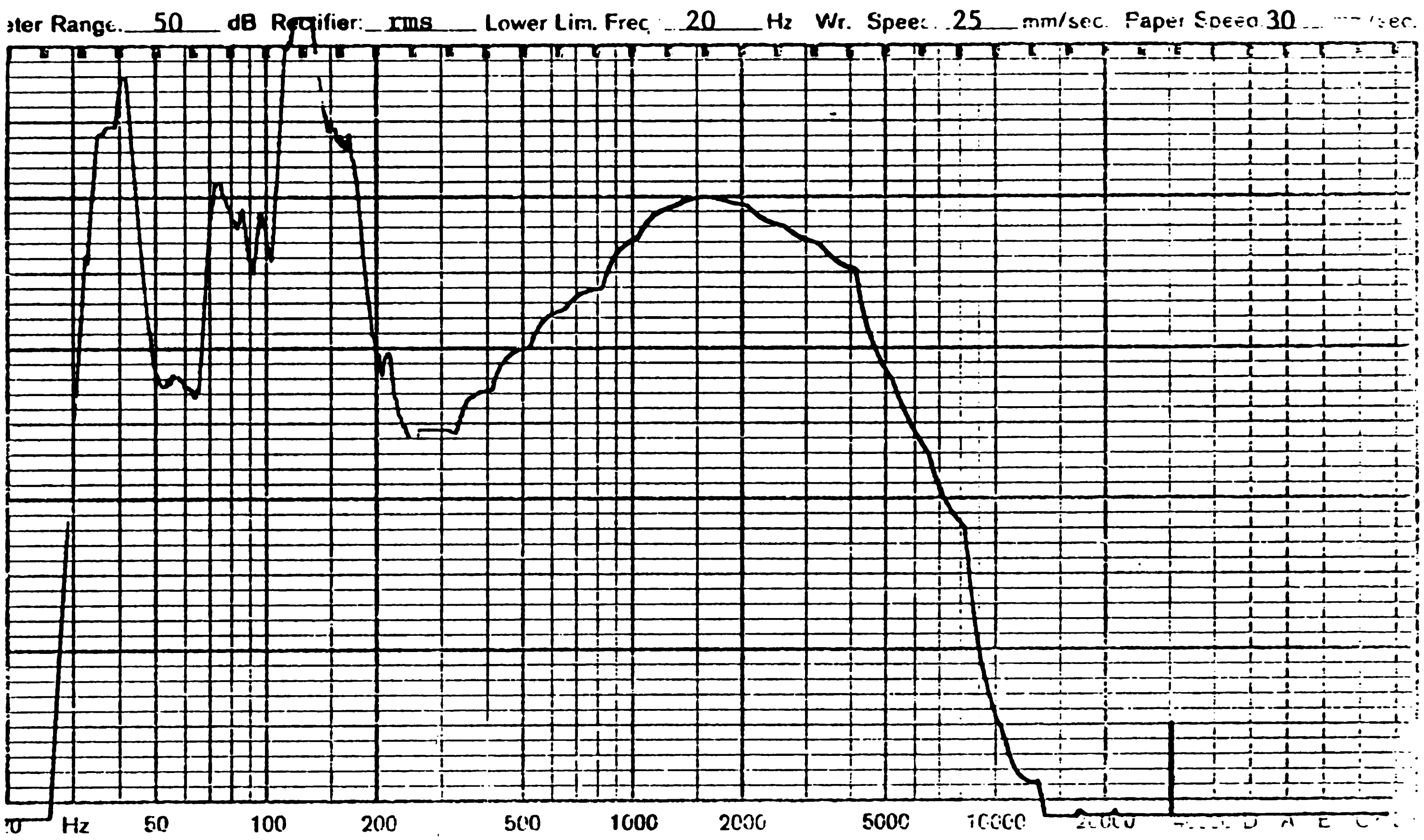


Figure 17. Third-octave spectrum of SYM stimulus/SA cushion generated in NBS-9A coupler.

Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

Figure 18. Third-octave spectrum of ASYM stimulus/SA cushion generated in NBS-9A coupler.

Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

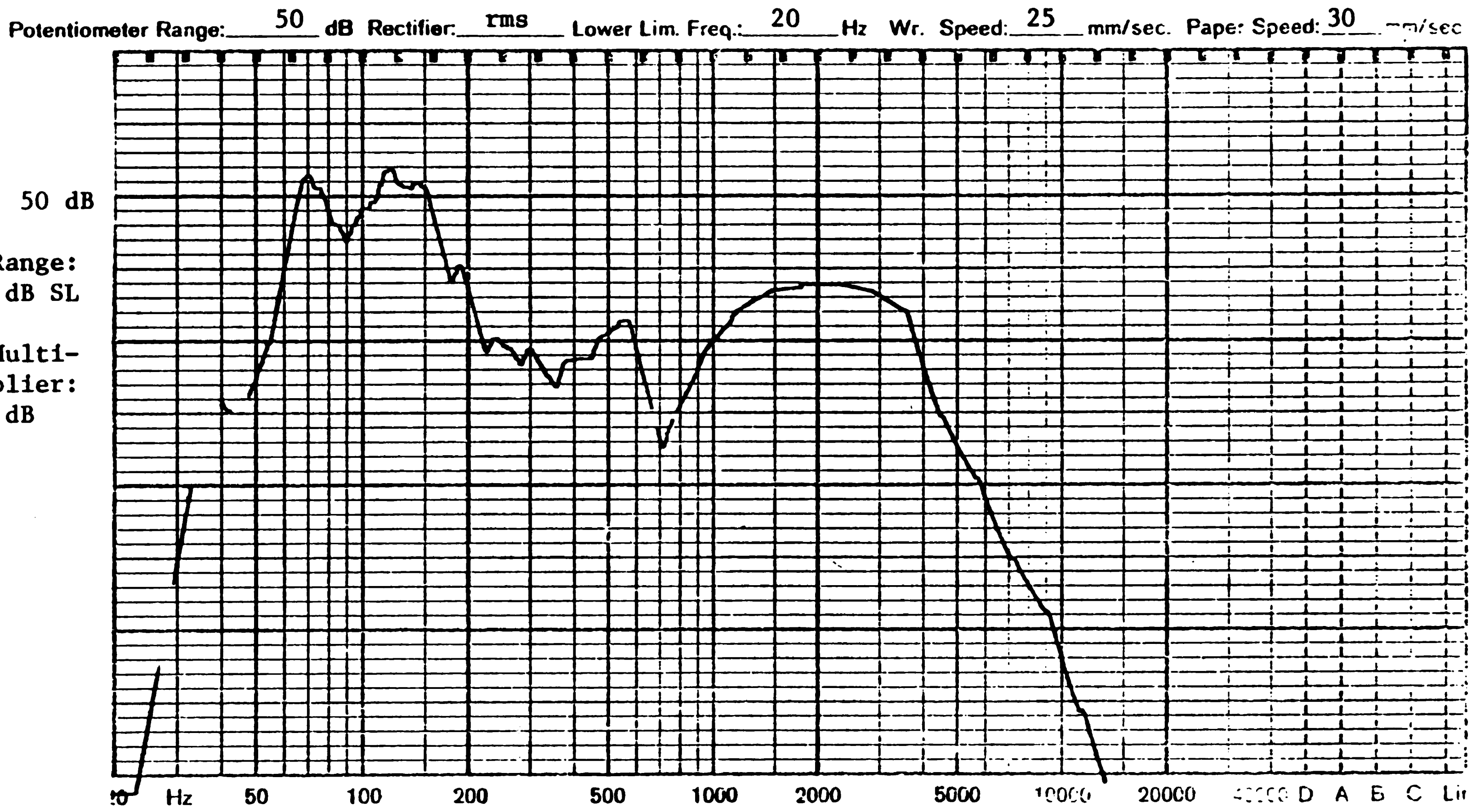


Figure 19. Third-octave spectrum of SYM stimulus/SA cushion generated in PSFP coupler.

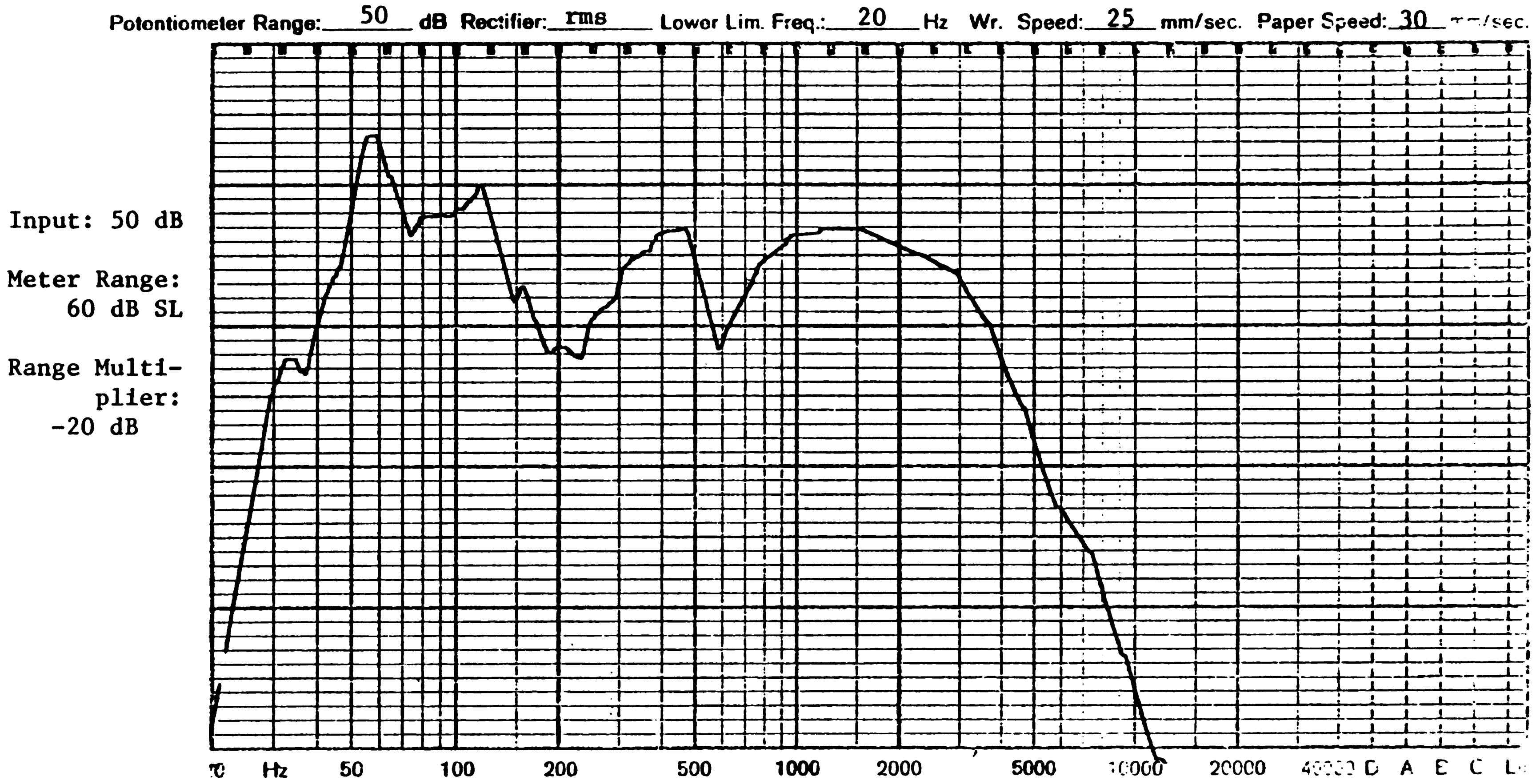


Figure 20. Third-octave spectrum of ASYM stimulus/SA cushion generated in PSFP coupler.

Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

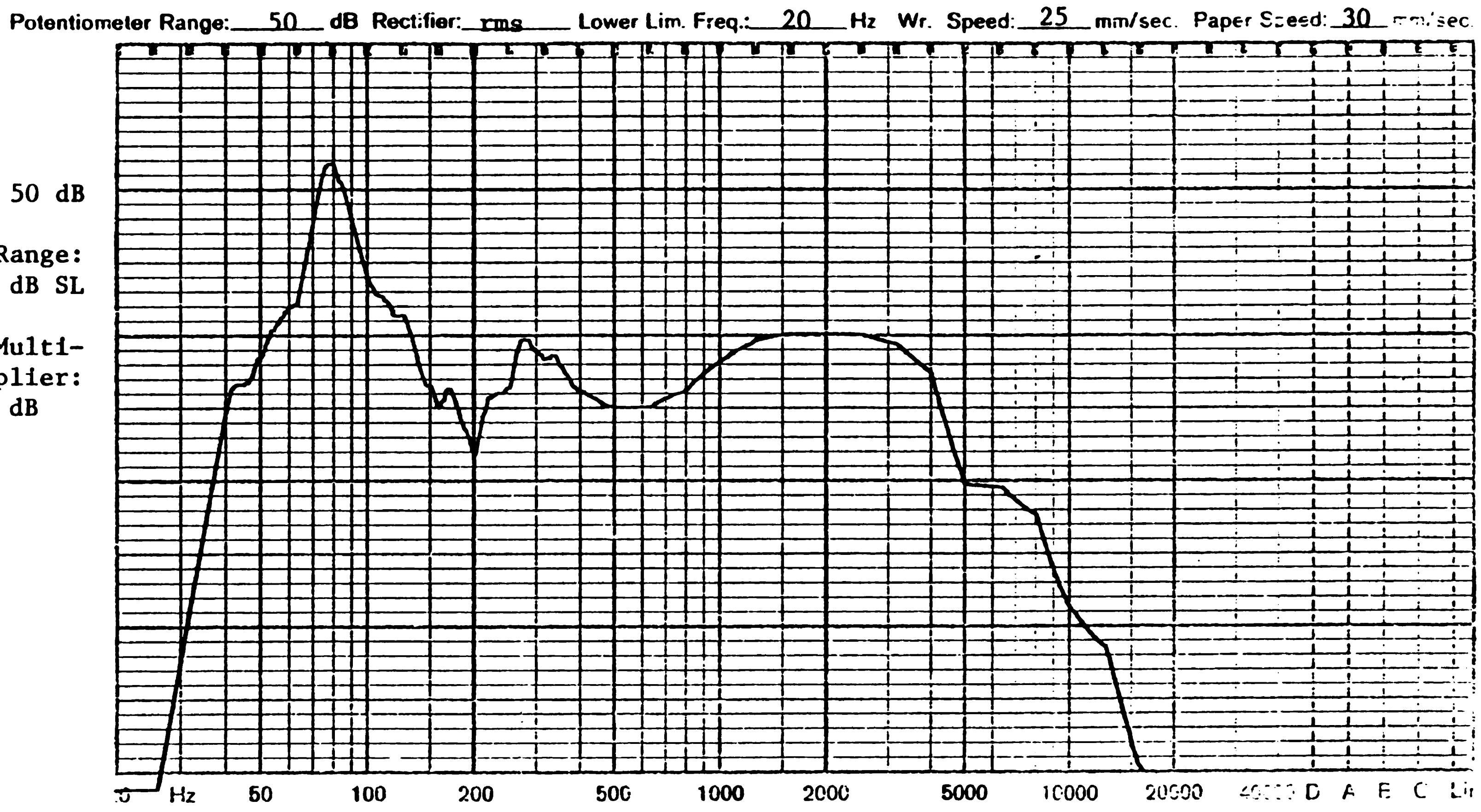
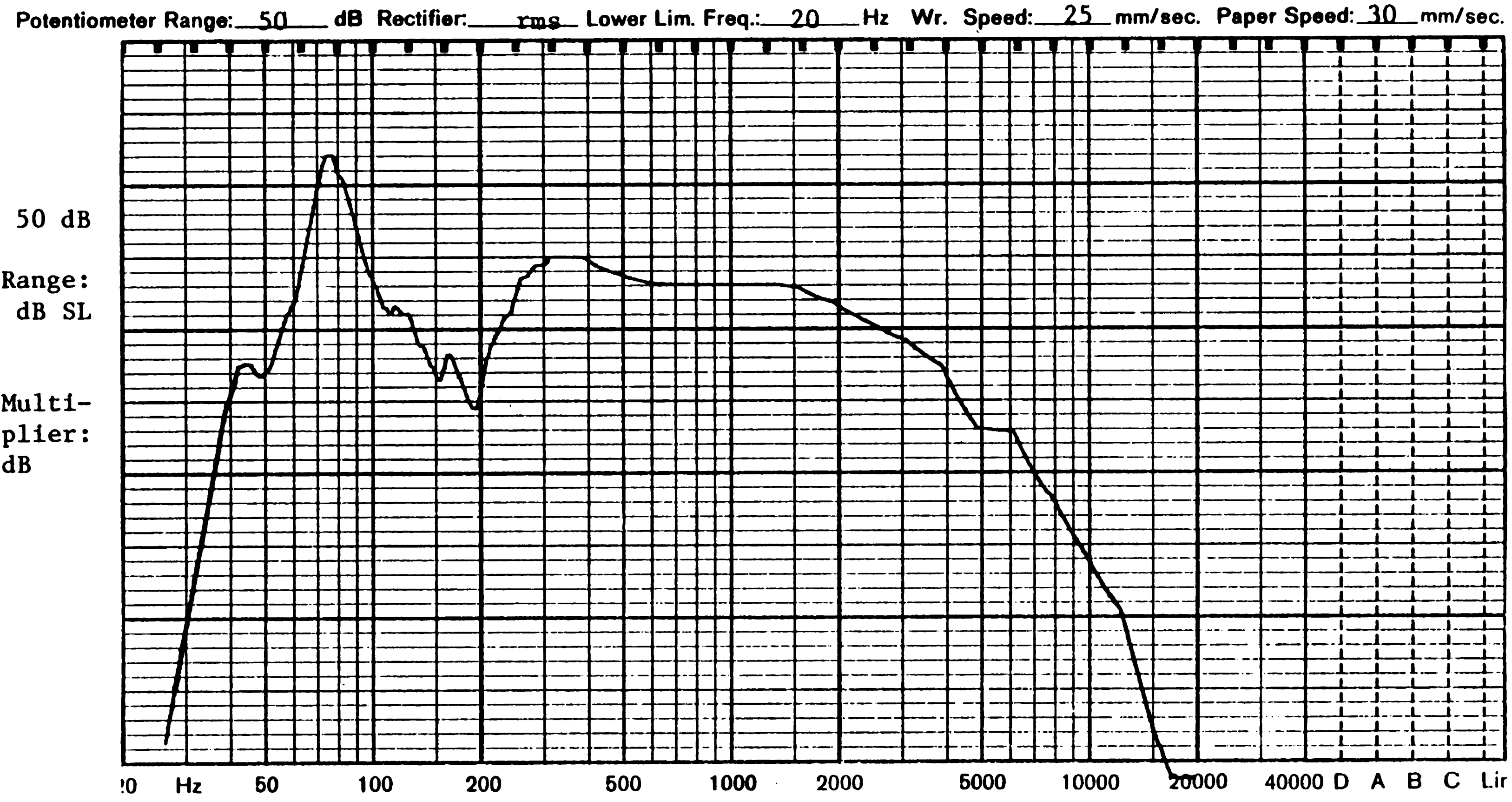


Figure 21. Third-octave spectrum of SYM stimulus/CA cushion generated in PSFP coupler.



Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

Figure 22. Third-octave spectrum of ASYM stimulus/CA cushion generated in PSFP coupler.

Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

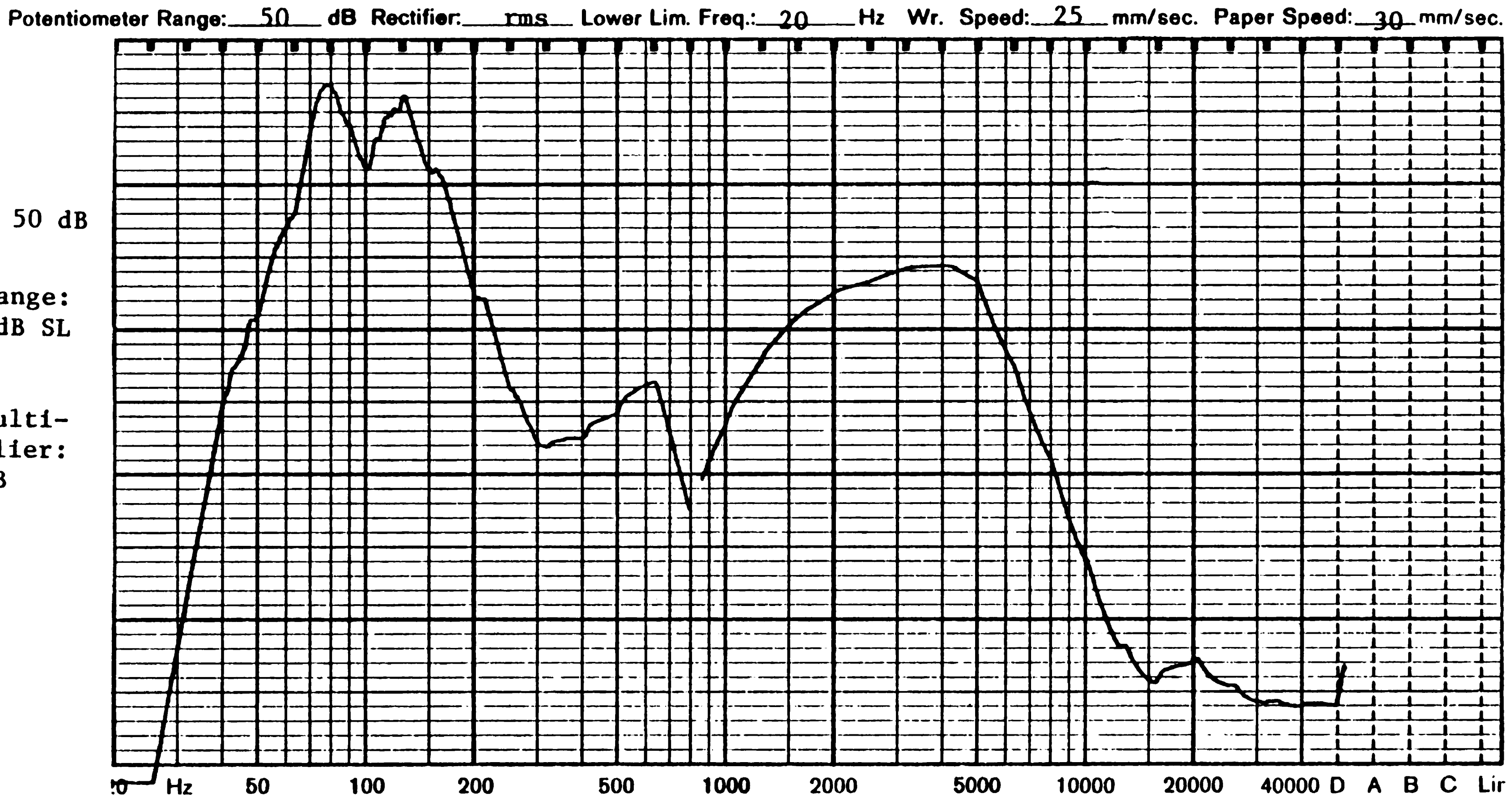


Figure 23. Third-octave spectrum of SYM stimulus/SA cushion generated in Zwislocki coupler.

Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

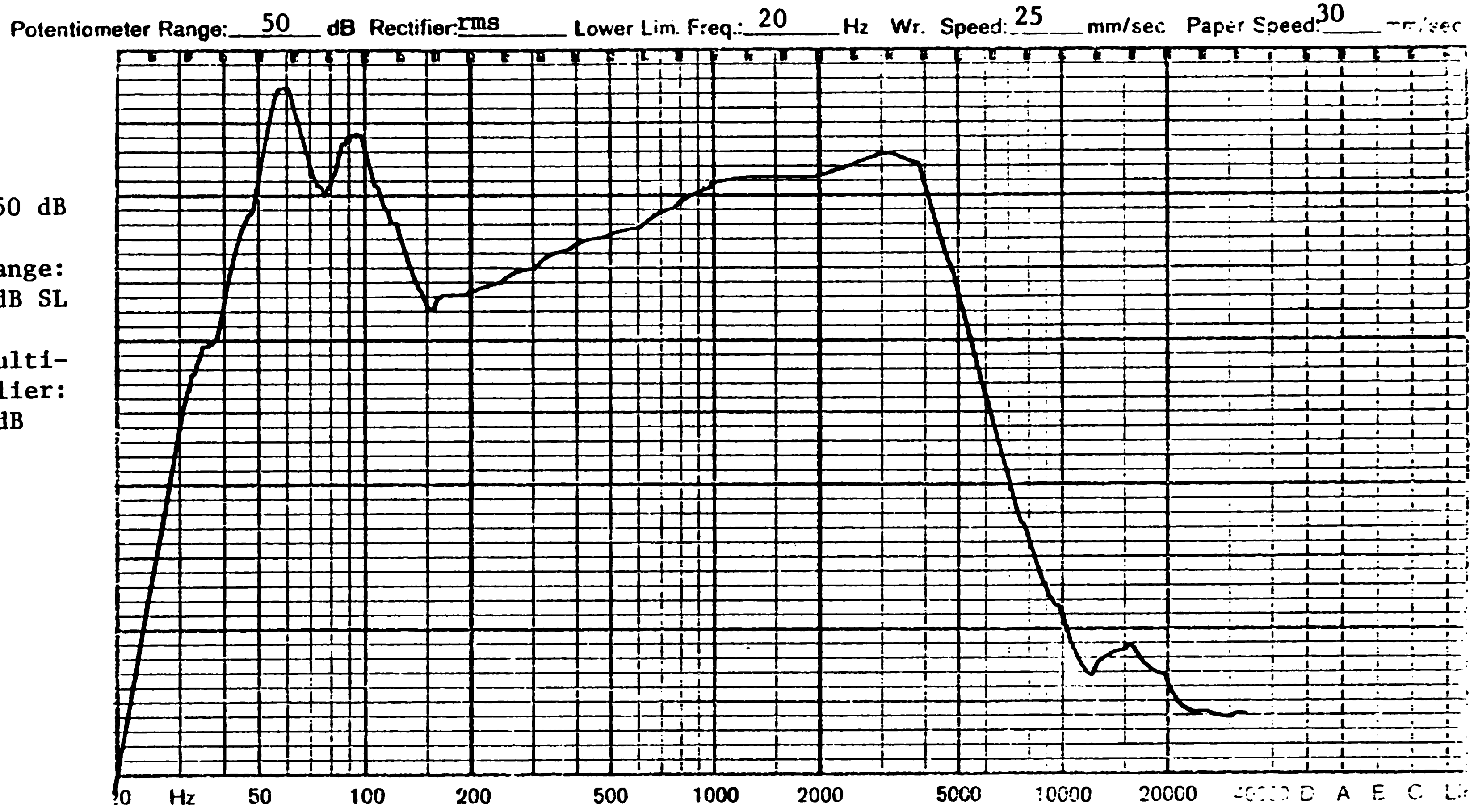
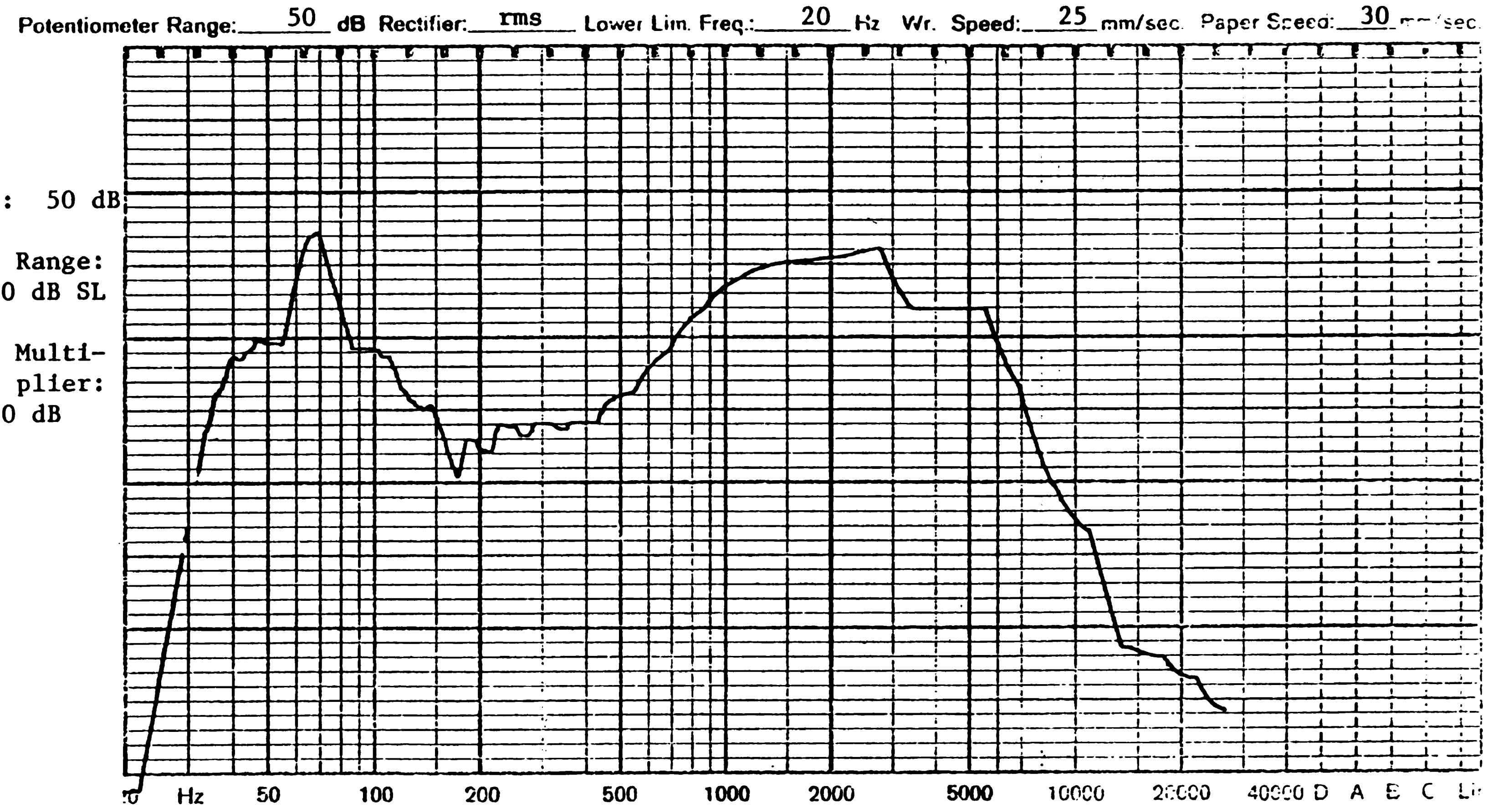


Figure 24. Third-octave spectrum of ASYM stimulus/SA cushion generated in Zwislocki coupler.



Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

Figure 25. Third-octave spectrum of SYM stimulus/CA cushion generated in Zwislocki coupler.

Input: 50 dB

Meter Range:
60 dB SL

Range Multiplier:
-20 dB

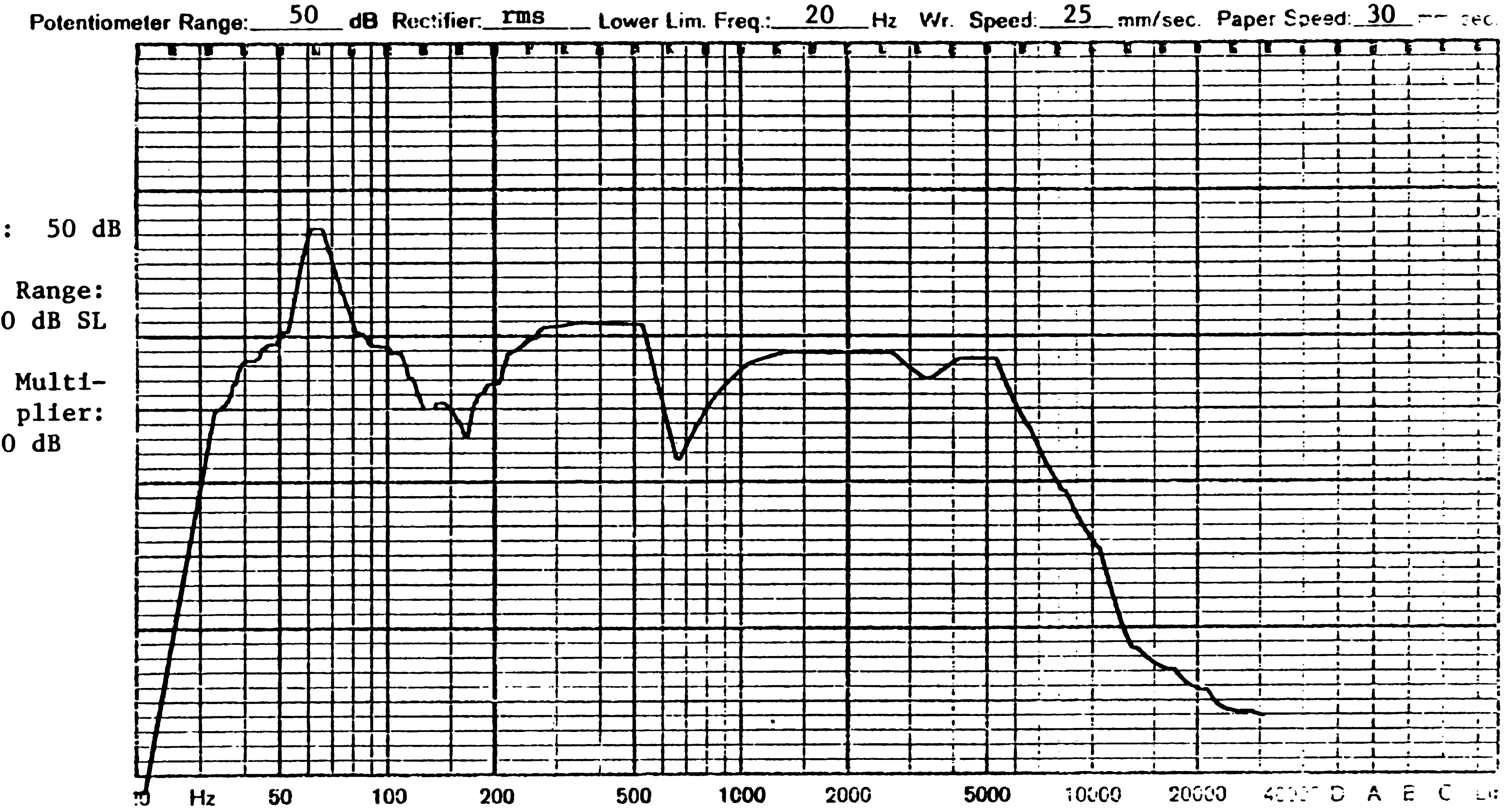


Figure 26. Third-octave spectrum of ASYM stimulus/CA cushion generated in Zwislocki coupler.

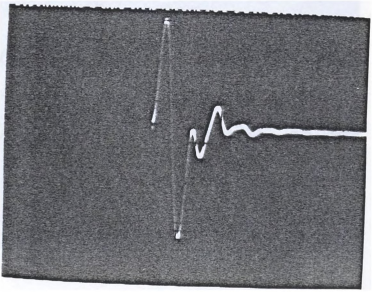


Figure 27. Acoustical waveform of SYM stimulus/ SA cushion generated in NBS-9A coupler.

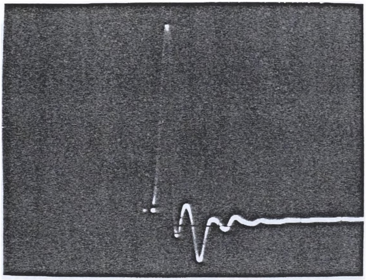


Figure 28. Acoustical waveform of ASYM stimulus/SA cushion generated in NBS-9A coupler.

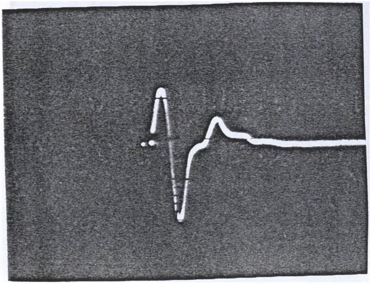


Figure 29. Acoustical waveform of SYM stimulus/SA cushion generated in PSFP coupler.

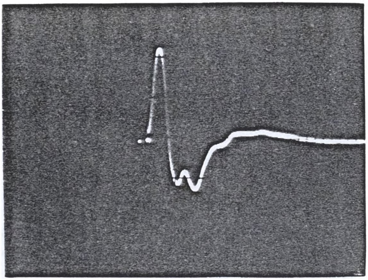


Figure 30. Acoustical waveform of ASYM stimulus/SA cushion generated in PSFP coupler.

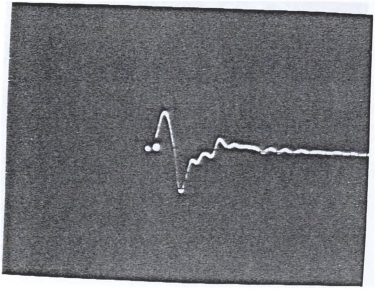


Figure 31. Acoustical waveform of SYM stimulus/CA cushion generated in PSFP coupler.

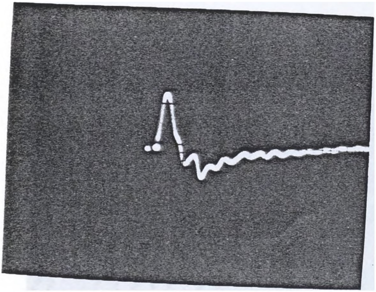


Figure 32. Acoustical waveform of ASYM stimulus/CA cushion generated in PSFP coupler.

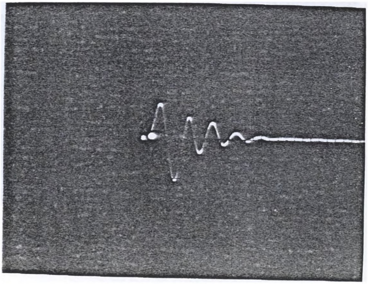


Figure 33. Acoustical waveform of SYM stimulus/SA cushion generated in Zwislocki coupler.

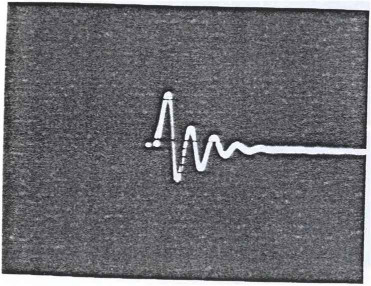


Figure 34. Acoustical waveform of ASYM stimulus/SA cushion generated in Zwislocki coupler.

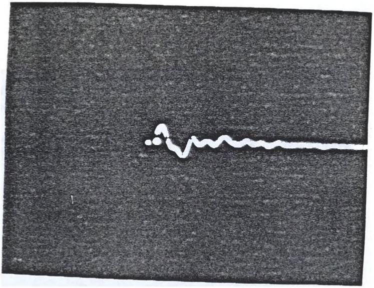


Figure 35. Acoustical waveform of SYM stimulus/CA cushion generated in Zwislocki coupler.

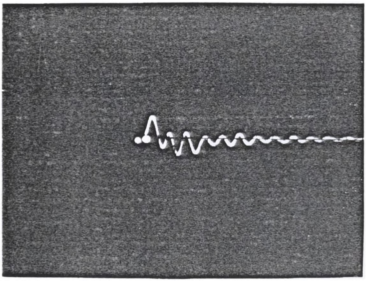


Figure 36. Acoustical waveform of ASYM stimulus/CA cushion generated in Zwislocki coupler.