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THE THRESHOLD OF THE STAPEDIUS REFLEX TO SELECTED ACOUSTIC STIMULI IN NORMAL HUMAN EARS

by

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CHAPTER I

INTRODUCTION AND HISTORY

The middle ear muscles

Knowledge of the acoustic reflex dates back to Hensen's observation in 1878 of the contraction of the middle ear muscles in dogs upon exposure to an intense acoustic stimulus (Wever and Lawrence, 1954; Jepsen, 1963). A number of significant animal investigations followed, but little was written about the acoustic reflex in man because the necessary instrumentation was not available for this precise study on the human ear. In 1946 Metz published his classic monograph which demonstrated that the contraction of the stapedius muscle causes measurable changes in the impedance measured at the tympanic membrane. The work of Metz led to numerous clinical and theoretical studies of the acoustic reflex in humans and animals. The extensive literature available on the middle ear muscles suggests that further study of the stapedius reflex may contribute significantly to more sophisticated clinical diagnosis of middle and inner ear conditions, as well as providing knowledge of the physiological function of the middle ear muscles (Jepsen, 1963).

Anatomy, physiology, and nerve supply

The middle ear of man (and other mammals as well) contains two small muscles, the tensor tympani and the stapedius. According to Wever and Lawrence (1954) the former was first described by Eustachius in 1564, the latter by Varolius in 1591.

The stapedius muscle is phylogenetically the older of the two muscles; it develops from the hyoid arch and can be recognized in 13.5 mm embryos. The tensor is developed from the first bronchial arch and can be identified in 22 mm embryos (Jepsen, 1963).

The tensor tympani originates in a slender canal that travels above the bony Eustachian tube and is separated from it by a very thin partition of bone and fibrous tissue. The tensor tendon runs from the muscle through a bony channel, makes a turn around a hook on the promontory called the cochleariform process, and enters the middle ear cavity; it inserts on the medial side of the manubrium of the malleus (Kobrak, 1959; Wever and Lawrence, 1954). The bony channel acts as a pulley to change the direction of action from anterior to antero-medial (Kobrak, 1959).

Wever and Lawrence (1954) found that the mean length of the human tensor tympani was 25 mm with a cross section of 5.85 sq. mm.

Contraction of the tensor tympani pulls inward and forward, at a right angle to the ossicular chain, causing movement of the tympanic membrane (Jepsen, 1963).

The stapedius muscle lies in a bony canal posterior to the middle ear cavity, adjacent to the canal of the facial nerve. The stapedius tendon leaves the canal through the pyramidal eminence and is inserted on the neck of the stapes (Wever and Lawrence, 1954; Kobrak, 1959).

Wever and Lawrence (1954) measured several samples of human stapedius muscle and found the mean length to be 6.3 mm and mean cross section to be 4.9 sq. mm.

The stapedius pulls in a posterior direction with reference to the main axis of the stapes; the tension applied by the stapedius is opposite in direction to the tensor (Wever and Lawrence, 1954; Kobrak, 1959).

The tensor tympani is supplied by the mandibular branch of the trigeminal (Vth cranial) nerve. The stapedius muscle is innervated by the stapedius branch of the facial (VIIth cranial) nerve (Wever and Lawrence, 1954; Kobrak, 1959).

Both muscles are difficult to visualize, even during surgery, because of their casings. Bekesy suggested that this type of structure prevented the muscles from vibrating laterally when sound passes through the ossicular chain, thereby preventing distortion and damping (Kobrak, 1959; Jepsen, 1963).

Reflex arc

The contraction of the stapedius muscle to the presentation of a sound stimulus is considered to be a reflex arc. The afferent portion of the arc is the cochlear nerve; the crossover to the efferent neuron is thought to occur in the superior olivary complex. The efferent branch of the arc is the facial nerve which delivers the impulse to the stapedius muscle (Jepsen, 1963). Lüscher demonstrated that a stapedius muscle contraction could be elicited in animals in the form of a conditional reflex (Jepsen, 1963).

As early as 1886 Pollack demonstrated that the acoustic reflex was bilateral in nature (Lilly, 1964). In other words, sufficient acoustic stimulation of either ear will result in the presence of an acoustic reflex in both ears.

The acoustic reflex

Methods of recording intratympanic muscle activity

A variety of methods has been used to study the acoustic reflex. Some are far more accurate than others and some are only applicable to animal studies; it is difficult, for example, to find human subjects who will allow electrode implantation at the round window or in the intratympanic muscles.

A number of studies have used direct microscopic observation of the human tympanic cavity, either through traumatic perforations of the eardrum or during surgery.

A large number of animal and some human studies have used the electromyographic technique; this involves the recording of action potentials from electrodes at the tympanic muscles.

Tympanometric techniques have been used to measure changes in pressure in the external auditory canal. These changes in pressure are associated with small movements of the tympanic membrane that accompany contractions of the tympanic muscles. Møller (1964) warns, however, that small contractions of the stapedius may not produce measurable changes in air pressure.

Investigators working with experimental animals have used changes in the cochlear microphonic level, which are due to contractions of the tympanic muscles, for middle ear muscle study. This technique has been used by Wever and Vernon (1955a), Galambos and Ruppert (1959), and Simmons (1959), among others.

Another method, which has been used extensively in the past 15 years, is the measurement of changes in the acoustic impedance at the eardrum. With proper instrumentation, this method is relatively easy to perform, sensitive and reliable (Lilly, 1964). More detailed description of the impedance method can be found in a later section of this paper.

Response to acoustic stimulation

According to Wever and Lawrence (1954) the first report of an acoustic reflex was made by Hensen in 1878. Working with dogs, he was able to observe the contraction of the tensor tympani upon the presentation of sound. Two years later, Bockendale noticed changes in eardrum tension upon presentation of an acoustic stimulus to dogs and cats; he noted that the amount of increase in tension seemed to be related to the loudness of the stimulus (Wever and Lawrence, 1954).

In 1913 Mangold reported a diminution of air pressure in the external canal associated with acoustic stimulation; this is attributed to inward movements of the eardrum (Wever and Lawrence, 1954).

Wever and Lawrence (1954) and Wersall (1958) cite Lüscher's 1929 paper as the first observation of stapedius contraction to acoustic stimulation in humans. Lüscher used microscopic observation through perforations in the tympanic membrane. This observation was confirmed by Potter (1936).

Kato observed stapedius movement in response to sound stimuli in cats and rabbits (Wever and Lawrence, 1954); in his classic 1913 paper he reported that the tensor tympani also contracted to acoustic stimulation but more intensity was required.

In 1933 Lorente de Nó reported an acoustic tensor reflex in cats and rabbits. Lorente de Nó and Harris (1933) were able to observe, through direct microscopic observation, the contraction of both intratympanic muscles in decorticated rabbits; responses were elicited to stimuli in the 128 to 1686 Hz range.

Eliasson and Gisselsson (1955) reported that electromyographic responses were recorded in decerebrated cats from both middle ear muscles; the threshold of the tensor tympani was 30 dB higher than the stapedius.

Wersall (1958), using a similar technique, obtained myographic responses in anesthetized rabbits from both muscles when a 1000 Hz tone was presented.

Galambos and Ruppert (1959) were also able to measure an acoustic tensor reflex in cats.

Klockhoff (1961) notes that Kato (1913) was unable to demonstrate an acoustic tensor reflex in monkeys, although contractions of the stapedius were observed.

There can be little doubt, based on the above studies and many others, that both intratympanic muscles of the dog, cat, and rabbit display an acoustic reflex. The data on human ears, which are discussed below, are considerably less clear.

Jepsen, in his 1955 dissertation, examined the acoustic reflex, by the impedance method, in seven patients with Bell's palsy, which is known to cause paralysis of the stapedius muscle. He was unable to demonstrate any acoustic reflex in these ears. He also studied two patients with tensor paralysis and was able to record changes in impedance in both of these ears upon the presentation of sufficient acoustic stimulation (Klockhoff, 1961). Based on these data, he concluded that in humans the acoustic reflex was in reality an acoustic stapedius reflex.

Klockhoff (1961) used the impedance method to examine 15 patients with unilateral facial palsy. All patients displayed an acoustic reflex on the contralateral side but none responded to a 1000 Hz pure tone at 120 dB SPL on the side with the palsy.

Klockhoff (1961) also examined five ears with suspected ossicular discontinuity; the diagnosis was confirmed surgically following his examination. He was unable to demonstrate an acoustic reflex in these ears, using the impedance method. Klockhoff felt that this conclusively demonstrated that, in man, only the stapedius muscle contracts to acoustic stimulation.

Feldman (1967b), using the Zwislocki acoustic bridge, studied several cases in which the stapedius muscle was inoperative due to pathological or post-surgical conditions. In each instance he was unable to observe an acoustic reflex. Feldman also examined five patients with sectioned tensor tympani muscles and was able to demonstrate a normal reflex in each case. He concluded that while using impedance monitoring, it had never been possible to document an acoustic tensor tympani response in man.

In 1958 Kawanta reported being able to observe movements in the slope of the manubrium in the human ear when stimulated by sound. Terkildsen (1957, 1960), while using tympanomanometry in man, recorded inward movements of the eardrum. He concluded that this must be due to contraction of the tensor tympani and suggested that the tensor response must be dominant over the concurrent stapedius responses.

Holst, Ingelstedt, and Ortegren (1964) were able to record eardrum movements, which they attributed to the tensor tympani, upon the presentation of an intense acoustic stimulus (127 dB SPL at 500 Hz). The authors accepted inward movement of the drum (a decrease in pressure) as evidence of a tensor response and outward movement of the drum (an increase in pressure) as probably indicative of a stapedius response. They also recorded biphasic movements which they attributed to a combined response of the two middle ear muscles. Holst, Ingelstedt, and Ortegren concluded that the middle ear muscle reflex is a contraction of both muscles simultaneously; they noted that the threshold for eliciting the tensor is about 15 to 20 dB higher if the stapedius has been sectioned. It must be noted that the intensity of the stimuli used by these experimenters was so high that they may well have caused a gross startle reaction. The authors denied this possibility.

Djupesland (1964) studied the acoustic reflex during 125 surgical procedures; he used impedance measurements, electromyography, and direct microscopic inspection to collect his data. Records were kept on responses to both acoustic and non-acoustic stimulation. He concluded that pure-tone stimulation in the range of 65-115 dB above threshold usually produced only a stapedius reflex. Tensor tympani muscle contractions could be obtained when the stimulus was unusually loud, especially if unexpected; the test subjects reacted to this type of stimulus by closing their eyes at the same time as contracting the tensor muscle. Djupesland concluded that the tensor tympani contraction is part of the startle-related cochleo-palpebral reflex and can be expected at 115-140 dB SPL.

This agrees with the opinions of Salmon and Starr (1963) who used electromyography in human subjects and recorded a tensor response following the stapedius response at high intensities.

It would appear from the available data that if the tensor tympani does have an acoustic reflex it does not normally alter the impedance of the middle ear. Therefore, the reflex measured by an acoustic bridge may properly be called the stapedius reflex. Furthermore, it appears probable that any contraction of the tensor tympani to acoustic stimulation can be thought of as a part of the generalized startle response. Further insight into the nature of the tensor tympani response can be found in the literature dealing with non-acoustic stimulation of the middle ear muscles.

Conclusive evidence of the relationship between inward movements of the tympanic membrane and contraction of the tensor tympani would solidify conclusions drawn from the tympanomanometry studies. This could be accomplished by showing that inward movements of the eardrum could not be obtained in ears with surgically sectioned tensor muscles.

Response to non-acoustic stimulation

The majority of early reports of a non-acoustic middle ear muscle reflex stemmed from accidental tactile stimulation in or around the ear canal. This response to tactile stimulation was noted in animals by Lorente de Nó (1933), Wiggers (1937), and Wersall (1958), among others. According to Jepsen (1963), Kato reported that the middle ear muscles contracted to a weak air current in the external canal. The 1933 Lorente de Nó article indicated that non-acoustic stimulation of the aural area of a cat was accompanied by bilateral contraction of the intratympanic muscles.

According to Klockhoff (1961), Lüscher occasionally noticed the contraction of the middle ear muscles in human subjects upon tactile stimulation of the canal. Both Metz (1946) and Jepsen (in Klockhoff, 1961) were unable to demonstrate this. Klockhoff (1961) used a cutaneous electric shock in the ear canal to elicit a middle ear muscle reflex. He found, using an impedance technique, that the electric shock stimulated only the stapedius muscle. Klockhoff (1961) demonstrated this with six subjects with unilateral facial palsy; he was able to elicit a response only on the ear contralateral to the paralysis. Klockhoff notes that in normal ears the cutaneous muscle response is unilateral, in contrast to the bilateral acoustic stapedius response.

Djupesland (1964) replicated this phase of Klockhoff's work using direct observation and electromyography in addition to impedance measures. He also recorded no response of the tensor tympani to electric shock in the canal; however, he found the response of the stapedius to be bilateral to cutaneous stimulation in the canal.

Klockhoff (1961) was able to demonstrate a non-acoustic tensor reflex to an orbital air jet. Using 18 ears in which a stapedius response had been precluded (ossicular discontinuities, stapedial fixations and sections, etc.), he was able to record responses which were more intense and of shorter latency than the stapedius reflex. Klockhoff considers this response to be a part of the generalized startle response. He suggests that in normal ears both muscles would contract to such stimulation. Linden and Norland (in Lindstrom and Linden, 1964) confirmed this by direct observation during surgery.

Djupesland (1964) states that he has been able to show contraction of the middle ear muscles during voluntary and reflex contraction of the periorbital muscles. He offers the following examples: coughing, laughing, yawning, touching the cornea, and touching the nasal mucosa.

In summary, it appears reasonable to conclude that all tympanic muscle responses to acoustic stimulation in humans at the sub-startle level can be attributed to the stapedius.

The responses of the tensor tympani are probably related to the cochleopalpebral reflex and are usually associated with very intense acoustic stimuli or other startle-inducing stimuli.

Threshold of the stapedius reflex

Only a brief review of the earlier studies on the reflex threshold will be presented. The use of electro-acoustic systems for sound stimulation has made it possible to produce well-defined signals. The numerical values for the sound intensities used in many earlier experiments are not directly comparable because different reference levels have been used. Furthermore, it is difficult to assess results of studies when nothing is known of the calibration procedures employed (Wersall, 1958).

Most of the early experiments employed experimental animals rather than human ears. Lilly (1964) notes that there is no experimental evidence to suggest that the threshold of the stapedius reflex in man is even close to that of the cat.

One of the most important early articles on the reflex threshold was done by Lorente de Nó and Harris (1933). They used rabbits and recorded the responses through microscopic observation. The thresholds given are with reference to the mean auditory threshold of four normal human subjects. They found the threshold of the stapedius to be approximately 65 dB at 500 Hz; the tensor had a threshold of 82 dB for the same frequency. The threshold of the stapedius was 42 dB at

1000 Hz and 58 dB at 2000 Hz; the corresponding tensor tympani thresholds were 55 and 60 dB respectively. The threshold for both muscles was approximately 45 dB at 4000 Hz.

Eliasson and Gisselsson (1955) used an electromyographic technique to record responses from decorticated cats and found the threshold of the stapedius to be 40 dB; tensor tympani responses were recorded at a level of 70 dB. Both values are with reference to normal human hearing.

Wever and Vernon (1955b) worked with cats under light anesthesia; testing was done three hours after the anesthetic was administered. They found the threshold for the acoustic reflex to lie between 80 and 100 dB SPL.

Wersall (1958) studied the acoustic reflex threshold in 11 rabbits with electromyography. He found that the stapedius responded at a mean level of 96 dB SPL while the tensor responded at a mean level of 104 dB SPL; the stimulus was a 1000 Hz tone. He noted that in some rabbits the thresholds for the stapedius and the tensor tympani were the same while in other rabbits the tensor reflex required as much as 22 dB of additional stimulation.

Simmons (1960) used a technique similar to Wersall's to study the acoustic reflex in nine cats. He found the mean threshold to a white noise stimulus to be about 50 dB SPL. The difference between the thresholds of the two muscles was found to be no more than 10 dB.

In 1936 Lindsay, Kobrak and Perlman observed the stapedius reflex in human ears and found that the threshold varied from 65 to 85 dB sensation level.[1] In 1951 Jepsen used the impedance method to measure stapedius sensitivity in 98 human ears. He found thresholds of about 80 dB SL in the 250 to 4000 Hz range.

Metz (1952) also used the impedance method to determine the stapedius reflex threshold in human ears. He found that the thresholds varied between 70 and 90 dB SL.

Jepsen (1963) determined the threshold of the stapedius reflex by the impedance method for 88 human ears; the number of subjects is not given. The approximate thresholds, which were extracted from a graphic presentation, indicate the threshold to be most sensitive to 1000 and 2000 Hz pure tones. The threshold at both of these frequencies is approximately 75 dB SL. Jepsen found the threshold for 250 Hz to be 85 dB SL, while the threshold for 500 Hz and 4000 Hz was 80 dB SL. The values are essentially in agreement with his 1951 study, but at that time he did not find that low and high frequency tones have somewhat higher thresholds than the middle frequencies.

Jepsen (1963) also found that the threshold of the stapedius reflex tends to decrease with age, especially at the higher frequencies. He attributed this decrease to recruitment.

Weiss, et al. (1962) used tympanomanometry to determine the threshold levels of the human acoustic reflex. They

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[1] Sensation level is the intensity, in decibels, above the auditory threshold of the individual observer; hereafter it will be abbreviated SL.

found the thresholds for the range of 400 to 6400 Hz to lie between 96 and 107 dB SPL. They also noted that it required less intensity to stimulate the reflex at 800 to 3200 Hz than it did at 400 or 6400 Hz. The thresholds presented by Weiss and his associates are somewhat higher than would be expected from other work in this area.

Lilly (1964) determined the stapedius reflex threshold to white noise in human ears using both the Zwislocki acoustic bridge and an acoustic bridge which he developed. He found a threshold of approximately 60 dB SL with his acoustic bridge and about 68 dB SL with the Zwislocki bridge; the sample size is not given. Dallos (1964) also used the Zwislocki acoustic bridge; he reported a mean threshold value of 72 dB SL when white noise was used to stimulate the reflex.

The experiments of Lilly (1964) and Dallos (1964), using a white noise stimulus, display somewhat lower reflex thresholds than other experiments using pure tone stimuli (Jepsen, 1951, 1963; Metz, 1952). Metz (1946) noticed that the reflex was more easily elicited by noise than by pure tones but presented no data to confirm this.

It should be noted that only one paper, reporting on three subjects, has been published comparing the thresholds of the stapedius reflex for noise and pure tones in the same subjects. Djupesland, Flottorp, and Winther (1967) found that the threshold to white noise was lower than to pure tones in all three subjects tested; the impedance method was employed. The data are highly variable (the three tresholds for white noise vary from 56 to 78 dB SL) and no quantitative conclusions can be drawn. They also determined the threshold of the stapedius reflex for 250, 1000, 2000 and 4000 Hz in 11 normal ears; the values lie between 87.3 and 91.2 dB SL. These thresholds are somewhat higher than those found by Jepsen (1951, 1963) but are lower than those published by Weiss et al. (1962).

Møller (1962a) has found that the threshold of the human stapedius reflex is slightly lower if the impedance is monitored in the ear that is stimulated rather than in the contralateral ear, as is the usual practice. He also notes that the reflex threshold is three decibels lower if the stimulus is presented binaurally. Møller (1962b) has suggested that the sensitivity of the stapedius reflex should be measured in terms of percent of impedance change rather than threshold; although this method may have some advantages, it would be difficult to compare results across methods.

In summary, it is noted that considerable variability can be found in the literature dealing with the threshold of the stapedius reflex in man. No systematic study of the differential response to noise and pure tone stimuli has been published; data on the response to narrow band noise are not available. Studies comparing the stability of the stapedius reflex threshold for the various pure tone stimuli are not in evidence; nor has the stability of the thresholds for noise and pure tone stimuli been compared. Our knowledge of this parameter of the stapedius reflex is not much greater than it was in 1952 when Metz found that the threshold of the acoustic stapedius reflex was in the 70 to 90 dB SL range.

Latency of the stapedius reflex

Lorente de Nó (1933, 1935), Metz (1951), and Okamoto, Sato, and Kirikae (1954) have all demonstrated that the latency is dependent upon the intensity of the stimulus; the greater the intensity, the shorter the latency.

Because of differences inherent in the many methods used to study latency, it is difficult to compare results (Wersall, 1958). It is generally known that the latency of the stapedius is shorter than that of the tensor tympani (Wever and Lawrence, 1954).

Perlman and Case (1939) found the latency of the stapedius reflex to be about 10 ms in humans; they recorded action potentials from the stapedius in patients with large eardrum perforations. Metz (1951) used impedance change recordings and found that the latency of the stapedius reflex in human subjects varied from 35 to 150 ms depending on the intensity of the (1000 Hz) stimulus. Møller (1958) found latencies in human ears varying from 25 to 32 ms when an intense acoustic stimulus was presented.

Eliasson and Gisselsson (1955) recorded latencies of 6 ms for the stapedius and 7 ms for the tensor tympani in cats, using an electromyographic technique. Okamoto, Sato, and Kirikae (1954) measured eardrum movement in cats and found a minimum latency of 7 ms. Galambos and Ruppert (1959) measured changes in the level of the cochlear microphonic to study the reflex activity in cats. Their results show latencies of 10 to 15 ms, depending on the stimulus.

Adaptation of the reflex

Metz (1946) in his studies on human ears using the impedance method found that the stapedius reflex could be maintained for long intervals before a gradual relaxation set in. This is noted to be an adaptation process because if the stimulus was stopped and then presented again without delay, the reflex reappeared in full strength (Wever and Lawrence, 1954). Also, Wersall (1958) found that if a second tone, of a different frequency, was presented during the process of adaptation, it reactivated the reflex completely.

Two recent experiments in human ears demonstrate that no short-term adaptation or fatigue is present to very intense stimuli. Dallos (1964) was able to maintain the stapedius contraction in human ears for two minutes without any indication of a loss of tension; the elicitor was 110 dB SPL of white noise. Lilly (1964) did not observe adaptation with high intensity noise stimulation lasting up to 10 minutes.

The difference in adaptation found may be attributable to the spectrum differences in pure tone and noise stimuli. No clarifying data are available at the present time.

Concept of acoustic impedance

Basic concepts

Before beginning the discussion of the measurement of impedance, it is appropriate to present a brief discussion of the impedance concept.

Acoustic impedance is comprised of three components: mass, elasticity, and resistance. Mass refers to the weight of an object. The elasticity of the system is usually discussed in terms of compliance and stiffness. A fixation of the incudo-stapedial joint, as seen in advanced otosclerosis, would cause a stiffness; an incudo-stapedial separation would cause the opposite extreme, a grossly compliant system (Feldman, 1964).

The stiffness and mass components of impedance are generally combined into one resultant measure called reactance. The reactance is a negative value when the system is characterized by stiffness and is positive in mass controlled systems. The effect of stiffness is greatest at low frequencies; the effect of mass is greatest at high frequencies (Zwislocki, 1961).

In all systems in which there is movement there is a certain loss due to friction; for example, an extreme viscosity in the middle ear would produce a strong internal friction when sound waves progress across the ossicles. The frictional contribution to impedance is called resistance.

The actual acoustic impedance is determined by inserting the values for the reactance and resistance into the following formula (Tonndorf, 1965):

$$Z \text{ (impedance)} = \sqrt{(\text{reactance})^2 + (\text{resistance})^2}$$

When an acoustic wave arrives at the tympanic membrane, part of the energy produces a vibration of the drum and is transmitted through the ossicular chain to the inner ear; a portion of the acoustic wave is reflected back into the external auditory meatus (Zwislocki, 1961). The reflected energy from the tympanic membrane is maximal when the middle ear system is stiff (low in elasticity), heavy (high in mass), and viscous (high in friction). A system which is compliant, light and relatively low in friction will have greater efficiency because reflected energy will be minimal (Zwislocki, 1963). Because of this variation in resistivity to motion (or impedance) that is associated with the condition of the middle ear, the study of the reflected wave at the tympanic membrane provides knowledge which is of clinical value.

It should be understood that factors which determine impedance, mass, elasticity and resistance, are the resultant of the anatomical structure of the ear. Some of the most important factors are the compliance and mass of the tympanic membrane, the compliance of the ligaments that hold the ossicular chain in place, the compliance of the incudo-stapedial joint, the mass of the ossicles, the compliance of the cochlear windows, and the input impedance of the cochlea (Zwislocki, 1962).

According to Zwislocki (1961) it is only necessary to determine the ratio of the reflected and the incident waves in order to measure the acoustic impedance at the tympanic membrane.

Effect of the acoustic reflex

The discussion until now has been concerned with the actual values of the resistance and reactance (absolute impedance measurement). Further comment on the clinical use of absolute impedance measurements will follow in the last section of this chapter.

It was stated earlier in this chapter that contraction of the stapedius muscle causes a change in tension on the ossicular chain. The resultant increase in stiffness has been shown to alter the impedance of the middle ear (Metz, 1946; Feldman and Zwislocki, 1965; Lilly and Shepherd, 1964; Dallos, 1964; and Møller, 1958, 1961a, 1961b and 1962a). The general finding of the majority of the studies is that contraction of the stapedius muscle causes an increase in reactance and a decrease in resistance; the former is commonly seen in stapedial fixations (e.g. otosclerosis) but the latter is not. It should be noted that the data of Lilly and Shepherd (1964) do not show a notable decrease in the resistance and more closely approximate the absolute impedance values associated with otosclerosis.

According to the data collected by Feldman and Zwislocki (1965), the predominant change caused by the stapedius reflex is an increase in the reactive component; this change is in the same direction as otosclerosis but smaller. They also find a smaller but consistent decrease in resistance; the authors suggest that this can be accounted for by a loosening of the incudo-stapedial joint in addition to the partial fixation of the stapes.

The existence of a measurable change in the resistance and reactance values associated with the contraction of the stapedius muscle is well established although attempts to measure the size of the change (and in some cases the direction) have indicated some variability (Møller, 1961a; Dallos, 1964). This variability does not hamper the use of the monitoring of impedance to detect the contraction of the stapedius muscle, since one is concerned only with a sudden change in the static impedance regardless of direction.

The acoustic bridge

The measurement of impedance

There are several ways in which the acoustic impedance at the eardrum can be measured. In 1957 Zwislocki described two psychoacoustic methods which he employed and found to yield comparable results to purely physical methods. The first is based on the measurement of attenuation produced by a perforated earplug. According to Zwislocki (1957), when the perforated earplug closes the ear canal a resonator is formed; the resonance frequency is dependent on the acoustic inertance of the perforation, the acoustic compliance of the enclosed volume of air and the impedance at the tympanic membrane. When the impedance of the perforation and the volume of air between the earplug and the eardrum are known, it is possible, with some time-consuming calculations, to determine the acoustic impedance at the eardrum.

The second psychoacoustic method described by Zwislocki is similar to the one described above but uses a binaural loudness balance technique; another difference is that this method uses sound localization (phase balance) to measure the phase shift introduced by the earplug.

Zwislocki (1957) notes that the psychoacoustic approach to impedance measurement is too time-consuming and lacks precision.

The use of an impedance tube was described by Zwislocki in 1961. In this method the sound produced by an earphone is fed to the ear canal by a narrow tube which is held in place by an earplug; the plug also serves to form an acoustic seal of the canal. An additional tube, which is fitted into the same earplug, is led to a microphone which is used to measure the sound pressure level in the ear canal. A cavity with rigid walls is used to calibrate the system. According to Zwislocki (1961) the acoustic impedance may be determined by comparing the sound pressure generated in the calibration cavity to the sound pressure generated in the ear canal. A correction for the volume of air in the canal is necessary. The calculations that must be used to convert the results of this method to impedance values are extensive.

Møller (1960, 1961a) used another technique to measure acoustic impedance. He had a probe tube with a microphone and a transducer; the output voltage of the microphone was measured as was the phase angle between the microphone and the transducer. An electrical analog was then used to convert the data into acoustic ohms.

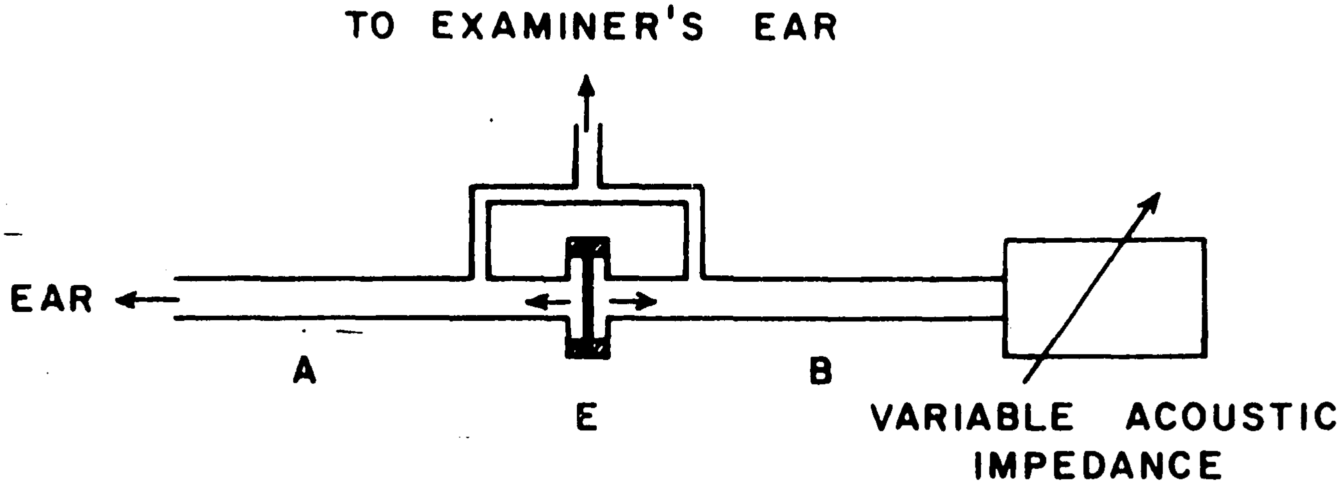

Figure 1. Schematic drawing of an acoustic bridge (Zwislocki, 1961,p.6)

The acoustic bridge principle

Figure 1 is a schematic drawing of a generalized acoustic bridge that demonstrates the construction principles used in all mechanical acoustic bridges. The bridge consists of a two-sided earphone (E) mounted between two tubes of equal diameter and length (A and B). The diaphragm of the earphone separates the two tubes; the two tubes are connected through a Y tube that bridges the earphone. The top of the Y tube is fed to the examiner's ear; tube A is secured into the subject's ear canal with an earplug; tube B is attached to a variable impedance device. The sound generated by the earphone (E) is of equal amplitude in both directions (A and B) but 180 degrees out of phase. Consequently, if the impedances terminating tubes A and B are equal, the reflected waves will also be of equal amplitude and cancel each other out (Tillman, Dallos, and Kuruvella, 1964).

The measurement is accomplished by adjusting the variable impedance device until the tone that is generated by the earphone is no longer audible at the top of the Y tube (a null is present). If the volume of the ear canal is determined, an equal volume can be added to the volume of tube B before measurement of the impedance. If this is done, the measurement is direct and no additional calculations are needed (Zwislocki,1961).

Earlier acoustic bridges

The acoustic bridge was invented in 1934 by Schuster; three years later Robinson built a second acoustic bridge. In 1938 Waetzmann adapted the Schuster bridge for use in human ear measurements (Metz, 1946). The history of the use of impedance measurements on normal and pathological ears begins with the 1946 Metz monograph in which he demonstrated that pathologic changes in the middle ear could be identified by measuring the impedance in the ear canal; he was also able to identify the presence of an acoustic reflex using his modified Schuster bridge.

The exact construction of the Schuster bridge is discussed in detail by Metz (1946, pp. 30-32) and Zwislocki (1963, pp. 310-311). It should be noted that the bridge Metz used in 1946 had several limiting features. The impedance matching device was a felt disk varied by means of a column of air in back of the disk. In this type of system the reactance and resistance may not be varied independently. The felt disk is subject to changes with time and use, thereby introducing an error factor. The results are not in their final form when read off the bridge and considerable time is consumed in conversion (Zwislocki, 1963).

Electroacoustic bridges

For a variety of reasons, several of which were mentioned above, absolute impedance measurements for middle ear diagnosis met with little clinical acceptance following the Metz (1946) monograph. In addition to those problems already mentioned, difficulties in accurately compensating for ear canal volumes were encountered by some investigators (Tillman, Dallos and Kuruvella, 1964); the resultant of these problems was considerable variability in absolute impedance values obtained.

Following the 1946 Metz article, a number of electroacoustic impedance bridges were constructed for clinical use; among these are the bridges of Morton and Jones (1956), Møller (1958), Terkildsen and Scott Nielsen (1960), and Klockhoff (1961).

Most of the clinical research with the electroacoustic bridge provided absolute impedance data which were highly variable and of little diagnostic value. Terkildsen and Scott Nielsen (1960) concluded that measures of absolute impedance may prove to be of little clinical value but that studies of relative impedance (the stapedius reflex) may be useful.

A large number of studies suggesting the clinical value of relative impedance measures were reported using electroacoustic bridges (Jepsen, 1953; Thomsen, 1955a,b,c; Terkildsen and Scott Nielsen, 1960; Klockhoff, 1961).

The several electroacoustic impedance bridges mentioned above were all based on the same principle, although there are some minor differences. A brief description of the bridge developed by Terkildsen and Scott Nielsen (1960) will be used to exemplify this type of instrument.

The electroacoustic bridge consists of an earphone and a microphone which are connected to the external auditory meatus by two narrow tubes. The tubes are held in place by an earplug which is encased in an inflatable rubber cuff; after the earplug is in place, the cuff is inflated, giving an air-tight seal of the canal. The tube from the earphone carries a 220 Hz test tone to the canal. The microphone is used as a sound probe; this signal is counter-balanced to zero by means of current from a 220 Hz sound generator. The degree of counter-balancing obtained is read on a vacuum tube voltmeter. This bridge does not provide individual reactance and resistance measures; only the total acoustic impedance is measured.

A newer version of this bridge is commercially available from Madsen Electronics (Electroacoustic Impedance Meter ZO 70); according to the manufacturer, this model also measures the volume of the ear canal automatically.

The Zwislocki acoustic bridge

The acoustic bridge developed by Zwislocki (1963), and manufactured by the Grason-Stadler Co., allows direct measurement of impedance components at the eardrum. Cavity V-1 (see figure 2 can be adjusted to match the volume of the ear canal being tested; with the volume of the canal added between the end of the B tube and the variable impedance matching device, the effect of the air column in the external meatus is compensated for (Zwislocki, 1963).

The A tube of the Zwislocki bridge is machined to fit

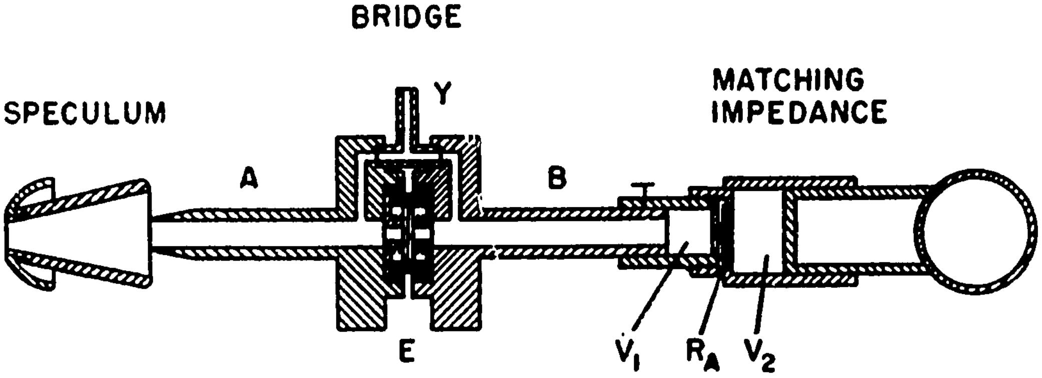

Figure 2. Schematic diagram of the Zwislocki acoustic bridge (Zwislocki, 1963, p. 311)

flush into a special otic speculum; the speculum has three sizes of adjustable plastic tips. The user must select the proper size tip to insure an air-tight seal of the external auditory meatus. The speculum is then inserted into the test ear and the canal is filled with alcohol to the bottom tip of the speculum. This is accomplished with a calibrated 2 cc syringe; the amount of injected alcohol is equal to the volume of the ear canal. The alcohol is then removed and tube A of the bridge is inserted into the speculum, after adjusting V-1 to the proper volume.

The variable impedance device at the end of tube B has two independent controls: resistance (Ra) and compliance (V-2).

According to Zwislocki (1963), compliance is measured rather than reactance because compliance is less frequency dependent than reactance, and by using compliance, it is possible to make the bridge calibration independent of frequency.

No calibration charts are necessary because the values are indicated directly on the controls; the resistance is measured in ohms, the compliance in cubic centimeters of air.

The symmetrical earphone (E) is connected to a sound source such as an audiometer; the sound source generates a test tone (or probe tone) of any frequency between 125 and 1500 Hz, which are the effective limits of the bridge. The probe tone is monitored by the examiner through a stethoscope which is attached to the top of the Y tube (Y).

The compliance control (V-2) is a small piston; the resistance control (Ra) is a ring around the bridge which is rotated to vary resistance.

The examiner works the two impedance controls back and forth until a null is obtained in the stethoscope (the principle of this has been explained earlier). The compliance and resistance values for that frequency (the probe tone frequency) are now read directly from the bridge. The same procedure can then be repeated for other frequencies within the useful range of the bridge.

It is absolutely necessary to point the tip of the bridge at the eardrum rather than towards the canal wall during all measurements. The examiner should move the bridge as little as possible during the measurement.

All parts of the Zwislocki bridge are machined from metal, eliminating materials such as felt, thereby increasing the stability of calibration (Zwislocki, 1963).

Visual display of the probe tone

The monitoring stethoscope can be removed and in its place a microphone can be coupled to the bridge. The output of the microphone can then be led to a suitable electronic apparatus (voltmeter, graphic level recorder, oscilloscope, etc.); the probe tone level can then be monitored visually and permanent records can be obtained in a manner similar to the recording technique used by Klockhoff (1961) with an electroacoustic bridge.

Measurement of the stapedius reflex

The stapedius reflex can be detected with the Zwislocki acoustic bridge by introducing a sufficiently intense acoustic stimulus into the contralateral ear after the bridge has been balanced (a null is present). The stapedius contraction changes the impedance of the system causing an unbalancing of the bridge (probe tone returns).

It should be noted that if one is interested only in detecting the acoustic reflex with the Zwislocki bridge, it is not necessary to measure the ear canal volume; this measurement is needed only for calibration of the resistance and compliance parameters, which are of no concern in relative impedance measures.

Reliability of measurements with the Zwislocki acoustic bridge

Three investigations of the reliability of impedance measurements obtained with the Zwislocki bridge have been reported in the literature. Tillman, Dallos, and Kuruvella (1964) presented data on 10 male adult subjects collected by each of the three experimenters; each subject was tested twice by each experimenter, so data are provided for both intra- and inter-experimenter reliability. They also present data on the reliability of ear canal volume measurements.

Nixon and Glorig (1964) published data on the reliability of measures with the Zwislocki bridge obtained by one investigator over four trials; 13 young normal adults served as subjects.

Feldman (1967a) presented reliability data on both ear canal measurements and impedance measurements. For this study one investigator collected the measurements on 33 subjects with normal hearing; an additional 24 were used for the data on ear canal volumes.

Compliance

All three articles indicate a relatively high test-retest reliability for the measurement of compliance (the reactance component of impedance) up to 750 Hz; data at 1000 and 1500 Hz were less stable and more dispersed due to the positive reactance of the system at these frequencies. The resultant of this is often no detectible change in the monitored signal with relatively gross movements of the compliance ad-

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justment.

Feldman (1967a) presents test-retest reliability coefficients ranging from .71 to .95 for compliance values at 125, 250, 500, 750, 1000, and 1500 Hz. Nixon and Glorig (1964) tested 200, 400, 600, 800, and 1000 Hz and obtained reliability coefficients in the range of .49 to .97; 7 of 10 coefficients presented exceed .85 and two of the three that did not exceed .85 were measurements taken at 1000 Hz.

Tillman, Dallos, and Kuruvella (1964) present reliability data for 250, 500, 750, 1000, and 1500 Hz for three experimenters. Reliability coefficients for compliance range from .73 to .92 for 250 through 750 Hz; significantly lower values are seen at 1000 Hz. It is important to note that inter-scorer reliability was also high for compliance (.75 to .99 for the 250 through 750 Hz range).

Resistance

The data of all three studies indicate that the resistance values obtained on the Zwislocki bridge are less stable than the compliance values and dispersed over a greater range. Feldman (1967a) suggests that resistance measures are therefore of less diagnostic value than compliance measures. Resistance, in contrast to compliance, becomes more stable as the frequency becomes higher; at higher frequencies, such as 1000 and 1500 Hz, small movements of the resistance adjustment cause critical changes in the probe tone level, whereas grosser movements of the compliance slide have little effect.

Feldman (1967a) found test=retest correlations for resistance ranging from .53 at 125 Hz to .77 at 1500 Hz.

Nixon and Glorig's data (1964) also show a reduction in the size of the reliability coefficients for resistance in comparison to compliance (except for 1000 Hz) although their values are somewhat higher than Feldman's. The range of the reliability coefficients is .78 to .92 for 200 through 1000 Hz.

Tillman, Dallos, and Kuruvella (1964) obtained poor reliability data for resistance measures. The reliability coefficients range from -.18 to .55; inter-scorer values were lower. It should be noted that these values were obtained using a rank-order correlation technique which is not appropriate for these data; the absolute difference between test and retest values was, at maximum, 4.4 (arbitrary) units on a scale of 60 units. Despite the data, Tillman, Dallos, and Kuruvella (1964) conclude that resistance measurements with the Zwislocki bridge are reliable; this conclusion agrees with the data and general conclusion of the two other studies.

Ear canal measurements

Both Feldman (1967a) and Nixon and Glorig (1964) report highly positive test-retest correlation coefficients for ear canal volume measurements. The former reports reliability coefficients of .96 for one series and .99 for another; the latter report .95 for one series and .93 for another. Tillman, Dallos, and Kuruvella (1964) present reliability coefficients of .84, .58, and .58 for each of the three experimenters. It should be noted that these authors admit to very limited practice with the bridge before the study. The accurate measurement of an ear canal volume is an absolute prerequisite to obtaining valid impedance measurements with the Zwislocki bridge; therefore, the data presented by Tillman, Dallos, and Kuruvella must be interpreted in the light of their comparatively poor intra-experimenter reliability. The inter-experimenter results for ear canal measurements that are presented in their study range from .002 to .77. Again, it should be noted that these results were obtained by the rank order correlation technique and may be somewhat artificially lowered by the nature of the statistic.

The mean canal volume reported by Nixon and Glorig (1964) of .80 cc is somewhat larger than the mean of .56 cc obtained by Feldman (1967a). This difference is related to the depth of insertion of the speculum and is unimportant as long as the insertion depth is held constant while using the bridge; the volume of the canal is compensated for before beginning the impedance measurements with the Zwislocki bridge. However, it should be noted that the weight of the bridge has a tendency to push the speculum in deeper as the bridge is used, reducing the volume of the canal beyond the speculum; a deeper initial insertion of the speculum would tend to minimize this error factor.

Conclusions

The use of the Zwislocki bridge to obtain absolute acoustic impedance measurements appears to be a reliable technique; results appear somewhat more reliable for the reactance (compliance) component of impedance than for the resistance component.

It should be noted that the sample sizes in both Nixon and Glorig (1964) and Tillman, Dallos, and Kuruvella (1964) were limited.

A crucial factor in obtaining reliable results with the bridge is the auditory threshold of the examiner. The more acute the examiner's hearing, the longer he will be able to follow the probe tone and the more precise a null he will obtain. The use of visual monitoring eliminates this important variable.

Feldman (1967a) notes a possible error introduced into any impedance study using "normal" ears: the existence of incipient pathology may well affect impedance measures before it can be observed either otoscopically or audiologically.

At the present time there is no study available dealing with the reliability of the Zwislocki bridge for the measurement of the stapedius reflex.

Clinical use of impedance

Absolute impedance measures

The first paper dealing with the use of acoustic impedance measures for differential diagnosis of middle ear pathology was presented by Metz (1946). For a number of reasons, some of which were discussed earlier, the methods suggested by Metz gained little acceptance as a clinical tool. Because they found absolute impedance measures to be unstable, a number of workers investigated the use of the stapedius reflex in clinical diagnosis (Jepsen, 1953; Thomsen, 1955a,b,c; Terkildsen and Scott Nielsen, 1960; Klockhoff, 1961). These studies were all done with electroacoustic impedance bridges that were basically similar to one another. In their investigation of the stapedius reflex, Terkildsen and Scott Nielsen (1960), using an electroacoustic bridge, reported that absolute impedance measures were insufficiently reliable for any clinical inference.

Mundie (1962), working with guinea pigs, suggested that the impedance is not stable; he believes that momentary changes in the impedance reflect a readjustment of the conductive mechanism. No evidence to support this in human subjects is available.

The development of the Zwislocki acoustic bridge has stimulated further research into the clinical use of absolute impedance measures (Feldman, 1963, 1964, 1967a; Feldman and Zwislocki, 1965; Zwislocki, 1963; Zwislocki and Feldman, 1963). These articles indicate that evaluation of the parameters of compliance and resistance provides significant information for the diagnosis of middle ear pathologies such as otosclerosis and ossicular discontinuity.

Feldman (1963) compared 40 normal and 55 otosclerotic ears and found that the pathological ears had consistently smaller compliance values (increase in negative reactance) than the normal ears. There is some overlap in the results, but this is minimal and may be attributable to incipient pathology; impedance changes have been observed in ears before the pathology was sufficient to alter the threshold. The otosclerotic ears also displayed greater resistance values in the lower frequencies; this difference was most marked at 125 and 250 Hz.

Feldman (1964) has shown that fluid in the tympanic cavity will result in changes in the impedance that are in the same direction as otosclerosis; however, such conditions as serous otitis media will produce even higher impedance than otosclerosis.

Ossicular discontinuity has been shown to produce changes in acoustic impedance that are opposite to otosclerosis (Feldman, 1963). In these ears the compliance value is quite large (indicating low reactance); the resistance is also somewhat lower than that found in the normal ear.

Feldman (1963) points out the value of acoustic impedance measures after stapes surgery to detect the condition of the prosthesis. The compliance is usually somewhat larger than normal with a prosthesis and will be considerably larger if the prosthesis has become dislodged.

Clinical use of the stapedius reflex

In 1946 Metz noticed that the stapedius reflex appeared to be absent in ears with a conductive impairment. Terkildsen and Scott Nielsen (1960) reported that their data indicated that a relatively normal ear is a prerequisite for the acoustic stapedius reflex. Klockhoff (1961) presented a number of cases of mild conductive impairment; he found the stapedius reflex to be absent in all of these cases and concluded that the presence or absence of the stapedius reflex is the equivalent of the presence or absence of any conductive component. Feldman (1967b) also demonstrated the absence of the stapedius reflex in ears having middle ear pathology.

Although no definitive studies on the minimal amount of middle ear disturbance necessary to cause a cessation of the stapedius reflex are available, it seems reasonable to conclude that the stapedius reflex is present only in substantially normal middle ears. The clinical importance of this fact is obvious.

Recruitment

Metz (1952) first demonstrated the use of the stapedius reflex as an indicator of recruitment. He found that the reflex was activated at unexpectedly low levels in ears showing recruitment on the alternate binaural loudness balance test. Additional data on the use of this technique have been presented by Thomsen (1955a) and Ewertsen, et al. (1958). Their results are somewhat sporadic but confirm the potential of the technique.

When the stapedius reflex threshold is used as a test of recruitment, one need not be concerned with such variables as severity of loss or reliability of the patient's judgments. Furthermore, unilateral and bilateral losses can be evaluated with equal ease.

This technique appears to have sufficient merit to warrant further study to determine which stimuli are most useful in demonstrating recruitment. In order to quantify this measure, data must be collected on the stability and reliability of the stapedius reflex threshold to various stimuli in both normal and recruiting ears.

Non-organic hearing loss

The use of the stapedius reflex to identify non-organic hearing loss was suggested by Jepsen in 1953; Lamb and Peterson (1967) also used this method to detect non-organic hearing loss.

The method would appear seriously limited in value because it cannot distinguish betwen non-organic hearing loss and recruitment, except in the case where a stapedius reflex is recorded at a level below the admitted threshold. The addition of another non-definitive test to the existing battery of tests which detect non-organic hearing loss but cannot aid in determining the organic threshold seems unwarranted.

Although data for standardization of the clinical use of the acoustic bridge are still lacking in many areas, the results now available are encouraging. The technique appears to be relatively easy to use, reliable, efficient, and independent of patient judgment.

Purpose of research

The aims of this study are to:

1. Determine the thresholds of the acoustic stapedius reflex for pure tone stimuli in normal human ears using the Zwislocki acoustic bridge.

2. Determine the thresholds of the acoustic stapedius reflex for white noise and several narrow-band noise stimuli in normal human ears. This will provide quantitative information on the differential sensitivity of the reflex to pure tone and noise stimuli.

3. Determine the variability and test-retest reliability of the acoustic stapedius reflex thresholds for each of the stimuli employed. The study of the threshold stability and the ease of reflex elicitation associated with each of the stimuli in normal ears should provide guidelines for the selection of stimuli for further investigations of recruitment with the acoustic bridge.

CHAPTER II

SUBJECTS AND PROCEDURES

The subjects for this experiment were 30 normal hearing young sailors and graduate students; the criterion accepted for normal hearing for this study was thresholds of 10 dB or better (ISO, 1964) at 250,500, 1000, 2000 and 4000 Hz. All subjects had essentially cerumen free external auditory canals, intact tympanic membranes and no significant history of ear pathology.

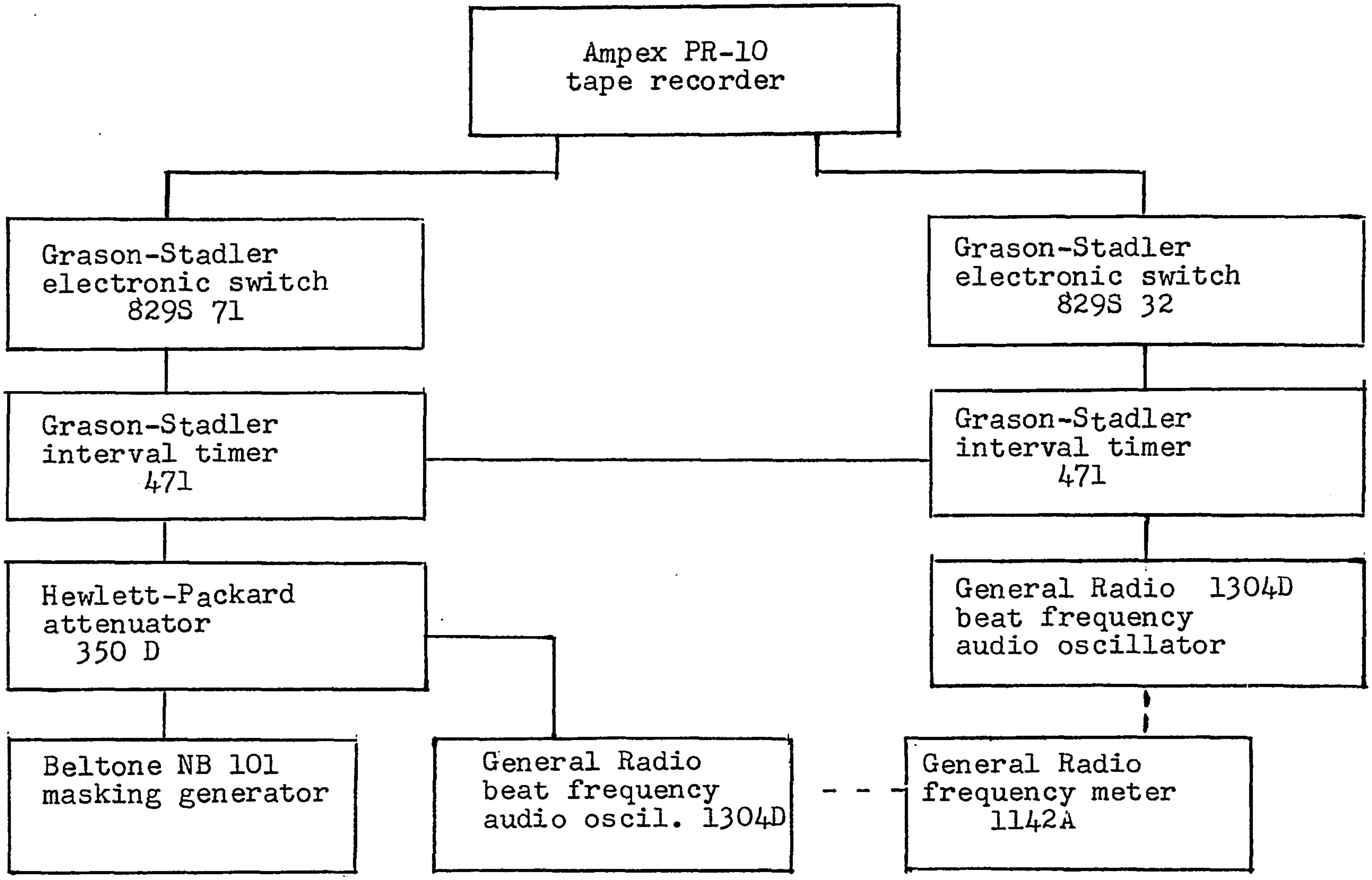
All data collection and threshold determinations were made in a large sound-treated and isolated room with an ambient noise level of 32 dB on the C scale of the General Radio 1551 C sound level meter. With the equipment running, the reading increased to 36-37 dB on the same scale when the meter was placed in the same position as the subject's head on the examination table.

Six stimuli were used for this study. They were: (1) white noise, (2) narrow-band noise centered at 2000 Hz, (3) narrow-band noise centered at 4000 Hz, (4) 2000 Hz pure tone, (5) 4000 Hz pure tone, (6) 250 Hz pure tone. The stimuli were always presented in the above sequence.

The stimuli were recorded on Scotch 202 magnetic tape. Figure 3 is a block diagram of the equipment used to record the stimuli on tape.

Channel one of the tape recorder received the stimuli which were produced by a Beltone masking generator and a General Radio beat frequency oscillator. The frequency of the oscillator was set with a General Radio frequency meter and discriminator. The output of the stimulus generator was

Figure 3. Block diagram of the recording system



adjusted so that the VU meter on the recorder read zero with the Hewlett-Packard attenuator set at zero decibels of attenuation. The Grason-Stadler electronic switch and Grason-Stadler interval timer were set so that the stimulus was on for 500 ms with a 5000 ms delay between stimuli; the rise-fall time was set at 5 ms.

The second channel of the tape recorder was used to record a marker tone of 100 Hz which was generated by a General Radio beat frequency oscillator. The channel two Grason-Stadler interval timer was wired to the channel one timer so that they triggered simultaneously. The Grason-Stadler electronic switch and the timer for channel two of the recorder were set to 150 ms on-time and 5350 ms off-time. The intensity of the 100 Hz tone was kept low to prevent cross-channel leakage.

The actual recording was done by placing 30 dB of attenuation in the channel one attenuator and manually decreasing the attenuation in two decibel steps until the original stimulus level was obtained; therefore, 16 steps were recorded for each stimulus representing a 30 dB span of intensity. The accuracy of the attenuator was checked with a Ballantine voltmeter before the recording was made.

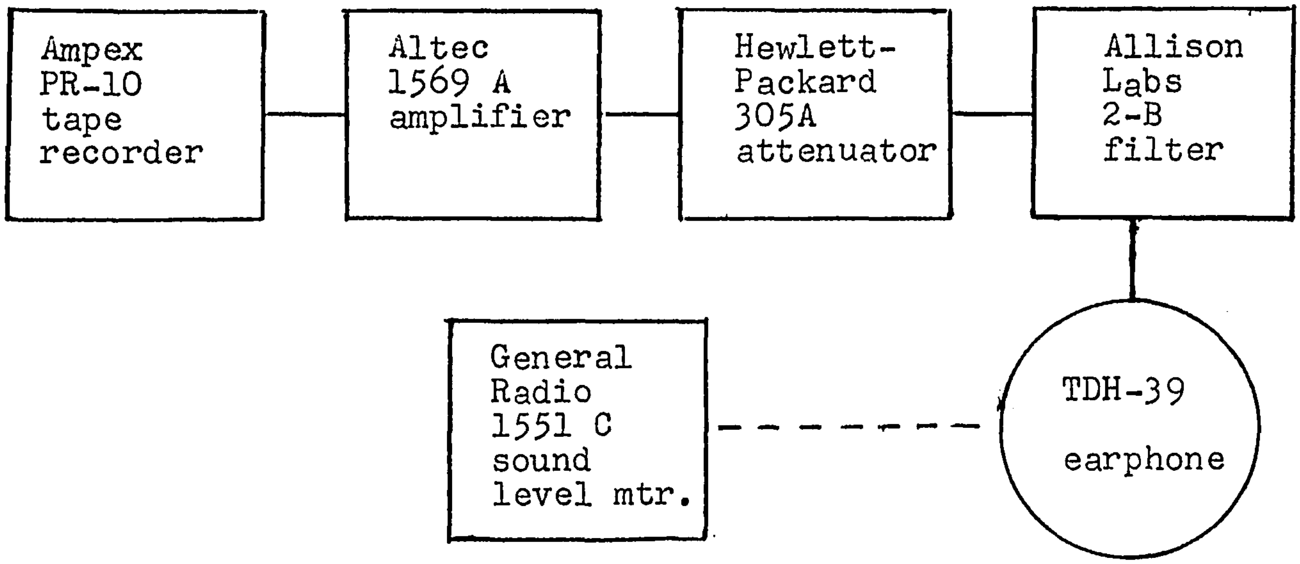
After all six stimuli were placed on tape in this manner, the tape was used to produce another tape; an additional Ampex PR-10 was used for this duplication. The new tape was recorded so that three runs of each stimulus train appeared consecutively with 10 second intervals between them.

At the beginning of the tape a 1000 Hz calibration tone, set to zero on the tape recorder VU meter, was recorded for 30 seconds using the General Radio beat frequency oscillator.

In summary, the completed tape contained three runs of the six stimuli, each over a 30 dB span, and a calibration tone; the total playing time was approximately 35 minutes.

Figure 4 represents the stimulus delivery system which always fed to the subject's left ear.

Figure 4. Block diagram of the stimulus delivery system.



The stimulus was played on an Ampex PR-10 tape recorder, amplified by an Altec amplifier, fed through a Hewlett-Packard attenuator and an Allison Labs filter into a TDH-39 phone. The filter was introduced to reduce the ambient noise in the system; it was set at a lower limit of 200 Hz and an upper limit of 4800 Hz. The attenuator was employed to allow flexibility in the stimulus presentation level. The output of the calibration tone was set at the start of each day to 110 dB SPL with the attenuator set at zero decibels of attenuation, using a General Radio 1551 C sound level meter and a 6 cc coupler (artificial ear); the accuracy of the attenuator was checked for two additional 10 dB steps at this time. The equipment was allowed to warm up sufficiently before calibration and was recalibrated after two subjects were tested. The calibration of the sound level meter was checked periodically throughout the course of the experiment.

Figure 5. Block diagram of the probe tone generation equipment.

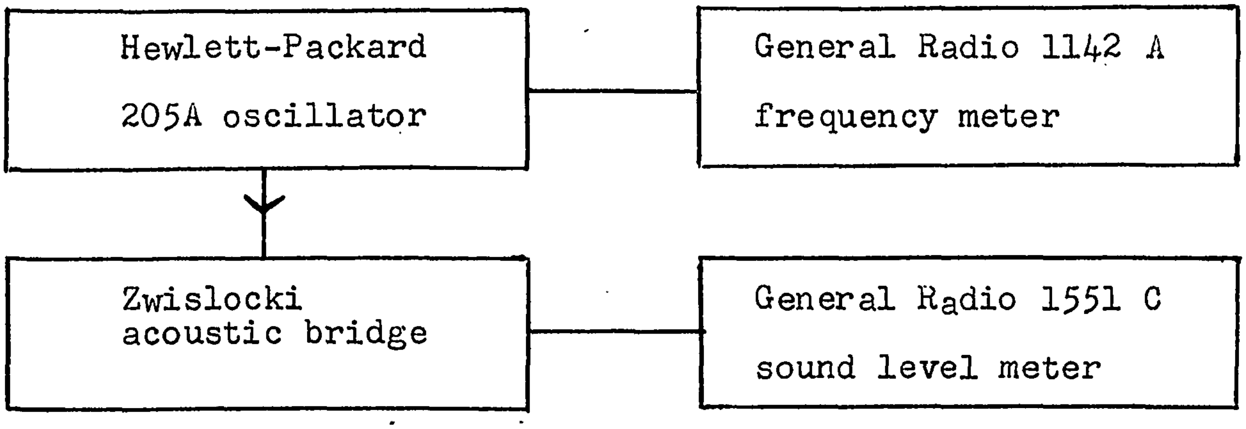
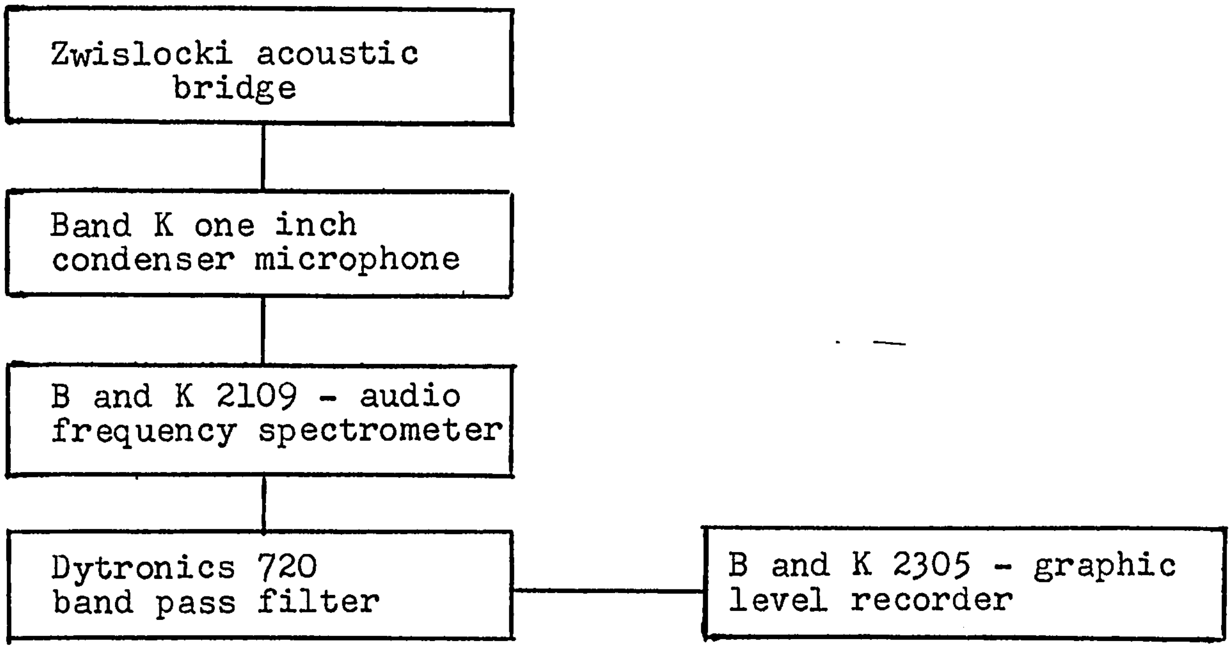


Figure 5 represents the probe tone delivery system to the acoustic bridge.

The Hewlett-Packard audio oscillator was calibrated to generate 500 Hz with the General Radio frequency meter and discriminator. The intensity of the probe tone was set to 55 dB HL by inserting the tip of the Zwislocki bridge into a specially built 2 cc coupler which was connected to the microphone of the sound level meter. This procedure assured that the intensity of the probe tone was below the threshold of the stapedius reflex. The output of the oscillator was checked throughout the experiment and was found to have high stability for both intensity and frequency.

Figure 6 represents the data recording system employed.

Figure 6. Block diagram of the data recording system.



The output of the acoustic bridge was coupled to the B and K condenser microphone by means of a short length of stethoscope tubing and a specially built brass adapter. This signal was fed to a B and K spectrometer which contains a third octave filter; the filter was set to center on 500 Hz. The spectrometer allowed display of the input signal on its decibel meter or the signal could alternatively be routed from the spectrometer, after filtering, to the B and K graphic level recorder. To further reduce the ambient noise in the system, a Dytronics band pass filter was placed in line between the spectrometer and the recorder. The filter was set for the highest sensitivity possible, providing a band width of 11.5 cycles around the center frequency of 500 Hz. This setting yielded 33 dB of rejection for the second harmonic and 38 dB of rejection for the third.

The graphic level recorder was used with a 50 dB logarithmic potentiometer and was generally used with a writing speed of eight inches per second and a paper speed of one millimeter per second; this combination seemed to offer the clearest data tracing for most subjects although it was sometimes helpful to increase the paper speed when a subject had responses of long duration.

The subject was in a prone position on a standard examination table with his left ear downward. The left ear was rested on the TDH-39 earphone shown in Figure 4 which was fitted into a foam rubber wedge for comfort. The acoustic bridge was supported by a specially built apparatus which was bolted to the examination table, as shown in Figure 7. The bridge was inserted in the subject's right ear and locked into place with the bridge holder.

At the start of each session, before the subject was placed on the examination table, his hearing was screened at 10 dB (ISO, 1964) at 250, 500, 1000, 2000, and 4000 Hz.

Figure 7

Photograph of the acoustic bridge support apparatus.

Thresholds were then recorded for the six test stimuli for the left ear, using the method suggested by Carhart and Jerger (1959) for pure tone testing. An ADC pure tone audiometer and a Beltone noise generator (type NB 101) were used for this purpose; both were fed through a set of Daven attenuators to allow testing at two decibel steps. The same phone was used for determining thresholds and delivering the test stimuli.

The only instructions given to the subject were to lie as still as possible and not to talk unless absolutely necessary. Any sudden movements by the subject were noted on the paper tape in the corresponding place by the examiner. The subject was also told that he would hear several series of sound bursts in his left ear.

After the subject was placed in the proper position on the examining table, a proper size tip for the ear speculum was selected and coated with petroleum jelly; the choice of a tip that effectively seals the external canal is essential. The bridge was then inserted in the subject's right ear and fixed in place with the mechanical bridge holder.

The bridge was balanced using the decibel meter on the spectrometer; finer adjustments were made by watching the pen of the graphic level recorder. When the point of minimal intensity of the probe tone had been reached, the first stimulus sequence was presented at such a level that the terminal stimulus was 110 dB SPL. If a response was seen in the middle or latter portion of the run, or if there was no response, the same series was repeated; if a response was seen in the early portion of the series, the second run was presented with an additional 10 dB of attenuation (terminal stimulus at 100 dB). If the results of either of the first two series were unclear, a third series was presented. This procedure was repeated for all six stimuli. For the last nine subjects, a third run of the white noise stimulus was presented regardless of the results of the first two runs. For the sake of clarity, the first scored run of any stimulus shall be called the "test" run; the second, "retest."

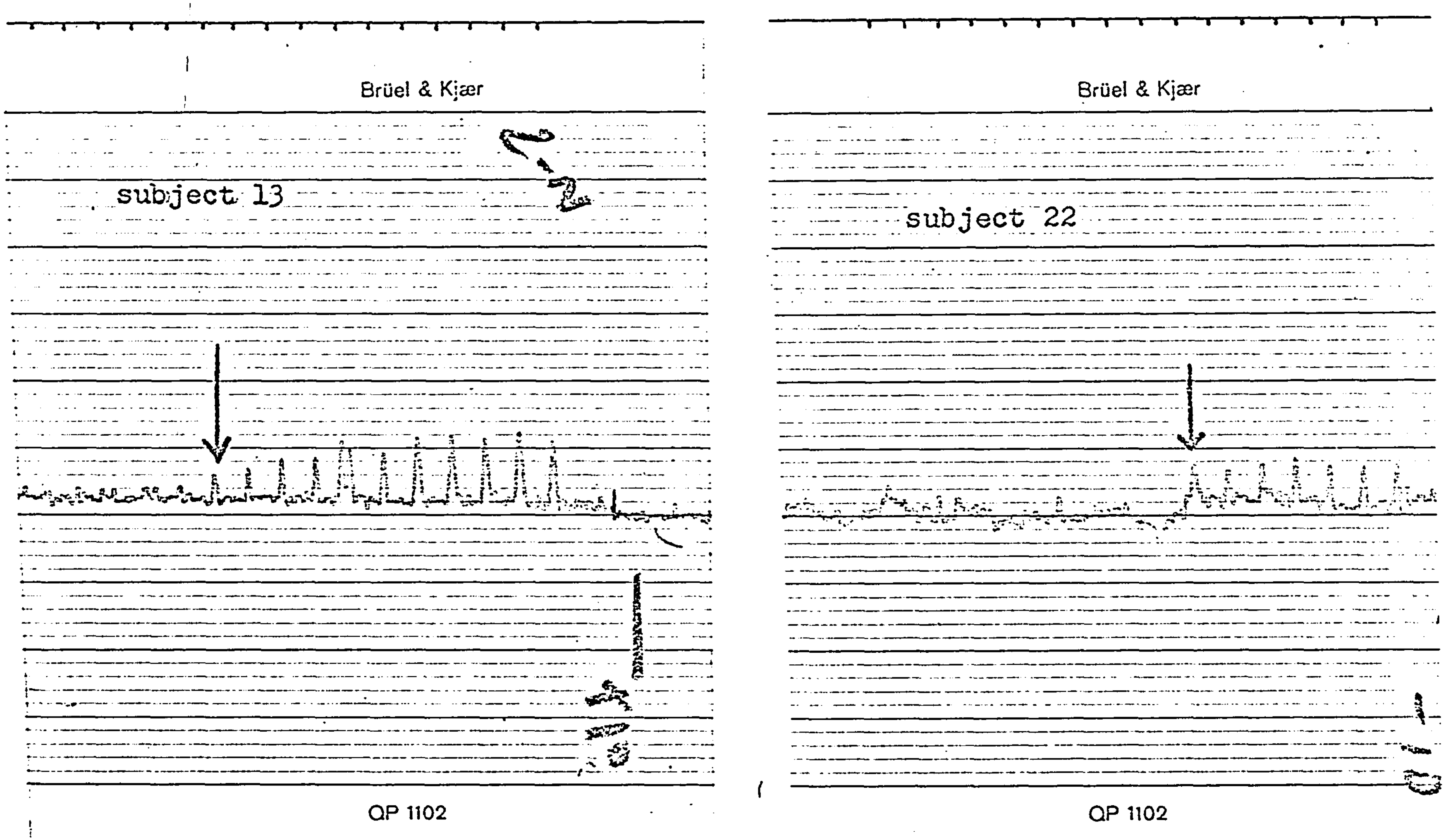
The intensity of the probe tone was carefully monitored throughout the experiment; it was frequently necessary to readjust the bridge between series to maintain a sharp null.

The 2305 recorder has a manual event marker; during the course of the experiment the investigator monitored the 100 Hz tone and recorded its occurrence with the marker. This allowed the scorer to determine the intensity at which the first response was recorded. This system, however, did not allow for measurement of the latency of response.

The record of responses to the stimuli was marked in a code so that the absolute level of the stimuli could not be determined by scorers other than the investigator. A sample of five records was randomly selected and scored by two additional scorers.

Figures 8 and 9 show the responses of the stapedius muscle to various stimuli as recorded on the B and K graphic

Figure 8. Stapedius response recordings to various stimuli at the normal recording speed (arrow indicates 1st response).



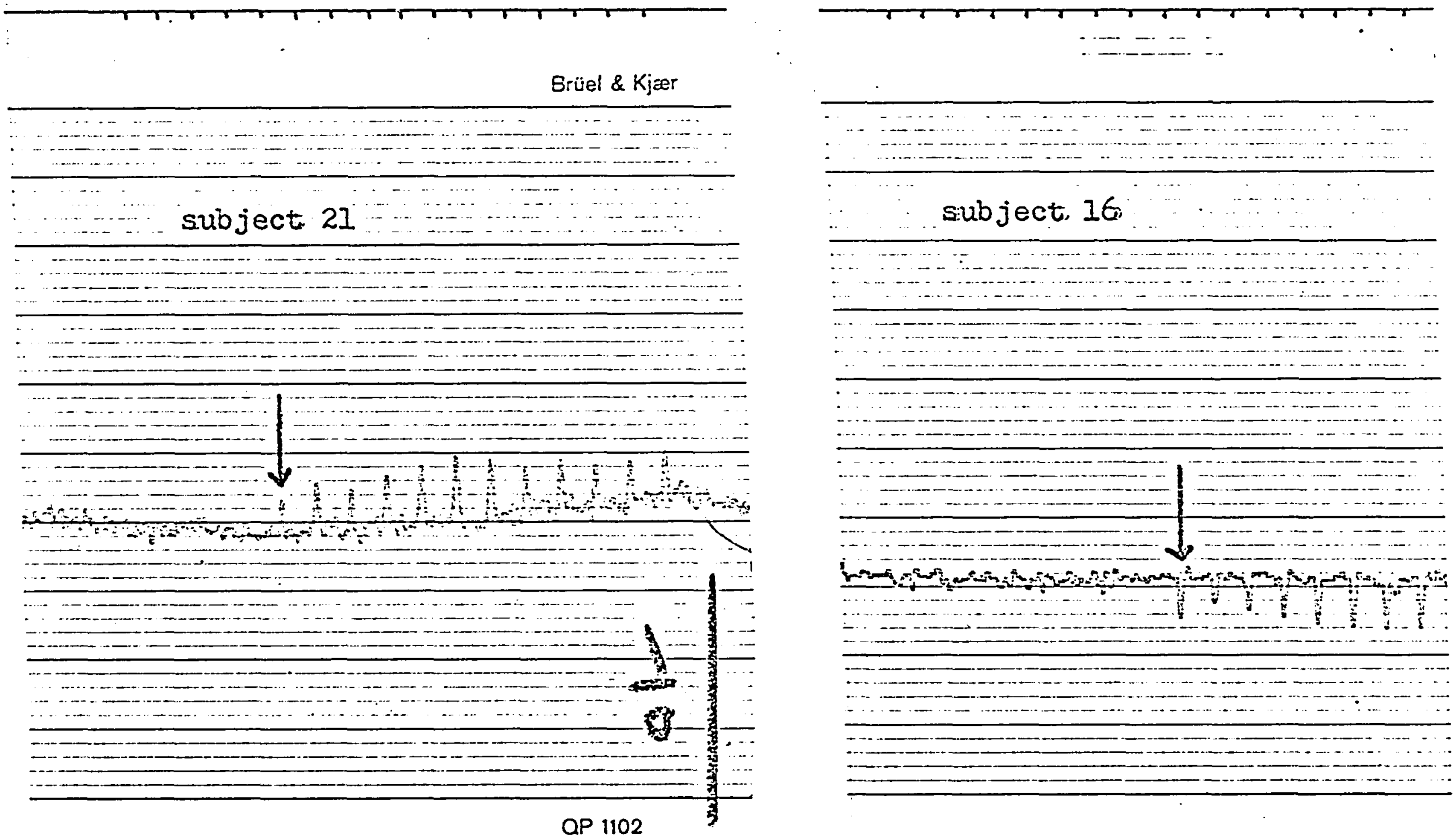
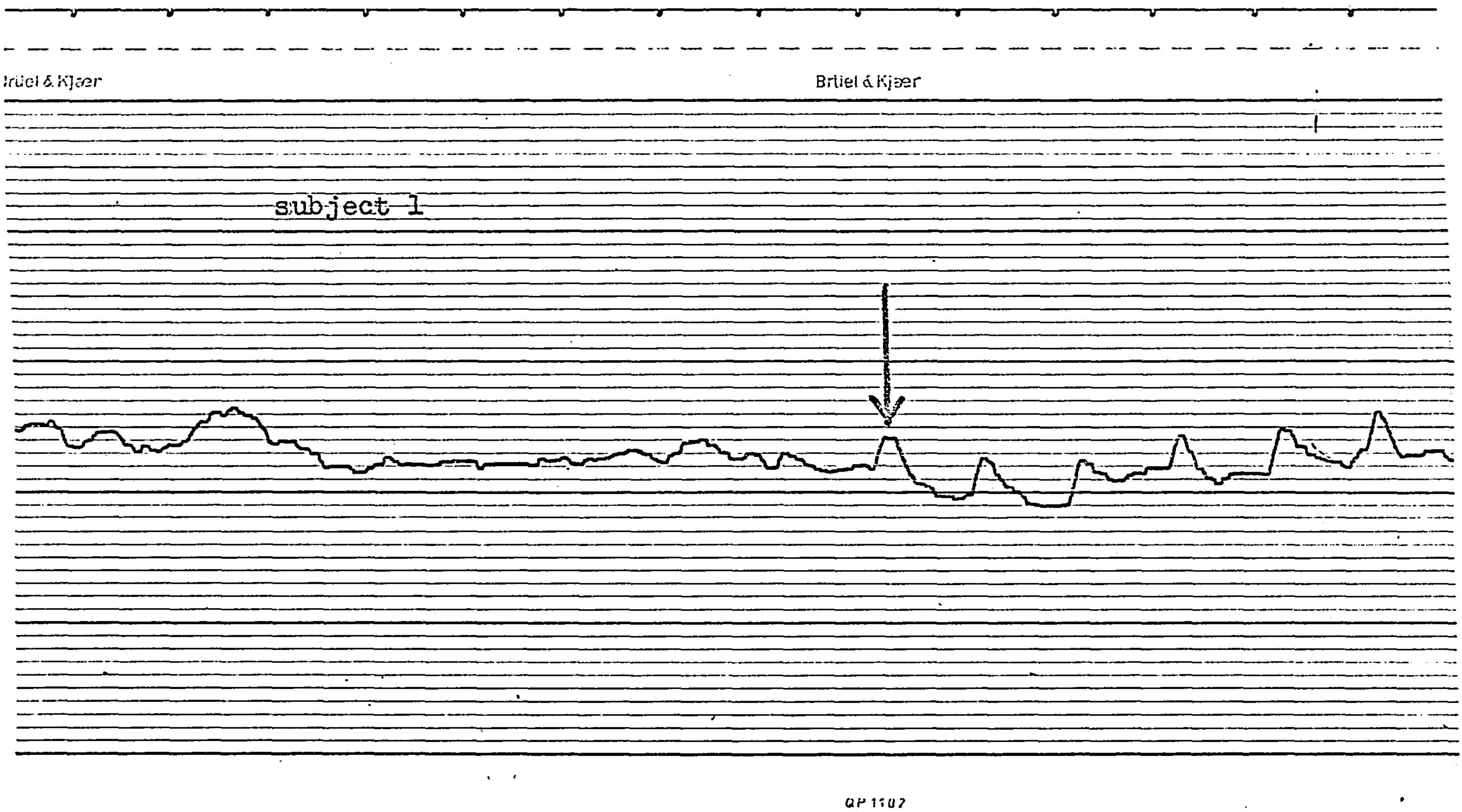


Figure 8. Continued.

Figure 9. Stapedius response recordings taken at the fast speed.



level recorder. The pip marks at the top of the recording indicate the onset of the stimulus.

All scorers adhered to the following six guidelines in scoring a record:

(1) In order to be accepted as a response, a peak must be part of a continuous series or chain of responses.

(2) Responses must be associated in time with the stimulus onset.

(3) Responses should be examined from the end of the series towards the beginning to take advantage of the increased clarity of the responses to higher intensity levels.

(4) The shape of a possible response in that series, in comparison with clearer responses in that series, may be used to aid in decision-making.

(5) The first two readable series will be used to determine the test and retest values for that record.

(6) If the initial point of response is unclear, a conservative point of view is to be adopted.

The statistical analyses employed in this study are all commonplace techniques; the formulas were taken from Dixon and Massey (1957) and Ferguson (1959) but are available in any standard text on the subject.

CHAPTER III

DATA

Table 1 summarizes the means, standard deviations and sample sizes for the six stimuli employed. Responses were not elicited from all subjects to all stimuli, so the "Number of subjects" column in Table 1 is not the same for each stimulus. All 30 subjects tested responded to the white noise and 4KHz narrow-band noise; 29 of the 30 subjects responded to the 2KHz narrow-band noise and 2KHz pure tone. Half of the subjects (15) responded to the 4KHz pure tone while responses to the 250 Hz stimulus were seen in only four subjects.[2]

The thresholds for the three noise stimuli, white noise, 2KHz narrow-band noise and 4KHz narrow-band noise are within a small range (61.57, 61.62 and 62.10 dB SL respectively). The responses to pure tone stimuli were at a notably higher level than those to the noise stimuli; the threshold to a 2KHz pure tone was found to be 81.59 dB SL and to a 4KHz pure tone to be 81.13 dB SL. These threshold values indicate that it required about 20 dB of additional stimulation to obtain a response when pure tones rather than noise were used as the stimuli.

The means for retest thresholds are also shown in Table 1. It can be seen that in all cases the retest threshold was lower than the initial threshold. This difference is exactly 1 dB for white noise, 1.31 dB for 2KHz narrow-band noise,

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[2] Because of the limited data collected for the 250 Hz stimulus, it will not be used in further analyses.

Table 1. Mean stapedius reflex thresholds (in dB SL) and associated standard deviations for both the test and retest conditions for the six experimental stimuli.

	white noise	narrow band 2KHz	narrow band 4KHz	2KHz pure tone	4KHz pure tone	250 Hz pure tone
Number of subjects	30	29	30	29	15	4
Mean (test)	61.57	61.62	62.10	81.59	81.13	73.50
Standard deviation	4.42	4.72	5.56	9.14	8.81	2.60
Mean (retest)	60.57	60.31	61.57	80.69	80.87	73.50
Standard deviation	5.24	6.24	5.55	8.51	8.52	2.96

.53 dB for 4KHz narrow-band noise, .90 dB for 2KHz, and .26 dB for 4KHz.

Table 2. Pearson product-moment correlation coefficients between test and retest threshold values.

	white noise	narrow band 2KHz	narrow band 4KHz	2KHz pure tone	4KHz pure tone
Correlation coefficient	.58	.67	.85	.93	.93

Table 2 shows the correlation coefficient between the test and retest stapedius reflex thresholds for each of the five stimuli having sufficient data for analysis. All the correlations are positive and significant at the .01 level using a two tail test. The coefficient is notably lower for white noise and 2KHz narrow-band noise (.58, .67) than for the other three stimuli (.85 to .93).

In the correlational analysis the size of the coefficient is dependent on the correspondence of the score for a subject in the test and retest situation. It can be seen in Table 1 that the retest means for white noise and 2KHz narrow-band noise, and to a lesser extent 4KHz narrow-band noise, are somewhat lower than the test means. Because of the differential degree of change from subject to subject, the relative positions of the various subjects changed from test to retest, and somewhat reduced correlation coefficients resulted for these stimuli.

This downward trend in threshold levels is confirmed by the data in Table 3, which shows that the difference between test and retest means is statistically significant for white noise and 2KHz narrow-band noise.

Table 3 shows the *t* value and level of significance for the difference between test and retest means for each of the stimuli employed. It can be seen that the mean differences for the white noise and 2KHz narrow-band noise stimuli are significantly different; the mean differences for the other stimuli are non-significant.

Table 3. Values of *t* and significance levels for the differences between the means of the test and retest thresholds.

	white noise	narrow band 2KHz	narrow band 4KHz	2KHz pure tone	4KHz pure tone
t value	2.06	2.73	.93	1.15	.40
significance level/1 tail	.05	.01	NS[a]	NS	NS

[a] NS = non-significant

Table 4 shows the mean stapedius reflex thresholds for nine subjects over three consecutive runs, with the white noise stimulus. The mean value decreased approximately two decibels with each repeat run. The difference between the means for run one and run two is significant at the .05 level and the

Table 4. Mean threshold values and tests for significant differences for three consecutive determinations of the threshold to the white noise stimulus (N=9).

	1st run		2nd run		3rd run
mean	60.44		58.44		56.67
t value (1vrs2, 2vrs3)		1.90		2.87	
significance level/1 tail		.05		.01	

difference between run two and run three is significant at the .01 criterion; obviously the difference between the first run and the third run means (3.77 dB) will be significant at the .01 level.

An examination of the standard deviations associated with the mean stimuli thresholds (see Table 1) shows that the standard deviations for the three noise stimuli are relatively homogeneous, the smallest being 4.42 and the largest being 5.56. The retest standard deviations increased for the white noise and 2KHz narrow-band noise stimuli (.82 and 1.52 additional, respectively); the retest standard deviation for 4KHz narrow-band noise showed no change from the initial value. The standard deviations for the pure tone stimuli are also relatively close to each other; the standard deviations for 2KHz were 9.14 and 8.51 (test, retest) and 8.81 and 8.52

for 4KHz.

It can be seen that the standard deviations for the pure tone stimuli are consistently larger than those associated with the noise stimuli.

Table 5. Tests for homogeneity of variance between test and retest variances.

	white noise	narrow band 2KHz	narrow band 4KHz	2KHz pure tone	4KHz pure tone
F ratio	1.41	1.74	1.00	1.15	1.07
significance level/1 tail	NS	NS	NS	NS	NS

Table 5 shows the F ratios for a comparison of the variances for the test and retest means for each of the experimental stimuli. All F values are non-significant indicating that any change in variance from the test to the retest condition may be attributed to chance factors.

Table 6 shows a comparison (F ratios) among the variances of the various stimuli used. None of the differences among the three noise stimuli reached significance at the .05 level; the difference between the two pure tone stimuli is also non-significant. All the comparisons between the variances of the noise and pure tone stimuli are significant at the .01 criterion (using 1 tail values).

Table 6. Tests for significant differences between the variances of the five test stimuli (F ratio is top number, 1 tail significance level is bottom number).

	narrow band 2KHz	narrow band 4KHz	2KHz pure tone	4KHz pure tone
white noise	1.14 NS	1.58 NS	4.28 .01	3.98 .01
narrow band 2KHz	-	1.39 NS	3.74 .01	3.48 .01
narrow band 4KHz	-	-	2.70 .01	2.51 .01
2KHz pure tone	-	-	-	1.08 NS

Table 7 shows the mean scores of three judges obtained by reading the data records for five subjects. The judges were guided by the rules for scoring that were listed in Chapter II.

Table 7. Mean SPL threshold values across all stimuli for the experimenter and two independent scorers (N=5).

	experimenter	scorer MB	scorer HN
mean threshold	88.39	88.17	88.78

It can be seen that the mean differences among the three scorers are exceedingly small. It was found that over 90% of both scorers' judgments are within two decibels of the experimenter's judgment.

The means are based on 46 of the 60 possible responses because 14 of the stimuli showed no response. It should be noted that there was total agreement among the three scorers on all of the stimuli in the no response category.

It is therefore concluded that the method of response recording used allows reliable inter-scorer judgments of the threshold of the stapedius response.

To determine the approximate shape of the distribution of the scores obtained, frequency polygons for each of the stimuli employed were drawn; these may be found in Appendix A. Considering the relatively small sample size, the curves are acceptable approximations of normality. All the curves are uni-modal and only 2KHz is skewed to any notable degree. Several of the curves appear to be more peaked than the normal function, indicating a large cluster of scores about the mean.

CHAPTER IV

DISCUSSION AND CONCLUSIONS

Discussion of the data

The stapedius reflex thresholds that were found for the 2000 Hz and 4000 Hz pure tone stimuli (81.6 and 81.1 dB SL respectively) are in general concurrence with those presented by Metz (1946), who found pure tone thresholds to lie between 70 and 90 dB SL, and Jepsen (1951) who found thresholds at approximately 80 dB SL for these frequencies. Both of these investigators utilized electroacoustic impedance bridges to collect their data.

All of these thresholds are in contrast to the data collected by Weiss, et al. (1962), who used tympanomanometry to record the reflex. Møller (1964), as was noted earlier, warns that small contractions of the stapedius muscle may not produce measurable changes in the air pressure in the external auditory meatus. The integration of this warning with the knowledge that the strength of the contraction of the stapedius is dependent on the intensity of the elicitor may account for the fact that the thresholds found by Weiss and his associates are approximately 10 dB higher than those indicated by the present research. If Møller's suggestion is valid, the investigation of the parameters of the stapedius would best be undertaken with the impedance method due to its superior sensitivity for this work.

Responses in only four of the 30 subjects tested were noted at 250 Hz. Jepsen (1963) noted difficulty in obtaining responses at 125 Hz and 8000 Hz but was able to obtain responses at 250 Hz. He reported a mean threshold for that frequency of

85 dB SL; however, the number of subjects responding at that frequency was not reported. This value is in agreement with the threshold of 87.3 dB SL reported by Djupesland, Flottorp and Winther (1967) for this frequency. It was noted in Chapter II that stimulus recordings were calibrated to allow tones and noise bursts up to 110 dB SPL, which would be equal to 85 dB with reference to normal human hearing (ISO, 1964). It is therefore possible that the intensity of the stimulus at 250 Hz was insufficient to elicit a reflex in the majority of the subjects; the four responses recorded to the 250 Hz stimulus, having a mean of 73.5 dB SL, may then represent lower extreme values. It would seem, however, that a larger number of responses in the area of 80 to 85 dB SL should have been recorded if the true mean were located only five decibels above the maximum intensity of stimuli presented.

Responses at the other end of the frequency spectrum utilized were also less consistent; only 15 of the 30 subjects tested responded to the 4000 Hz stimuli. This cannot be attributed to lack of stimulus intensity because 110 dB SPL at 4000 Hz is equal to 101 dB with reference to normal hearing (ISO, 1964). Further study into stapedius response to high and low frequency stimuli is necessary to clarify this matter.

One subject did not respond to the 2KHz narrow-band noise stimulus and another did not respond to the 2000 Hz pure tone stimulus; both subjects responded at several other frequencies tested. This occurrence has been noted a number of times in the literature. It is important to note that if a subject's response could be recorded on the test run to a certain stimulus, it was also recorded on the retest run; if no response was recorded to a certain stimulus by a subject during the test run, the retest run always confirmed this finding.

The mean thresholds of the stapedius reflex to all three noise stimuli employed in this study were substantially equal (61.6, 61.6 and 62.1 dB SL). The value for white noise is in agreement with the value presented by Lilly (1964) using his own acoustic bridge (60 dB SL); it is somewhat lower than the 69 dB SL threshold to white noise Lilly found with the Zwislocki acoustic bridge. Dallos (1964) found the mean response level to white noise to be 72 dB SL using the Zwislocki bridge. These reports were based on very limited samples (Lilly, N=5, Dallos, N=6) and cannot be considered to be population estimates; the distribution of thresholds to the white noise stimuli in this study (see Appendix A) appears to be a satisfactory approximation of the normal distribution.

The reports which noted that the stapedius threshold to noise is lower than to pure tones (Metz, 1946; Jepsen, 1963; Møller, 1962a; Djupesland, Flottorp, and Winther, 1967) are confirmed by the data of the present study. The differences between the thresholds for 2KHz and 4KHz pure tones and those for the various noise stimuli are approximately 20 dB. This finding is in sharp contrast to Møller's (1962a) report that there was a five decibel difference between the stapedius response to noise and a 1450 Hz pure tone; no other comparative study is available.

The standard deviations associated with the mean stapedius thresholds for all noise stimuli were found to be significantly smaller than those associated with both of the pure tone stimuli, indicating significantly less dispersion of scores for the noise stimuli (see Table 6).

When the mean test and retest stapedius thresholds were compared, it was found that the retest values only for white noise and for 2KHz narrow-band noise were significantly lower. To investigate this finding further, a third series of white noise stimuli was added to the design for the final nine subjects; the mean difference in the threshold between the second and third run was significant, as was the difference between the first and second run. This indicates that the stapedius threshold to white noise and 2KHz narrow-band noise decreases with stimulation. A smaller non-significant difference can be seen for the 4KHz narrow-band noise stimulus, but no such trend is apparent for the pure tone stimuli (see Table 1).

Simmons (1960) reported a temporary improvement in the reflex threshold in cats after short exposure to 80-90 dB SPL of noise. He studied the reflex threshold using cochlear microphonics and electromyography and noted changes of 7 to 40 dB which persisted from a minimum of five to a maximum of 40 minutes. He attributes this to a phenomenon called post-tetanic potentiation which is thought to be a function of the hyper-excitability of certain brain stem structures following acoustic stimulation.

The phenomenon of auditory sensitization in humans has been reported by Hughes (1954) and Hughes and Rosenblith (1957). Hughes states that the principle that neural systems suffer fatigue effects following stimulation is an over-generalization; sometimes, he continues, the threshold falls instead of rising. He notes in his study of absolute thresholds that the sensitization produced by a pure tone is non-specific; that is, a given tone can sensitize the whole auditory mechanism to a wide range of frequencies. A mean audiometric threshold improvement of six decibels following exposure to a 500 Hz tone at 100 dB SPL was reported in three subjects.

It should be noted that the existence of this change in threshold precludes the use of computerized averaging techniques to study the smallest responses of the stapedius muscle, which might not clearly be seen in a single trial.

Because of the significantly smaller variability seen in response to the noise stimuli and their effectiveness as elicitors, it would appear that white noise and narrow-band noise are potentially the best stimuli for use in recruitment testing. Changes due to auditory sensitization which will appear with repeat testing (approximately two decibels) are probably small enough to be ignored for this purpose.

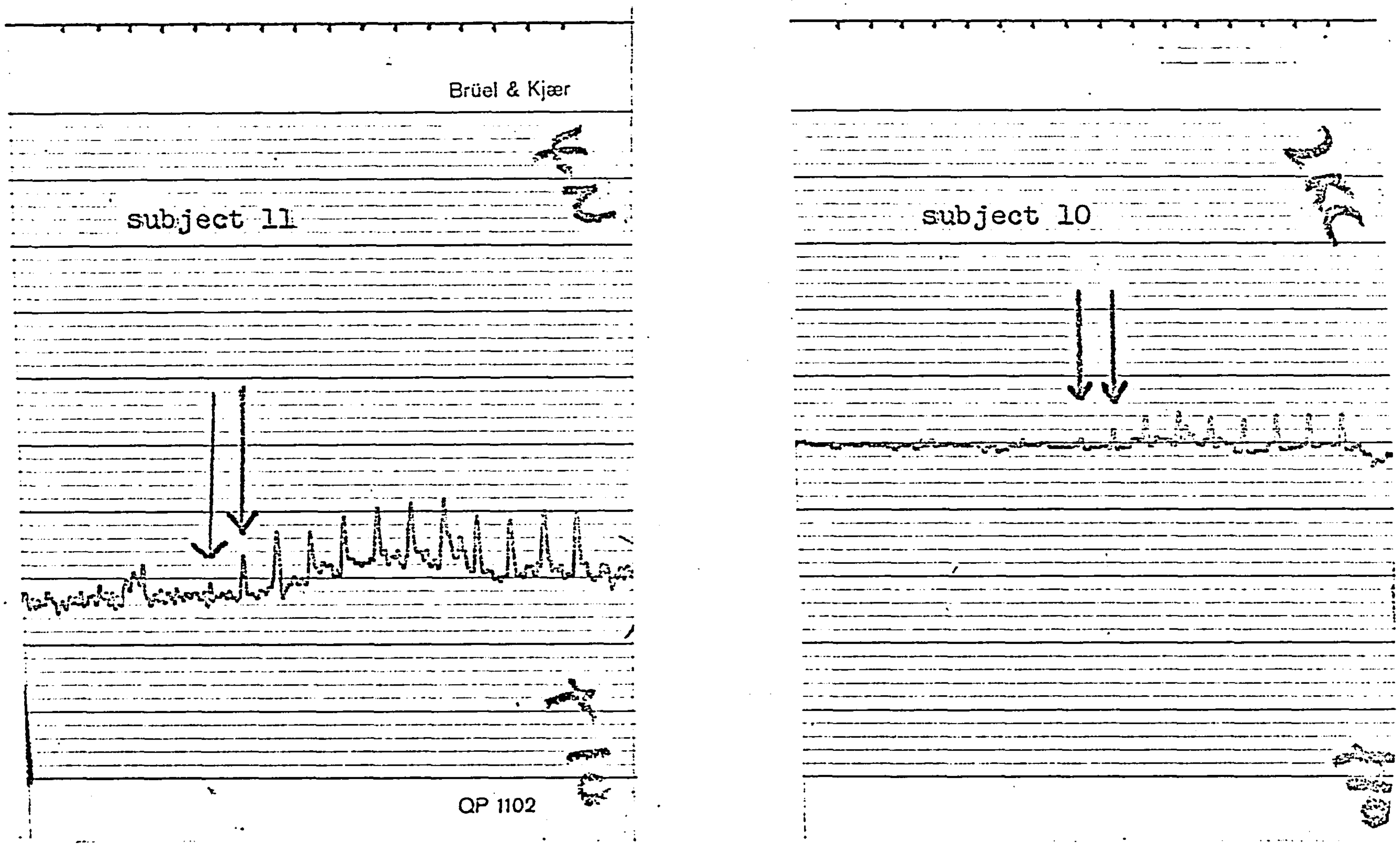
Klockhoff (1961) states that, provided that no non-organic hearing loss is present, the stapedius reflex test of recruitment will be unexceptionable. If validated, the method has the advantage of being objective, but one should note that the presence of an incidental conductive impairment would preclude the stimulation of the reflex. In other words, if the reflex is to be used as a conclusive test of the presence or absence of recruitment, the possibility of confounding results due to a conductive pathology must be ruled out. Klockhoff suggests that this can be done with the cutaneous stapedius reflex test; the observation of a cutaneous stapedius response, in the absence of an acoustic stapedius response, would then be interpreted to indicate the absence of recruitment. If no cutaneous stapedius response is observable, this approach to recruitment testing is inapplicable.

It should be noted that a small constant error may have affected the means for the stapedius threshold. In some cases it was difficult to identify the first response of a series because the near-threshold responses were relatively small (see the records in Figure 10). Following the sixth scoring rule (see Chapter II), the more conservative (higher) response was chosen. The maximal effect this might have had on the mean threshold values obtained is estimated at one to two decibels.

The system designed to record the stapedius reflex for this study was sufficiently sensitive to allow identification of changes of one to two decibels in the probe tone level. Most near-threshold responses were seen to cause one and one-half to three decibel changes in the probe tone level; responses to more intensive stimuli caused changes of 11 decibels (see Figures 8 and 9 for sample response recordings).

It was noted earlier that many initial responses caused changes in the probe tone level of less than two decibels.

Figure 10. Stapedius response recordings showing a questionable first response (arrows indicate possible choices-2nd was accepted).



This would indicate that aural monitoring of the probe tone level to detect the threshold of the stapedius response is inappropriate because such a small change may not be noted by the examiner. This may account for the difference between the threshold for white noise found in this study and the threshold reported by Lilly (1964). Lilly used aural monitoring of the Zwislocki bridge and found a threshold of 69 dB SL; he may not have been able to perceive the small changes caused by the initial responses.

Further comment on the stapedius reflex

Lilly (1964) has reported that the threshold of the stapedius reflex may be dependent on the probe tone frequency used. He reports that the mean stapedius reflex threshold for white noise recorded with the Zwislocki bridge was 69 dB SL using the same monitoring frequency as was used in this study (500 Hz); he notes that he obtained a threshold of approximately 59 dB SL using a probe tone of 866 Hz (the best probe tone frequency, according to Lilly). The explanation for this difference is obscure if the intensity of the probe tone was kept safely below the threshold of the reflex, as is obviously necessary; the intensity of the probe tone used in the 1964 Lilly study is not reported.

Reger (in Jepsen, 1963) has measured the threshold shift caused by voluntary contraction of the tympanic muscles; he reports a threshold shift of 30 to 35 dB at 125, 250 and 500 Hz. A shift of about 15 dB was noted at 1000 Hz and no effect was recorded at 2000, 4000 and 8000 Hz. These shifts are somewhat larger than the 15 dB shift reported by Shipley (in Jepsen, 1963) at 250 Hz. Although the exact values are not known, there is sufficient evidence in the literature to conclude that a stapedius contraction has a degrading effect on sound transmission efficiency for the lower frequencies. The results of the present study indicate that the exposure of a normal ear to about 75 dB SPL of white noise will cause a stapedius reflex; the effect of the reflex on a pure tone threshold in the contralateral ear appears to be a generally unrecognized error factor in audiometry employing masking. One can only speculate as to how much of the threshold shift commonly accounted for as a central masking effect is due to this factor.

It has been reported in the literature that the stapedius response is absent in the presence of a significant conductive pathology. It has also been demonstrated that an acoustic stapedius response is present in subjects with a severe sensori-neural hearing loss of cochlear origin. In view of this, it is of clinical importance to note that the impedance method can be used to determine if a secondary conductive pathology exists in an ear which has a severe enough sensori-neural loss to preclude the determination of clinical bone conduction thresholds. The absence of the reflex (acoustic and cutaneous) would be indicative of middle ear pathology.

The use of a visual display apparatus with the Zwislocki acoustic bridge has several distinct advantages over aural monitoring. With this system, the hearing sensitivity of the examiner is not a confounding variable. Furthermore, permanent records may be obtained for further analyses and cross-validation of scoring methods. The substitution of a data recorder or a storage oscilloscope for the graphic level recorder would allow measurements of the latency of the stapedius response.

It has yet to be determined if this electroacoustic system would allow for the detection of null points that are as accurate as aural monitoring. The difference, if any, would appear to be small based on the experience of this writer.

Suggestions for further research

The results of this study indicate that the mean threshold values for the noise stimuli are approximately 62 dB SL. The standard deviations associated with these means are about 5. It is known that 99% of the normal population will fall within three standard deviations of the mean; therefore, it may be stated that 99% of the normal population will have a stapedius reflex threshold to (for example) white noise that is higher than 47 dB SL. It would then appear logical to hypothesize that a stapedius reflex threshold of less than 47 dB SL is abnormal; this statement is associated with a statistical confidence level of .99. One should note that the only disorder known to cause a lowering of the stapedius reflex threshold is recruitment.

Validity studies for the use of the stapedius reflex test of recruitment are the next logical step in the standardization of the procedure. The initial study should employ patients who demonstrate significant recruitment on the alternate binaural loudness balance test and the monaural loudness balance test; the comparison of the results of the above recruitment measures with the stapedius reflex test would allow the determination of validity coefficients.

Further study into the identification of partial recruitment should follow. It would appear possible, with the stapedius reflex test, to develop a numerical scale defining the amount of recruitment present. A study of a sample of mildly recruiting ears should be undertaken to determine if these ears are effectively separated from the lower extreme values of the normal population.

The data presented by Jepsen (1963) indicated that the stapedius reflex threshold decreases with age. The first decrease that can be detected from his graphs appears in the sample of 60 year old subjects, and is more pronounced in the group of 70 year old subjects. Assuming that this finding is confirmed, separate norms for these age groups must be established.

The stimuli for this study were 500 ms in duration, with a rise-fall time of 5 ms. Lilly (1964) has reported that the stapedius reflex threshold is somewhat lower for pulsed stimuli than for steady stimuli. This parameter of stapedius reflex elicitation, as well as such other parameters as the effect of rise-fall time variation and the effect of shortening the stimulus on-time, must be investigated.

Further study of the reflex threshold obtained by monitoring the impedance change in the ear that is stimulated is needed to define the differences found, if any, when using contra-lateral stimulation, as in the present study.

Further investigation into the adaptation of the stapedius muscle seems indicated. Although the stapedius is known not to fatigue, it is commonly thought to display adaptation behavior to auditory stimulation; Dallos (1964) and Lilly (1964) have suggested that this is not the case with intensive stimulation. A comparison of the muscle's behavior, with respect to this parameter, in response to high intensity noise and pure tone stimuli is needed to clarify the situation.

The delimitation of the minimal pathology which will preclude the elicitation of the stapedius reflex is of clinical importance; if it should be true that any clinical pathology of the middle ear precluded the reflex, the contribution to otological diagnosis and especially otological screening with children would be considerable.

Inasmuch as the introduction of middle ear pathology in measured doses appears to be the most direct method of study, the use of human ears is impractical. Kato (see Chapter I) noted that he was unable to elicit an acoustic tensor tympani response in monkeys, while contractions of the stapedius were observed. It is possible that study of the effect of pathology on the middle ears of monkeys may shed some additional knowledge on the problem.

Thorough definition of the parameters of the effect of post-tetanic potentiation seems to be overdue. The absolute size of the effect and the relation of the bandwidth and frequency of the stimulus to the size of the effect are essential to complete understanding of the nature of the stapedius reflex.

The relationship between the firing of the tensor tympani and the stapedius muscles and movements of the eardrum has not been clearly defined. The equivalence of inward movement of the drum and a tensor response could be demonstrated with a patient having a sectioned tensor but a normal stapedius; the inability to record inward movements of the drum to acoustic stimuli would be strong evidence for the existence of this relationship. A subject afflicted with Bell's palsy could be used to determine if outward movements of the eardrum to acoustic stimulation could only be accounted for by stapedius contractions; to accept this assumption one must be unable to record outward movement of the eardrum in this subject. Also, on remission of the palsy, outward movements of the eardrum to acoustic stimulation should be recordable.

The comparative sensitivity of tympanomanometry and the impedance method for measuring stapedius contractions is of importance. The comparison of the reflex thresholds determined by the two methods in subjects with inoperative tensor tympani muscles should provide this information.

Summary and conclusions

The threshold of the stapedius reflex in normal human subjects was studied using contralateral stimulation with the Zwislocki acoustic bridge. The results indicated that:

1. The stapedius reflex thresholds for 2KHz and 4KHz pure tones were found to be approximately 81 dB SL; the reflex thresholds for the noise stimuli studied were found to be approximately 62 dB SL. Therefore, the threshold for various noise stimuli was about 20 dB lower than for 2KHz and 4KHz pure tones. All stimuli were 500 ms in duration and had a rise-fall time of 5 ms. The monitor tone frequency used in this study for all measurements with the acoustic bridge was 500 Hz.
2. The mean threshold values for noise stimuli were associated with smaller standard deviations than were the mean threshold values for the pure tones tested. The reflex threshold was seen to have a high test-retest reliability regardless of stimuli employed.
3. The thresholds for white noise and 2KHz narrow-band noise were seen to decrease with repeated stimulation. This finding was discussed in a framework of auditory sensitization.
4. It was concluded that noise stimuli would be preferable to pure tones for recruitment studies with the acoustic bridge because of their greater effectiveness

in reflex elicitation and the greater stability of the noise-stimulated reflex threshold.

APPENDIX A

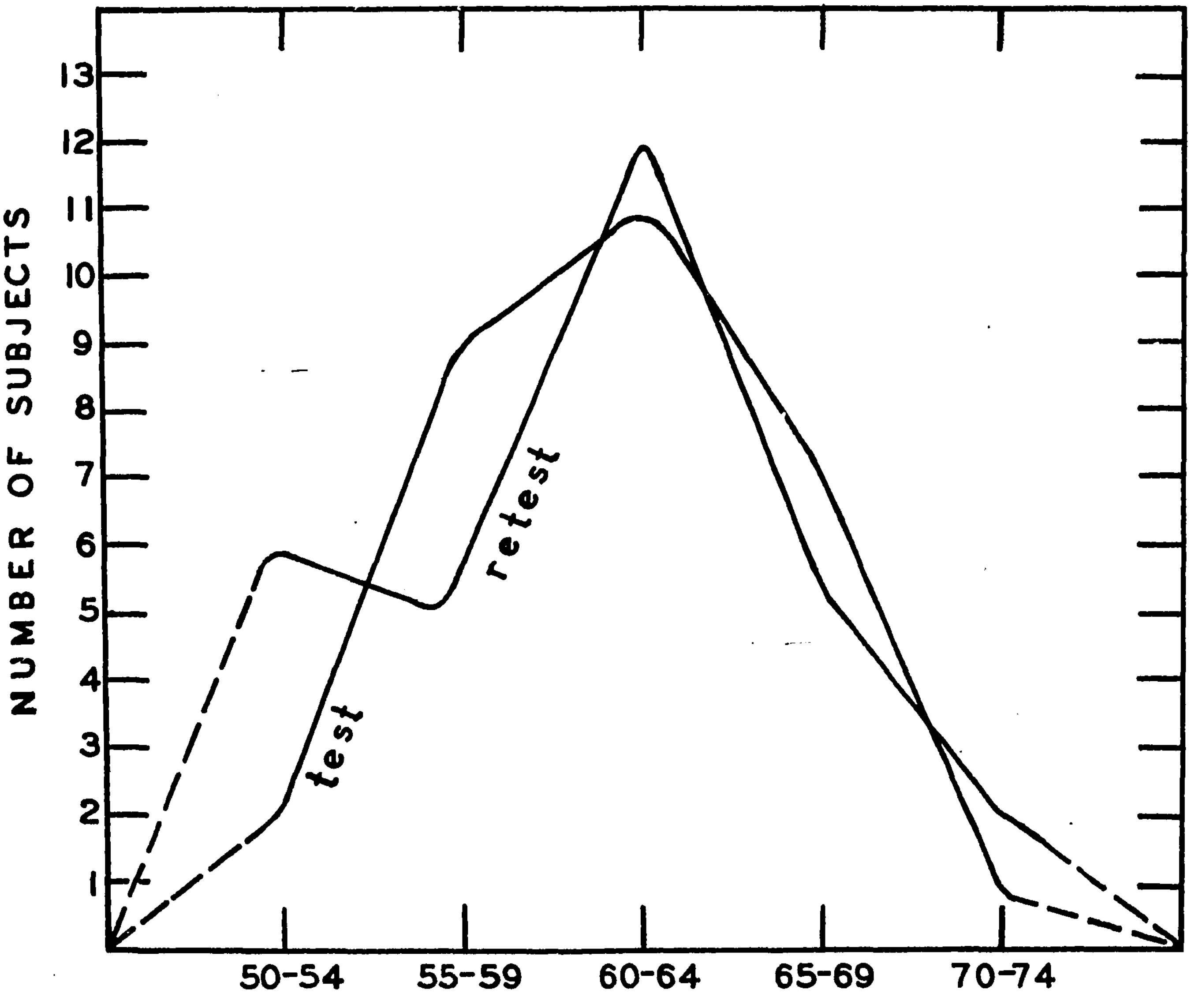


Figure 11. Distribution of thresholds for white noise (N=30).

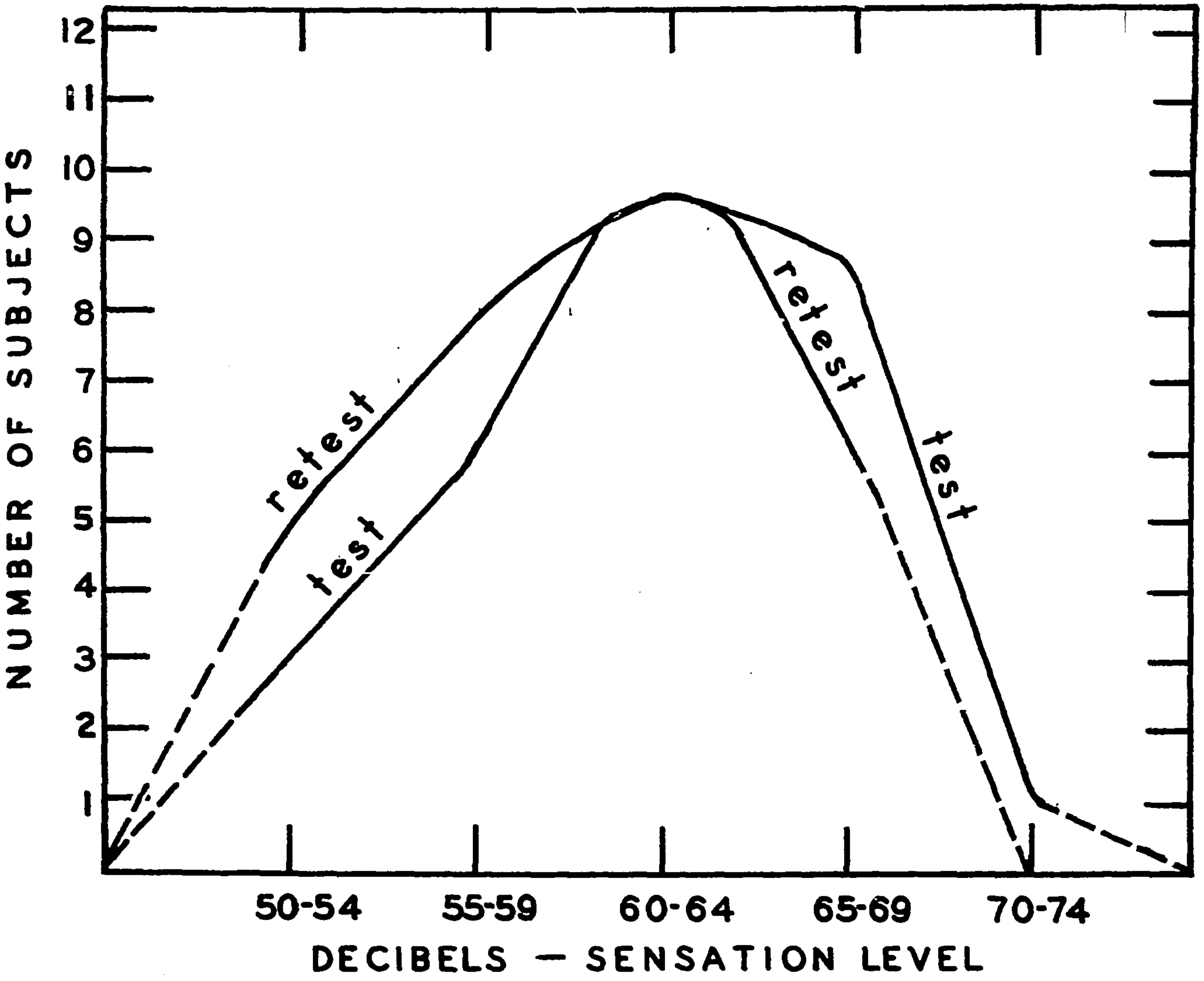


Figure 12. Distribution of thresholds for 2KHz narrow-band noise (N=29).

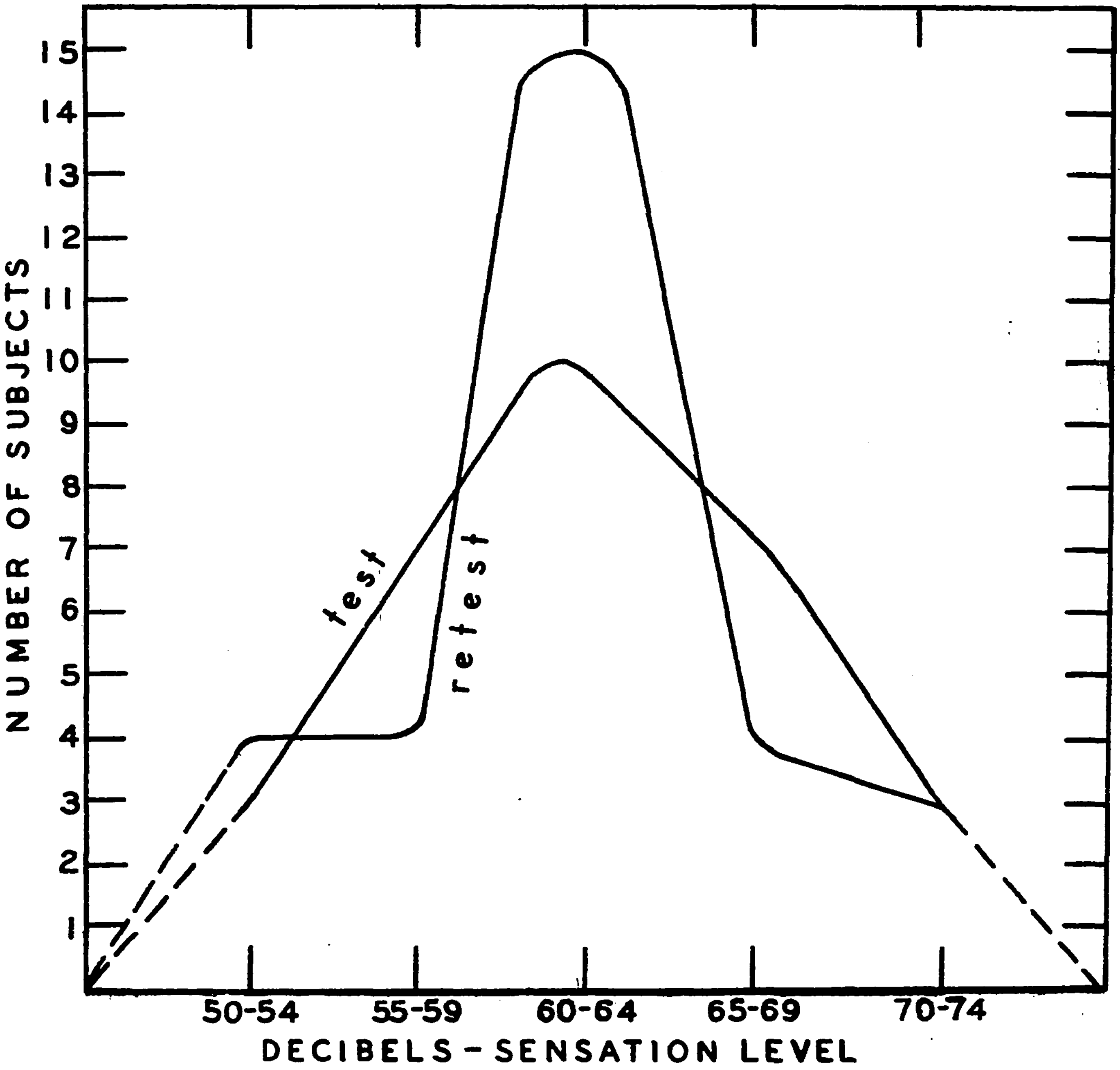


Figure 13. Distribution of thresholds for 4KHz narrow-band noise (N=30).

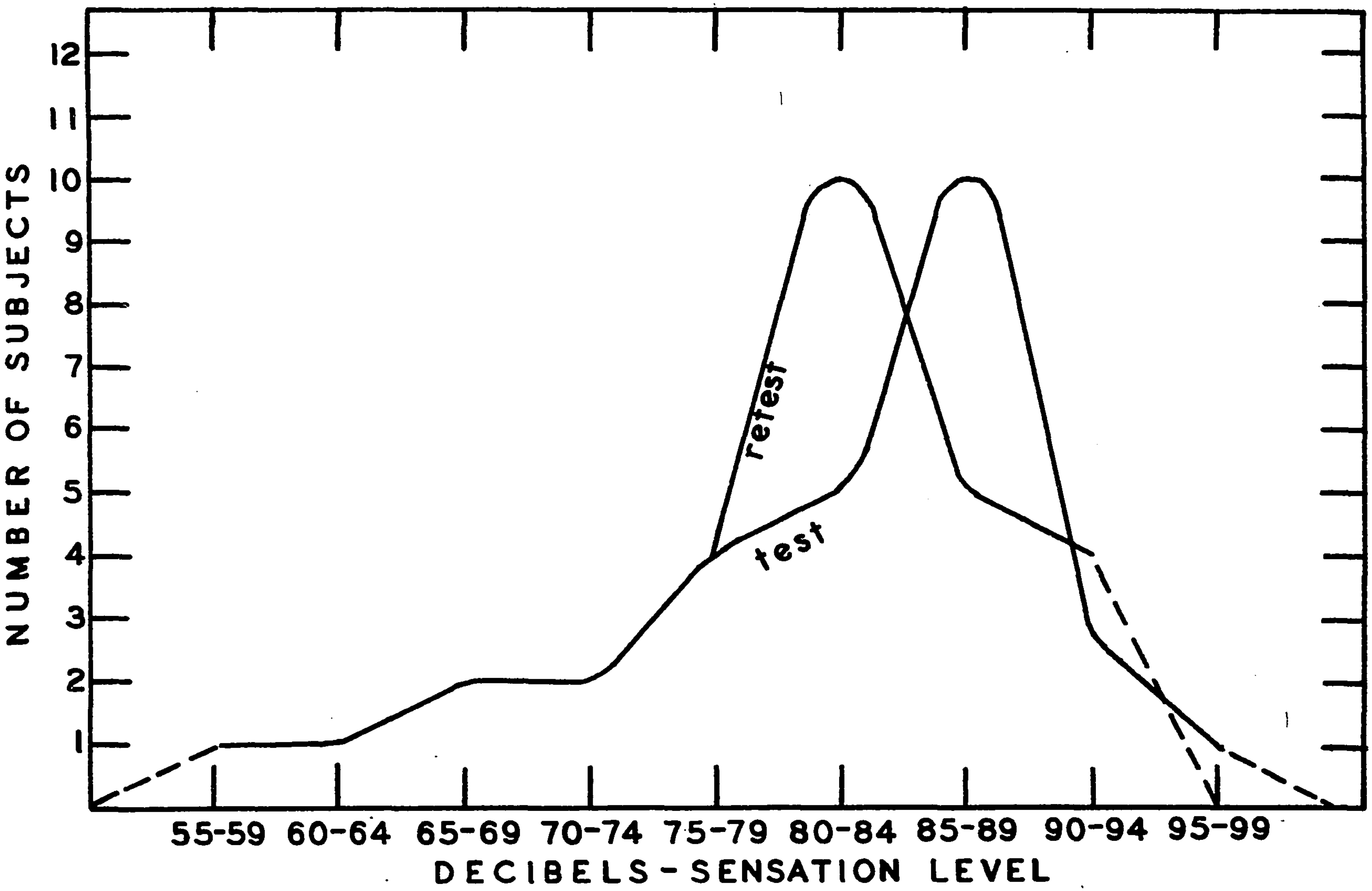


Figure 14. Distribution of thresholds for 2KHz pure tones (N=29).

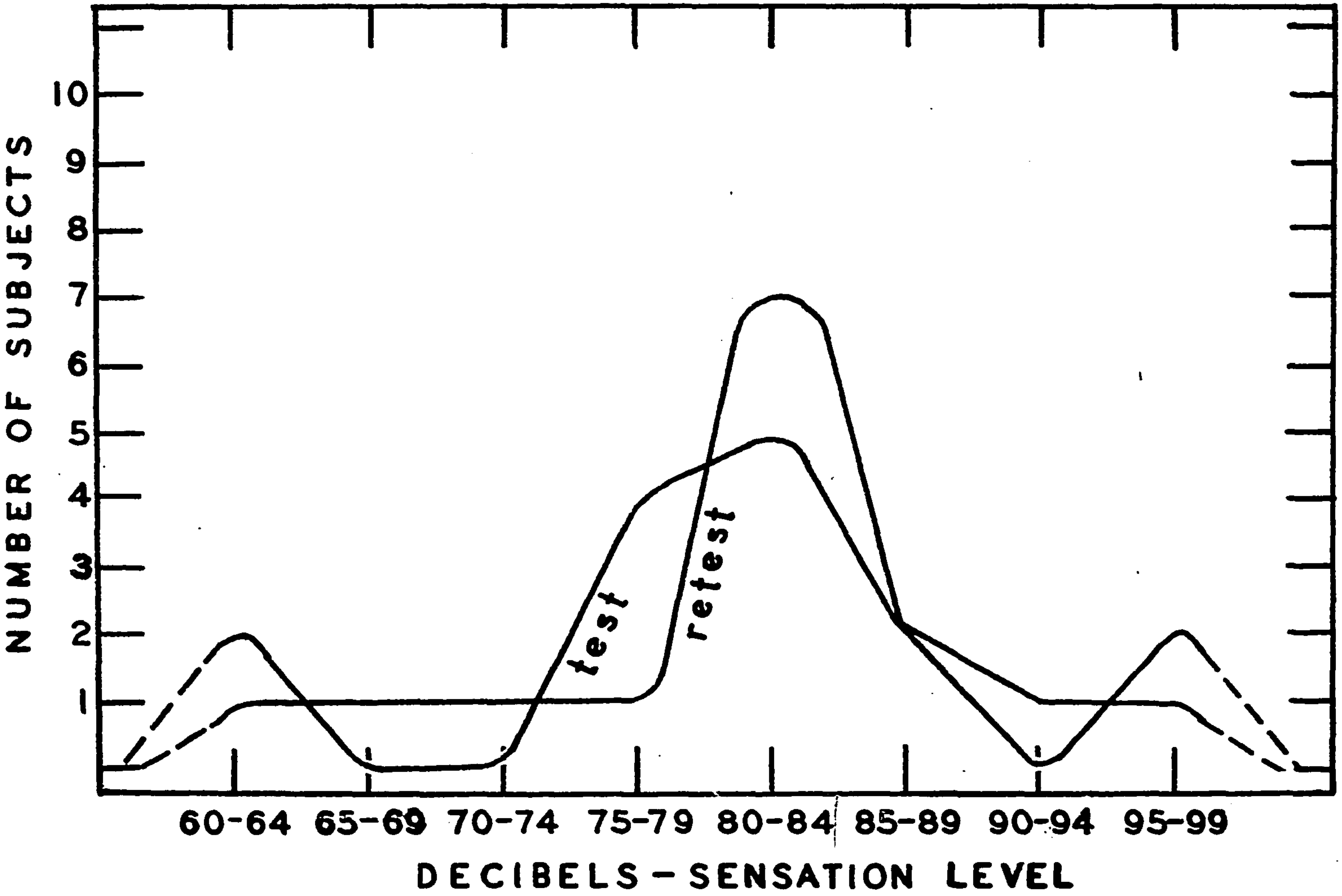


Figure 15. Distribution of thresholds for 4KHz pure tones (N=15).

APPENDIX B

Individual subject responses and
audiometric thresholds (values in SPL).

Subject Number	White noise			N-B 2 KC			N-B 4 KC			2000 HZ			4000 HZ			250 HZ		
	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL
1	84	25	59	90	22	68	94	22	72	90	2	88	86	5	81	NR	23	
1 RT	86		61	88		66	88		66	86		84	94		89	NR		
2	78	20	58	80	16	64	86	20	66	NR	3	--	NR	4		NR	27	
2 RT	80		60	82		66	82		62	NR		--	NR			NR		
3	86	22	64	86	22	58	94	30	64	88	1	87	NR	4		98	29	69
3 RT	86		64	82		54	92		62	90		89	NR			98		69
4	92	34	58	98	32	66	98	30	68	98	9	89	NR	12		NR	23	
4 RT	96		62	96		64	92		64	100		91	NR			NR		
5	100	28	72	88	22	66	94	22	72	92	17	75	NR	0		NR	28	
5 RT	98		70	88		66	94		72	92		75	NR			NR		
6	76	20	56	74	16	58	80	26	56	84	2	82	NR	4		NR	23	
6 RT	72		52	74		58	80		56	78		78	NR			NR		
7	88	30	58	NR	28	--	90	28	62	98	9	89	94	7	87	NR	33	
7 RT	84		54	NR		--	96		68	100		91	92		85	NR		
8	92	40	62	94	33	61	90	35	55	96	10	86	NR	20		106	31	75
8 RT	94		62	92		59	86		51	92		82	NR			104		73
9	90	30	60	94	28	66	92	26	66	84	6	78	NR	4		102	27	75
9 RT	88		58	96		68	94		68	86		80	NR			102		75
10	96	30	66	92	28	64	90	30	60	98	4	94	NR	2		NR	28	
10 RT	98		68	86		58	94		64	96		92	NR			NR		
11	92	26	66	86	21	65	86	21	65	92	-3	95	94	-1	95	NR	28	
11 RT	90		64	88		67	82		61	84		87	90		91	NR		
12	98	33	65	86	28	58	94	30	64	90	2	88	98	1	97	NR	23	
12 RT	96		63	90		62	94		64	92		90	100		99	NR		

Subject Number	White noise			N-B 2 KC			N-B 4 KC			2000 HZ			4000 HZ			250 HZ		
	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL
13	92	25	67	82	22	60	84	23	61	96	12	84	100	15	85	NR	33	
13 RT	90		65	82		60	84		61	94		82	98		83	NR		
14	92	25	67	88	21	67	92	31	61	98	12	86	104	20	84	NR	29	
14 RT	94		69	90		69	94		63	94		82	102		82	NR		
15	94	28	66	80	22	58	80	24	56	82	2	80	NR	4		NR	33	
15 RT	88		60	76		54	86		62	82		80	NR			NR		
16	84	22	62	86	20	66	98	24	74	84	-3	87	NR	-6		NR	23	
16 RT	88		66	72		62	94		70	82		85	NR			NR		
17	88	33	55	96	30	66	88	31	57	100	6	94	96	15	81	NR	33	
17 RT	82		51	94		64	92		61	96		90	96		81	NR		
18	92	28	64	84	24	60	84	24	60	92	6	86	NR	7		NR	31	
18 RT	90		62	84		60	88		64	90		84	NR			NR		
19	84	30	54	80	26	54	80	26	54	74	15	59	80	16	64	NR	35	
19 RT	86		56	78		52	78		52	74		59	78		62	NR		
20	86	24	62	84	22	62	80	22	58	80	10	70	NR	14		NR	33	
20 RT	82		58	80		58	78		56	74		64	NR			NR		
21	72	18	54	66	16	50	70	16	54	72	8	64	76	12	64	NR	31	
21 RT	70		52	68		52	68		52	74		66	80		68	NR		
22	78	16	62	74	14	60	68	14	54	70	2	68	80	2	78	NR	27	
22 RT	70		54	72		58	66		52	74		72	82		80	NR		

Subject Number	White noise			N-B 2 KC			N-B 4 KC			2000 HZ			4000 HZ			250 HZ		
	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL	SPL	Th	SL
23	80	20	60	78	20	58	78	20	58	82	4	78	NR	6		NR	28	
23 RT	78		58	78		58	78		58	80		76	NR			NR		
24	88	30	58	82	26	56	84	27	57	80	12	68	90	14	76	NR	33	
24 RT	90		60	82		56	82		55	86		74	88		74	NR		
25	86	24	62	80	20	60	82	21	61	80	3	77	84	5	79	NR	31	
25 RT	84		60	76		56	82		61	84		81	84		79	NR		
26	84	26	58	86	22	64	88	26	62	90	10	80	90	12	78	106	31	75
26 RT	84		58	82		60	86		60	88		78	92		80	108		77
27	88	24	64	80	18	62	84	20	64	96	12	84	96	12	84	NR	27	
27 RT	84		60	80		62	80		60	96		84	92		80	NR		
28	82	18	64	80	14	66	84	16	68	94	8	86	92	8	84	NR	31	
28 RT	84		66	78		64	84		68	96		88	88		80	NR		
29	96	28	68	92	22	70	92	24	68	102	10	92	NR	10		NR	35	
29 RT	98		70	86		64	94		70	98		88	NR			NR		
30	76	20	56	80	16	54	86	20	66	80	8	72	NR	6		NR	28	
30 RT	74		54	78		52	84		64	76		68	NR			NR		

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