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A

TEMPORAL INTEGRATION OF THE ACOUSTIC-REFLEX THRESHOLD

AND ITS AGE-RELATED CHANGES

by

Michele B. Emmer

A dissertation submitted to the Graduate Faculty in Speech and Hearing Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, City University of New York

2000

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THE CITY UNIVERSITY OF NEW YORK

Abstract

Temporal Integration of the Acoustic-Reflex Threshold and its Age-Related Changes

by

Michele B. Emmer

Adviser: Dr. Shlomo Silman

This study investigated age-related effects and changes on temporal integration of the acoustic-reflex threshold (ART) for broad-band noise (BBN) and 1000-Hz tonal activators. There were forty subjects comprised of 20 young adults (10 females and 10 males) and 20 older adults (10 females and 10 males). For both activating stimuli, temporal integration of the ART was investigated using 1-dB intensity increments and a high-resolution strip-chart recorder for the following activating stimulus durations: 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec.

Temporal integration for both BBN and 1000-Hz tonal stimulus activators was analyzed using analysis of variance (ANOVA), analysis of covariance (ANCOVA), and analysis of trend. The results indicated the absence of a significant age-related effect on temporal integration of the ART for the 1000-Hz tonal activator. In contrast, a significant age-related effect was present for temporal integration of the ART for the BBN activator. This age-related effect for temporal integration for the BBN activator was observed at activator stimulus durations of over 200 msec.

The absence of an age-related effect for temporal integration for the tonal activator, and its presence for the BBN activator, were explained primarily in relation to age-related changes of the outer-hair cells (OHCs) which are known to be first affected by age. This change in the OHCs was theorized to be the major factor for the age-related effects on the BBN ART. Clinical and research data were presented to support this hypothesis.

Acknowledgments

This dissertation is the culmination of 11 years work in the doctoral program. Empires have risen and fallen in that time. There were numerous occasions throughout those 11 years (perhaps every other day) when I believed I'd had enough and felt the desire to go back to my life. The fact that I stuck it out was due, in large measure, to the strong support and encouragement provided by those around me.

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Chapter 1

Introduction

The acoustic reflex is a bilateral contraction of the stapedius muscle which occurs in response to moderately intense acoustic stimuli. Its presence can be inferred from middle-ear immittance change, electromyographic measurement, or microscopic observation through an open tympanic membrane.

The seminal work by Metz (1946), who was the first to monitor both the dynamic and static characteristics of the middle ear with an electroacoustic impedance device, led to two major paths of investigation. One focus was on monitoring the activity of the acoustic reflex (dynamic) and the other was on evaluating the status of middle-ear static-acoustic immittance. These investigations led to the introduction of impedance audiometry. Since Metz's time, a plethora of articles has appeared dealing with the clinical applications and scientific interpretation of the middle-ear and auditory systems both with regard to the acoustic reflex and to the middle-ear static-acoustic immittance.

Special attention has been given to the acoustic reflex (AR) in light of research that has shown it to be reliable and present in the vast majority of the population. Therefore, it was extensively investigated both for its clinical application and for its scientific significance and merit. The focus of an entire text on the basic principles and clinical applications of the AR attests to its importance (Silman, 1984).

Several aspects of the acoustic-reflex threshold (ART) in humans have been investigated. These include: **identification** of middle-ear, cochlear and retrocochlear pathology (Jepsen, 1963; Anderson, Barr & Wedenberg, 1969, 1970; Jerger, 1970; Jerger, Anthony, Jerger & Mauldin, 1974a; Jerger & Jerger, 1975; Bosatra, Russolo & Poli, 1976; Feldman, 1976; Hall & Weaver, 1976; Bluestone, 1980; Brooks, 1980; Fiellau-Nikolajsen, 1983; Green & Margolis, 1983; Green & Margolis, 1984; Margolis & Heller, 1987; Silman & Gelfand, 1981a; Silman & Gelfand, 1981b; Nozza, Bluestone, Kardatzke, & Bachman, 1992; Silman, Silverman & Arick, 1992; Silman & Emmer, 1995; and so forth); **prediction** of hearing loss (Jerger, Burney, Mauldin & Crump, 1974b; Keith, 1977; Silman & Gelfand, 1979; Popelka, 1976; Margolis & Fox, 1977; Hirsch, Margolis, & Rykken, 1992); **threshold-measurement techniques** such as signal-averaging, ascending versus descending techniques, size of the immittance change, visual monitoring versus recording, mode of recording the response (digital versus analog); **mode of activating-signal presentation** (ipsilateral versus contralateral); **activator-signal parameters** which include intensity, duration, interstimulus interval (ISI) and the effect of bandwidth; **probe-tone parameters** including frequency, continuous versus interrupted presentation and multiplex versus non-multiplex circuitry (Flottorp, Djupesland & Winther, 1971; Deutsch, 1972; Peterson & Liden, 1972; Jerger, Anthony, Jerger & Mauldin, 1974a; Margolis & Popelka, 1975a; Silman, Popelka & Gelfand, 1978; Silman, 1979; Silman & Gelfand, 1981; Wilson, 1978, 1979; Weatherby & Bennett, 1980; Bennett & Weatherby, 1982; Jakimetz, Silman, Miller & Silverman, 1989; Lutolf, 1996); **subject parameters** which include degree and type of hearing loss, age, sex and pathology (Anderson, Barr & Wedenberg, 1969, Brooks, 1980; Silman & Gelfand, 1981a; Olsen, Noffsinger & Kurdziel, 1975; Silman, 1979; Gelfand, 1984; Osterhammel & Osterhammel, 1979; Jerger, 1975; Silman, Popelka & Gelfand, 1978; Jerger, Anthony, Jerger & Mauldin, 1972; Wilson, 1979).

Other characteristics of the AR, including adaptation, latency, morphology, magnitude and temporal integration, also have been studied. (Anderson, Barr & Wedenberg, 1969; Wilson, Shanks & Lilly,1984; Dallos, 1964; Hung & Dallos, 1972; Silman & Gelfand, 1982; Bosatra, Russolo & Silverman, 1984; Ruth & Niswander, 1976; Clemis & Sarno, 1980; Lynn, 1988; Silman, Popelka & Gelfand, 1978; Beedle & Harford, 1973; Wilson, 1979; Wilson, 1981; Silman & Gelfand, 1981b; Silman, 1984; Djupesland & Zwislocki, 1971; Wright, 1972; Djupesland, Sundby & Flottorp, 1973; Bazorov & Moroz, 1975; Richards, 1975; Woodford, Henderson, Hamernik & Feldman, 1975; Barry & Resnick, 1976; Singh & Greenberg, 1976; Jerger, Mauldin & Lewis, 1977; Feldman & Katz, 1978; Gelfand, Silman & Silverman, 1981).

Recently, age-related effects on both static-acoustic admittance and on the ART have been extensively studied. With respect to static-acoustic admittance, Holte (1996) and Wiley, Cruickshanks, Nondahl, Tweed, Klein and Klein (1996) reported a positive correlation between tympanometric width and increased age. Wiley *et al.* (1996) noted that external ear canal volume tends to decrease as a function of age. A decrease in acoustic admittance with increased age has been reported (Jerger, Jerger & Mauldin, 1972; Blood & Greenberg, 1977; Gates, Cooper, Kannel & Miller, 1990; Hall, 1979; Hall & Weaver, 1979).

With regard to the AR, several investigators (Handler & Margolis, 1977; Silman, 1979a; Gelfand & Piper, 1981; Silverman, 1982) reported that the ART for the broad-band noise (BBN) activator is higher in the older than younger adult. Wilson (1981) found a significant difference in the ART for the 4000-Hz activator between younger and older adults. Several investigators (Thompson, Sills, Recke & Bui, 1980; Silman & Gelfand, 1981a; Wilson, 1979, 1981) found a significant decrease in the magnitude of the AR as a function of age. Bosatra, Russolo, and Silverman (1984) found increased latencies of the AR response in the older adult. It has been noted noted that the procedures for predicting hearing loss in the older adult differ from those used to identify hearing loss in the young (Silman (1984); Wallin, Mendez-Kurtz, & Silman (1986); Silman, Gelfand, & Emmer, 1987).

It appears that age has an effect on the majority of AR parameters. However, thus far, there has been no investigation of age-related effects on temporal integration of the ART. Temporal integration is the relation (tradeoff) between intensity and duration when the time frame is less than about one second. With increased duration of the stimulus, less intensity is required for threshold – up to a critical point; the critical point is the duration at which threshold plateaus. At the plateau, further increases in duration no longer improve threshold. The critical point usually is called temporal integration for threshold. Temporal integration occurs for threshold, for loudness, and for the AR. The mechanism of temporal integration is based on the time required by the nervous system to optimally integrate energy.

Methodologic problems confound the results of existing studies on age-related effects on temporal integration of the AR, leading to a diversity of findings. The majority of the studies used subjects of unspecified age. And the preponderance of studies used very small sample sizes, such as two or three subjects; sample size never exceeded ten subjects, and few studies employed such a sample size. These small samples diminish the ability of the investigators to generalize their findings. Nearly all of the investigators reported large variability among subjects and across studies. Other methodologic limitations of previous studies, which also may contribute to the diversity of findings, include the following: (a) use of different criteria to determine the ART; (b) use of diverse instrumentation; (c) use of different activating signals; (d) different calibration; (e) lack of specification of instrument parameters such as resolution, time constant, and rise and fall times; and (f) lack of randomized stimuli.

To investigate age-related effects on temporal integration of the AR, a large sample with appropriate statistical power and high-resolution instrumentation should be used, and strict criteria should be employed for quantification of temporal integration. This methodologic approach would help control for many of the variables creating the variability in temporal-integration findings (Barry & Resnick, 1976; Singh & Greenberg, 1976; Woodford *et al.*, 1975; Feldman & Katz, 1978; Korabic & Cudahy, 1984). In turn, the reduced variability could enhance the use of temporal integration of the AR in auditory diagnosis. Perhaps further investigation of temporal integration of the ART for a BBN activator will help explain the disparity in ART between younger and older normal-hearing subjects found at a duration of one or more seconds. From a scientific perspective, the study of age-related effects on temporal integration would further strengthen our understanding of the physiology and mechanism of the AR.

The noise-tone difference refers to the difference in decibels between the ART for the BBN activator and that for tonal activators. The NTD usually is about 20 dB in normal-hearing persons, with the BBN ART about 20 dB better than the tonal ART. The NTD is narrowed in persons with sensorineural hearing loss because the loss elevates the BBN ART. In addition, a narrowed NTD is commonly found in the normal-hearing older adult. This phenomenon has complicated the prediction of hearing loss based on the NTD in this population. The NTD, while having been thoroughly investigated for activator duration of at least 1000 msec, has not been investigated for duration less than 1000 msec. The inclusion of the BBN activator in this study will provide information about the NTD in older versus younger adults for activator duration of less than one second. Such information about the NTD may allow us to reopen the use of these measures for prediction of hearing loss in the elderly.

Although no studies specifically measured electromyographic (EMG) age-related changes of the AR, the classical investigation by Zakrisson, Borg, and Blom (1974) may shed some light on age-related effects on the AR. These researchers found that the change in electromyography during AR activation is strongly correlated with the acoustic-immittance change. Based on Zakrisson *et al.* (1974), it can be hypothesized that the difference in the acoustic-immittance changes during AR activation for younger versus older subjects, when temporal integration is measured, represents age-related differences.

Age-related changes in temporal integration of the ART were evident in a limited pilot study that we conducted. In this pilot study, while the threshold of temporal integration of the ART (the plateau) for tonal and BBN activators could be easily identified for the younger adults, it was unclear in the older adults. For example, some subjects demonstrated lack of plateau (the inverse relationship continued to the end) while others showed an absence of temporal integration, that is, the threshold remained constant as duration increased. These results suggested the need for a large-sample study to clarify the effect of age-related changes on temporal integration of the ART for both tonal and BBN activators (see 2nd Level Project entitled: *The Effect of Age on Temporal Integration of the Acoustic-Reflex Threshold"* - March 17, 1997).

Therefore, the primary purpose of this study was to investigate age-related effects on temporal integration of the ART for both BBN and for 1000 Hz activators (using an adequate sample size as determined by statistical power analysis) for the following durations: 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec and 1000 msec.

Problem

To investigate temporal integration of the ART and its age-related changes in normal-hearing adults.

Subproblems

1. To investigate whether temporal integration of the ART in the older subjects differs from that in the younger subjects for a BBN activator for the following durations: 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec.

2. To investigate whether temporal integration of the ART in the older subjects differs from that in the younger subjects for a 1000-Hz tonal activator for the following durations: 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec.

3. To investigate whether the NTD in the older subjects differs from that in the younger subjects for the following durations: 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec.

4. To describe the characteristics of temporal integration of the ART for the BBN and tonal activators in the younger and older adults.

Definition of Terms

Acoustic admittance: The measure of the ease with which acoustic energy flows through a system. It is mathematically defined as the ratio of volume velocity to sound pressure ($Y_a = U/P$). Expressed in mhos, it is the reciprocal of impedance. The components of acoustic admittance include acoustic stiffness susceptance ($+B_a$), acoustic mass susceptance ($-B_a$), and acoustic conductance (G_a). Total acoustic admittance can be calculated from the formula:

$$Y_a^2 = B_{ta}^2 + G_a^2 \textbf{ or } Y_a = \sqrt{B_{ta}^2 + G_a^2}$$

Acoustic admittance meter: A device constructed on the basis of the acoustic-admittance formula: $Y_a = U/P$.

Acoustic immittance: A global term representing both acoustic admittance (acceptance of energy flow) and acoustic impedance (opposition to energy flow) of the middle-ear system.

Acoustic impedance: The total opposition to the flow of energy through a system. It is mathematically defined as the ratio of sound pressure to volume velocity ($Z_a = P/U$). Expressed in ohms, it is the reciprocal of admittance. The components of acoustic impedance include acoustic mass reactance ($+X_a$), acoustic stiffness reactance ($-X_a$), and acoustic resistance (R_a). Total acoustic impedance can be calculated from the formula:

$$Z_a^2 = R_a^2 + X_T^2 \textbf{ or } Z_a = \sqrt{R_a^2 + X_T^2}$$

Acoustic impedance meter: A device that is constructed on the basis of the acoustic-impedance formula: $Z_a = P/U$. This device also is termed a relative acoustic-impedance meter.

Acoustic millimho (mmho): The unit of measurement of acoustic admittance or its components (conductance or susceptance).

Acoustic ohm: The unit of measurement of acoustic impedance or its components (reactance and resistance).

Acoustico-mechanical model: According to Van Camp, Margolis, Wilson, Creten, and Shanks (1986), the ear is an "acoustico-mechanical" system containing acoustical as well as mechanical impedance components. Together, these elements determine the acoustical impedance of the ear.

Acoustic reflex: The bilateral reflexive contraction of the intra-aural muscles in response to sound of sufficiently high intensity. The AR also is termed the acoustic stapedial reflex. It is commonly accepted that the AR in humans is due mainly, and probably exclusively, to contraction of the stapedius, rather than the tensor tympani muscle. The tensor tympani contracts only at extremely intense sounds, around 140 dB SPL, as part of the startle reflex. Activity of the AR can be inferred from monitored changes in the acoustic immittance of the ear (Jepsen, 1955 as cited by Møller, 1984; Lilly, 1964; Metz, 1951; Møller, 1958, 1961a; Terkildsen & Nielsen, 1960). The change in acoustic immittance of the middle ear as a result of stapedius-muscle contraction forms the basis for the ART and AR decay tests (Silman and Silverman, 1991).

Acoustic reflex adaptation (decay, fatigue, or relaxation): The decrease in AR magnitude during sustained (several seconds) acoustic stimulation. The decrease in AR magnitude is attributed to the relaxation of the middle-ear muscles. The magnitude change is gradual, reaching the baseline values prior to stimulus onset (Wilson *et al.* 1984). During contralateral acoustic-reflex adaptation (ARA) testing, the activating stimulus is presented to one ear and the AR magnitude is monitored in the contralateral ear. During ipsilateral ARA testing, the activating stimulus is presented to one ear and the AR magnitude is monitored in the same ear.

Acoustic reflex arc: The stapedius-muscle reflex arc comprises three to four neurons: (1) a primary auditory neuron in the VIII nerve (the afferent or sensory neuron) which carries impulses from the cochlear hair cells to the cochlear nucleus; (2) a second-order neuron from the ventral cochlear nucleus to the medial superior olive; (3) the interneuron from the superior olivary complex to the ipsilateral and contralateral facial motor nucleus; and (4) the efferent facial motor neuron to the stapedius muscle. There are actually four reflex arcs, two ipsilateral and two contralateral (Borg, 1973).

Acoustic reflex - contralateral (crossed): The AR measured when one ear receives the activating stimulus and the change in middle-ear impedance or admittance is monitored in the other ear.

Acoustic reflex growth function (ARGF): The plot of changes in acoustic immittance with increases in activator intensity.

Acoustic reflex - ipsilateral (uncrossed): The AR measured when the activating stimulus and the change in middle-ear impedance or admittance is monitored in the same ear.

Acoustic reflex latency: The time for the first detectable impedance change resulting from middle-ear muscle contraction following an acoustic stimulation (Bosatra *et al.*, 1984).

Acoustic reflex magnitude: The amount of acoustic-immittance change in mmhos at the tympanic membrane that results from a contraction of the AR (Silman, 1984).

Acoustic reflex morphology: The characteristics of magnitude, rise and fall of the AR, and latency.

Acoustic reflex threshold: The lowest activator stimulus intensity which causes a just-noticeable change in the acoustic immittance of the middle ear (or its components), resulting from contraction of the stapedius muscle; this acoustic-immittance change is time-locked with the stimulus.

Generally, the intensity eliciting an AR response is accepted as threshold when further increases in the stimulus bring about further changes in the acoustic immittance.

Activating stimulus: A stimulus of a given SPL, which is delivered either contralaterally or ipsilaterally into the ear canal, to elicit the AR.

BBN activator: A BBN stimulus that is used to elicit the contralateral or ipsilateral AR.

Broad-band noise (BBN): A noise with a wide bandwidth that is shaped by the frequency response of a transducer.

Fall time: The time in milliseconds required for the tone to fall from 1 dB below the set level to 20 dB below the set level.

Middle-ear transmission: A transfer function that describes the spectral changes that take place as a sound travels from its source to the tympanic membrane.

Modified bivariate-plotting procedure: Silman, Gelfand, Piper, Silverman, and Van Frank (1984) and Silman, Silverman, Showers, and Gelfand (1984) endeavored to improve the predictive accuracy of the traditional bivariate-plotting procedure. The hit rate of the traditional decreases considerably (approaching chance level) when the sample includes patients with mild and high-frequency sensorineural hearing impairment (which occurs much more often in adults than children) or persons over 44 years of age. With the modified bivariate procedure, the data from those more than 44 years of age are excluded, the line segments are based on the data points from hearing-impaired as well as normal-hearing ears, and the line segments are drawn to maximize the hit rate without incurring a large false-alarm rate. These modifications enhance the predictive accuracy of the bivariate procedure.

Multiplexing circuit: An acoustic-immittance system circuit whereby the probe tone is continuously on and the activating signal is pulsed during AR measurement. While the activating signal is on, the probe microphone is off so that acoustic immittance changes, which are possibly confounded by artifacts, are not recorded. While the elicitation signal is off, the probe microphone is on to record changes in acoustic immittance without the confounding effects of artifacts. The multiplexing circuit not only minimizes artifacts, but also allows for higher intensity presentation levels (Sells *et al.* 1997).

Probe tone: A tone delivered into the ear canal during acoustic-admittance measurement, which does not elicit the AR. When impedance (Z) change is measured, the volume velocity (U) of the probe is kept constant and Z is derived from the probe-tone sound pressure level (SPL). When admittance (Y) change is measured, the SPL of the probe tone is kept constant and Y is derived from U.

Reversing frequency: The lowest probe-tone frequency at which the net change in acoustic impedance during acoustic-reflex contraction is a net decrease in the acoustic impedance because of the substantial decrease in the resistive component and minimal increase in the reactance component.

Rise time: The time in milliseconds required for the tone to rise from 20 dB below the set level to 1 dB below the set level.

SPAR (sensitivity prediction from the acoustic reflex) procedure: This approach to the prediction of hearing loss (Jerger *et al.*, 1974) is based on the assumption that the difference between the tonal ARTs and the BBN ART decreases linearly as the magnitude of the hearing impairment increases. The ART data for 500, 1000, and 2000 Hz, and BBN activating signals are entered into a set of formulas which yield a mean NTD. The value of the NTD does not attempt to predict the exact amount of hearing loss in dB; instead, it categorizes hearing as normal, or mild-moderately, severely, or profoundly impaired.

Stapedius muscle: One of two intratympanic muscles, the other being the tensor tympani muscle. The stapedius is the smallest muscle in the body. It is generally accepted that the AR in humans is due mainly, if not exclusively, to contraction of the stapedius muscle.

Strip-chart: A graphic representation of the acoustic immittance (or its components) over time.

Strip-chart recorder: An instrument that produces a graphic representation of the acoustic impedance (or its components) over time.

Temporal integration: The relationship between duration of the stimulus presentation and the intensity to elicit a given response. As duration increases, the intensity required to elicit behavioral threshold will decrease until a critical duration is reached. The threshold does not change with duration exceeding the critical duration. The critical duration is termed the behavioral threshold of temporal integration.

Threshold of temporal integration: The critical duration beyond which additional increases in time will no longer change the threshold.

Time constant: The time constant of an acoustic-immittance device is the time it takes the device to track the acoustic-reflex response to full magnitude. According to Silman and Gelfand (1982) and Lilly (1984) the instrument requires 5 time constants to track the acoustic-reflex response to full magnitude. The first time constant tracks to 63% of the full response, the second to 86.5% of full response, the third to 95%, the fourth to 98% and the fifth to 100% of full response.

Tonal activator: A pure-tone stimulus, usually 500, 1000 or 2000 Hz, that is used to elicit the contralateral or ipsilateral AR.

Traditional bivariate-plotting procedure: Popelka, Margolis, and Wiley (1976) and Popelka (1981) attempted to overcome limitations of the methods of Niemeyer and Sesterhenn (1974) and Jerger *et al.* (1974) via this method. With this technique, the ARTs are used to predict the presence, rather than the magnitude, of a hearing loss. Two AR variables that increase concomitantly with hearing loss are plotted as coordinates on a bivariate graph. To construct the plot, a group of young normal-hearing subjects is tested and their ART data are plotted on the graph. A vertical line and a negatively sloped diagonal line are then drawn so that at least 90% of the normal-hearing subjects' data are located below and to the left of the lines on the graph. These line segments on the graph thus form a template for clinical applications. When a particular patient is tested, the obtained ART values are plotted on the template. The interpretation of the presence vs. absence of hearing impairment is based on the location of the plotted point with respect to the two line segments.

Chapter 2

Review of the Literature

The review of the literature will be discussed under the following headings: principles of acoustic immittance; background information on the acoustic reflex; anatomical and physiological aspects of the middle-ear muscles, including the reflex arc; methods of measurement of the acoustic reflex, including instrumentation; developmental aspects of the acoustic reflex; age-related effects on the auditory system in general, and on the neuroanatomy and physiology of the acoustic reflex, specifically; and temporal integration of the acoustic reflex.

Principles of Acoustic Immittance[1]

The concept of impedance is used with mechanical, electrical and acoustic systems. The definition in each case is particular to the discipline. Mechanical impedance is defined as the ratio between an applied force and the resultant velocity with which the system moves. Electrical impedance is defined as the ratio of the applied voltage to the current flow, In an acoustic system, the definition relates the applied sound pressure to the volume velocity. Volume velocity is defined as the volume (cm^3) of the sound-conducting medium that flows in a given area in a given amount of time (in s).

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[1] Figures were taken, with permission of the authors, from Chapter 3 of S Silman and CA Silverman (1991). *Auditory Diagnosis: Principles and Applications.* San Diego: Singular Publishing.

Impedance (Z) = force/velocity. There are three components to impedance. The opposition offered by mass is termed mass reactance ($+ X_M$). The "+" indicates that the force attains a maximum value prior to the velocity achieving a maximum value when an alternating force is applied to an object with mass (i.e., the force leads the velocity by 90°). The impedance offered by a spring is called stiffness reactance ($- X_S$). The "-" indicates that, in this case, the force attains a maximum value after the velocity achieves a maximum value when an alternating force is applied to a spring or to an object with stiffness (i.e., the force lags the velocity by 90°). The opposition that results from friction is called resistance (R). For each component, mass reactance, stiffness reactance, and resistance, the impedance is equal to the force divided by the velocity.

If an alternating force is applied to a system containing several masses in series, then the total impedance of this system is the arithmetic sum of the mass reactance of each of the mass components. A simple sum can be obtained since the relation between force and velocity is the same for each of the reactance components (i.e., force leads velocity by 90°). If a system consists of an alternating force applied to several springs in series, then the total impedance of the system is the sum of the stiffness reactance offered by each spring. Again, a simple sum can be obtained because the relation between force and velocity is the same for each of the stiffness reactance components (i.e., velocity leads force by 90°). If an alternating force is applied to several frictional surfaces in series, then the total impedance of this system is the arithmetic sum of the resistance offered by each frictional surface. Once again, a simple sum can be obtained because the relation between force and velocity is the same for each of the resistance components (i.e., velocity is in phase with the force). We can say, then, that when a system consists of components that are of the same type and are in series, the total impedance is the sum of the individual impedance.

However, if a system incorporates all three types of impedance, as is usually the case, total impedance cannot be the simple sum of the individual impedance components, since the relation between force and velocity is different for each of the elements in this complex system. Therefore, a vector system (see Figure 1) is necessary in order to obtain the sum of the impedance elements.

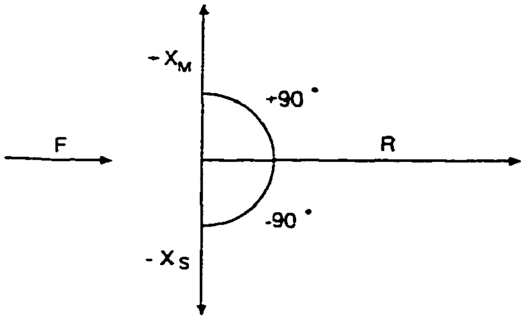


Figure 1. A vectorial representation of the impedance components. + X_M is the mass reactance, - X_S is the stiffness reactance, R is the resistance, and F is the applied alternating force.

In the above figure, resistance (R) is represented as a vector that begins at the origin and projects to the right; this placement indicates that for this component, the velocity is in phase with the force. Mass reactance ($+ X_M$) is represented as a vector beginning at the origin and projecting upward along the positive ordinate; this placement represents the fact that, in the case of this component, the velocity leads the velocity by 90°. Stiffness reactance ($- X_S$) is represented as a vector beginning at the origin and projecting downward, along the negative ordinate representing the fact that in the case of this element, the velocity leads the force by 90°. Note that the mass reactance ($+ X_M$) and the stiffness reactance ($- X_S$) are 180° out-of-phase. The total reactance (X_T) is the difference in the magnitudes of the ($+ X_M$) and ($- X_S$) vectors and projects in the direction of the longer reactance vector. If the system has more stiffness than mass reactance, the net reactance, (X_T), will be negative. If the system has more mass than stiffness reactance, the net reactance, (X_T) will be positive.

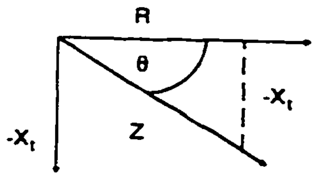


Figure 2. The vectors for the total impedance (Z), resistance, (R) and the net reactance ($-X_T$). The phase angle (θ) is also shown in the figure.

The resultant impedance is the vector sum of the resistance and net reactance. The magnitude of the impedance vector (the diagonal line in Figure 2) can be calculated using the Pythagorean theorem. According to this theorem, the hypotenuse squared equals the sum of the squares of the other two sides of a right triangle. Thus,

$$Z^2 = R^2 + X_T^2$$

and

$$Z = \sqrt{R^2 + X_T^2}$$

The magnitude of the resulting vector is $|Z|$, which is the magnitude of the impedance without consideration of sign or phase. Sign and phase are given by the phase angle θ, which is calculated using the formula

$$\cos\theta = R/Z$$

or

$$\sin\theta = X_T/Z$$

"The phase angle represents the temporal relationship between the velocity response of a complex system and the sinusoidally applied force" (Margolis, 1981, p. 126).

The mechanical impedance of a system also varies as the frequency of the applied force varies. The relation between mechanical stiffness reactance, stiffness, and frequency is illustrated by the formula

$$-X_S = S/(2\pi f)$$

where S is stiffness and f is frequency. According to this formula, the stiffer the spring, the larger the mechanical stiffness reactance; the higher the frequency, the smaller the stiffness reactance. Therefore, the stiffness reactance can be increased by increasing the stiffness or by decreasing the frequency; it can be decreased by decreasing the stiffness or by increasing the frequency.

The mass reactance also changes with frequency. The relations among mechanical mass reactance, mass, and frequency are illustrated in the formula

$$+X_M = 2\pi fM$$

According to this formula, the mass reactance increases as the mass or frequency increases; it decreases as the mass or frequency decreases. Since mechanical mass reactance decreases whereas mechanical stiffness reactance increases as frequency decreases, and vice versa, there is a frequency at which the stiffness and mass reactance are equal. At this frequency, there is no mass or stiffness reactance. This frequency is known as the resonance frequency, which can be calculated with the formula

$$f_o = (1/2\pi)(S/M)$$

where f_o is the resonant frequency, S is stiffness, and M is mass. If there is no mass reactance at one frequency, one cannot conclude there is no mass reactance in the system; it may be present at other frequencies. Resistance, unlike mass or stiffness reactance, does not change with frequency (i.e., resistance is independent of frequency).

Acoustic Impedance

There are three types of elements that offer impedance. In a mechanical system, these are mass, spring and friction. Analogous quantities exist in acoustics. According to Van Camp, Margolis, Wilson, Creten, and Shanks (1986), the ear is an "acoustico-mechanical" system that contains acoustical as well as mechanical impedance components. Together these elements determine the acoustical impedance of the ear. Figure 3 illustrates the mechanoacoustic model of the middle ear.

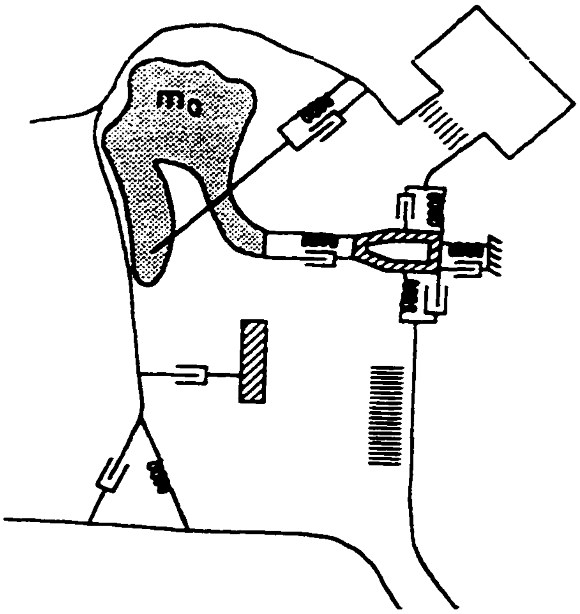


Figure 3. Mechanoacoustical model of the ear, containing masses, springs, and friction elements as mechanical elements, together with open and closed air-filled volumes as acoustical elements.

Mechanical mass components include the pars flaccida (Shrapnell's membrane) of the tympanic membrane, the ossicles and the perilymph of the cochlea. The mechanical spring components include the pars tensa of the tympanic membrane, and the associated ligaments and tendons. Elements of mechanical friction include the friction of the tympanic membrane, tendons and ligaments. The acoustic mass components are the air particles in the mastoid (resembling a tube that is open at both ends). Acoustic spring components include the air enclosed in the outer-ear canal, and in the middle ear (resembling air in a tube that is closed at both ends). The acoustic friction component is the air viscosity. The mechanoacoustic impedance of the middle ear is generally termed the acoustic impedance (Z_a) of the middle ear. The total acoustic impedance (Z_a) consists of acoustic mass reactance ($+X_a$), which is the acoustico-mechanical mass; acoustic stiffness reactance ($-X_a$), which is the acoustico-mechanical stiffness reactance; and acoustic resistance (R_a) which is the acoustico-mechanical resistance.

For impedance measurement in an acoustic system, sound pressure (expressed in dynes/cm^2) is applied and the resultant volume velocity (expressed in cm^3) is measured. Volume velocity is defined as the volume (cm^3) of the sound-conducting medium that flows in a given area in a given amount of time (in s). The acoustic impedance, therefore, can be expressed as

$$Z_a = P/U$$

where P is the sound pressure (in dynes/cm^2), U is the volume velocity (in cm^3), and Z_a is acoustic impedance in acoustic ohms.

Mechanical Admittance

The ability of a system to transfer energy can be expressed either in terms of its rejection of energy, or in terms of its acceptance of energy. If you express energy transfer in terms of acceptance, we then apply the term admittance, rather than impedance. Mechanical admittance is the reciprocal of mechanical impedance. It can therefore be calculated using the formula

$$Y = V/F$$

where Y is mechanical admittance, V is velocity, and F is force. The unit of admittance is mho. Just as there are three components of impedance, there are three components of admittance. The ease with which energy flows into a mass is called mass susceptance ($-B_M$). The ease with which energy flows into a spring or an object having stiffness is termed stiffness susceptance ($+B_S$). The ease with which energy flows into friction is termed conductance (G). The (G) is placed along the abscissa for the admittance vectors, as was the case for the impedance vectors. The relations among the admittance vectors are as follows: conductance is plotted along the abscissa, stiffness susceptance is plotted on the positive rather than on the negative ordinate, and the mass susceptance is plotted on the negative, rather than the positive ordinate. Using the Pythagorean theorem, the admittance vector is

$$Y^2 = B_t^2 + G^2$$

The relations among stiffness susceptance, mass, and frequency are given by the formulas

$$+B_S = (2\pi f / S)$$

and

$$-B_M = 1/(2\pi f M)$$

According to the formulas, we see that stiffness susceptance increases as the frequency increases or as the stiffness decreases; it decreases as the frequency decreases or as the stiffness increases. The mass susceptance increases as the frequency or mass decreases; it decreases as the frequency or mass increases.

Acoustic Admittance

Acoustic admittance is defined as the ease with which acoustic energy passes through a system. It is mathematically expressed as the ratio of volume velocity to sound pressure ($Y_a = U/P$). The unit of acoustic admittance is mho. Admittance components include acoustic stiffness susceptance (+B_a), acoustic mass susceptance (-B_a), and acoustic conductance

(G_a). Total admittance can be calculated from the formula

$$Y_a^2 = B_{ta}^2 + G_a^2$$

Rectangular versus Polar Notation

The acoustic admittance or impedance of a system is expressed using rectangular or polar notation. In rectangular notation, one value is given to the acoustic conductance or resistance and one value to the net acoustic susceptance or reactance component. For example, acoustic impedance can be written, using rectangular notation, as $Z_a = 2000 - j1000$. The "*j*" is taken from the notation used to represent complex numbers and represents $\sqrt{-1}$. In practical terms, according to Margolis (1981) "the *j* serves as a reminder that *R* and *X* cannot be combined by simple addition due to the 90° phase difference between them" (p. 127). In polar notation, such as $Y_a = 0.6 < +30°$ the impedance or admittance of the system is represented by the magnitude of the impedance $|Z|$ or admittance $|Y|$, and one number represents the phase angle, θ (in degrees) of the impedance or admittance vector.

Anatomical and Physiological Aspects of the Middle-Ear Muscles

Acoustic stimulation presented either monaurally or binaurally at sufficiently intense levels will elicit a bilateral contraction of the stapedius muscle in the middle ear. This reflex contraction is also termed the acoustic stapedial reflex (Djupesland, 1980). The presence and properties of the acoustic reflex are dependent upon the anatomy and physiology of the middle-ear system, the cochlea, the acoustic and facial nerves, and the pathways of the brainstem.

It has long been known that there exist two middle-ear muscles - the stapedius, accurately described for the first time by Varolius in 1591, and the tensor tympani, first described by Eustachius in 1564. The facial nerve (N VII) innervates the stapedius muscle and the trigeminal nerve (N V) innervates the tensor tympani (Politzer, 1861 as cited by Møller, 1984).

Early research on the anatomy of the middle-ear muscles was conducted on animals by Kato in 1913, Lorente de Nó in 1935, and by Wersäll in 1958.

The results of this early research showed that in the cat and rabbit, both the tensor tympani and stapedius muscles contract in response to sound as an acoustic reflex. However, at levels below 140 dB SPL, the human acoustic reflex is due mainly, and probably exclusively, to contraction of the stapedius muscle (the smallest muscle in the human organism), rather than to contraction of both the stapedius and tensor tympani muscles (Jepsen, 1963; Saloman & Starr, 1963). The tensor tympani contracts only at extremely intense sounds, around 140 dB SPL, as part of the startle reflex (Djupesland, 1964); such a level is beyond the output limits of conventional acoustic-immittance devices.

The stapedius muscle is wholly encased within the pyramidal eminence on the posterior wall of the tympanic cavity, (Jepsen, 1963) and originates from the walls of its own canal. Its tendon exits through the apex of the pyramid and courses horizontally to insert on the posterior aspect of the neck of the stapes. Upon contraction, the stapes is pulled in a downward and outward direction, stiffens the ossicular chain and, generally, causes outward movement of the tympanic membrane (Feldman, 1975).

Neurological Aspects of the Acoustic Reflex Arc

Although the anatomy of the middle-ear muscles has been established for some time, the neural organization of the AR arc is not yet completely known. The available information is based primarily upon studies by Borg (1973); Rasmussen (1946) and others. The AR center is located in the superior olivary complex of the brainstem. The AR arc comprises three to four neurons: (a) a primary auditory neuron in the VIIIth cranial nerve (the afferent or sensory neuron), which carries impulses from the cochlear hair cells to the cochlear nucleus; (b) a second-order neuron from the ventral cochlear nucleus to the medial superior olive; (c) the interneuron from the superior olivary complex to the ipsilateral and contralateral facial motor nucleus; and (d) the efferent facial motor neuron to the stapedius muscle.

There are actually four AR arcs, two ipsilateral and two contralateral (Borg, 1973). One ipsilateral AR arc consists of the following neurons: (a) the primary auditory neuron of the eighth cranial nerve (the afferent or sensory neuron) from the haircells of the cochlea to the ventral cochlear nuclei; (b) the second-order neuron from the ventral cochlear nuclei through the trapezoid body to the ipsilateral facial-nerve nuclei; and (c) the third-order neuron (the facial nerve) from the ipsilateral facial-nerve nuclei to the ipsilateral stapedius muscle. The other ipsilateral AR arc consists of (a) the primary auditory neuron of the eighth cranial nerve to the ipsilateral ventral cochlear nuclei; (b) the second-order neuron from the ipsilateral ventral cochlear nuclei to the ipsilateral superior olivary complex; (c) the third-order neuron from the ipsilateral superior olivary complex to the ipsilateral facial-nerve nuclei; and (d) the fourth-order neuron from the ipsilateral facial-nerve nuclei to the ipsilateral stapedius muscle.

One contralateral AR arc consists of (a) the first-order neuron (primary auditory neuron of the eighth cranial nerve) to the ipsilateral ventral cochlear nuclei; (b) the second-order neuron from the ipsilateral ventral cochlear nuclei to the ipsilateral superior olivary complex; (c) the third-order neuron from the ipsilateral superior olivary complex to the contralateral facial-nerve nuclei; and (d) the fourth-order neuron from the contralateral facial-nerve nuclei to the contralateral stapedius muscle. The other contralateral AR arc is comprised of (a) the first-order neuron from the hair cells of the cochlea to the ipsilateral ventral cochlear nuclei; (b) the second-order neuron from the ipsilateral ventral cochlear nuclei to the contralateral superior olivary complex; (c) the third-order neuron from the contralateral superior olivary complex to the contralateral facial-nerve nuclei; and (d) the fourth-order neuron from the contralateral facial-nerve nuclei to the contralateral stapedius muscle.

In addition to the direct pathways for the AR, Borg (1973) and Courville (1966) found evidence suggesting the existence of numerous indirect pathways involving multi-synaptic chains in the lateral zone of the reticular formation. The indirect pathways are slower and more sensitive to barbiturates (Borg, 1973; Borg & Møller, 1975), the degree of wakefulness, and the integrity of other parts of the central nervous system (Baust & Berlucchi, 1964 and Salomon, 1966, as cited by Møller, 1984) than the direct pathways.

Methods of Recording of the Acoustic Reflex

The contraction of the middle-ear stapedius muscle, which stiffens the ossicular chain of the middle ear, elicits an acoustic-impedance change. Resultantly, the tympanic membrane becomes less mobile, as evidenced by a change in the acoustic impedance of the ear. Although several methods have been used to record and measure middle-ear muscle contraction in humans (and in animals), none is as convenient as acoustic impedance/admittance approach. Acoustic impedance is noninvasive, and does not influence the function of the middle ear or that of the middle-ear muscles (Møller, 1984).

Methods other than those based on recording changes in the acoustic impedance of the ear have been used to examine the contraction of the middle-ear muscles. Two of these methods, which involve direct measurement of the tension of the muscles (Lorente de Nó, 1935; Wersäll, 1958) and recording of the electrical activity, electromyography of the muscles (Eliasson & Gisselsson, 1955), have been used in animal experiments. Electromyography also has been used, under special circumstances, to study the contraction of human middle-ear muscles (Borg & Zakrisson, 1975). A third method used to study middle-ear muscle contraction is based upon the fact that contraction of the stapedius muscle alters the transmission properties of the middle ear. In this method, the cochlear-microphonic potential is recorded near or on the round window (Galambos & Ruper, 1959; Price, 1963). Møller (1964) reported a fourth method of measurement, that of recording the change in air pressure in the ear canal resulting from tympanic membrane displacement. This method also is noninvasive, and has been used both with animals and humans.

The method based on acoustic impedance/admittance is certainly the most widely used and convenient method for recording middle-ear muscle contraction. Currently available acoustic-immittance devices essentially are constructed on the basis of the acoustic-impedance or acoustic-admittance formula. Instruments constructed on the basis of the acoustic-impedance formula are called acoustic-impedance meters. Devices constructed on the basis of the acoustic-admittance formula are called acoustic-admittance meters.

The acoustic-impedance meter has a probe assembly, which is inserted into the outer ear canal. The probe assembly contains a loudspeaker (the driver) which introduces a constant volume velocity in the ear canal by applying voltage from a source in the acoustic-impedance meter to the diaphragm of the driver. When the voltage is applied to the diaphragm, the air molecules in the ear canal are set in motion (the volume velocity). In addition to the loudspeaker, the probe assembly also contains a microphone that transduces the sound pressure resulting from the volume velocity into electrical voltage; the electrical voltage is read in acoustic ohms.

There are some disadvantages inherent in the acoustic-impedance meter. Some can be offset, and others cannot. For example, acoustic impedance at the probe tip is affected by ear-canal volume, since sound pressure and volume are inversely related. To avoid the effect of ear-canal volume on sound pressure and thus on the acoustic impedance at the probe, acoustic-immittance devices which measure acoustic impedance incorporate additional methods for keeping sound pressure constant at the probe. A balance meter in the instrument functions to maintain sound pressure at a predetermined level.

Another disadvantage of the impedance meter (one that cannot be offset) is that the amplitude of the tympanogram produced by such a device cannot be expressed in physical units, such as acoustic ohms, because of nonlinearity in the impedance change during the ear-canal air-pressure change. The amplitude of the tympanogram is therefore expressed in arbitrary units for these instruments. Because arbitrary units are used, such devices are called relative acoustic-impedance meters.

When an acoustic-admittance meter is used, the acoustic admittance is derived from the volume velocity rather than from the sound pressure as is done for acoustic-impedance instruments. The pressure (*P*) is kept constant, so Y_a is directly proportional to volume velocity (*U*). An alternating voltage is applied to the loudspeaker and to a rectifier filter that rectifies the voltage, which is displayed as Y_a at the probe tip.

The effect of ear-canal volume on sound-pressure level in the ear canal is kept constant by a circuit that constantly adjusts the driver voltage depending on the voltage at the microphone. Acoustic-admittance meters do not have the drawback of nonlinearity in acoustic-admittance changes with ear-canal air-pressure changes in tympanometry because the acoustic admittance is calculated from the volume velocity rather than from the sound pressure.

Methods for Monitoring the Acoustic Reflex

Various methods have been used for monitoring the AR. Some outputs supply a permanent record (chart recordings, averaged response tracings, taped record). Permanent records enable retrospective analysis of the responses. When outputs do not supply a permanent record, instruments (analog or digital meter, oscilloscope, "reflex indicator" light) monitor the responses at the time of testing. Event markers can be used when recording the AR responses to indicate the temporal relation between the stimulus and response.

In most clinical studies, the acoustic-immittance change has been monitored visually by observing needle deflection on the sensitivity scale, and 5-dB intensity increments have been used (Beattie & Leamy, 1975; Forquer, 1979; Gelfand, Piper, & Silman, 1983; Jerger, Anthony, Jerger, & Mauldin, 1974; Jerger, Harford, Clemis, & Alford, 1974; Jerger, Jerger, Mauldin, & Segal, 1974; Keith, 1977; Niemeyer & Sesterhenn, 1974; Ruth & Niswander, 1976). The use of 5-dB increments was largely an outgrowth of the traditional audiometric increment. On the other hand, the majority of laboratory studies have used a strip-chart recording of the AR responses (Handler & Margolis, 1977; Jakimetz, Silman, Miller, & Silverman, 1989; Margolis & Popelka, 1975b; Peterson & Lidén, 1972; Popelka, Margolis, & Wiley, 1976; Ritter, Johnson, & Northern, 1979; Silman, 1979; Silman & Gelfand, 1979; Silman, Popelka, & Gelfand, 1978; Silverman, Silman, & Miller, 1983; Thompson, Sills, Recke, & Bui, 1980). The activator run is either increased from below the expected ART or decreased from above, usually in 1- or 2-dB increments. Stimulus events are indicated by an event marker on the recording of acoustic-immittance changes. The ART is generally accepted as the lowest activator level that results in an observable acoustic-immittance change. A response is usually considered as such when its pattern is distinguishable from background noise, and is determined to be acceptable if it is repeated over three trials (Silman, Popelka, & Gelfand, 1978).

Both ascending and descending methods have been used to measure the ART. Though early findings (Jepsen, 1963) suggested that descending runs might occasionally result in lower ARTs than ascending stimuli, several later studies (Lilly & Franzen, 1970; Peterson & Lidén, 1972; Wilson, 1979) showed no significant differences between ascending and descending ARTs. In fact, there is striking agreement among the data generated by various researchers irrespective of the direction of the activator run.

The recorder output of the acoustic-immittance change may be directed to a computer so the digitized record of AR responses can later be transformed to hard-copy output or analyzed in terms of statistically significant deviations from the baseline acoustic immittance (Block & Wightman, 1977; Wilson, 1979, 1981; Wilson, Shanks, & Velde, 1981). When computer-monitored acoustic-immittance changes are employed, the ART is usually taken as the lowest activator necessary to yield a particular criterion value, such as 0.01-mmho change from the baseline.

Other techniques for monitoring the output of the acoustic-immittance device include visual detection of the change on an oscilloscope (i.e., voltage change from the baseline) (Djupesland & Zwislocki, 1971; Kaplan, Gilman & Dirks, 1977; Margolis & Popelka, 1975a; Robinette, Rhoads & Marion, 1974; Woodford, Henderson, Hamernick & Feldman, 1977), and computer-averaged responses (Cacace, Margolis & Relkin, 1991; Jerger, Mauldin & Lewis, 1977; Johnsen & Terkildsen, 1980; Stach & Jerger, 1984; Terkildsen, Osterhammel & Bretlau, 1973; Zito & Roberto, 1980). Stach and Jerger (1984) describe an approach to AR measurement based on a signal averaging technique designed to examine both threshold and suprathreshold characteristics of the AR.

Middle-Ear Transmission during AR Contraction

Contraction of the stapedius muscle adds stiffness to the middle ear thereby impeding the motion of the ossicles. In addition, contraction of the stapedius muscle may reduce sound transmission by decoupling the incus from the stapes (Møller, 1984). The effect of contraction of the middle-ear muscles on the transmission of sound through the middle ear has been studied in animals by several researchers, among them Price (1963, 1966) and Wever and Bray (1937, 1942), and in human subjects (Borg, 1968; Reger, 1960; Smith, 1943; Ward, 1961; Zakrisson, 1975).

The results of several studies in humans show that the effect of contraction of the middle-ear muscles on sound transmission increases with the intensity of the sound that activates the reflex (Borg, 1968). The effect is largest at low frequencies (500 Hz) and smallest at 1450 Hz. These results were obtained on patients with unilateral facial paralysis involving the stapedius muscle. Results also demonstrated that at 500 Hz, contraction of the stapedius muscle reduces the transmission of sound through the middle ear by 0.6 to 0.7 dB for each 1 dB that the stimulus tone is increased.

Developmental Aspects of the Acoustic Reflex

Several studies have reported a high percentage of absent contralateral ARs for the 220-Hz probe tone in neonates (Sprague, Wiley, & Goldstein, 1985; McMillan, Bennett, Marchant, & Shurin 1985; Bennett, 1975; Keith, 1973; Keith & Bench, 1978; Stream, Stream, Walker, & Breningstall, 1978). When the contralateral ARs are present in neonates, for the 220-Hz probe, they are generally present at elevated levels (Abahazi & Greenberg, 1977; Himmelfarb, Shanon, Popelka, & Margolis, 1978). The neonatal AR is essentially impossible to measure using a 226-Hz probe-tone frequency. The aforementioned researchers note an increasing percentage of detectable ARs with increases in probe-tone frequency. By 800 Hz, the ARs of neonates are present in close to the same proportion as those of the adult population. Weatherby and Bennett (1980), and McMillan *et al.* (1985) point out that the detection threshold for the newborn's AR varies with probe tone, as does the adult's threshold. The proportion of neonates with ARs, using high-frequency probe tones, is higher for the BBN than tonal activating signal.

Examination of adult versus neonate static-acoustic impedance data can perhaps explain why the differences between the adult and the newborn ARs exist. The generally high newborn acoustic impedance is related to the dimensions of the system at time of birth. There is a marked dip in acoustic impedance for the newborn into a resonance trough at approximately 200 Hz, possibly related to the properties of the tympanic membrane very early in life (Weatherby & Bennett, 1980). At low frequencies, the reduced acoustic impedance of the eardrum effectively shunts the higher acoustic impedance of the middle ear, and we cannot measure the small acoustic impedance changes caused by the AR; high acoustic impedance cannot be measured through a low acoustic-impedance medium.

According to the models presented by Bennett and Weatherby (1979, 1982) and Weatherby and Bennett (1980), the effects of probe-tone frequency and maturation are observed on the AR. The $|Z|$ of young adult ears generally increases from 220 to 700 Hz, and decreases from 700 to 1600 Hz. The newborn AR patterns over the probe-frequency range are similar, but the frequencies at which the patterns are present are displaced to a much higher frequency range. For example, the adult reversing frequency is 665 Hz; that for the newborn is 1200 Hz. This phenomenon is a reflection of the disparate characteristics of the ear canal and middle-ear structures of the neonate versus adult. The implication here is apparent. A 220-700 Hz probe tone is appropriate for an adult whereas use of a higher probe-tone frequency, i.e., 800-1200 Hz for the neonate ear, will allow us to obtain ARs at levels comparable to those of an adult (Bennett and Weatherby, 1982).

Age-Related Changes on the Auditory System

Aging is associated with anatomical and physiological changes throughout all sensory systems in the body; there is abundant substantiation of these changes. For example, in the visual system alone, there are changes in absolute threshold, visual acuity, accommodation (ability of the eye to discriminate detail), visual dark adaptation, and so forth (Corso, 1971). Numerous studies have documented senescent changes in auditory structure and function at all levels, from the conductive mechanism to the cortex. A loss of stiffness in the cartilaginous portion of the external auditory meatus becomes a problem when an earphone is placed on the pinna. Arthritic middle ear joints (e.g., incudo-malleolar and incudo-stapedial joints) become more common with increasing age (Colletti, Fiorino, Bruni, & Biasi, 1997; Etholm & Belal, 1974; Harty, 1953; Schow, Christensen, Hutchinson, & Nerbonne, 1978) but appear to have no effect on hearing sensitivity (Colletti, et al., 1997; Etholm & Belal, 1974). The hearing problems in older listeners are caused by changes in the cochlea, eighth nerve, central auditory nervous system, or central nervous system in general (Marshall, 1981).

Studies have described changes of the cochlear nerve with aging (Schow et al., 1978). Schuknecht (1955, 1964) characterized four different types of age-related sensorineural hearing loss, known as presbycusis, (sensory, metabolic or strial, mechanical or cochlear conductive, and neural) and related etiology to audiometric configuration. Sensory presbycusis (deterioration of basal hair cells and supporting structures) is distinguished by an abrupt high frequency loss; metabolic presbycusis (atrophy of the stria vascularis) is indicated by a flat audiometric pattern; mechanical presbycusis (diminution in the function of cochlear mechanics) is associated with a gradually sloping high frequency loss (the configuration seen in most normative data), and neural presbycusis (reduction in the number of viable neurons) is considered the culprit when speech recognition ability is poorer than expected based upon the audiogram. Kirikae, Sato, and Shitara (1964) found atrophy of neural structures in the ventral cochlear nuclei, the superior olivary complex, and more central nuclei throughout the auditory nervous system, including the cortex. Given the known neurophysiological changes that coexist with aging, one would also expect auditory acuity to diminish in the older population.

Presbycusis is prevalent among the older population. The most commonly occurring audiometric configuration is that which progresses gradually for the high frequencies and increases with advancing age. Presbycusic subjects tend to be heterogeneous in their performance on various audiologic measures. Their heterogeneous performance probably reflects such factors as (a) methodological problems in past research, (b) disagreement about the definition of presbycusis, and (c) difficulty in separating hearing losses caused by aging from those caused by other factors, such as noise and disease (Marshall, 1981).

In Corso's (1963a,b) classic work, the pure-tone threshold data were based on a large sample (912 subjects) and the subjects were exposed to minimum levels of industrial noise. The data are stratified by age (18 to 24 years; 26-32 years; 34-40 years; 43-49 years; 51-57 years; and 59 to 65 years) and gender. The youngest age group demonstrated the best hearing sensitivity. The mean threshold values for the various age groups were compared to the 18-to-24-year-old baseline. Two major points emerged from the analysis of the data:

1. The frequency that showed the maximal age effect was 4000 Hz for men and 6000-8000 Hz for women.
2. The decline in hearing occurs in distinctive stages. From 26 to 40 years (mean age of 33.5 years), there is relatively little change in the hearing sensitivity of men; then there is a marked drop in sensitivity but no further pronounced changes from 43 to 57 years (mean age of 50.5 years). This is followed by a second major drop in the between 59 and 65 years (mean age of 62.5 years).

It appears, therefore, that marked changes in the hearing of men occur on average in steps of about 15 years. Overall, the patterns are similar for women, except for the absence of the discrete changes that were seen in the data for men. For women, the rate of deterioration of hearing is fairly uniform as a function of age.

Age-Related Changes on the AR Parameters

ART

Tonal stimuli

Several classic studies showed that normal ARTs occur at approximately 85-100 dB SPL for tonal activators (Deutsch, 1972; Jepsen, 1963; Metz, 1946, 1952; Møller, 1961, 1962; and others). Past studies that examined the systematic relation between aging and the ART yielded disparate results, even within the same investigator. Two early clinical studies suggested possible aging effects on the ARTs. For example, Jepsen (1963) investigated tonal ARTs using subjects age range 10 to 80 years. He found that while the threshold of hearing increased with age (presbycusis) the ART decreased. It was, however, problematic that Jepsen expressed the ART in sensation level (SL). The expression of ARTs in dB SL re: HL is misleading in that the SL criterion ignores the relation between hearing level and ART. When the ART data are expressed in dB SPL, the age effect becomes negligible.

Jerger, Hayes, Anthony, and Mauldin (1978) retrospectively analyzed clinical ART findings on 214 normal-hearing subjects (defined as auditory thresholds ≤ 20 dB HL through 4000 Hz) across six decades (age 0 – 59 years). The authors found that ARTs for frequencies below 4000 Hz systematically decreased with age. This decrease with age, which was approximately 7 dB, was observed for tonal activators (except at 4000 Hz) but not for the BBN activator. For the BBN activator, the average ARTs tended to remain stable (± 2 dB) across all decades. These conclusions by Jerger *et al.* (1978) directly contradicted the findings on the ARTs from an earlier study by Jerger, Jerger, and Mauldin (1972), in which no changes in the ARTs for tonal stimuli as a function of age were observed.

To date, all laboratory ART studies have failed to show decreasing tonal ARTs (500 Hz, 1000 Hz, and 2000 Hz) as a function of age (Osterhammel & Osterhammel, 1979; Silman, 1979; Thomas, Sills, Recke, & Bui, 1980; Gelfand & Piper, 1981b; Handler & Margolis, 1977; Silverman, 1982; Silverman *et al.*, 1983; Wilson, 1981). For example, Silman (1979) investigated age-related effects on the ARTs in a group of 20 young normal-hearing adults (age 21- 36) and 20 older normal-hearing adults (age 60-79). In this study, normal-hearing sensitivity was defined as pure-tone thresholds less than or equal to 20 dB HL at frequencies between 500 and 4000 Hz. Silman found that the mean ARTs for the tonal activators, expressed in dB SPL, did not differ significantly between the two groups. His results are in close agreement with previously published data by Margolis and Popelka (1975), Margolis and Fox (1977), and Popelka *et al.* (1976).

Gelfand and Piper (1981) replicated Silman's (1979) study, but modified criteria for subject selection to extend normal-hearing sensitivity to

8000 Hz. These authors also found no statistically significant difference in the tonal ARTs (500-Hz, 1000-Hz, and 2000-Hz activators) between the two groups.

There is a consensus among the majority of studies, especially those conducted under laboratory conditions, that age does not affect the ART for 500 Hz, 1000 Hz and 2000 Hz tonal activators. Methodological differences, such as the use of 5-dB versus 2-dB activator increments and visual monitoring methods versus graphic display techniques, may explain the discrepancy between the early findings by Jerger *et al.* (1978) and those by Silman (1979), Thompson *et al.* (1980) and Gelfand and Piper (1981).

BBN stimuli

Several classic studies demonstrated that the ARTs for wide-band stimuli occur at levels approximately 20 dB lower than those for tonal activators in young, normal-hearing subjects (Deutsch, 1972; Djupesland, Flottorp, & Winther, 1967; Jepsen, 1963; Klockhoff, 1961; Margolis & Popelka, 1975; Metz, 1946, 1952; Møller, 1961, 1962; Peterson & Lidén, 1972). The difference in ART between tonal and BBN stimuli, or NTD, has been associated with a critical-band phenomenon (Flottorp, Djupesland & Winther, 1971). The NTD is reduced in persons with sensorineural hearing loss, essentially because of an elevated ART for the BBN signal. The reduced NTD difference in hearing-impaired subjects has been related to an abnormally wide critical bandwidth that can occur with cochlear involvement (Jerger *et al.*, 1974).

Handler and Margolis (1977) demonstrated an elevated BBN ART, which results in a reduced NTD, in elderly subjects. Subsequently, other researchers (Silman, 1979; Gelfand & Piper, 1981; and Wilson, 1981) reported comparable findings. For example, Silman (1979) reported an approximately 20-dB NTD for his younger subjects, whereas his older subjects demonstrated an approximately 10-dB NTD. One should note that activator step-size as well as the manner in which the AR is monitored will affect BBN ARTs across studies (Gelfand, 1984). The expected 20-dB NTD is found only in those studies that employ high-resolution techniques. The results of research based on a more clinical approach (i.e., 5-dB steps and visual monitoring) reveal smaller NTDs. Silverman (1982) demonstrated that a more clinical methodology may obscure the finding of an age effect on the BBN ART.

Gelfand and Piper (1981) closely matched the auditory thresholds of young and older adult subjects. The results of their study were in strong agreement with Silman (1979). The mean BBN ART was 76.2 dB SPL (S.D. = 6.5 dB SPL) for the younger group and 84.2 dB SPL (S.D. = 7.9 dB SPL) for the older group; this represented an 8-dB difference between the groups. The results of a later study by Wilson (1981) corroborated the reduced NTD in older subjects.

We can conclude, then, that there is an age effect on the BBN ART even in normal-hearing individuals. Silman (1979) posited the following explanation for the elevated BBN ART in older subjects. He postulated that when diffuse, mild deterioration of the outer-hair cells occurs, the effect on ART parallels that found in subjects with mild sensorineural hearing loss (SNHL). That is, in subjects with mild SNHL, the BBN ART is elevated because of the widening of the critical band. Although the tonal ART remains stable with magnitude of hearing impairment up to approximately 50-55 dB HL, the tonal ART increases as the magnitude of the hearing loss increases beyond 50-50 dB HL (Gelfand, Piper, & Silman, 1983; Keith, 1979; Popelka, 1981; Silman & Gelfand, 1979). Silman (1979) theorized that the elevated BBN ART may reflect age-related sensory-cell degeneration that is not great enough to cause a pure-tone hearing loss. This explanation is consistent with findings that outer hair-cell loss is associated with aging (Bredberg, 1968) and that outer hair-cell loss does not necessarily lead to clinical hearing loss (Lipscomb, Axelsson, Vertes, Roettger, & Carroll, 1979).

Silverman, Silman, and Miller (1983) further hypothesized that complex signals such as BBN may detect mild slight diffuse disorders associated with aging earlier than simple signals like pure tones. They also suggested that aging causes deterioration of the BBN ART and degraded speech-recognition ability before deterioration of the tonal ARTs and the hearing sensitivity for pure tones. Their finding that the age effect on the BBN ART becomes apparent in the fifth decade of life has a parallel in the literature on the effects of age on other auditory measures such as speech-recognition performance.

AR Magnitude and Growth

The AR magnitude is defined as the amount of acoustic-immittance change at the tympanic membrane resulting from AR contraction (Silman, 1984). The AR magnitude is quantified in impedance units relative to a baseline (or resting) acoustic impedance. The AR magnitude should be quantified in terms of acoustic impedance (Z_A) change at the tympanic membrane because static Z_A at the tympanic membrane seems to be stable over time, whereas the Z_A of the total ear is associated with poor test-retest reliability (Dallos, 1964). Research has shown that AR magnitude varies directly with intensity of the activating stimulus within a certain dynamic range above the ART. The plot of changes in acoustic immittance with increases in activator intensity is termed the acoustic-reflex growth function (ARGF).

Age-related effects on the ARGF have been well-documented in the literature. Beedle and Harford (1973) were the first to suggest that aging processes could result in a diminished growth of AR magnitude. Thompson *et al.* (1980) conducted the first detailed study of age-related effects on the ARGF in normal-hearing subjects. Their subjects consisted of 30 females, 5 in each decade from 20-29 years to 70-79 years, who had hearing levels less than or equal to 20 dB at the frequencies between 250 Hz and 4000 Hz. The activating stimuli included the tonal (500 H, 1000 Hz, and 2000 Hz) as well as white noise high-pass filtered at 1000 Hz. Thompson *et al.* (1980) found that the growth of AR magnitude (in amplitude of the acoustic-impedance change) decreases linearly with increase in age decade. This is the case regardless of whether magnitude is expressed in conductance (G_A) or susceptance (B_A) units for the tonal and filtered white-noise activators. The linear decrease with age was most evident for the noise activator.

Silman and Gelfand (1981) confirmed Thompson *et al.'s* (1980) finding of decreased growth of AR magnitude in the older versus younger subjects. They obtained ARGFs for 14 ears of 8 normal-hearing subjects aged 61-76 years and 16 ears of 9 subjects with SNHL aged 60-84 years. The ARGFs for the two older adult groups were then compared to those for a young group based on 26 ears of 13 normal-hearing subjects (ages 9 to 28 years); the data from the young group had been obtained from a previous study (Silman, Popelka, & Gelfand , 1978). The criteria for normal-hearing sensitivity for both young and older groups were air-conduction thresholds less than or equal to 20 dB HL within the 250-to-4000-Hz frequency range. The degree of SNHL for the remaining older group ranged from mild to severe across the frequency range.

Statistical analysis of the AR magnitude data of the two older groups (normal hearing and hearing impaired) showed no significant hearing-loss effect for tonal activating stimuli when the data were expressed in terms of dB SL re: ART. This finding is in agreement with those reported by Silman *et al.* (1978), who found that the mean ARGFs for the tonal activators were not significantly altered by cochlear hearing loss in young subjects. An analysis of variance (ANOVA) showed a significant difference in AR magnitude between the two older groups of subjects for the BBN activating stimulus. The AR magnitude growth in the older group with SNHL was reduced compared that in the normal-hearing elderly group. In addition, comparison of the ARGFs for the two elderly groups (Silman & Gelfand, 1981) with those of Silman *et al.* (1978) showed a substantially smaller mean AR magnitude in the elderly compared with the younger subjects.

Wilson (1981) compared the ARGFs of 18 young subjects (< 30 years of age) with those of older subjects (≥ 50 years of age) using tonal (250-, 500-, 2000-, 3000-, 4000-, and 6000 Hz) and BBN activators. He reported that the magnitude of the ARGF was significantly smaller in the older than in the younger group at each sensation level re: ART. This finding was true whether the data were expressed in Z or Y units.

Wilson, Shanks, and Velde (1981) measured the ARGFs in a young group (<30 years of age) and an older group (> 50 years of age). Hearing sensitivity was normal for both groups from 500 to 4000 Hz. These investigators found that the magnitude of the AR was considerably smaller for the older than younger group of subjects.

Silman and Gelfand (1981) and Wilson (1981) also discovered that the ARGF saturates more frequently in elderly than in young subjects. Silman and Gelfand (1981) found that saturation of the ARGF occurs in the elderly but not in the young subjects for 1000-Hz, 2000-Hz, and BBN activators. Interestingly, the young, but not the elderly subjects, showed saturation for the 500-Hz activator.

It is apparent, then, that age has an effect on the magnitude of the AR. Similar to other AR parameters, the age effect was noted in normal-hearing subjects. This finding of reduced AR magnitude in the older subject is consistent with the findings of other research on age-related changes in the auditory system and stapedius muscle (Bredberg, 1968; Hansen, & Reske-Nielsen, 1965; Schuknecht, 1964). Silman and Gelfand (1981) postulated that the presence of saturation in the elderly could be the result of deterioration of the structure and function of the auditory system leading to a decreased amount of energy that is used by the system. They also suggested that the presence of saturation at activating signal frequencies above 500 Hz in the elderly was consistent with evidence that the effect of aging upon hearing sensitivity is most marked at the higher frequencies (Bredberg, 1968; Schuknecht, 1967).

AR Latency

Acoustic-reflex latency (ARL) can be defined as the time between stimulus onset and the first detectable Z change resulting from middle-ear muscle contraction (Bosatra, Russolo, & Silverman, 1984). The ARL has been demonstrated to increase concomitantly with a number of pathological conditions including auditory brainstem lesions (Bosatra, Russolo, & Poli, 1975), and retrocochlear pathology (Clemis & Sarno, 1980; Mangham, Lindeman, & Dawson, 1980). Although data are limited with respect to age-related effects on the ARL, previous work in the area does suggest that ARL increases with advancing age (Bosatra *et al.*, 1984).

Bosatra and his colleagues (1984) described the ARL results for 120 subjects with normal-hearing sensitivity ($\leq$ 10 dB HL at 500, 1000, and 2000 Hz). Subjects were divided into decade groups ranging from 20-29 to 70-79 years of age. The ARL results for crossed stimuli were measured at levels of 10, 20, and 30 dB SL re: ART for tonal (500, 1000, 2000 Hz) and BBN activating stimuli. Their results indicated that the mean ARL did not vary significantly among the decade groups up to 50-59 years. The maximum ARL for crossed stimuli in normal-hearing subjects between 20 and 59 years of age was 178 msec. The mean ARL increased approximately 30 msec for all activators in the 60-69 and 70-79 year-old groups as compared with the youngest decade group.

It was noted that the mean ARL for uncrossed stimuli did not vary across decade groups up to 50-59 years. The maximum ARL for the 20-59 years groups did not surpass 146 msec. In the two oldest decade groups, the mean ARL increased slightly, but the maximum ARL did not exceed 166 msec.

AR Adaptation

Acoustic-reflex adaptation (ARA) is defined as the decrease in the magnitude of the AR during sustained stimulation (Wilson, Shanks, & Lilly, 1984). This phenomenon has variously been called AR decay, fatigue, or relaxation. The ARA measure has been used clinically since Anderson, Barr, and Wedenberg (1969, 1970) reported that patients with eighth-nerve lesions frequently demonstrate abnormally rapid ARA, even with low-frequency activating stimuli such as 500 and 1000 Hz. Numerous subsequent studies upheld the finding of Anderson *et al.* (1969, 1970). Consequently, most clinics have incorporated measures of ARA into audiologic clinical protocols for purposes of differential diagnosis.

The ARA is generally quantified in one of two ways: (a) the time (re: activator onset) for 50% reduction in AR magnitude, or (b) the percentage of maximum AR magnitude at a specified time (e.g., 5, 10, or 15 seconds) re: onset of the activating signal. The ARA measurements typically are made at 10 dB SL re: ART.

Although measurements of ARA are widely used by many audiology clinics for purposes of differential diagnosis, many aspects of ARA have not been thoroughly investigated. To date, for example, only one study has examined age-related effects on ARA (Lynn, 1988). Numerous studies have been performed on the ARA characteristics in young, normal-hearing subjects. The majority of these studies have focused on the effects of frequency, intensity and bandwidth on ARA. The effects of activator frequency on ARA for normal listeners have been thoroughly investigated (Djupesland, Flottorp, & Winther, 1967; Johansson, Kylin, & Langfy, 1967; Kaplan, Gilman & Dirks, 1977; Wilson, Steckler, Jones, & Margolis, 1978; Wilson, Shanks, & Lilly, 1984). The results of the aforementioned studies have yielded the following findings:

1. As the activating stimulus frequency increases, the rate of ARA increases;
2. The amount of ARA for the lower-frequency (500-Hz and 1000-Hz) tonal activators is less than that for the higher-frequency (2000-Hz and above) tonal activators; and
3. The onset of ARA occurs earlier for high-frequency than low-frequency activators.

The relation between ARA and activator intensity level in normal-hearing subjects is not as clearly defined as that between ARA and activator frequency. A lack of consensus exists on the latter relation. Depending on the investigation, ARA in the normal auditory mechanism has been shown to increase, decrease, or remain unchanged as a function of activator intensity. In addition, some research has indicated that the effects of activator intensity on ARA are frequency dependent. With the exception of Wiley and Karlovich (1975) and Kaplan, Gilman and Dirks (1977), most researchers have reported that ARA decreases as the intensity of a low-frequency (e.g., 500 or 1000 Hz) activator increases (Djupesland *et al.*, 1967; Givens & Seideman, 1979; Rosenhall, Liden, & Nilsson, 1979; Wilson *et al.* 1977). The effects of intensity on BBN and high-frequency tonal activators (2000 Hz) remain unclear.

The effects of activator bandwidth on ARA have been examined in the literature (Dallos, 1964; Djupesland *et al.*, 1967; Wiley & Karlovich, 1975; Wilson, 1984). There is general agreement that the rate of ARA adaptation is slower for BBN than most tonal activators.

Lynn (1988) studied the effects of age on ARA in three groups of subjects. The first group comprised 12 young subjects (age range of 20-29 years) with normal-hearing sensitivity (air-conduction thresholds ≤ 20 dB HL from 250 Hz through 8000 Hz). The second group comprised 12 older subjects (age range of 60-69 years) with normal-hearing sensitivity (≤20 dB HL from 250 Hz to 8000 Hz). The third group comprised 2 presbycusic subjects (age range of 60-69 years) with hearing sensitivity typical for their age (according to Corso, 1971 and Spoor, 1967). The criteria for the air-conduction thresholds in the presbycusic group were thresholds less than or equal to 25 dB HL from 250 Hz to 1000 Hz, between 25 dB and 40 dB HL at 2000 Hz, and between 25 dB and 55 dB HL above 2000 Hz. Subjects in this presbycusic group were matched with respect to age (± 2 years) to subjects in the older, normal-hearing group.

The ARA functions were measured on each subject by monitoring contralateral reflex activity using a 220-Hz probe tone. The AR activators consisted of tonal (500 Hz, 1000 Hz, and 2000 Hz) and BBN stimuli presented at 10 dB and 15 dB SL re: ART. In addition to calculating the rate of ARA for each function, the morphology of the curves was examined for trends. Four different curve patterns were described. Lynn (1988) found that the rate of ARA was not significantly affected by age or by presbycusis. In agreement with previous literature, the rate of ARA was found to be dependent on stimulus type and sensation level. When the morphology of curve patterns was analyzed, a significant age effect was discovered. No significant effect of presbycusis was found. Morphology, as well as rate of ARA, was dependent on stimulus type and sensation level.

Prediction of Hearing Loss from the ART

Various researchers have used ART measurements to identify and predict hearing impairment in adults and children. This technique is noninvasive, inexpensive, requires little patient cooperation, and is, therefore, clinically helpful in predicting hearing sensitivity in the difficult-to-test patient. The fundamental principle underlying prediction of hearing impairment from the ART is based upon the relation between the tonal and noise ARTs in persons with SNHL as compared with normal-hearing individuals.

The method of prediction of hearing loss from the ARTs, which was proposed by Niemeyer and Sesterhenn (1974), attempted to estimate the pure-tone average (PTA) of the hearing threshold levels at 500, 1000, 2000, and 4000 Hz. Their technique emerged from two observations:

1. The difference in ART between the tonal and BBN activators decreases inversely with the magnitude of the hearing loss; and
2. The difference between the average of the ARTs for the 500-, 1000-, 2000-, and 4000-Hz activators and the PTA for the threshold levels at 500, 1000, 2000, and 4000 Hz decreases linearly with the magnitude of the hearing loss.

Niemeyer and Sesterhenn (1974) showed that the difference between the average of the ARTs for the tonal activators and the PTA is greater by a factor of 2.5 than the difference between the average of the tonal ARTs and the BBN ART.

An essentially similar approach proposed by Jerger, Burney, Mauldin, and Crump (1974b) was referred to as the SPAR method, or sensitivity prediction from the AR. Jerger *et al.* entered the ART data for 500-Hz, 1000-Hz, 2000-Hz, and BBN activating signals into a set of formulas which yielded the NTD, expressed in decibels. The magnitude of the NTD formed the basis for categorization of the hearing sensitivity as normal, mild-moderately, severely, or profoundly impaired. The SPAR was further modified by Jerger (1975) and again by Jerger, Hayes, Anthony, and Mauldin (1978). Jerger *et al.* (1978) pointed out that the decreased NTD in the normal aged subjects made prediction of hearing loss in this population unreliable.

Silman, Gelfand, Piper, Silverman, and Van Frank (1984) reviewed data from several studies using the Niemeyer and Sesterhenn and SPAR methods. Their review revealed that the false-positive rates were as high as 25-40%, the false-negative rates were sizable, especially for studies that used large samples, and predictive accuracy with respect to hearing loss severity categories was poor.

Popelka (1981) and Silman, Gelfand, Piper, Silverman, and Van Frank (1984) noted the limitations of the methods for prediction of hearing impairment based on the ART as follows:

1. These methods did not control for age. Several studies have shown that the NTD decreases as a function of age (Gelfand & Piper, 1981; Silverman *et al.*, 1983).
2. These methods were based on the assumption that the NTD decreases as the severity of the hearing loss increases. However, research has indicated that this assumption holds only for mild-to-moderate hearing impairment up to 40-50 dB HL. Additional

increases in hearing impairment beyond 40-50 dB HL result in an elevation of the ART for the tonal, but not BBN activator. Therefore, the NTD increases with increases in the magnitude of hearing impairment beyond 50 dB HL.

Popelka, Margolis, and Wiley (1976) and Popelka (1981) attempted to overcome the limitations of these techniques with a bivariate-plot method. With this method, the ARTs are used to predict the presence, rather than the magnitude, of a hearing loss. The hit rate of the classical bivariate procedure is about 90% and the false-alarm rate is about 5% in children (Silman *et al.*, 1984a). The hit and false-alarm rates are slightly improved when ART measurements are made with 1-dB or 2-dB increments and a strip-chart recorder instead of 5-dB increments with visual inspection of needle deflection. The hit rate approaches chance level, however, when the sample includes persons with mild or high-frequency sensorineural hearing impairment (which occurs much more often in adults than in children) and persons more than 44 years of age (Handler, & Margolis, 1977; Silman, Silverman, Showers, & Gelfand 1984b).

The predictive accuracy of the classical bivariate-plotting procedure in adults with mild or high-frequency hearing loss can be enhanced by (a) excluding the ART data of those older than 44 years of age; (b) plotting the ART data from the hearing-impaired as well as the normal-hearing ears before drawing the line segments; and (c) drawing the line segments to maximize the hit rate without obtaining a large false-alarm rate (Silman *et al.* 1984a,b). This modified bivariate graph is then used for prediction of the presence of a hearing impairment of any magnitude, including high-frequency hearing impairment.

Neither the classical nor the modified bivariate procedure should be used with persons more than 44 years of age. The classical procedure should be used with children and the modified procedure should be used with adults under 44 years of age.

Keith (1977) suggested that the BBN ART alone could be used to identify hearing loss in children. Among 26 normal-hearing subjects and 48 with hearing loss (ages unreported), Keith found that the BBN ART exceeded 85 dB SPL in only 7 of the 52 normal-hearing ears (13.5%). In contrast, the BBN ART exceeded 85 dB SPL in 93 of the 96 ears (96.9%) with hearing loss. Keith therefore suggested that the BBN ART procedure, with a cutoff at 85 dB SPL, was an effective in screening for hearing impairment. There were some weaknesses to Keith's proposal, however. Ears with mild hearing loss were not included in Keith's data. In addition, Keith did not consider the effects of isolated high-frequency sensorineural hearing loss on the BBN ARTs. Unfortunately, the degree of overlap in BBN ART among the normal-hearing and hearing-loss groups makes it impossible to directly apply Keith's (1977) 85-dB SPL criterion to the adult population. However, examination of the BBN ARTs indicates that the BBN ARTs for the normal-hearing group generally fell below 80 dB SPL, whereas those of the subjects with significant hearing loss fell, without exception, above 85 dB SPL. One may conclude that if the BBN ART exceeds 85 dB SPL, then the presence of some degree of hearing loss is highly likely. Normal-hearing sensitivity would be expected if the BBN ART does not exceed 79 dB SPL. The interpretation is ambiguous if the BBN ART falls between 80 and 85 dB SPL. Recently, Keith's data were supported on a population of children and adults with cerebral palsy (Emmer & Silman, in preparation).

Silman *et al.* (1984b) developed criteria for the identification of hearing impairment in the over-44-years-of-age group based on the following absolute ART levels: (a) an ART greater than or equal to 105 dB SPL for the 1000- and/or 2000-Hz activator; or (b) an ART greater than 90 dB SPL for the BBN activator. They used 1-dB intensity increments and a strip-chart recorder. Silman and his colleagues reported that these criteria correctly identified 87% of their normal-hearing adult subjects. However, the ability to identify mild and/or high-frequency hearing impairment approached the chance level.

Wallin, Mendez-Kurtz, and Silman (1986) evaluated the accuracy of prediction of hearing loss based on the ART criteria developed by Silman *et al.* (1984b) for the older adult population, when routine clinical procedures for ART measurement (5-dB increments and visual monitoring of needle deflection) were used. Their sample included 126 ears of 83 subjects between 45 and 84 years of age. Wallin *et al.* (1986) reported that 90% of the ears with significant loss were identified as having at least a mild or high-frequency hearing impairment. Still, the predictive accuracy for the mild and/or high-frequency hearing-impaired ears remained problematic. About half of these ears had ARTs that did not exceed the proposed criteria and the other half had ARTs meeting the suggested criteria. The predictive accuracy for the normal-hearing ears was 93%. The findings of Silman *et al.* (1984b) and Wallin *et al.* (1986) suggest that these ART criteria can be used as a screening technique to identify the presence of hearing loss in difficult-to-test adults who are more than 44 years of age. Still, about 50% of the mild and/or high-frequency hearing-impaired ears will be misidentified.

Temporal Integration of the AR

Temporal integration can be defined as the relation (tradeoff) between stimulus intensity and duration when the time frame is less than about 1 second. The longer the duration of the stimulus, the less the intensity that is required for threshold, up to the plateau. Beyond the plateau, further increases in duration no longer improve threshold. This plateau point is usually called temporal integration for threshold. Temporal integration occurs for threshold, loudness, and the AR. It is based upon the fact that the nervous system needs time to optimally integrate energy. For shorter durations, more energy is required; for longer durations, up to a point, less energy is required. Temporal integration involves the integration of neural rather than acoustic, energy (Zwislocki, 1960; 1969). Since no means for integration of acoustic energy is available in the peripheral auditory system, it must be neural energy that is stored following sensory transduction (Zwislocki, 1969). The relation between intensity and duration is generally expressed as the level change (in decibels) needed to offset a decade (10 times) change in duration, as seen on a threshold-duration function. For example, reducing the stimulus duration from 200 to 20 msec might require that the stimulus level be raised from 82 to 92 dB in order to reach ART. In this case, then, a decade change would be offset by a 10-dB level change. Alternatively, the threshold intensity decreases by 10 dB when the duration of a tone is increased from 20 msec to 200 msec.

The tradeoff between intensity and duration is usually plotted with stimulus duration on the abscissa and intensity level on the ordinate or in terms of threshold difference in dB relative to the point of the plateau. With the latter approach, the threshold difference is plotted on the ordinate and the intensity is on the abscissa. The intensity-duration tradeoff is usually described in terms of slope (intensity change per decade of duration).

Methods of Recording and Measuring

In general, there have been four approaches employed for the recording and measurement of temporal integration: (a) use of a "criterion response," which is a predetermined point (e.g., 50% or 20% of the maximum acoustic-immittance change); (b) use of visual monitoring (Visual

Detection Threshold or VDT) involving the identification of the smallest noticeable acoustic-immittance change on a meter or oscilloscope; (c) use of strip-chart recorded data; and (c) use of an averaging method. Woodford *et al.* (1975); Feldman and Katz (1978) employed visual monitoring; Jerger *et al.* (1977) used an averaging technique; Djupesland *et al.* (1973) used a criterion response; and several investigators (Barry & Resnick, 1976; Richards, 1975; Singh & Greenberg, 1976; Gelfand *et al.*, 1981) utilized strip-chart recorded data. Some researchers have combined more than one of these methods within a study. For example, Djupesland and Zwislocki (1971) used VDT and a criterion response; Korabic and Cudahy (1984) employed "traditional" methods such as VDT along with a signal averager and an X-Y plotter to record the final averaged response. Cacace *et al.* (1991) used signal averaging and different threshold response criteria.

Gelfand (1984) enumerates the clear advantages, in terms of validity and reliability, provided by recorded AR responses as opposed to VDT, a method commonly seen in the literature. The most notable problem with any visual-monitoring approach is that the investigator must make an immediate decision about whether a particular meter deflection or deviation from oscilloscope baseline is, in fact, an AR response. In addition, the investigator is unable to re-evaluate the decision once made. According to Gelfand, "the requirement for an immediate decision frequently leads to variations in the tester's criterion for an immittance change indicative of a reflex response"

(p. 140). The often used criterion of smallest (reliable) meter deflection can easily be modified moment-by-moment because of changes in background meter activity, ballistics, etc., that may or may not be time-locked with the stimulus. The "smallest (reliable) meter deflection" may not, therefore, be the smallest, nor the most reliable.

A major impetus for the introduction of a computer-averaging technique was the need to obtain an ART at lower levels than those obtained via conventional methods. However, in the majority of those studies that used averaging methods, the computer-averaged ART was similar to the ART that was acquired using 1-2 dB increments (laboratory conditions) with a strip-chart recorder. For example, the results obtained by Cacace *et al.* (1991), using averaging, revealed a contralateral ART between 92-97 dB SPL (depending upon the criterion used) for a 1000-Hz tonal activator of 500 msec duration. Korabic and Cudahy (1984) and Morgan *et al.* (1977), also using averaging, achieved an ART of about 90 dB SPL for the 1000-Hz tonal activator of 500 msec duration. Gelfand (1984) notes the ART values obtained across 12 studies employing a 1000-Hz tonal activator, 1-2 dB intensity increments, and a strip-chart recorder (see Table 1-next page). The range of values for the ART is between 89 and 93 dB SPL. If we disregard the ARTs obtained by Wilson (1981), the ART range is between 90-92 dB SPL; this range is indeed very narrow.

Table 1

Typical Acoustic-Reflex Threshold Means
(Standard Deviations) (dB SPL): Laboratory Conditions

	N	250Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	BBN
Beedle & Harford ('73)	10		93.9	90.3	89.2		
Gelfand & Piper ('81)	12 ears		93.0 (4.2)	89.4 (5.2)	92.1 (4.9)		76.2 (6.5)
Handler & Margolis ('77)	17		94.1 (6.1)	90.4 (5.1)	91.8 (5.2)	96.2 (9.0)	75.4 (8.4)
Margolis & Fox ('77)	17		94.0	90.0	92.0	96.0	75.0
Margolis & Popelka ('75b)	5	99.7 (3.2)	97.7 (3.0)	91.1 (3.4)	90.3 (3.5)	91.5 (4.3)	77.2 (4.7)
Ritter *et al.* ('79)	10	107.8 (10.2)	96.1 (9.0)	92.1 (5.3)	89.9 (6.8)		
Silman ('79)	20 ears		91.7 (5.0)	89.5 (4.6)	91.6 (6.6)		72.7(11.3)
Silman & Gelfand ('79)	22 ears		90.6	89.0	90.8		76.8
Silman *et al.* ('78)	26 ears		93.0 (6.2)	91.3 (5.6)	93.4 (4.4)		76.3 (6.2)
Wilson ('79)[a]	36			91.6 (5.0)	93.7 (5.2)		76.4 (9.4)
Wilson ('81)[b]	18	104.3 (6.3)	90.9 (4.7)	89.8 (4.5)	91.1 (4.6)	92.8 (5.9)	71.4 (8.6)
Wilson *et al.* ('81)	48 ears		97.9 (5.4)	93.4 (6.0)	94.7 (6.9)		77.9 (10.5)

[a]Mean (SD) was 93.0 dB (4.9) at 750 Hz.

[b]Mean (SD) was 90.6 dB (4.4) at 750 Hz and 97.7 dB (8.0) at 6000 Hz. (From Gelfand, 1984).

The only investigators to obtain a remarkably lower ART for a 1000-Hz activating stimulus of 500-msec duration were Jerger *et al.* (1977) and Zito and Roberto (1980). In the former study, the tonal ART was approximately 72 dB SPL, and in the latter, never-replicated study, the tonal ART was found to be close to behavioral threshold, which raises the issue of whether the response was an artifact. The general lack of methodologic uniformity across studies with respect to the total number of sweeps averaged has made it difficult to determine how many sweeps are desirable. Jerger *et al.* (1977) averaged 8 or 16 sweeps, Silman (1981) 4 sweeps, Korabic and Cudahy (1984) 32 sweeps, Zito and Roberto (1980) 40 sweeps, and Cacace *et al.* (1991) a minimum of 8, and a maximum of 16 sweeps. Even when the same number of sweeps was used (Jerger *et al.* and Cacace *et al.*), the results have differed. It is apparent from the literature that computer averaging does not yield better resolution than a strip-chart recorder with 1-2 dB steps, particularly when a digital-to-analog recorder is used.

Popelka (1981) also recounts the numerous advantages of a strip-chart recorder:

> In addition to overcoming the problems associated with nonrecording output devices, this display method (the strip-chart recorder, or X-Y plotter) has several other advantages. First, a multichannel device is able to record both the ongoing immittance and the temporal aspects of the activating stimulus. This allows a more precise determination

> of whether or not immittance changes are associated with activating stimuli. It also allows the determination of the presence or absence of artifacts, the removal of the large static immittance value (if DC offset capability is present) so that small changes in immittance may be observed, and the capability for varying the sensitivity of the measurement system (p. 51).

Perusal of the literature on temporal integration for the ART reveals widely disparate intensity-duration findings, particularly for hearing-impaired listeners. Temporal integration ranges from 10-35 dB from study to study and among subjects within a single investigation (Gelfand *et al.*, 1981; Gelfand, 1984). Several investigators (Jerger *et al.*, 1977; Morgan *et al.*, 1977; Gelfand *et al.*, 1981; Korabic & Cudahy, 1984) have postulated that the disparate results stem from: (a) varied definitions of the ART; (b) instrumentation differences (e.g., Morgan *et al.* comment on the reduced sensitivity of the Zwislocki bridge relative to the Madsen Z0-70 meter, which at least partially results from difficulty in balancing the Zwislocki instrument when using a low-frequency probe); and (c) differences in measurement/recording techniques.

Djupesland and Zwislocki (1971), using the Zwislocki electromechanical bridge, examined the ART as a function of stimulus duration for 6 young normal-hearing subjects (age range 19-23 years). The ART was defined as the smallest detectable baseline deflection (acoustic-immittance change) on an oscilloscope. Stimulus intensity was adjusted to satisfy one of three criteria: (a) VDT; (b) 20% of the maximum impedance change; and (c) 50% of the maximum impedance change. The contralateral AR was elicited with a 2000-Hz tonal activator; the activator duration varied from 5 to 3000 msec, the interstimulus interval was 5 sec, and 1-dB activator intensity increments were used over the 80-140 dB SPL range.

The results of Djupesland and Zwislocki's (1971) study revealed that the activator duration has a marked effect on the ART. The median threshold intensity decreased by approximately 25 dB when the duration of the 2000-Hz activator was increased tenfold from 10 to 100 msec. Thus, a decade change was offset by a 25-dB level change. The effect was noted to be about the same for all criterion levels (i.e., VDT and 20%, and 50% of maximum acoustic impedance change. The effective time constant (threshold) of temporal integration of the ART was about 200 msec. This time constant is the same as that for the threshold of audibility and for loudness.

In a later study, Jerger *et al.* (1977) concluded that the approach used by Djupesland and Zwislocki to analyze ARTs based upon a criterion of a constant proportion of maximum observable amplitude at any given duration, is unsuitable for temporal integration studies. Jerger *et al.* note that "such a criterion is based on the implicit assumption that the slope of the amplitude function is constant across duration. But our data place this assumption in doubt" (p. 191). Specifically, Jerger *et al.* (1977) showed that the mean 1000-

Hz ARGFs for two subjects became shallower with decreasing activator duration. Jerger *et al.* also remarked that the change in the slope of the AR amplitude as a function of signal duration could interact with inherent instrument noise to affect temporal integration as measured by VDT methods. According to Jerger *et al.* (1977) a system with low background noise will measure less temporal integration than a system with comparatively higher background noise.

In 1973, Djupesland, Sundby, and Flottorp studied temporal integration of the ART in 5 young subjects with normal hearing sensitivity. The AR was elicited by contralateral stimulation of the left ear by using octave bands of noise centered at frequencies between 250 and 4000 Hz. Activator duration was varied from 5 to 3000 msec, with an interstimulus interval of 4 sec. The results indicated that the duration of short acoustic stimuli has a notable effect on the ART. For activating stimulus duration shorter than 50-80 msec, the relation between intensity and stimulus duration was found to be about the same for the various activating stimuli, indicating that temporal integration of the ART is independent of the type of stimulus, when the stimulus is of short duration.

For durations longer than about 80 msec, the investigators noted several time constants of integration. Djupesland *et al.* characterized each of the obtained temporal integration functions by two lines that met to form a "knee." Specifically, it was found that for all bands of noise activators, the slopes of the temporal-integration functions were equivalent up to a critical duration; this duration varied as a function of the center frequency. For noise bands centered at 250, 500 and 1000 Hz, the critical duration was between 50 and 80 msec, whereas the higher frequency bands and the white noise had critical durations between 500 and 600 msec. The slopes of the functions above the knee-point were much less steep than those below the knee-point, but they increased as a function of the center frequency. The authors offered the following possible explanation for the observed difference in the knee-point for frequencies below and above 1000 Hz: The lower knee-point for low- as compared with high-frequency activators may correspond to the effect of the transmission loss observed by Borg (1968). The median slope across durations below the knee-point was 22 dB for a tenfold change in time; this finding was in agreement with Djupesland and Zwislocki (1971). Bazarov and Moroz (1975) also reported a slope in excess of 20 dB per tenfold change in activator duration using a BBN stimulus. In contrast, however, Gnewikow (in 1974, as cited by Jerger *et al.*, 1977), reported slope values in the range of 12-23 dB. For the 500-Hz activator, Gnewikow obtained a slope of 12 dB, whereas Djupesland *et al.* reported a 25.5 dB slope. It is interesting to note that Woodford *et al.* (1975) and Gnewikow (in 1974, as cited by Jerger *et al.*, 1977) using fundamentally the same instrumentation, demonstrate very similar results.

Singh and Greenberg (1976) observed that the ARTs in their study occurred at lower intensities than those obtained by Djupesland *et al.* (1973). They proposed that the variation could be explained by differences in the ART criteria used. Whereas Singh and Greenberg recorded both stimulus and response for analysis, the response criterion used by Djupesland *et al.* was 50% of the maximum acoustic-impedance change. The authors hypothesized that to obtain this amount of acoustic-impedance change, "more signal intensity is certainly required" (p. 13).

Richards (1975) studied temporal integration in 10 normal-hearing young (mean age of 24.5 years) adults. The contralateral ART was obtained for activator tone bursts of 500, 1000, 2000 and 4000 Hz at the following durations: 1000, 640, 320, 160, 80, 40 and 20 msec. An American Electromedics Model 81 meter was used to observe acoustic-impedance changes that were monitored on a strip-chart recorder. The interstimulus interval was randomly varied between 4 and 10 sec. Richards reported, as did all previous researchers, that there was a tradeoff between ART and duration for all activator frequencies studied. He noted, too, that the relation was frequency dependent. At 500 and 1000 Hz, between 12 to 13 dB additional intensity was required for ART with decade reduction from 200-20 msec. At 2000 Hz, 17 dB was needed, and at 4000 Hz, 27 dB was required. The slopes for this study for the 2000-Hz tonal activator were somewhat smaller than those found by Djupesland and Zwislocki (1971) and

Djupesland *et al.* (1973), with 22 dB for one decade duration in the former study, and 23 dB for one decade duration in the latter. Richards' difference was 17 dB at 2000 Hz. It is important to again note, in light of the high slope variability, that sample sizes were small for all studies (between 5 to 10 subjects).

Richards (1975) comments that although his study, and that of Djupesland *et al.* (1973), both show that the slope of temporal integration of the ART is frequency dependent, the course of the dependence differs. The data of Djupesland *et al.* (1973) indicate two patterns not reproduced in the study by Richards:

1. The slope of temporal integration of the ART remained relatively uniform (approximately 22 dB/decade time) up to a critical duration point, the value of which increased with frequency; and
2. The slope of temporal integration of the ART was frequency-dependent at durations greater than the knee-point, increasing as a function of increased frequency. Richards' results showed the frequency effect to be present for all activating stimulus durations, not solely for those beyond the knee-point. In addition, the data of Richards do not demonstrate clearly apparent knee-points.

We should be cognizant of the fact that there is no mention of the resolution of the recorder used by Richards (1975). Because the frequency resolution of the recording device is unknown, the question arises as to its ability to track small changes. In addition, there is no mention of the time constant of the recording device. It is difficult to compare results of studies that differ in terms of their instrumentation as well as criteria for acoustic-impedance change.

Barry and Resnick (1976) explored the ART as a function of activating stimulus frequency and duration. Subjects included 6 young adults (4 females and 2 males of unspecified age range) whose pure-tone thresholds did not exceed 10 dB HL. The ARTs were obtained at each of four activating stimulus frequencies (500, 1000, 2000, and 4000 Hz) for durations of 10, 30, 100, 300, and 1000 msec. The authors detected the monitored the ART with the Madsen ZO-70 acoustic-immittance device, in conjunction with a dc amplifier and strip-chart recorder. The criterion for ART was the minimum stimulus level at which the investigator observed a deflection of the trace, occurring on 2 of 3 successive presentations, which was time-locked to the activating stimulus. Generally, Barry and Resnick observed a smaller improvement in the mean ART with increase in duration than Djupesland and Zwislocki (1971) and Woodford *et al.* (1975). But Barry and Resnick's data are in very good agreement with those obtained in 1972 by Morgan and Bower (as cited by Resnick and Bower), who used similar equipment. In later studies by Jerger *et al.* (1977) and Morgan *et al.* (1977) this point is reiterated. Even the same investigators, using dissimilar equipment, achieve disparate results. Additionally, and in agreement with most other investigators, Barry and Resnick found a frequency effect with a considerably steeper slope for higher (2000 and 4000 Hz) frequencies than for lower (500 and 1000 Hz) frequencies. These authors point out, in accord with previous literature, that although the mean ART data appear to be quite orderly in appearance, examination of individual data shows striking inter-subject differences in the magnitude of the change in ART as a function of stimulus duration.

Jerger, Mauldin, and Lewis (1977) examined the interaction of signal intensity and signal duration at VDT and at varying suprathreshold signal levels in 10 normal-hearing young subjects (age range of 21-35 years). A signal-averaging technique was used to minimize AR measurement system noise. The response was displayed on an oscilloscope or printed out on a strip-chart recorder. Sixteen sweeps were used to define a single AR response; when amplitude-intensity functions were generated, 8 sweeps per response were used. The impetus for this study was the presence, in the literature, of the divergent results mentioned earlier for temporal integration of the ART. It was the initial contention of these investigators that the discrepancies in findings among different investigators and regarding reflex levels and slopes of temporal integration, could be explained by procedural differences and as artifacts of instrumentation. As the investigation progressed, however, Jerger *et al.* became aware that other factors, chiefly a bandwidth effect, contributed to these discrepancies.

Jerger *et al.* (1977) measured the ARTs in 2 male and 8 female subjects for a 1000-Hz tonal activator at durations of 10, 20, 50, 100, 200 and 500 msec. Activator intensity was varied in 1-dB steps, and ART was defined as the lowest SPL producing a visually detectable vertical displacement of the averaged horizontal oscilloscopic baseline. In 2 of the original 10 subjects, additional signals of 500 Hz, 1000 Hz, 3000 Hz, 4000 Hz, BBN, and band-pass filtered noise also were investigated. In addition, in these 2 subjects, amplitude-intensity functions were generated for each signal duration (AR responses were recorded with a strip-chart recorder, and activator intensity was varied in 5-dB increments from VDT to a maximum of 135 dB SPL). In a group of 3 normal listeners, amplitude-intensity functions were generated at 5-dB intervals for both a 1000-Hz tonal activator and for broad-band Gaussian noise. The ART data revealed a 10-11 dB decade tradeoff for the 500-, 1000-, and 2000-Hz tonal activators. The slope of the temporal integration function was somewhat steeper at 3000 Hz, and considerably steeper at 4000 Hz. The slope of the temporal-integration function for Gaussian noise was similar to that for the 4000-Hz tonal activator, which led to an additional experiment showing a bandwidth effect on temporal integration of the ART.

Jerger *et al.* (1977) compared their temporal integration findings for the 1000-Hz tonal activator (VDT) with those of Djupesland and Zwislocki (1971) for the 2000-Hz activator and Woodford *et al.* (1975) for the 1000-Hz activator. The results were widely dissimilar. Jerger *et al.* proposed that the divergence was due only in part to a frequency difference, and more fundamentally to "an interaction between reflex VDT and the instrumentation used to detect reflex response" (p. 186). It is the contention of Jerger *et al.* that the dissimilarities are best explained as artifacts of equipment because of difference in background noise level of the measurement systems used in the three studies. The ART data of all studies, however, do show a frequency effect.

Using two normal listeners, Jerger *et al.* (1977) measured AR amplitude for the 1000-Hz tonal activator at 100 to 135 dB SPL over signal duration ranging from 10 to 500 msec. The results indicated the following:

1. At the longest activator durations, AR amplitude rises rapidly and then asymptotes at 120 dB SPL;
2. As activator duration decreases, the slope of the amplitude-duration function becomes more gradual.

According to Jerger *et al.*, there are three very important implications of these findings. Firstly, temporal integration data that are based upon a constant-proportion-of-maximum-observable-amplitude criterion are questionable, because such a criterion is based on the "implicit assumption that the slope of the amplitude function is constant across duration" (p. 191). According to Jerger *et al.*, this assumption is erroneous. Secondly, the change in slope can have an effect on data on temporal integration of the

ART based on the VDT method. Jerger *et al.* believe that because of the differences in slope of the amplitude-duration functions, the level of background noise in the measurement system will impact on the temporal integration measured by a VDT technique in the following manner. When VDT is the criterion method, systems with high background noise levels will demonstrate a greater amount of temporal integration than systems with low background noise levels. Thirdly, because the amplitude functions in this study seem to extrapolate downward to a common origin, it can be inferred that if there were no measurement system noise there would be little, if any, temporal integration of the ART. Jerger *et al.* (1977) suggest, therefore, that relatively large differences among the findings of previous research are explained by the interaction between measurement system noise and the slope of the amplitude function when the criterion of temporal integration is VDT.

Jerger *et al.* (1977) also measured AR amplitude in 3 normal listeners at 5-dB increments from 70 to 130 dB SPL for both tonal (1000-Hz) and BBN activators. A substantial slope difference was noted between the 1000-Hz and BBN signals. It was postulated that this difference has an important implication for the amount of temporal integration measured by VDT: the background noise level of the measuring system would have a greater effect on temporal integration of the ART for BBN than for tonal activators. The substantial changes in slopes of amplitude functions highlights the difficulties in interpretation of ART data obtained with the VDT method.

Jerger et al. (1977) reported that an examination of amplitude-duration functions for 1000 Hz and BBN activators yielded the following observations:

1. The amount of temporal integration of AR amplitude increases with signal intensity;
2. The threshold of temporal integration of AR amplitude occurs at a signal duration which decreases as a function of signal intensity; and
3. The threshold of temporal integration of AR amplitude at high intensities is the same (100 ms) for either the 1000 Hz or the BBN tonal activating signal. Jerger *et al.* suggest that this last finding implies that the technique based on the amplitude-duration function may be a more advantageous method for examining temporal integration of the AR than that based on the VDT.

Gelfand, Silman, and Silverman (1981) obtained ARGFs for tonal activators of 500 Hz, 1000 Hz, 2000 Hz and BBN on 4 subjects (3 female and 1 male, age range of 22 to 31 years). The activator duration tested included 1000, 200, and 20 msec. Acoustic-immittance change was monitored using an electroacoustic immittance meter (American Electromedics model 83), and was recorded on one channel of a two-channel strip-chart recorder

(Gould Brush model 220). The second channel served as an event marker of stimulus presentations. The AR magnitude was obtained by subtracting the acoustic impedance preceding activator onset from that occurring during stimulation. The ARTs for the 1000-msec duration activators averaged about 90 dB SPL for tones and about 70 dB SPL for BBN, consistent with previous findings (Silman, Popelka, & Gelfand, 1978). The degree of temporal integration was noted to be quite variable among subjects. This finding was also in concordance with results reported by other investigators (Djupesland & Zwislocki, 1971; Djupesland *et al.*, 1973; Bazarov & Moroz, 1975; Woodford *et al.* 1975; Jerger *et al.*, 1977). Gelfand *et al.* noted greater variability (in agreement with Hung & Dallos, 1972) with respect to ARGF patterns between subjects than within subjects across activators, a fact that would seem to preclude the use of simple systems of pattern types for purposes of diagnosis. Gelfand *et al.* did mention, however, that it is usual for all ARGFs for 1000-msec activators to augment in AR magnitude with increasing activator level. This augmentation occurs over a rather large range of SPLs before a point of saturation. According to Silman *et al.* (1978), this is the case for the BBN ARGF as well, although a "tail" of slow or no AR growth occurs near threshold.

Gelfand *et al.* (1981) described several important observations about temporal integration with respect to the ARGF. The ART is elevated at activator duration well below a second, and rate of AR growth with activator level appears to decrease with shorter duration stimuli, that is, the slope of the ARGF is shallower for shorter duration; the effect is increased at higher activator frequencies. Jerger *et al.* (1977) also found that the slopes of the ARGFs for the 1000-Hz activator decreased with decrease in signal duration. The ARGFs for the BBN activator are similar to those for the highest frequency tonal activator (2000 Hz). This finding is consistent with the temporal integration data for the ART reported by Jerger *et al.* (1977).

When the ARGF is normalized at ART for all activator durations, the following results are demonstrated:

1. Growth in AR magnitude is similar among the three durations at 500 Hz.
2. At 1000 Hz, growth in AR magnitude is slower at 20-ms duration than at 200 and 1000 msec.
3. At 2000 Hz, growth in AR magnitude becomes progressively slower with decreasing duration from 1000 to 200 to 20 msec.

There was no particular pattern demonstrated by the normalized BBN growth function.

Cacace, Margolis, and Relkin (1991) echo a finding so often noted in the literature. They reported that threshold of temporal integration of the ART depends upon instrumentation as well as the criteria used to measure the ART. In addition, these authors indicated that mode of presentation (i.e., ipsilateral versus contralateral) impacts on the ART and on temporal integration of the ART. The results of statistical analysis of their data show that stimulus duration, AR response criteria, and recording conditions were significant factors contributing to the changes observed in ART. However, there seems to be an interaction effect between AR response criteria and duration, and between AR response criteria and mode of presentation. The ipsilateral ART is consistently lower than that for contralateral stimulation by about 5 dB. At 100-msec duration across all intensities, the ipsilateral, but not contralateral, AR magnitude at suprathreshold levels seems to attain temporal integration. Temporal integration of contralateral AR magnitude occurred at suprathreshold levels for the activator duration of about 200 msec, similar to the temporal integration findings reported in previous literature.

Morgan, Gilman, and Dirks (1977) noted that even the same investigators obtain disparate results when they use different instrumentation. They cite Wilson, Morgan, and Dirks (1972) who, using a Madsen ZO-70 electroacoustic impedance meter, observed an intensity-duration tradeoff of approximately 10 dB with a 2000-Hz activator at durations between 25 and 1000 msec. Morgan and Bower (1972) conducted a similar experiment with different subjects using a Zwislocki Bridge (Model 3). The results of the latter study were in sharp contrast to the results of the former, but interestingly, in close agreement with findings of Djupesland and Zwislocki (1971), who also used the Zwislocki Bridge (Model 3). The authors suggested that the differences seen were most likely due to differing equipment characteristics associated with each of the impedance-measuring systems, as well as to procedural differences, rather than to any real differences between subjects. As a result, Morgan *et al.* (1977) conducted several experiments to determine the operating characteristics of two acoustic-impedance measurement systems (Madsen, model ZO-70 and Grason-Stadler Zwislocki Bridge, model 3). In addition, they sought to measure (a) the ART; (b) the ARGF; and (c) temporal integration of the ART for several tonal activators.

Morgan *et al.*'s (1977) first experiment was designed to determine and contrast the sensitivities and temporal characteristics of both the Madsen (model ZO-70) and the Zwislocki Bridge. The examiners noted that a smaller acoustic-impedance change could be identified with the Madsen ZO-70 than with the Zwislocki bridge; they attributed this finding primarily to the reduced noise-floor of the Madsen device. As a follow-up study, they used a computer-averaging technique to determine "whether a response to an impedance change existed within the Zwislocki Bridge noise-band and whether our ability to extract it visually was limited by the equipment" (p. 171). A clear response for the Zwislocki Bridge was identified with computer averaging, thus supporting Morgan *et al.*'s contention that temporal-integration differences among studies, as well as discrepancies in absolute ART are due, at least partially, to differing instrument characteristics. Therefore, Morgan *et al.* stress the importance of accurate specification of the measurement characteristics of acoustic-impedance devices, as well as consistent definition of ART.

Morgan *et al.* (1977) also conducted an experiment to measure temporal integration of the AR at threshold and suprathreshold levels using the two aforementioned acoustic-immittance devices. The investigators obtained ARTs and ARGFs from 3 young adults with normal hearing (no specification of age range or criteria for normalcy). Six activating signal durations (non-randomized) were employed (25, 50, 100, 250, 500, and 1000 msec) for 2000-Hz and BBN stimuli. The ART was determined via a visual-detection method. The ARGFs for the 50- and 500-msec stimuli were specified in terms of percent of the maximum voltage change measured for the 1000-msec stimulus. The results indicated clear differences in the ART data obtained by the two instruments. The difference in ART between the two instruments was greater for short-duration stimuli (25, 50, and 100 msec) and less for the long-duration stimuli (250, 500, and 1000 msec). At all durations, the Madsen instrument permitted detection of the threshold change in acoustic impedance at lower SPL than the Zwislocki device. The NTD was approximately the same for both instruments, but the intensity-duration tradeoff differed considerably between the two, being about 25 dB for the Zwislocki bridge and about 7 dB for the Madsen device. Interestingly, only slight differences existed between the two instruments at suprathreshold levels (i.e., at the SPL associated with an impedance change that represents 20% of the maximum). The ART difference between 25 and 250 msec is 26-29 dB for the 2000-Hz stimulus and 29-32 dB for the BBN stimulus. Observing the large inter-instrument differences for threshold and not for suprathreshold AR measurements, Morgan *et al.* hypothesized that as the intensity of the activating stimulus is increased, concomitantly increasing the acoustic-impedance change, the instrumentation differences disappear. In addition, Morgan *et al.* postulated that the instrumentation differences noted at threshold and not suprathreshold levels suggest a change in the temporal-integration function between these levels when the functions from the most sensitive impedance-measurement system are compared. The data demonstrated, in agreement with Jerger *et al.* (1977), an increase in the slope of the temporal-integration function between threshold and suprathreshold levels.

Lastly, using the more sensitive Madsen ZO-70, Morgan *et al.* investigated the effect of tonal activator frequency (250-4000 Hz) on temporal integration of the ART for activator duration of 25, 50, 100, 250, 500, and 1000 msec. Subjects comprised 6 normal-hearing adults (unspecified age and criteria for normal-hearing sensitivity). In agreement with the findings of previous investigators such as Djupesland *et al.* (1973), who used narrow-band noise, and Richards (1975), Woodford *et al.* (1975) Barry and Resnick (1976), and Jerger *et al.* (1977), who used pure tones, Morgan *et al.* found a frequency effect. In agreement with Richards (1975), the AR temporal-integration data indicated a steeper slope for higher than lower frequencies. Morgan *et al.* asserted that evidence from their data does not necessarily support the explanation of Djupesland *et al.* (1973) of integration-function difference across frequency on the basis of middle-ear muscle contraction effects. They postulated that differences in calibration procedures could account for the apparent ART differences among the tonal activators. Additionally, the slope differences, when plotted in dB/msec-change, do not support a clear boundary between frequencies above and below 1000 Hz, as suggested by Djupesland *et al.* (1973).

Goodman and Richards (1977) commented upon the considerable diversity among the studies with respect to thresholds, slopes, and morphology of the temporal integration functions for the ART. Goodman and Richards cited the hypothesis of Morgan *et al.* (1977) and Jerger *et al.* (1977) that the diversity of results may be attributed to "instrument noise and to an interaction between instrument noise and differences in rate of growth of amplitude of the acoustic reflex as a function of signal duration" (p. 191). Goodman and Richards postulated that there are sources of noise in addition to instrument noise. These comprise, according to the authors:
(a) experimenter "noise" including differences in criteria for ART;
(b) experimenter bias; (c) use of VDT techniques; (d) perhaps the observer's

visual acuity; and (e) physiologic noise. Morgan *et al.* (1977) also commented on the inherent problems of experimenter bias with use of VDT methods. Block and Wightman (1977) particularly note the lack of agreement on an operational definition of the ART.

Given the general plethora of problems with respect to the measurement of temporal integration that has been cited by many investigators, Goodman and Richards (1977) attempted, primarily, to address the questions of within-subject variability both within and between sessions and inter-subject variability. They used bands of noise (centered at 1000 and 4000 Hz) as the activating stimuli for 11 young adult subjects (8 females and 8 males, age range of 22 to 25 years). The hearing threshold levels did not exceed 15 dB HL (unspecified range of frequencies). An American Electromedics Model 81 impedance meter was used to monitor contralateral changes in impedance. Threshold was bracketed. The ART was the level at which a clear time-locked meter deflection was observed by each of two or three investigators in at least 50%, and most often 70-100%, of approximately 10 trials. One of the purposes of the study was "to use a criterion and procedure for determination of reflex threshold that (1) would decrease within-subject variability, (2) would be simple to replicate, (3) would lessen experimenter bias, (4) would reduce some of the effects of instrument noise, and (5) would make use of relatively simple equipment available in clinical laboratories" (p. 202).

The results indicate that Goodman and Richards (1977) were successful in reducing within-subject variability within-session, that within-subject variability between sessions was minimal, and that to some extent, overall inter-subject variability was diminished. But significant differences still exist in the intensity-duration functions, particularly at 4000 Hz (for the decade of 20 to 200 msec), between this study and other studies (Richards, 1975; Woodford *et al.*, 1975; Jerger *et al.*, 1977; Morgan *et al.*, 1977; Djupesland *et al.*, 1973; Richards and Goodman, 1977). The disparity in results can appear even greater depending upon the decade studied or the criterion for ART. In addition to being aware of differences in data *across* studies, one must also be cognizant of the large range of temporal integration values among subjects *within* a single study, associated with a general lack of consistency in frequency dependence. Goodman and Richards feel that both differences (differences across, and differences within studies) are important and relevant to establishing normative values for clinical studies and that "examination of the latter may shed some light on the former" (p. 198). They suggest that a signal-averaging procedure along with a precisely defined criterion for ART should supplant any VDT method. But, as mentioned earlier, although computer-averaging techniques were introduced to obtain an ART at a lower levels than that obtained via conventional methods, the ART acquired by the former method is similar to that acquired by using 1-2 dB increments with a strip-chart recorder (Gelfand, 1984; Popelka, 1981).

Whereas previous research had investigated temporal integration of the ART in only normal-hearing subjects, Woodford, Henderson, Hamernik and Feldman (1975) studied temporal integration of the ART for tonal activators (500-4000 Hz) in both normal-hearing (5 males and 5 females) and hearing-impaired (3 males with sensorineural hearing loss of cochlear origin) subjects. The investigators used three different acoustic-immittance meters in this study: (a) Madsen Z0-70; (b) Grason-Stadler 1720; and (c) Grason-Stadler-Zwislocki model 3. The results were determined to be independent of the device used, since no ART differences exceeding 4 dB were found among instruments. In contrast to Djupesland and Zwislocki (1973), Woodford *et al.* found their data demonstrated a 15-dB rather than 25-dB tradeoff per decade change. Woodford *et al.* also noted (as did Djupesland *et al.*, 1973) a slight frequency effect on the temporal integration of the ART function with the lower frequencies (500 and 1000 Hz) having a flatter function than the higher frequencies (3000 and 4000 Hz). Although this research pointed to a gender effect, with males showing a uniformly flatter ART temporal integration function than females, the authors were quick to point out the admitted exposure to high-level noise experienced by each of the five male subjects, with consequent "subclinical noise-induced cochlear pathology" (p. 53). Woodford *et al.* reported that the generally flattened integration curves of the hearing-impaired subjects demonstrated considerable overlap with functions of the "normal-hearing" males, but not with those of the normal-hearing females. One must be cognizant, however, of the very limited number of hearing-impaired subjects in this study (n = 3), as in all studies using hearing-impaired subjects.

Singh and Greenberg (1976) and Feldman and Katz (1978) followed Woodford *et al.* (1975) with studies of ART temporal integration in normal-hearing and hearing-impaired subjects. There is, however, extensive variation in the amount of temporal integration, as well as overlap among the data for the normal-hearing and hearing-impaired subjects reported by these researchers. This is important in light of the small number of subjects in each of the studies. Singh and Greenberg (1976) obtained AR temporal integration measures on normal-hearing and sensorineural hearing-impaired subjects. Activating stimuli consisted of one-third octave-band noises (center frequencies of 500 to 4000 Hz); their duration ranged from 15 to 300 msec. The subjects consisted of 16 young normal-hearing males and females (mean age of 21 years) as well as 6 hearing-impaired persons (3 with bilateral Ménière's disease and 3 with presbycusis).

Singh and Greenberg (1976) reported a reduced amount of temporal integration for the sensorineural hearing- impaired subjects; the amount of temporal integration was in general agreement with that reported by Woodford *et al.* (1975). They noted that the ears with Ménière's disease are clearly differentiated from normal ears with respect to temporal integration measurements that is, the amount of AR temporal integration for the subjects with Ménière's was less than that for the normal-hearing subjects. The amount of AR temporal integration for the presbycusic subjects fell between that for the normal subjects and that for subjects with Ménière's. But the amount of temporal integration for the normal-hearing subjects was 16-20 dB, in contrast to the findings of previous researchers (Djupesland and Zwislocki, 1971; Djupesland *et al.*, 1973; Woodford *et al.*, 1975), who observed AR temporal integration amounts ranging between 20-35 dB, using pure-tone stimuli and octave-noise bands. Singh and Greenberg suggested that the differences between studies might be due to the use of stimuli of differing durations. Singh and Greenberg also obtained ARTs for one-third-octave-band noises at lower sound pressure levels than those obtained by Djupesland *et al.* (1973). They proposed that the ART differences are due to a difference in AR response criteria. In contrast to the findings of Woodford *et al.* (1975), Singh and Greenberg's ARTs for the normal-hearing subjects generally failed to show any differences in the shape of the temporal integration curves as a function of frequency.

Feldman and Katz (1978) investigated the effects of activating stimulus duration and interstimulus interval on the ART in 10 normal-hearing subjects and 10 subjects with mild sensorineural hearing loss of cochlear origin. The activating stimulus was a 1000-Hz pure tone with on-off times of

500-500 and 30-30 msec. Feldman and Katz found the same effect for both groups of subjects.

Investigators have suggested that the relation between the ART and the duration of the activator presents a potential area of exploration for the development of an objective site-of-lesion test. Korabic and Cudahy's (1984) study attempted to clarify the effect of stimulus duration on the contralateral ART for both normal and sensorineural ears. Three normal hearing and three sensorineural hearing loss individuals (22 to 33 years of age) were used as subjects. The criteria for the normal subjects were pure-tone thresholds less than or equal to 5 dB HL from 250 to 8000 Hz. For the sensorineural subjects, the pure-tone thresholds were less than or equal to 10 dB HL at 1000 Hz with an average loss at 2000, 3000, and 4000 Hz of at least 25 dB HL. The range in magnitude of loss at 3000 Hz was 20 to 40 dB HL. The ARTs were elicited by three stimuli (1000-Hz, 3000-Hz, and BBN) across six durations between 20 and 500 msec. The authors used both clinical methods and signal averaging. In order to observe the effect of criteria for establishing the threshold of the AR on the ART and ART temporal integration, the AR data were analyzed using three ART criteria: (a) baseline change threshold (BCT), defined as the lowest intensity resulting in a time-locked base-line shift in acoustic immittance in a positive or negative direction for an average of 16 presentations of the signal; (b) visual-detection threshold (VDT), defined as the lowest intensity resulting in a time-locked positive base-line shift in acoustic immittance for an average of 16 signal presentations; and (c) meter-change threshold (MCT), defined as the lowest intensity resulting in an observable time-locked positive deflection of the meter on the Madsen ZO-70.

In correspondence with the literature on temporal integration, Korabic and Cudahy (1984) found that the ART methods and definitions used have a notable influence on both ART and ART temporal integration for both normal and sensorineural hearing-impaired subjects. For example, for a 1000-Hz tonal activator of 20-msec duration, the median ART was 94 dB SPL using BCT, 100 dB SPL using VDT, and 105 dB SPL using MCT. Thus, the ART varies by as much as 11 dB, depending on ART methods and definition. In addition, as the duration of the activating stimulus decreases, the difference in the ART between the BCT and VDT methods, as well as the difference in ART between the BCT and MCT methods increases. The dependence of the ART on definition increases as the duration of the activating stimulus decreased, with the difference as great as 26 dB between definitions for a 20-msec activating stimulus. Korabic and Cudahy emphasize that "since the ART will vary depending on the definition of reflex threshold, and this effect is dependent on duration, it follows that reflex temporal integration measured at threshold will also vary depending on reflex threshold definition" (p. 335).

The VDT data of Korabic and Cudahy (1984) are in accord with the VDT data obtained by Jerger *et al.* (1977). It is of interest to note that the MCT results obtained by the former authors are not in agreement with those of Woodford *et al.* (1975) and Djupesland and Zwislocki (1971), who also employd the MCT method. Instrumentation differences may account for the discrepancies among these investigators.

Korabic and Cudahy's (1984) data also revealed a frequency effect. As frequency increases, the amount of ART temporal integration increases for MCT. This frequency effect previously was observed by Djupesland and Zwislocki (1971), Jerger *et al.* (1977), Morgan *et al.* (1977), and Woodford *et al.* (1975). Korabic and Cudahy noted little or no frequency effect on the ARTs elicited by BCT and VDT with respect to amount of temporal integration. As for the normal-hearing subjects, the individual and median ART data for the 1000- and 3000-Hz tonal activators from the sensorineural subjects revealed that the ART varies with definition. The smallest differences in ART between the normal and sensorineural hearing-impaired subjects were obtained with the BCT definition, whereas the largest differences in ART between the groups were obtained with the MCT definition. The sensorineural hearing-impaired subjects also demonstrated a frequency effect whereby the amount of ART temporal integration increases as activator frequency increases. The median results suggest that the sensorineural listeners have poorer ARTs than normal-hearing subjects, independent of the ART definition. Woodford *et al.* (1975) suggested that the amount of temporal integration for the ART is reduced in ears with sensorineural hearing loss of cochlear origin (sample size of 3 subjects). The ART data of Korabic and Cudahy (1984) using MCT are in agreement with those of Woodford *et al.* The ART results using VDT imply that the amount of temporal integration for ART for sensorineural subjects is somewhat greater than that for normal-hearing persons. The ART using BCT suggest small, if any, differences in amount of temporal integration for the ART between groups. However, these data must be interpreted with caution as they are based on a very small sample size (n = 3 for Korabic & Cudahy, 1984 and Woodford *et al.*, 1975). The absence of statistical power in the pathological subjects because of inadequate sample size makes it difficult to generalize from the data or to draw appropriate conclusions.

Korabic and Cudahy's (1984) also reported a lower ART for the BBN than tonal activator. This finding is in agreement with the literature (Djupesland & Zwislocki, 1973; Flottorp *et al.*, 1971; Margolis & Popelka, 1975; Popelka *et al.*, 1976; Silman, 1979; Silverman *et al.*, 1983). Moreover, the ARTs for the sensorineural subjects were elevated relative to those for the normal subjects, as reported by other investigators (Jerger *et al.*, 1974; Margolis & Fox, 1977; Popelka *et al.*, 1976; Silman *et al.*, 1978, 1984). For BBN activating stimuli, the amount of temporal integration of the ART was similar for both groups using VDT and MCT. But the amount of temporal integration for the ART using BCT did show a difference between groups. The greatest difference (19 dB) between groups was found for a BBN activator of 20-msec duration. The hearing-impaired group demonstrated a greater amount of temporal integration of the ART than the normal-hearing group.

Chapter 3

Methodology

1. Subjects

The subjects consisted of two groups of normal-hearing adults: one group of 20 young adults (10 men and 10 women between 18-29 years of age) and one group of 20 older adults (10 men and 10 women between 59-75 years of age).

All subjects in both groups met the following criteria: (a) air-conduction thresholds less than or equal to 20 dB HL at the octave frequencies from 250 Hz to 8000 Hz (ANSI, 1989); (b) bone-conduction thresholds (ANSI, 1981) from 250 Hz to 4000 Hz within 5 dB of the air-conduction thresholds; (c) tympanometric peak pressure within ± 50 daPa; (d) static-acoustic middle-ear admittance not less than 0.35 mmho (Jerger, 1970; Silman & Silverman, 1991); (e) contralateral acoustic reflexes present (for the 500-Hz, 1000-Hz and 2000-Hz tonal activators) within the 90th percentiles (Silman & Gelfand, 1981); (f) normal otoscopic findings; and (g) negative otologic and neurologic histories. (The subject informed consent form appears in Appendix B.)

Tables 2a and 2b show the means, ranges, and standard deviations for pure-tone thresholds for younger and older subjects, respectively. The individual data for hearing-threshold levels can be found in Appendix A.1.

The individual tympanometric peak pressures and static-acoustic middle-ear admittances are shown in Appendix A.2. The individual clinical ART data are shown in Appendix A.3.

Table 2a

Means, Ranges, and Standard Deviations (in dB HL)
for Pure-Tone Thresholds for Younger Subjects

		250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Right Ear	**Mean**	3.00	2.00	2.75	1.25	1.00	1.00
	Range	0-10	0-5	0-10	0-10	0-5	0-5
	SD	3.40	2.51	3.43	2.75	2.05	2.05
Left Ear	**Mean**	2.75	2.50	3.25	1.00	1.75	2.50
	Range	0-10	0-10	0-5	0-10	0-10	0-5
	SD	3.43	3.44	2.45	2.62	2.94	2.56

Table 2b

Means, Ranges, and Standard Deviations (in dB HL)
for Pure-Tone Thresholds for Older Subjects

		250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Right Ear	**Mean**	10.25	10.0	10.0	9.25	11.0	15.5
	Range	5-20	5-20	5-20	5-20	0-20	0-20
	SD	4.99	4.87	6.34	6.34	5.98	5.83
Left Ear	**Mean**	9.55	9.25	7.5	8.75	11.75	16.25
	Range	0-20	0-20	0-20	0-20	0-20	5-20
	SD	4.74	6.13	5.50	6.46	5.68	5.35

2. Procedure

The order of ear and activating stimulus tested was counterbalanced. The activating stimulus duration was randomized. Six seconds was selected as the inter-stimulus interval; Jerger and Oliver (1987) identified this inter-stimulus interval as optimal. The contralateral mode of activating signal presentation was employed whereby the earphone was placed on the test ear and the acoustic-admittance change was monitored in the contralateral ear with a digital strip-chart recorder. (Appendix C.1 illustrates the principle of operation of a linear array recorder.) The activating stimulus was presented below the expected ART and the intensity of the activating stimulus was increased in 1-dB increments until there was an observed, reliable ART. The ART was determined by visual inspection of the strip-chart recorder. Each response was considered as such if its pattern was distinguishable from background noise. The response was considered acceptable if it was repeatable over 3 trials at the same level (Silman, Popelka & Gelfand, 1978). See Figure 4 for an example of a typical subject's AR response.

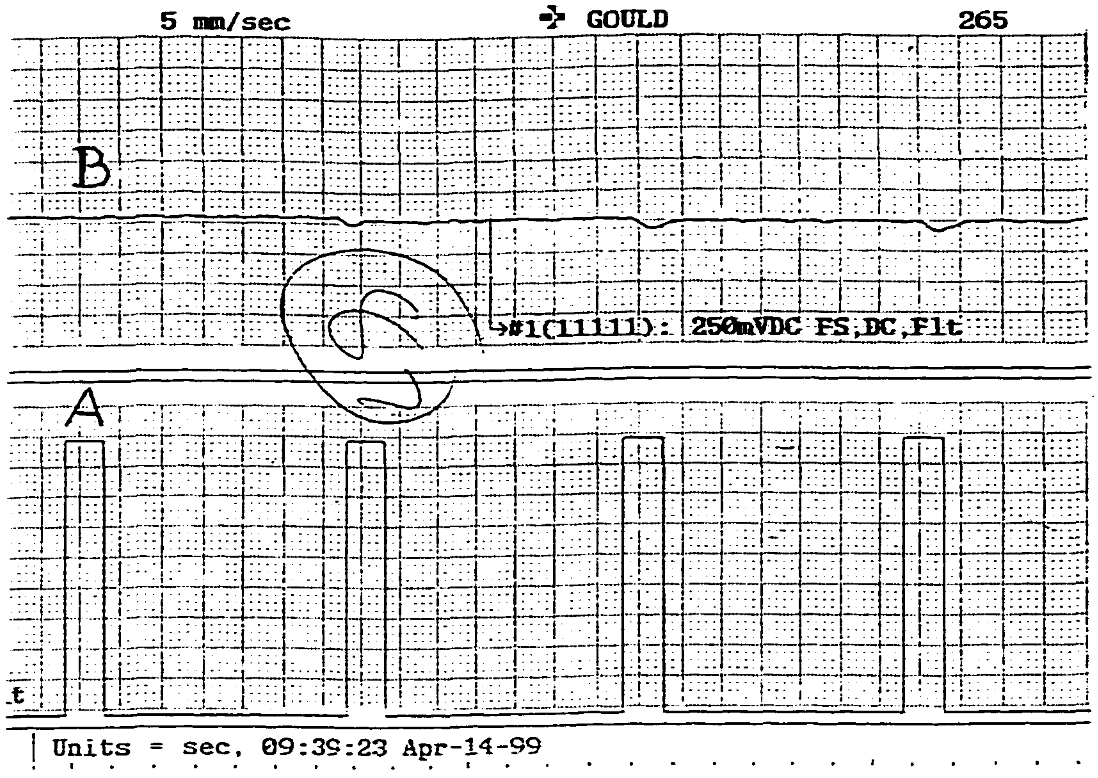


Figure 4. Example of a typical AR response. (A) shows the stimulus intensity and duration and (B) shows the acoustic-immittance change during AR activation.

3. Instrumentation and Calibration

See Appendix C.2 for a block diagram of instrumentation and set-up.

The air-conduction and bone-conduction thresholds were obtained in an IAC double-walled sound-treated booth (Acoustics Systems, Model 18997A). The air conduction pure-tone thresholds were obtained using a GS-16 audiometer with TDH-49 air-conduction transducers mounted in (MX-41AR) cushions. The bone-conduction thresholds were obtained with a Radioear (Model B-71) transducer.

Calibration for bone-conduction stimuli was done periodically, according to ANSI standards (1989), with biologic checks prior to each test session. The air-conduction signals were calibrated using a digital sound-level meter (Quest Model OB-300) with a third-octave band analyzer, condenser microphone, 6-cm^3 coupler (NBS 9-A), 500-gm weight, and frequency counter (Quest Audiometer Analyzer, Model AA-175). All sound-pressure level (SPL) values are in dB re: 2×10^{-5} N/m^2. The air-conduction signals for a TDH-49 earphone met ANSI specifications (S3.6-1989) (see Appendix D.1, which shows the results for a typical calibration). The total harmonic distortion and rise and fall times of the signal met ANSI (S3.6-1989) specifications. Each frequency of the diagnostic audiometer was found to be within 3% of the nominal frequency, according to ANSI (S3.6-1989) (see Appendix D.2). The attenuator linearity also met ANSI (S3.6-1989) specifications. The ambient noise inside the audiometric sound-treated suite did not exceed the levels specified in ANSI 1977 (R1986).

Measurement of the latency of the acoustic-immittance device (GS-1723) was done using the procedure described by Silman and Gelfand (1982) involving measurement of the first detectable acoustic-immittance change in a cavity. The latency of the electroacoustic immittance device is defined as "the time from stimulus onset to the first detectable immittance change" (p.126). The latency was established to be 12 msec, consistent with other commercially available devices.

The acoustic-immittance measurements and temporal integration for the AR were measured in a laboratory. This laboratory was found to be adequately quiet for those procedures as indicated by the 1/3 octave-band measurements of ambient noise made with the digital sound-level meter (linear weighting). The ambient noise level at 1000 Hz was 40.4 dB SPL, far below the level that might elicit the AR. In addition, attenuation by the earphone was approximately 20 dB, further reducing any ambient noise reaching the ear. The overall intensity of the ambient noise in the laboratory, using the C-weighting scale, was 64.7 dB SPL. Again, when considering the additional attenuation of about 20 dB for the earphone, the noise in the room was much below the levels that could evoke the AR.

The activating stimuli consisted of a 1000-Hz pure tone and a BBN signal. A 1000-Hz tonal activator was selected because it is less likely to be affected by adaptation than higher-frequency activators (Wilson, Shanks, & Lilly, 1984). A BBN activator was employed because BBN activators are employed in prediction of hearing impairment from the ART and BBN signals frequently show aging effects prior to tonal signals.

The 1000-Hz signal was generated by a signal generator (Model S 81-06) and the BBN signal was generated by a white-noise generator (Model S 81-02). Each signal was routed first into a programmable attenuator (S 85-08) and up-down counter (S 41-28), for control of intensity. The output of the up-down counter was directed to the electronic switch (S 84-04) that controlled the rise and fall of the stimulus (3 msec rise/fall). The signal from the electronic switch was directed into an S 82-24 amplifier, the electrical output of which was routed to a TDH-49 transducer (encased in a Telephonics Corp. P/N 510C017-1 cushion) that delivered the activating signal. The activating stimulus duration and inter-stimulus interval were controlled by the timers (Universal C 53-21 and S 53-21), that controlled the on-off cycle of the electronic switch.

The acoustic-admittance change for the 220-Hz probe tone was monitored with an electroacoustic immittance device (GSI 1723 Middle Ear Analyzer) connected to one channel of a two-channel digital strip-chart recorder (Gould-Easy Graf TA 240 Strip Chart Recorder with a resolution of 5000 Hz). The second channel of the recorder was used as an event marker and was controlled by the Coulbourn computer output (Model S 62-06). The decision to use a digital strip-chart recorder for recording the response was based upon the observation of many investigators that the range of ART values between and among studies is narrowest when using this device (see the review of literature and Gelfand, 1984).

The activating signals were calibrated in a digital sound-level meter (Quest Model OB-300) with a coupler (Model EC-9A) and frequency counter (Quest AA-175). All sound-pressure level (SPL) values are in dB re 2×10^{-5} N/m^2.

In order to account for the time constant of the sound-level meter for short-duration signals, the following procedure was performed: First, the intensity was measured for a signal duration of over 60 seconds using the Fast mode; its value in SPL was recorded and its voltage value was noted on the oscilloscope (Model 510 3N Tektronix). Next, the SPL was measured for each of the eight durations (12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec). The difference between the recorded SPL at a specified short duration and the SPL at 60 seconds was measured for each of the short-duration stimuli. These differences were assumed to reflect the time-constant of the sound-level meter and were then added as a correction factor. Figure 5a indicates the manufacturer's values for the relation between signal duration and intensity. Figures 5b and 5c show the intensity values obtained at each duration during the aforementioned calibration) for a 1000-Hz signal and BBN signal, respectively. Note the high degree of similarity between the manufacturer's values and the values obtained from our calibration. Therefore, based on these results, we judged the calibration of the duration of the stimulus activator to the relative response in the SLM to be reliable.

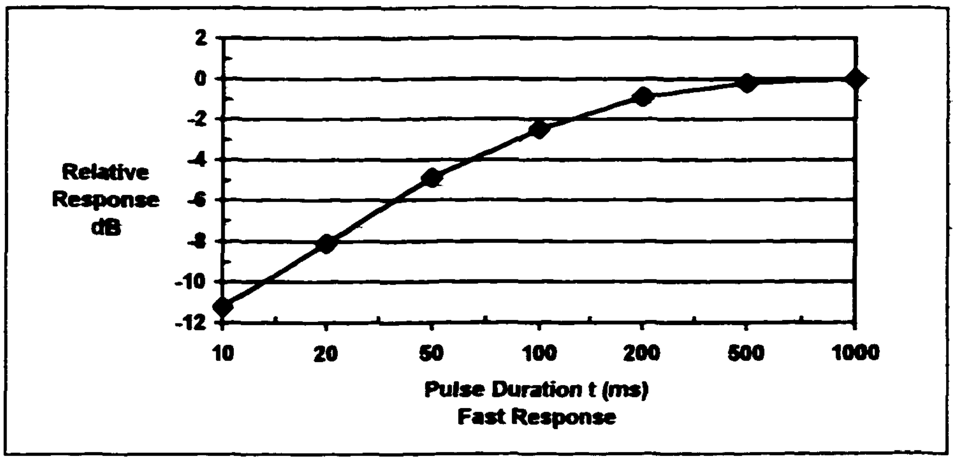


Figure 5a. Manufacturer-determined relation between the duration of the stimulus activator and relative response in dB (adapted from Quest manual).

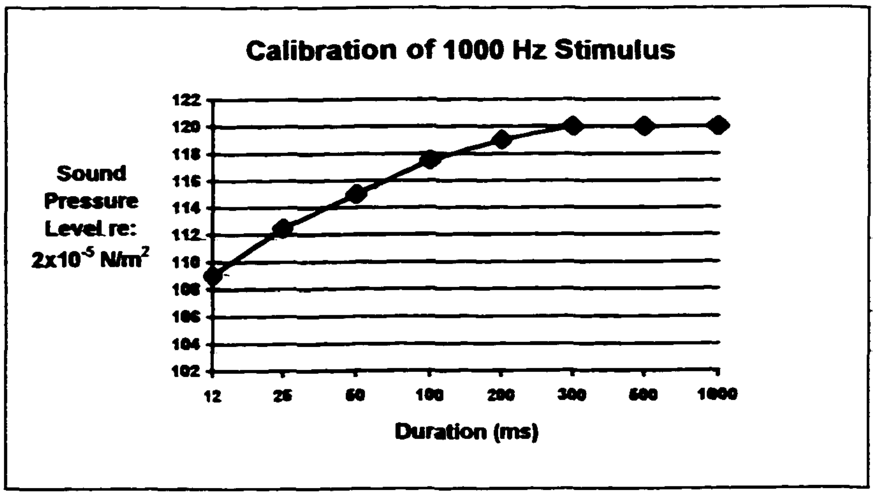


Figure 5b. The relation between the duration of a 1000-Hz stimulus activator and intensity (dB SPL) based on our calibration.

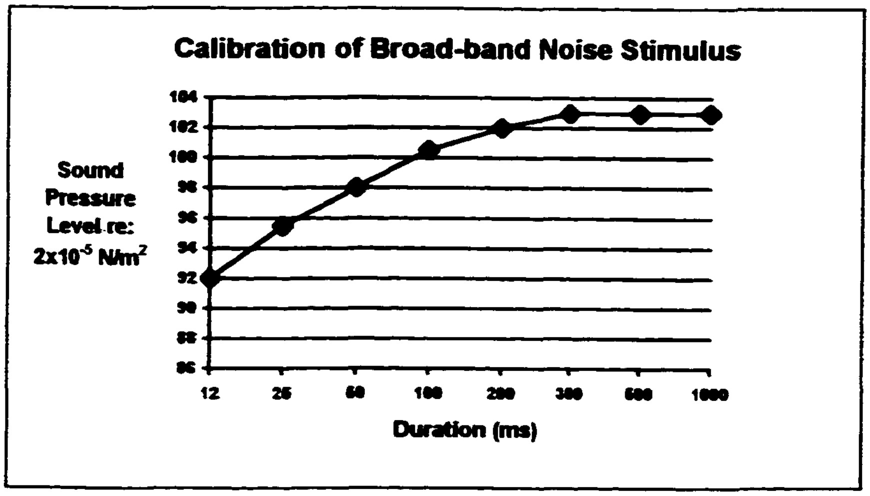


Figure 5c. The relation between the duration of a BBN stimulus activator and intensity (dB SPL) based on our calibration.

The acoustic-admittance device was calibrated to a standard volume of 2 ml for static-acoustic admittance. The sensitivity of meter deflection during AR set to full scale of 0.5 ml (which recorded a full deflection) was equal to 0.5 ml, as specified by the manufacturer. This calibration was confirmed by coupling the probe assembly to a microsyringe (Gilmont Model S1200) set to a full-scale deflection of 0.5 ml. Such calibration insures that any meter deflection will correspond with the values (in μl) indicated in the manufacturer's instrument manuals and in our own calibration.

Duration, inter-stimulus interval, and rise and fall times of the experimental stimuli, controlled by the electronic switches (S 84-04) and timers (C 53-21 and S 53-21), were checked by a B&K Precision Dynascan 20 MHz digital storage oscilloscope (Model 2520). The rise and fall times also were calibrated using the Quest Audiometer Analyzer (Model AA-175). Bandwidth was measured at the ½ power points as viewed on the Hewlett Packard Spectrum Real-Time Analyzer (Model 3582A). The 1000-Hz tonal activating stimulus (12-msec duration) exhibited a bandwidth of 120 Hz (60 Hz on each side of the center frequency). The first lobe was noted to be well below 30 dB on each side of the center. This insured that spectral splatter had a limited effect on the measurement of the ART. At 999 msec duration, the intensities of second and third harmonics were more than 30 dB below that of the first harmonic.

The spectral analysis of the signals was done acoustically in the following manner: The output from the amplifier was routed to the TDH-49 earphone coupled with a 6-cc coupler (Quest – Model EC-9A) to the digital sound-level meter (Quest Model OB-300). The AC output of the sound-level meter was routed to the Hewlett Packard Spectrum Analyzer (Model 3582A). Spectral analysis of the BBN activating signal was accomplished in the same manner as that for the 1000-Hz stimulus. A uniform spectrum was indicated up to approximately 6,280 Hz, the 3-dB down point, at which frequency rollover of approximately 20 dB/octave continued until 10,000 Hz. This was the case for both the 1000- and 12-msec activating signal durations. The frequency response of the TDH-49 earphone was measured and is shown in Appendix D.3. Initial calibration of the experimental stimulus also included measurement of attenuator linearity.

4. Statistical Design and Data Analysis

In order to investigate subproblems 1 and 2, a two-factor design with repeated measures on the second factor was used. The dependent variables were the ART for a BBN activator and ART for a 1000-Hz tonal activator at a specified duration.

The analysis of variance design took the following form:

Source of Variation	SS	*df*	MS	F	*p*
Between Subjects Age (Young vs Older) Error (1)					
Within Subjects Duration Age x Duration Error (2)					

The independent variables were age (young versus older) and activating signal duration (eight durations)

Furthermore, for subproblems 1 and 2, an analysis of trend was made for the best fit polynomial to the relation (linear, cubic, quadratic) between the ARTs and signal duration for both groups.

The data for subproblem 3 resulted from the simple subtraction (NTD) of the BBN ART from the tonal ART in the young and older groups at each duration

In order to investigate subproblem 4, descriptive statistics (mean, mode, median, standard deviation, standard error of the mean, range, skewness, minimum value, maximum value) were obtained for each signal at each duration, for each group.

Power Analysis

The design used in this study was a two-factor design with repeated measures on the second factor. The data collection took the following form:

DURATION

	Subjects	12	25	50	100	200	300	500	1000
Younger	1 . . . . N								
Older	1 . . . . N								

The between-subjects factor was age (younger versus older adults) and the within-subjects factor was activator duration (repeated measures).

Using Cohen's table (8.3.12), the required sample size for a power of 0.80 and effect size of 0.60, is 20 younger subjects and 20 older subjects, yielding a total of 40 subjects.

The power analysis table took the following form:

Source of Variation	***df***	**Effect Size**	**Power**
Between Subjects			
Age (Young vs Older)	1	0.60	0.80
Error (1)	22		
Within Subjects			
Duration	7	0.65	0.80
Age x Duration	7		
Error (2)	154		

The within-subjects effect size and power are provided by formulas given in Cohen (1988) and using table 8.3.17. The effective sample size is given by formula (8.3.4)

$$n' = \frac{\text{denominator } df}{u+1} + 1$$

and is equal to 20. With a power of 0.80, the moderate effect size is equal to approximately 0.65.

Chapter 4

Results

This study addressed four subproblems relative to temporal integration of the acoustic-reflex threshold and its age-related changes. These included: (a) the investigation of whether temporal integration of the BBN ART in the older subjects differs from that in the younger subjects; (b) the investigation of whether temporal integration of the 1000-Hz ART in the older subjects differs from that in the younger subjects; (c) the investigation of whether the NTD in the older subjects differs from that in the younger subjects; and (d) the description of the characteristics of temporal integration of the ART in the younger vs. older adult subjects.

The data were analyzed using the *General Linear Models* statistical package, which is part of the *Statistical Package for the Social Sciences*.

Analysis of Subproblem 1: The investigation of whether temporal integration of the BBN ART in the older subjects differs from that in the younger subjects at the following activator durations: 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec.

The data were analyzed using a repeated measures analysis of covariance. The between-subjects factor was age and the within-subjects factor was BBN activator duration. The fixed, or "constant" covariate was hearing threshold level at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz). For this subproblem, it was preferable to use the multivariate design supplemented by the more conservative corrected univariate Greenhouse-Geisser procedure. Because the within-subjects factor in this subproblem has more than two levels (there are eight durations) certain symmetry conditions, or assumptions, are made. If these assumptions are violated, the statistical results for the univariate test (the Greenhouse-Geisser) are too likely to yield significant results.

In order to test for symmetry conditions, we used the following two tests: Box's Test of Equality of Covariance Matrices and Mauchly's Test of Sphericity. Box's Test of Equality determines whether the correlation between the two age groups, i.e., between the younger and older subjects, is equal. Mauchly's Test of Sphericity investigates the existence of a significant correlation within the pooled group of subjects. The results of Box's Test (see Table 3) were significant ($p = .043$) suggesting a lack of correlation between the groups. Mauchly's Test of Sphericity indicated significance ($p = 0.000$) suggesting absence of correlation within the pooled group (see Table 4). The latter result violated the condition of symmetry; therefore, the analysis of subproblem 1 depended largely on the multivariate design which does not rely on the symmetry condition.

Table 3

Box's Test of Equality of Covariance Matrices

Box's M	67.164
F	1.440
df1	36
df2	4859
Sig.	0.043

Table 4

Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	Df	Sig.
DURATION	0.008	165.038	27	0.000

Inspection of the multivariate results for this subproblem (see Table 5) indicates a significant main effect (p = 0.000) for duration, the within-subjects variable. That is, as the activator duration increases, the BBN ART decreases. Figure 6 (the within-group estimated marginal means) indicates this effect, i.e., as duration increases, ART for BBN decreases for both groups. For example, the BBN ART at 12 msec is approximately 114 dB SPL whereas it decreased to about 91 dB SPL at 1000 msec. Further perusal of Table 5 reveals the absence of a significant interaction effect for duration x age (p = 0.264). Inspection of Table 6 (tests of between-subjects effects) reveals a significant main effect (p = 0.041) for age. That is, threshold for the younger group is significantly different from threshold for

Table 5

Multivariate Tests for Subproblem 1
Temporal Integration for the ART
for the BBN Activator

Effect		Value	F	Hypothesis df	Error df	Sig.
DURATION	Pillai's Trace	.716	11.162	7.000	31.000	.000
	Wilks' Lambda	.284	11.162	7.000	31.000	.000
	Hotelling's Trace	2.521	11.162	7.000	31.000	.000
	Roy's Largest Root	2.521	11.162	7.000	31.000	.000
DURATION * HEARING LEVEL	Pillai's Trace	.115	.576	7.000	31.000	.770
	Wilks' Lambda	.885	.576	7.000	31.000	.770
	Hotelling's Trace	.130	.576	7.000	31.000	.770
	Roy's Largest Root	.130	.576	7.000	31.000	.770
DURATION * AGEGROUP	Pillai's Trace	.233	1.344	7.000	31.000	.264
	Wilks' Lambda	.767	1.344	7.000	31.000	.264
	Hotelling's Trace	.303	1.344	7.000	31.000	.264
	Roy's Largest Root	.303	1.344	7.000	31.000	.264

the older group (see Figure 7). Because the curves for the two groups appear to be visually different, we opted to apply the Greenhouse-Geisser procedure (the univariate procedure which is stronger than the multivariate test and whose results are generally used to substantiate the multivariate) in order to test for an interaction between duration and age group. Note the significant interaction (p = 0.019) in Table 7.

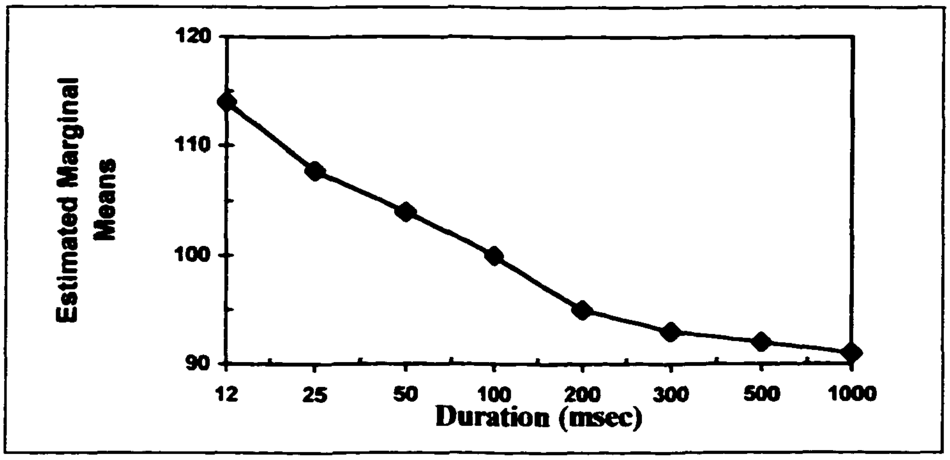


Figure 6. Within Group Estimated Marginal Means of Response for Subproblem 1

An examination of the polynomial trends for the duration effect reveals an essentially linear effect based on the Type III Sum of Squares (see Table 8 and Figure 7. (For individual BBN ART data for both groups and all durations, see Appendix A.8)

Table 6

Tests of Between-Subjects Effect for Subproblem 1
Temporal Integration for the BBN ART

Source	Type III Sum Of Squares	df	Mean Square	F	Sig.
Intercept	385334.504	1	385334.504	1044.246	.000
HearingLevel	779.709	1	779.709	2.113	.154
AGEGROUP	1663.145	1	1663.145	4.507	.041
Error	13653.275	37	369.007		

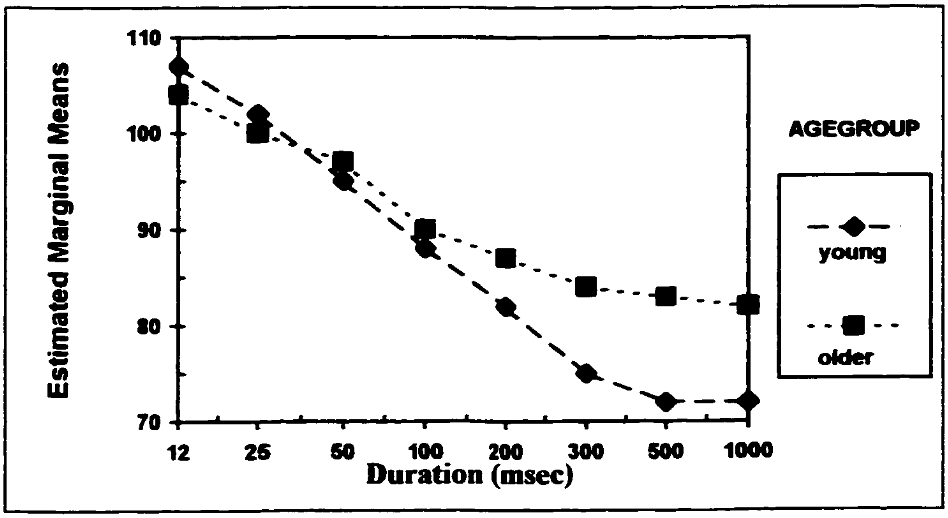


Figure 7. Estimated Marginal Means of Response for Subproblem 1

Table 7

Tests of Within-Subjects Effects
for Subproblem 1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
DURATION	Sphericity Assumed	4089.438	7	584.205	34.146	.000
	Greenhouse-Geisser	4089.438	2.938	1391.911	34.146	.000
	Huynh-Feldt	4089.438	3.391	1205.803	34.146	.000
	Lower-bound	4089.438	1.000	4089.438	34.146	.000
DURATION*HRNGLEVEL	Sphericity Assumed	45.038	7	6.434	.376	.916
	Greenhouse-Geisser	45.038	2.938	15.329	.376	.766
	Huynh-Feldt	45.038	3.391	13.280	.376	.794
	Lower-Bound	45.038	1.000	45.038	.376	.543
DURATION*AGEGROUP	Sphericity Assumed	415.842	7	59.406	3.472	.001
	Greenhouse-Geisser	415.842	2.938	141.539	3.472	.019
	Huynh-Feldt	415.842	3.391	122.614	3.472	.014
	Lower-Bound	415.842	1.000	415.842	3.472	.070
Error(DURATION)	Sphericity Assumed	4431.178	259	17.109		
	Greenhouse-Geisser	4431.178	108.706	40.763		
	Huynh-Feldt	4431.178	125.484	35.313		
	Lower-Bound	4431.178	37.000	119.762		

Table 8

Tests of Within-Subjects Contrasts for Subproblem 1
(Decomposition of the Duration Effect
into Constituent Polynomial Trends)

Source	Duration	Type III Sum of Squares	df	Mean Square	F	Sig.
DURATION	Linear	2547.696		2547.696	61.258	.000
	Quadratic	1273.340		1273.340	54.918	.000
	Cubic	201.012		201.012	15.719	.000
	Order 4	31.718		31.718	2.315	.137
	Order 5	10.035		10.035	.828	.369
	Order 6	14.053		14.053	1.734	.196
	Order 7	11.585		11.585	1.401	.244
DURATION*HEARINGLEVEL	Linear	.169	1	.169	.004	.950
	Quadratic	8.616	1	8.616	.372	.546
	Cubic	10.914	1	10.914	.853	.362
	Order 4	3.215	1	3.215	.235	.631
	Order 5	12.717	1	12.717	1.049	.312
	Order 6	3.491	1	3.491	.431	.516
	Order 7	5.916	1	5.916	.716	.403
DURATION*AGEGROUP	Linear	220.935	1	220.935	5.312	.027
	Quadratic	157.496	1	157.496	6.793	.013
	Cubic	16.454	1	16.454	1.287	.264
	Order 4	.175	1	.175	.013	.911
	Order5	12.342	1	12.342	1.018	.320
	Order 6	.166	1	.166	.020	.887
	Order 7	8.274	1	8.274	1.001	.324
Error(DURATION)	Linear	1538.806	37	41.589		
	Quadratic	857.885	37	23.186		
	Cubic	473.155	37	12.788		
	Order 4	507.005	37	13.703		
	Order 5	448.569	37	12.123		
	Order 6	299.907	37	8.106		
	Order 7	305.851	37	8.266		

Analysis of Subproblem 2: The investigation of whether temporal integration of the 1000-Hz tonal ART in the older subjects differs from that in the younger subjects for the following durations: 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec.

The data were analyzed using a repeated measures analysis of covariance. The between-subjects factor was age and the within-subjects factor was tonal-activator duration. The fixed, or "constant" covariate was hearing-threshold level at 1000 Hz. The multivariate design supplemented by the more conservative corrected univariate Greenhouse-Geisser procedure was employed. Because the within-subjects factor in this subproblem has more than two levels (there are eight durations), certain symmetry conditions, or assumptions, are made. If these assumptions are violated, the statistical results for the univariate test (the Greenhouse-Geisser) are too likely to yield significant results.

In order to test for symmetry conditions, we used the following two tests: Box's Test of Equality of Covariance Matrices and Mauchly's Test of Sphericity. Box's Test of Equality determines whether the correlation between the two age groups, i.e., between the younger and older subjects, is equal. Mauchly's Test of Sphericity investigates the existence of a significant correlation within the pooled group of subjects. The results of Box's Test (see Table 9) revealed a lack of significance ($p = 0.283$) suggesting a correlation between the groups. On the other hand, Mauchly's

Test of Sphericity indicated significance (p = 0.000) suggesting absence of correlation within the pooled group (see Table 10). The latter result violated the condition of symmetry. Therefore, analysis of subproblem 2 depended largely on the multivariate design, which does not depend on the symmetry condition.

Table 9

Box's Test of Equality of Covariance Matrices

Box's M	52.333
F	1.122
df1	36
df2	4859
Sig.	0.283

Table 10

Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	Df	Sig.
DURATION	.006	175.396	27	.000

The results of multivariate testing indicate a significant main effect (p = 0.000) for the within-subjects factor of duration, (see Table 11) and a non-significant main effect (p = .889) for the between-subjects factor of age, (see Table 12). As Table 11 shows, no significant interactions involving the within-subjects factor of duration occurred.

Table 11

Multivariate Tests for Subproblem 2

Effect		Value	F	Hypothesis df	Error df	Sig.
DURATION	Pillai's Trace	.883	33.343	7.000	31.000	.000
	Wilks' Lambda	.117	33.343	7.000	31.000	.000
	Hotelling's Trace	7.529	33.343	7.000	31.000	.000
	Roy's Largest Root	7.529	33.343	7.000	31.000	.000
DURATION * HEARINGLEVEL	Pillai's Trace	.083	.403	7.000	31.000	.893
	Wilks' Lambda	.917	.403	7.000	31.000	.893
	Hotelling's Trace	.091	.403	7.000	31.000	.893
	Roy's Largest Root	.091	.403	7.000	31.000	.893
DURATION *AGEGROUP	Pillai's Trace	.192	1.051	7.000	31.000	.417
	Wilk's Lambda	.808	1.051	7.000	31.000	.417
	Hotelling's Trace	.237	1.051	7.000	31.000	.417
	Roy's Largest Root	.237	1.051	7.000	31.000	.417

Table 12

Tests of Between-Subjects Effect for Subproblem 2
Temporal Integration for the 1000-Hz tonal ART

Source	Type III Sum Of Squares	df	Mean Square	F	Sig.
Intercept	1445973.573	1	1445973.573	4137.370	0.000
HearingLevel	1015.312	1	1015.312	2.905	0.097
AGEGROUP	6.960	1	6.960	0.020	0.889
Error	12931.167	37	349.491		

An examination of the polynomial trends for the duration effect (see Table 13) reveals that the linear and quadratic trends account for greater than 87% of the variance in the duration effect (4233.09 + 2231.05/7397.66 = 87%). However, it seems reasonable to characterize the duration effect as essentially linear, based on the Type III Sum of Squares indicated in this table (see also Figure 8). For the individual 1000-Hz tonal ART for both groups and all durations, see Appendix A.9).

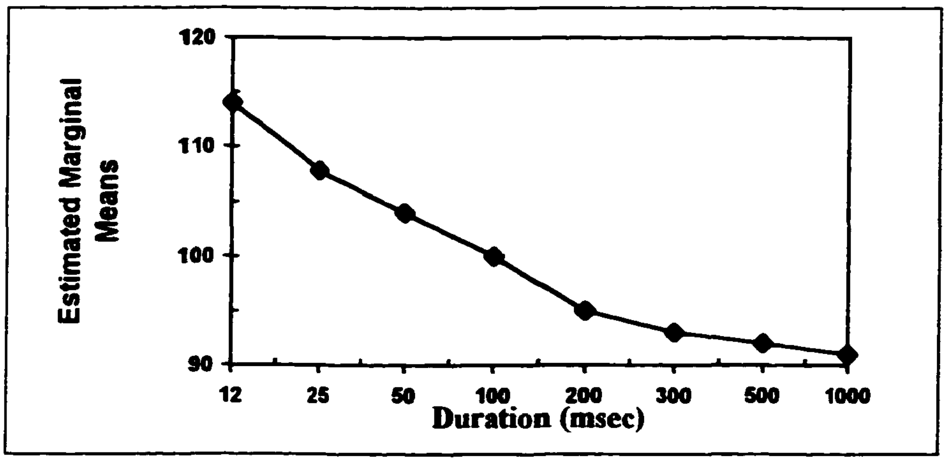


Figure 8. Estimated Marginal Means of Response for Subproblem 2

Table 13

Tests of Within-Subjects Contrasts for Subproblem 2
(Decomposition of the Duration Effect
into Constituent Polynomial Trends)

Source	Duration	Type III Sum of Squares	df	Mean Square	F	Sig.
DURATION	Linear	4233,088	1	4233,088	154,927	,000
	Quadratic	2231,050	1	2231,050	116,884	,000
	Cubic	602,696	1	602,696	51,477	,000
	Order 4	156,730	1	156,730	13,561	,001
	Order 5	103,300	1	103,300	13,717	,001
	Order 6	63,504	1	63,504	15,733	,000
	Order 7	7,294	1	7,294	1,172	,286
DURATION*HEARINGLEVEL	Linear	21,835	1	21,835	,799	,377
	Quadratic	33,158	1	33,158	1,737	,196
	Cubic	11,959	1	11,959	1,021	,319
	Order 4	3,397	1	3,397	,294	,591
	Order 5	,595	1	,595	,079	,780
	Order 6	1,063	1	1,063	,263	,611
	Order 7	1,456E-02	1	1,456E-03	,002	,962
DURATION*AGEGROUP	Linear	,939	1	,939	,034	,854
	Quadratic	59,863	1	59,863	3,136	,085
	Cubic	50,635	1	50,635	4,325	,045
	Order 4	22,067	1	22,067	1,909	,175
	Order5	2,360	1	2,360	,313	,579
	Order 6	6,879E-03	1	6,879E-03	,002	,967
	Order 7	2,049	1	2,049	,329	,570
Error(DURATION)	Linear	1010,955	37	27,323		
	Quadratic	706,247	37	19,088		
	Cubic	433,200	37	11,708		
	Order 4	427,633	37	11,558		
	Order 5	278,641	37	7,531		
	Order 6	149,350	37	4,036		
	Order 7	230,259	37	6,223		

Analysis of Subproblem 3: The investigation of whether the NTD in the older subjects differs from that in the younger subjects.

This subproblem has the same design structure but not the same dependent variable as in subproblems 1 and 2. The dependent variable in subproblem 3 is the simple difference between the tonal ART and BBN ART at each activator duration. Inspection of the multivariate results (see Table 14) for the within-subjects factor suggests the absence of any main effect or interaction. Inspection of the results of the "Tests of Within-Subject Contrasts" (see Table 15) finds no trend to the data through the 7th order polynomial. Examination of the data in Table 16 (tests of between-subjects effects) reveals that neither age group nor the covariate, hearing threshold level, is statistically significant.

In summary, the results of this analysis indicate the absence of main effects or interactions. Therefore, the degree of difference between the tonal and BBN ARTs does not appear to be systematically related to age, activator duration, the interaction of age and duration, the covariate, or the interaction of the covariate with either age or duration.

Table 14

Multivariate Tests for Subproblem 3

Effect		Value	F	Hypothesis df	Error df	Sig.
DURATION	Pillai's Trace	.129	.655	7.000	31.000	.707
	Wilks' Lambda	.871	.655	7.000	31.000	.707
	Hotelling's Trace	.148	.655	7.000	31.000	.707
	Roy's Largest Root	.148	.655	7.000	31.000	.707
DURATION * HEARINGLEVEL	Pillai's Trace	.066	.315	7.000	31.000	.942
	Wilks' Lambda	.934	.315	7.000	31.000	.942
	Hotelling's Trace	.071	.315	7.000	31.000	.942
	Roy's Largest Root	.071	.315	7.000	31.000	.942
DURATION *AGEGROUP	Pillai's Trace	.171	.916	7.000	31.000	.507
	Wilk's Lambda	.829	.916	7.000	31.000	.507
	Hotelling's Trace	.207	.916	7.000	31.000	.507
	Roy's Largest Root	.207	.916	7.000	31.000	.507

Table 15

Tests of Within-Subjects Contrasts for Subproblem 3
(Decomposition of the Duration Effect
into Constituent Polynomial Trends)

Source	Duration	Type III Sum of Squares	df	Mean Square	F	Sig.
DURATION	Linear	206.017	1	206.017	3.232	.080
	Quadratic	152.062	1	152.062	3.023	.090
	Cubic	3.478	1	3.478	.131	.719
	Order 4	2.101	1	2.101	.118	.733
	Order 5	24.620	1	24.620	1.616	.212
	Order 6	10.697	1	10.697	1.086	.304
	Order 7	1.023	1	1.023	.065	.800
DURATION*HEARINGLEVEL	Linear	6.505	1	6.505	.102	.751
	Quadratic	11.540	1	11.540	.229	.635
	Cubic	1.633E-04	1	1.633E-04	.000	.998
	Order 4	.864	1	.864	.049	.827
	Order 5	33.224	1	33.224	2.181	.145
	Order 6	1.699	1	1.699	.172	.680
	Order 7	2.432	1	2.432	.154	.697
DURATION*AGEGROUP	Linear	168.271	1	168.271	2.640	.113
	Quadratic	17.882	1	17.882	.355	.555
	Cubic	3.600	1	3.600	.136	.715
	Order 4	6.119	1	6.119	.344	.561
	Order5	22.743	1	22.743	1.493	.230
	Order 6	4.527	1	4.527	.459	.502
	Order 7	1.653	1	1.653	.105	.748
Error(DURATION)	Linear	2358.397	37	63.740		
	Quadratic	1861.371	37	50.307		
	Cubic	982.409	37	26.552		
	Order 4	657.795	37	17.778		
	Order 5	563.766	37	15.237		
	Order 6	364.603	37	9.854		
	Order 7	582.840	37	15.752		

Table 16

Tests of Between-Subjects Effect on the for Subproblem 3

Source	Type III Sum Of Squares	df	Mean Square	F	Sig.
Intercept	7212.967	1	7212.967	30.969	.000
HearingLevel	163.818	1	163.818	.703	.407
AGEGROUP	149.887	1	149.887	.644	.428
Error	8617.749	37	232.912		

Analysis of Subproblem 4: The description of the characteristics of temporal integration of the BBN and tonal ARTs in both normal-hearing younger and normal-hearing older adult subjects.

As the results for subproblems 1 and 2 have revealed, an age effect exists for the BBN ART, but not for the 1000-Hz tonal ART. In view of the absence of an age effect on the tonal ART, and the presence of very similar tonal ART values for both groups, the data for temporal integration of the tonal ART were collapsed across both age and duration. Table 17 presents the pooled sample for the tonal activator (see Appendices A.4, A.5 for the unpooled tonal ARTs). The pooled sample shows the mean, standard error of mean, median, mode, standard error of the mean, standard deviation, skewness, range, minimum and maximum values. Two observations regarding these pooled data are worth noting: first, the inverse relationship between duration and tonal ART for the tonal activator is consistent with the literature (Djupesland & Zwislocki, 1971; Djupesland *et al.*, 1973; Gelfand *et al.*, 1981; Jerger *et al.*, 1977; Woodford *et al.*, 1975); secondly, the small

Table 17

Pooled Sample for Subproblem 4
Tonal Activator

Statistics

		TMS12	TMS25	TMS50	TMS100	TMS200	TMS300	TMS500	TMS1000
N	Valid	40	40	40	40	40	40	40	40
	Missing	0	0	0	0	0	0	0	0
Mean		114.4625	108.8750	104.3125	100.5000	96.2500	93.4875	92.3875	91.6625
Std. Error of Mean		1.0578	1.2047	1.2045	1.3290	1.2644	1.1731	1.1470	1.0815
Median		116.5000	110.2500	105.2500	101.0000	96.0000	93.5000	92.0000	92.0000
Mode		121.00	114.00	92.00	101.00	86.00	93.00	95.00	93.00
Std. Deviation		6.6904	7.6189	7.6180	8.4056	7.9968	7.4192	7.2541	6.8401
Skewness		-1.293	-.709	-.271	-.082	-.063	.159	.094	-.096
Range		25.00	29.00	28.00	33.00	30.00	33.00	35.00	31.00
Minimum		96.00	92.00	90.00	83.00	80.00	78.00	75.00	75.00
Maximum		121.00	121.00	118.00	116.00	110.00	111.00	110.00	106.00

variability of these data is a finding which runs counter to the results of the majority of previous studies (Barry & Resnick, 1976; Singh & Greenberg, 1976; Woodford *et al.*, 1975; Feldman & Katz, 1978; Korabic & Cudahy, 1984), which showed large variability in temporal integration of the tonal ART. The small variability is demonstrated by the closeness of the mean, median, and mode, the small standard error of mean, and is also demonstrated by the skewness, which approximates a normal distribution. The 95% confidence intervals for the pooled data for the tonal ART (see Figure 9) reveal a small standard deviation across all activator durations. (See Appendices A.6, A.7 for unpooled 95% confidence intervals for younger and older subjects).

The finding of a significant age effect as well as the notable interaction between duration and age for the BBN ART necessitated the generation of separate data for the younger and older subjects. See Tables 18 and 19 for descriptive statistics for younger and older subjects for the BBN ART. As was the case for the tonal ART, the mean, mode, median, and the skewness suggest small variability and a normal distribution throughout the durations. Observe too, the 95% confidence intervals in Figures 10 and 11 for the BBN ART again presented separately for the younger and older subjects; here again, variability is small and similar.

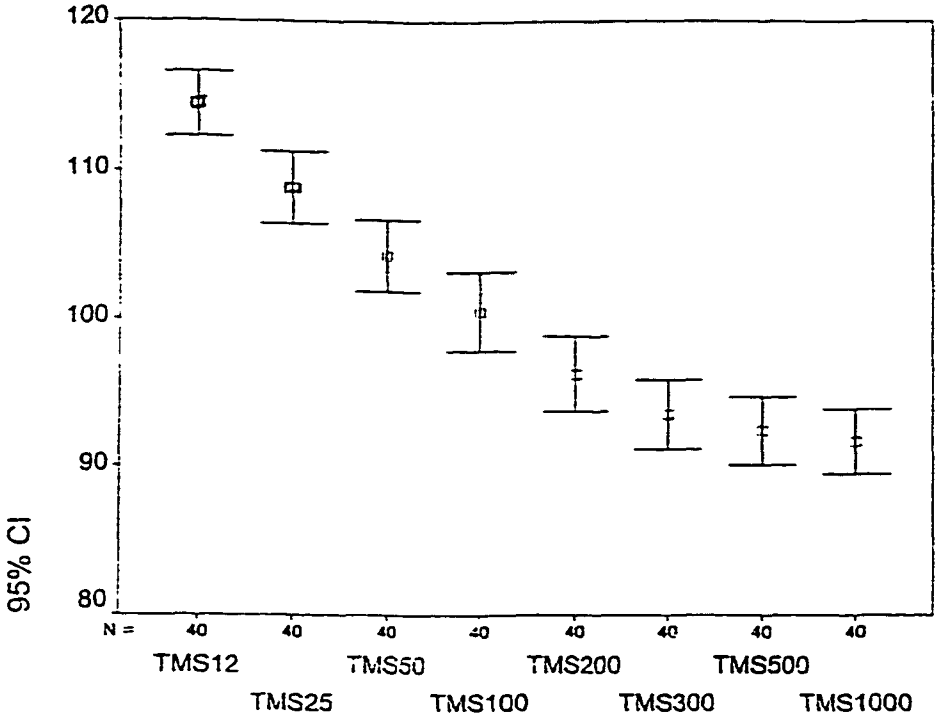


Figure 9. 95% Confidence Intervals for Pooled Data for the 1000-Hz Tonal Activator

Table 18

Descriptive Statistics for Younger Subjects for Subproblem 4 for BBN Activator

		BMS12	BMS25	BMS50	BMS100	BMS200	BMS300	BMS500	BMS1000
N	Valid	20	20	20	20	20	20	20	20
	Missing	0	0	0	0	0	0	0	0
Mean		106.7000	101.3500	95.3000	89.4500	82.3000	76.3500	73.9000	73.9250
Std. Error of Mean		2.0855	2.1102	1.9268	2.2085	1.8593	2.0743	1.5384	1.6272
Median		109.5000	101.5000	96.0000	89.5000	82.0000	74.5000	74.5000	74.7500
Mode		115.00	98.00	104.00	87.00	81.00	73.00	76.00	78.00
Std. Deviation		9.3265	9.4369	8.6167	9.8767	8.3152	9.2766	6.8798	7.2770
Skewness		-1.060	-.119	-.541	-.303	-.509	.475	.201	.204
Range		31.00	32.00	29.00	38.00	34.00	36.00	27.00	29.00
Minimum		84.00	83.00	79.00	68.00	63.00	61.00	62.00	61.00
Maximum		115.00	115.00	108.00	106.00	97.00	97.00	89.00	90.00

Table 19

Descriptive Statistics for Older Subjects
for Subproblem 4 for BBN Activator

		BMS12	BMS25	BMS50	BMS100	BMS200	BMS300	BMS500	BMS1000
N	Valid	20	20	20	20	20	20	20	20
	Missing	0	0	0	0	0	0	0	0
Mean		105.4250	100.5500	96.750	90.5250	87.2250	83.8750	83.0250	82.4750
Std. Error of Mean		1.6461	1.7453	1.9589	1.6285	1.3281	1.4409	1.2662	1.3810
Median		107.5000	101.0000	98.0000	91.0000	88.0000	84.0000	83.0000	83.0000
Mode		105.00	100.00	89.00	95.00	85.00	84.00	82.00	83.00
Std. Deviation		7.3615	7.8050	8.7604	7.2828	5.9393	6.4438	5.6626	6.1761
Skewness		-2.072	-.845	-.778	-.550	-.802	-.541	-.422	-.713
Range		33.00	30.50	37.00	29.00	22.00	25.00	20.00	24.00
Minimum		81.00	80.50	74.00	73.00	73.00	70.00	72.00	69.00
Maximum		114.00	111.00	111.00	102.00	95.00	95.00	92.00	93.00

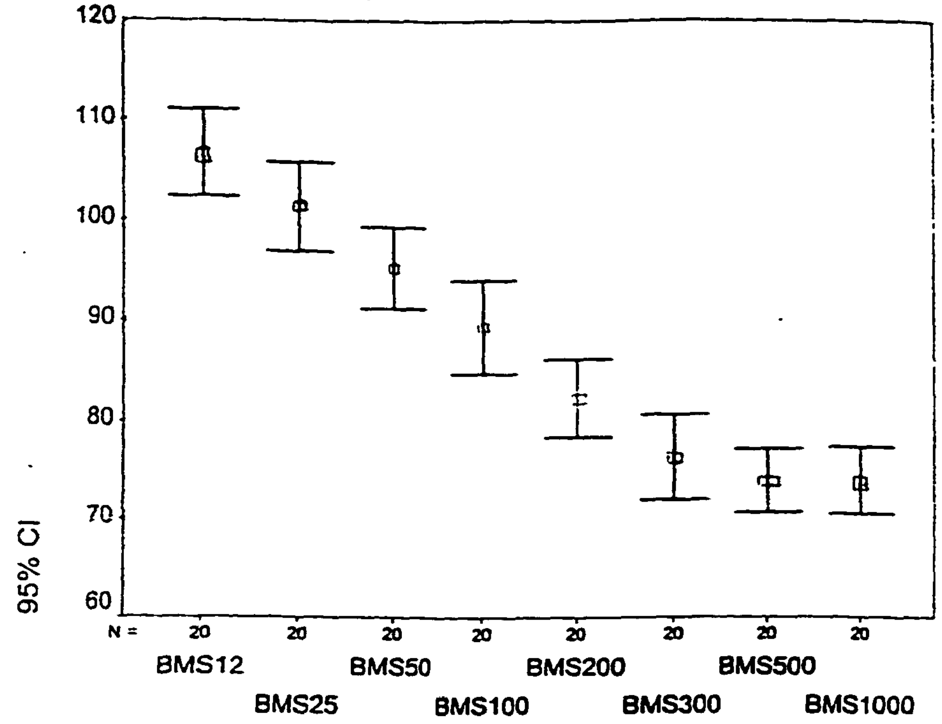


Figure 10. 95% Confidence Intervals for Younger Subjects for the BBN Activator

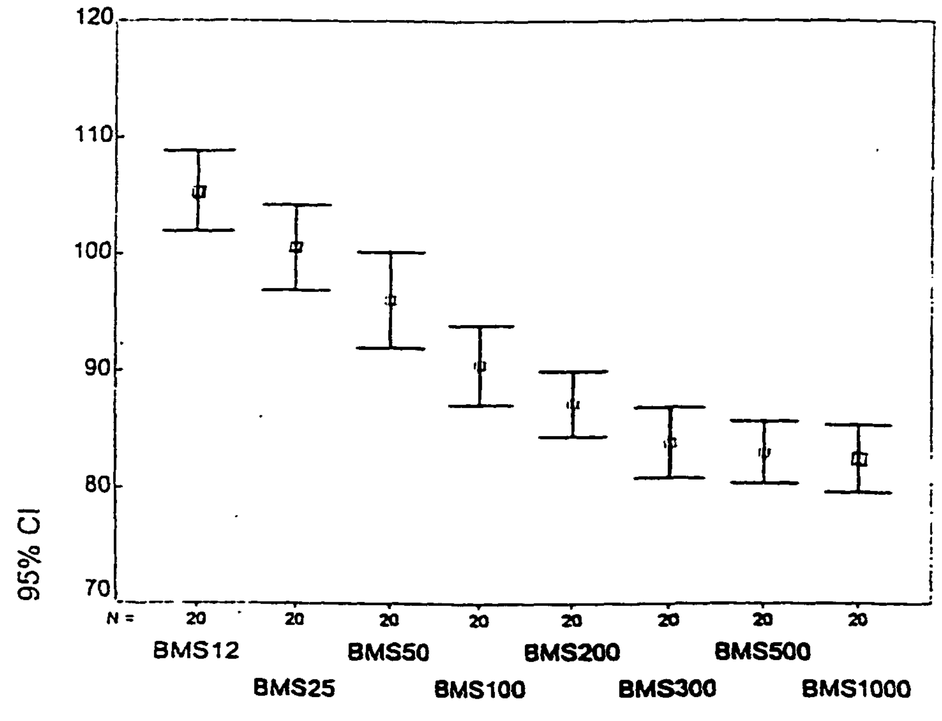


Figure 11. 95% Confidence Intervals for Older Subjects for the BBN Activator

Chapter 5

Discussion

The multivariate analysis of variance for subproblem 1 reveals two findings. The first finding, as indicated by the within-group analysis, is that of an inverse relationship between duration and BBN ART. Specifically, as the activator duration increases, the BBN ART systematically decreases for both groups. This finding is consistent with previous research (Barry & Resnick, 1976; Bazarov & Moroz, 1975; Djupesland, Sundby, & Flottorp, 1973; Djupesland & Zwislocki, 1971; Jerger *et al.*, 1977; Richards, 1975; Woodford *et al.*, 1975). The second finding, revealed by the between-group analysis, shows a significant main effect for age for the BBN ART.

It was previously mentioned (see Results section, subproblem 1) that despite the slight differences in the function relating ART to activator duration for the two age groups (see Figure 7), apparent upon visual inspection, the results of multivariate analysis indicated a lack of significant interaction between age and duration.

Recall from the Results section that further analysis was performed using the Greenhouse-Geisser procedure to examine the question of interaction between age and duration. The limitation of the Greenhouse-Geisser procedure is that analysis may falsely reveal a significant difference when there is an absence of symmetry between groups. A significant difference, when there is absence of symmetry, may be accepted if there is other supporting evidence. Although there was an absence of symmetry between the two age groups, we are inclined to accept the results of this procedure relating to the presence of an interaction. First, visual inspection of the two functions (see Figure 7) reveals that the function relating BBN ART to activator duration for the young group is steeper and plateaus later than that for the older group. Second, pairwise analysis (see Table 20) indicates a statistically significant difference between the two age groups beginning at 200 msec. Both the levels of significance and the differences in the means of the BBN ART between the younger versus older subjects generally become larger as a function of activator duration. As Figure 7 shows, the tradeoff between activator duration up to 300 msec and BBN ART is 33 dB for the younger group and 21 dB for the older group. Therefore, there seems to be a significant interaction between age and duration on the BBN ART, in addition to the main effect of age on the BBN ART.

Furthermore, comparison of the slopes of the function relating ART to activator duration (as measured between 12 ms and 300 ms—the plateau point) for younger and older subjects indicates that the slope of the function for the BBN activator in the young group (see Figure 7) is much steeper (33 dB) than that for the tonal activator in the pooled group (21 dB) (see Figure 8). These results are consistent with those of Jerger et al (1977) who also

Table 20

Pairwise Comparisons for Subproblem 1

Duration (ms)	(I) AGEGROUP	(J) AGEGROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
12	1.00 Younger	2.00 Older	-2.812	5.402	.606	-13.758	8.134
	2.00 Older	1.00 Younger	2.812	5.402	.606	-8.134	13.758
25	1.00 Younger	2.00 Older	-2.438	5.591	.665	-13.767	8.891
	2.00 Older	1.00 Younger	2.438	5.591	.665	-8.891	13.767
50	1.00 Younger	2.00 Older	-7.209	5.511	.199	-18.376	3.957
	2.00 Older	1.00 Younger	7.209	5.511	.199	-3.957	18.376
100	1.00 Younger	2.00 Older	-8.369	5.465	.134	-19.442	2.704
	2.00 Older	1.00 Younger	8.369	5.465	.134	-2.704	19.442
200	1.00 Younger	2.00 Older	-10.193*	4.586	.032	-19.485	-.900
	2.00 Older	1.00 Younger	10.193*	4.586	.032	.900	19.485
300	1.00 Younger	2.00 Older	-14.642*	5.010	.006	-24.793	-4.490
	2.00 Older	1.00 Younger	14.642*	5.010	.006	4.490	24.793
500	1.00 Younger	2.00 Older	-14.566*	3.961	.001	-22.592	-6.540
	2.00 Older	1.00 Younger	14.566*	3.961	.001	6.540	22.592
1000	1.00 Younger	2.00 Older	-13.700*	4.274	.003	-22.361	-5.040
	2.00 Older	1.00 Younger	13.700*	4.274	.003	5.040	22.361

Based on estimated marginal means

*. The mean difference is significant at the .05 level

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustment) reported a steeper function for the BBN than tonal activator in the younger subjects.

It is interesting to note that the slope of the function relating ART to duration for tonal activator in the pooled group is similar to that for the BBN activator in the older adult group. Observation of Figure 7 indicates that threshold for temporal integration for the BBN ART in younger subjects differs from that in older subjects. The BBN ART temporal integration function for older subjects plateaus at approximately 300 msec, whereas that for the younger subjects plateaus at approximately 400 msec. This suggests that when evaluating temporal integration for BBN ART in the normal-hearing subjects, age must be controlled. These results cannot be compared to previous literature since the effect of age on AR temporal integration was not previously investigated.

The observed 10-dB difference in BBN ART between the younger and older adults at 1000 msec is consistent with previous studies that investigated the effect of age on the BBN ART at this duration (Silman, 1979; Gelfand & Piper, 1981; Handler & Margolis, 1977). It has been suggested that this age-related difference in BBN ART at 1000 msec is related to the slight differences in hearing sensitivity between the normal-hearing young adult and the normal-hearing older adult (Jerger, 1978; 1979). Further examination of Figure 7, reveals that at short durations such as 12 msec and 25 msec, the BBN ART is slightly higher, by approximately 2 dB, in the younger than older subjects. If the difference in BBN ART at 1000 or more msec between the younger and older subjects is related to the difference in hearing sensitivity between these groups, then we would expect magnitude of the BBN ART at 1000 or more msec to be maintained at other signal durations. As we see from figure 7, this was not the case.

Bredberg (1968) reported that diffuse linear degeneration of outer hair cells (OHCs) occurs as a function of age. He noted that a high-frequency hearing loss appears when age-related degeneration of the sensory cells becomes more marked both apically and basally. Lipscomb, Axelsson, Vertes, Roettger, and Carroll (1977) supported Bredberg's findings that clinical hearing loss does not necessarily coexist with degeneration of the OHCs. Therefore, it is possible that when diffuse, mild degeneration of OHCs occurs, it will have its effect on BBN ART but not pure-tone thresholds. When the degeneration becomes more marked, reduction of hearing sensitivity will occur. It is therefore likely that the difference in BBN ART between the two age groups is due to age-related reduction in the number of OHCs.

To elaborate on this point, observe that at shorter durations, the BBN ARTs for the older and younger groups are essentially similar and do not differ statistically (see Figure 7 and Table 20). As duration increases, the BBN ART for the two age groups begins to diverge. As noted earlier, the temporal integration for BBN ART (i.e., point of plateau in ART) occurs earlier for the older group (just prior to 300 ms) than for the younger group (just prior to 500 ms). Expanding upon Bredberg's model, it is possible to hypothesize that as duration increases, the younger group still has sufficient viable OHCs to recruit, thereby continuing to improve the BBN ART. Conversely, since there is diffuse degeneration of OHCs concomitant with aging, as duration increases, the older group has fewer OHCs available to recruit. Consequently, the BBN ART does not continue to improve with increases in signal duration. Thus, we observe an earlier plateau for this group.

The similarity in BBN ART for younger and older subjects at durations less than 200 msec, and the subsequent divergence between the two age groups at durations equal to or greater than 200 msec can be explained. In both age groups, the BBN ARTs at shorter durations (i.e., 12 msec, 25 msec, 50 msec, and 100 msec), are similar for both the younger and older subjects. Also, the BBN ARTs in both age groups are substantially higher at shorter durations (< 100 msec) than longer durations (> 100 msec). At these lower durations, the spectrum level for BBN is roughly 60 dB. This spectrum level reflects the contribution of the IHCs which are apparently unaffected by age. The equal and high spectrum level for BBN explains the similarity in BBN ART across the two age groups at shorter durations. However, at longer durations (≥ 200 msec) the BBN ART is significantly lower than that at shorter durations. At these longer durations, the BBN spectrum level is less than 60 dB. The lower spectrum level reflects the contribution of the OHCs but not IHCs. Further explanation of spectrum levels and the role of the OHCs and IHCs in signal processing will follow.

In order to strengthen the above theoretical proposal to explain the difference in ART for BBN between young and older subjects, it behooves us to find a phenomenon proven to be directly affected by the integrity of the OHCs. Such a phenomenon should behave similarly to BBN for the older subjects.

Otoacoustic emission (OAE) levels appear to decrease with age in a fashion that is independent of the pure-tone threshold. It has been established that OAEs (Kimberley & Nelson, 1989; Nelson & Kimberley, 1992; Kimberley *et al.*, 1994a; Kimberley *et al.*, 1994b; Lonsbury-Martin, Cutler, & Martin, 1991; Stover & Norton, 1993) are a reflection of the fundamental nonlinear response property of the cochlea thought to be responsible for its sharp frequency selectivity. It is also generally accepted that these nonlinear responses are associated with the OHC system (Bromwell, 1990). Many of the insults to the auditory system that result in hearing loss not exceeding moderate levels result from damaged OHCs. Damage to OHCs also produces a number of other changes in auditory function. These include a reduction in frequency selectivity and a loss of nonlinear responses (such as two-tone suppression and combination-tone generation), as well as hearing threshold elevation (Brown, McDowell, & Forge, 1989; Dallos, Harris, Relkin, & Cheatham, 1980; Evans, 1974; Liberman & Dodds, 1984; Liberman & Kiang, 1978). These changes in auditory function occur when the OHCs sustain damage or are reduced in number because of aging (Dallos, 1988). Dallos (1988) reported that the OHCs are the first to be affected by the aging process. We can logically assume that OAEs will be reduced or absent with injury to OHCs since damage to the OHCs results in the loss of the normal nonlinear processes upon which OAEs rest. These facts are fundamental to the use of OAE measures in the identification of hearing loss.

Therefore, if the effect of age on the BBN ART is similar to that on the OAEs, it is possible to strengthen the hypothesis that elevation of the BBN ART with age is related to changes in the OHCs. As the magnitude of a sensorineural hearing impairment increases up to 60 dB HL, the BBN ART increases. No further elevation in BBN ART occurs as the magnitude of the loss exceeds 60 dB HL (Popelka, 1981) (see Figure 12). Note that the 60 dB plateau point for the BBN ART as a function of hearing threshold level occurs at a level associated with the loss of distortion product OAEs.

This theory will be further enhanced if the BBN ART and amplitude of the OAEs are both measured in subjects and the data for both reveal similar age effects. Silman, Silverman, and Emmer (study in progress) are currently testing the relation between the BBN ART and amplitudes of the transient OAEs in younger vs. older normal-hearing subjects. Preliminary

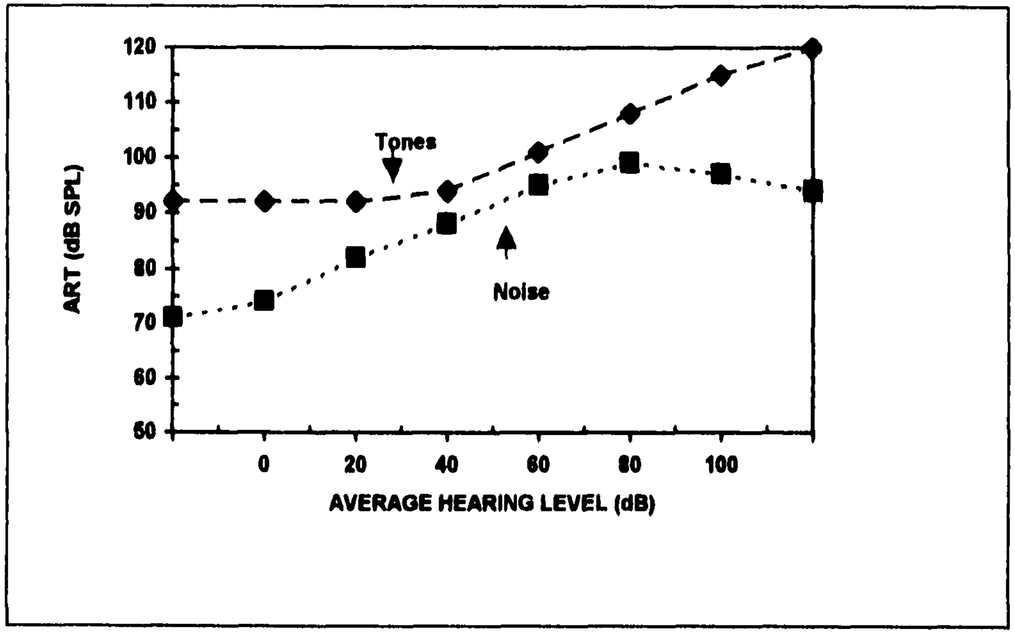
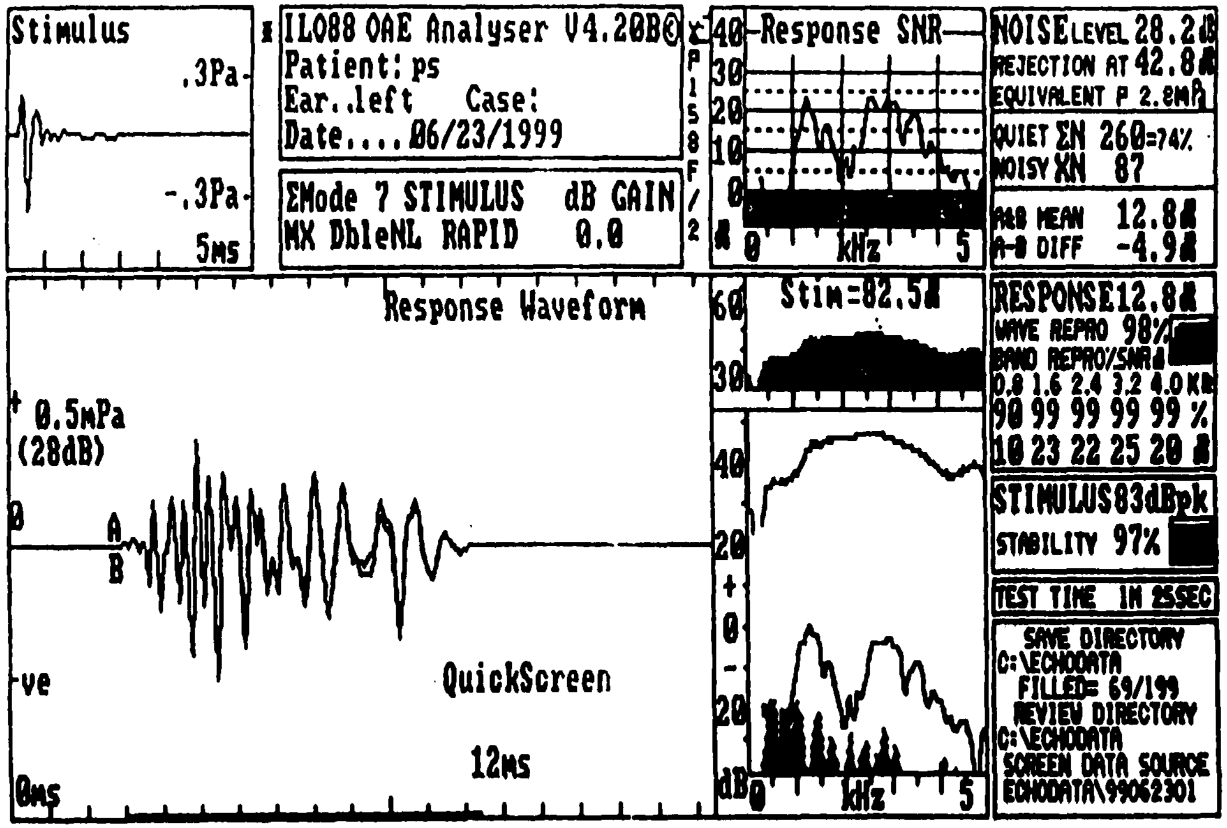


Figure 12. Acoustic-reflex thresholds for tones (averaged over 500, 1000, and 2000 Hz) and for BBN in dB SPL as a function of average hearing level for 500, 1000, and 2000 Hz in dB HL. The lines represent the best-fit functions. (Adapted from Popelka, G.R. The acoustic reflex in normal and pathologic ears. In G.R. Popelka (Ed.), *Hearing assessment with the acoustic reflex.* New York: Grune & Stratton, 1981, pp. 5-21.

data show that magnitude of elevation of the BBN ART is inversely related to the amplitudes of the OAEs. That is, an elevated BBN ART appears to be accompanied by a reduction in the magnitude of OAE (see Figures 13 and 14). Figure 13 displays the transient OAE findings for a 23-year-old female with hearing threshold levels not exceeding 15 dB HL throughout the frequency range (250 – 8000 Hz). The tonal ARTs (500-, 1000-, and 2000-Hz activators) were within the 90th percentiles (Silman & Gelfand, 1981). The BBN ART was elicited at an expected level (75 B HL) (Silman, 1979; Gelfand & Piper, 1981; Wilson, 1979). Note that the amplitudes of the transient OAEs are robust and clear.

Figure 14 illustrates the transient OAEs for a 45-year old female with hearing threshold levels not exceeding 15 dB HL throughout the frequency range (250 to 8000 Hz). The tonal ARTs (500-, 1000-, and 2000- Hz activators) were within the 90th percentiles. This subject demonstrated an elevated BBN ART at 90 dB HL, a level that is expected given her age (Silman, 1979a; Gelfand & Piper, 1981; Wilson, 1979). Observe that amplitudes of the transient OAEs are significantly reduced.

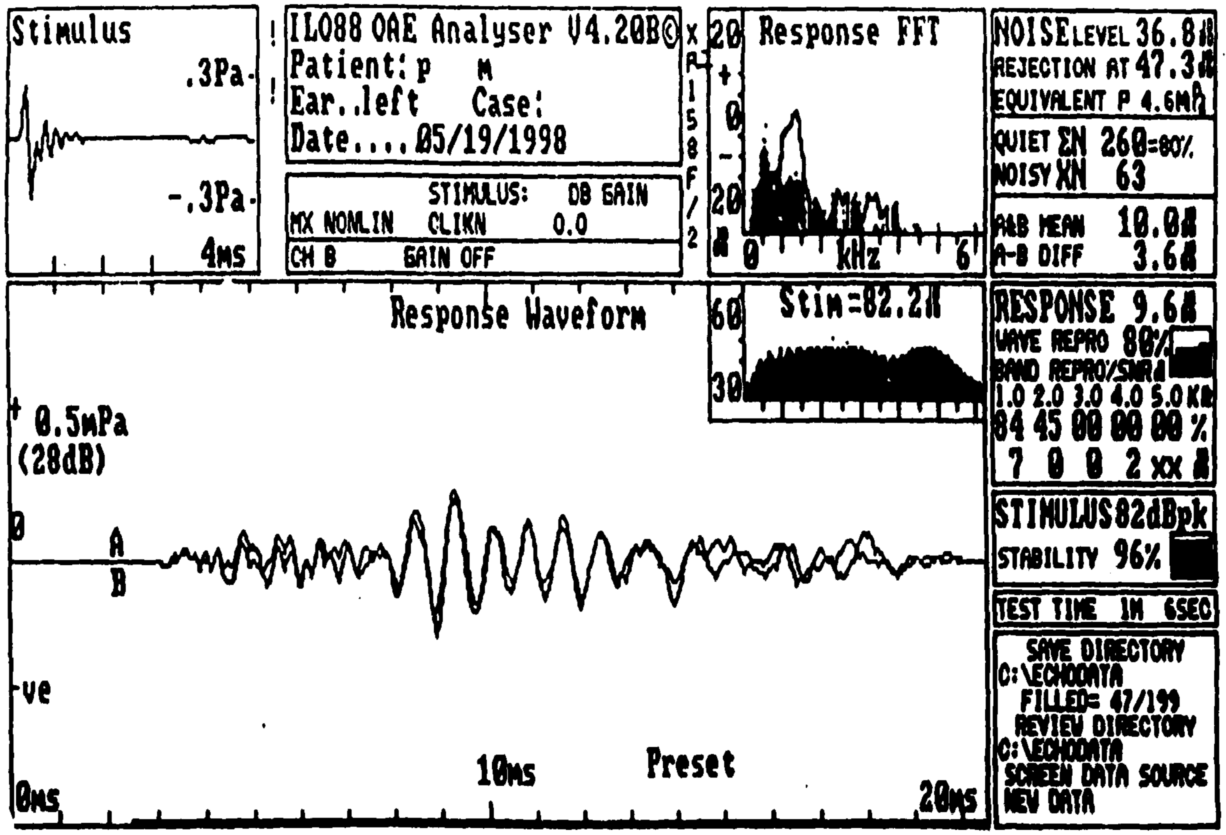


ILO88 OAE Analyser V4.20B©
Patient: ps
Ear..left Case:
Date....06/23/1999

ΣMode 7 STIMULUS dB GAIN
MX DbleNL RAPID 0.0

NOISE LEVEL 28.2dB
REJECTION AT 42.8dB
EQUIVALENT P 2.8mPa
QUIET ΣN 260=74%
NOISY XN 87
A&B MEAN 12.8dB
A-B DIFF -4.9dB
RESPONSE 12.8dB
WAVE REPRO 98%
BAND REPRO%SNRdB
0.8 1.6 2.4 3.2 4.0 KHz
90 99 99 99 99 %
10 23 22 25 20 dB
STIMULUS 83dBpk
STABILITY 97%
TEST TIME 1M 25SEC
SAVE DIRECTORY
C:\ECHODATA
FILLED= 69/199
REVIEW DIRECTORY
C:\ECHODATA
SCREEN DATA SOURCE
ECHODATA\99062301

Figure 13 presents OAE results for a 23-year old female with hearing ≤ 15 dB HL across the frequency range 250 Hz through 8000 Hz. ARTs for 500- Hz, 1000- Hz, and 2000-Hz tonal activators were within the 90th percentile (Silman & Gelfand, 1981b), ART for BBN was 75 dB HL as expected for a normal-hearing young adult (Silman, 1979a; Gelfand & Piper, 1981; Wilson, 1979). Note that the magnitude of the OAE is robust and clear.



ILO88 OAE Analyser V4.20B©
Patient: p M
Ear..left Case:
Date....05/19/1998

STIMULUS: DB GAIN
MX NONLIN CLIKN 0.0
CH B GAIN OFF

NOISE LEVEL 36.8dB
REJECTION AT 47.3dB
EQUIVALENT P 4.6mPa
QUIET ΣN 260=80%
NOISY XN 63
A&B MEAN 10.0dB
A-B DIFF 3.6dB

RESPONSE 9.6dB
WAVE REPRO 80%
BAND REPRO/SNR dB
1.0 2.0 3.0 4.0 5.0 KHz
84 45 00 00 00 %
7 0 0 2 xx dB

STIMULUS 82dBpk
STABILITY 96%

TEST TIME 1M 6SEC

SAVE DIRECTORY
C:\ECHODATA
FILLED= 47/199
REVIEW DIRECTORY
C:\ECHODATA
SCREEN DATA SOURCE
NEW DATA

Figure 14 presents OAE results for a 45-year old female with hearing ≤ 15 dB HL across the frequency range 250 Hz through 8000 Hz. ARTs for 500- Hz, 1000 Hz, and 2000-Hz tonal activators were within the 90th percentile (Silman & Gelfand, 1981b), ART for BBN was 90 dB HL consistent with levels for her age (Silman, 1979a; Gelfand & Piper, 1981; Wilson, 1979). Observe that magnitude of the OAE is significantly reduced.

Some results of recent electrophysiological and psychoacoustic studies may lend support to the aforementioned theory. Injuries affecting the OHCs have been shown to affect the tip but not tail of the tuning curves, and the condition of the OHCs seems to correlate with the tip of the tuning curve (Khanna & Leonard, 1986; Leonard & Khanna, 1984; Liberman & Dodds, 1984). Such changes in the tip of the tuning curve are found in the absence of basal membrane aberrance (Kelly & Khanna, 1984a; Kelly & Khanna, 1984b). The implication of these findings is that the tip component of the cochlear mechanical tuning curve is associated with the OHCs in general, and to the condition of the stereocilia, in particular.

Smith, Moody, Stebbins, and Norat (1987) provided behavioral support for the contribution of the OHCs to the fine-tuning and sensitivity of the cochlea. The investigators obtained psychoacoustic tuning curves, which are behavioral measures of frequency selectivity similar to the auditory neuron tuning curves, from patas monkeys before and after producing OHC damage. The drug, dihydrostreptomycin, which was used by Smith and colleagues (1987), caused 50 dB or greater elevation of hearing threshold level, as well as obliteration of the sharp tips of the psychoacoustic tuning curves. Only the broad, low-pass filter characteristics of the curves remained. Histological examination of the cochleas revealed a complete loss of the OHCs but complete preservation of the inner-hair cells (IHCs) at frequency regions corresponding to the changes on the psychoacoustic tuning curves. Since tuning-curve sharpness and frequency selectivity are affected by the integrity of the OHCs, one might infer that broadening of frequency selectivity is related to the destruction of the OHCs.

The importance of OHCs for the sharp tuning and low thresholds of auditory nerve fibers, and hence, by extension, of the basilar membrane, was originally demonstrated by Kiang, Moxon, and Levine (1970) in cats poisoned with the ototoxic antibiotic, kanamycin. This agent selectively damages the OHCs with a much less discernible effect on the IHCs. Kiang *et al.* showed that in auditory nerve fibers recorded from the areas of OHC damage, the sharply-tuned low-threshold tip of the neural tuning curve was raised, while the high-threshold, low frequency tail was unaffected. The result was a broadly tuned curve with a high threshold.

The OHCs can also be selectively affected by stimulation of the crossed olivocochlear bundle, the centrifugal (efferent) pathway running from the brainstem to the cochlea (Pickles, 1988, pgs. 236-246 – the olivocochlear bundle). The crossed component of the bundle, which travels from the contralateral superior olivary complex, ends mainly on OHCs. Stimulation of the bundle raises and broadens the tip region of the neural tuning curve. The result has subsequently been repeated for IHC receptor potentials. Inasmuch as the crossed olivocochlear bundle primarily innervates the OHCs, this result suggests that normal OHC function is in some way essential for the sharp tuning and sensitivity of the IHCs.

Jakimetz, Silman, Miller, and Silverman (1989) investigated the effect of signal bandwidth and spectral density on the ART in the elderly. Their findings revealed that as spectral density increased from one to five components, the mean ART decrease was 5.6 in the elderly subjects versus 8.1 in the younger subjects. Also, the plateau in ART decrease with increases in spectral density occurred earlier in older adults (5 components) than in younger adults (7 components). These findings suggest that the auditory system of the elderly has a reduced ability to summate the sound energy from the components of a multitone complex signal, which are presented simultaneously within a particular bandwidth. This result was interpreted as a weakening of the frequency selectivity of the cochlea in the elderly following the reduction in the number of OHCs due to aging.

In order to substantiate the theory relating the effect of age on the BBN ART to the contribution of the OHCs vs. IHCs, we analyzed the BBN ART spectrum level mathematically at low, medium, and high durations for both groups. The first step in this analysis involved the conversion of the frequency range of the BBN delivered by the TDH-49 earphone. This was accomplished by first converting 6000 Hz, the bandpass of the earphone, into decibels:

1. dB = 10 *log* 6000 Hz
2. dB = 10 *log* 6 x 1000 Hz
3. dB = mantissa of 6 + (3 x 10)
4. dB = 0.78 + (3 x 10) = 30.78

The total frequency range of the BBN activator delivered through the earphone is therefore equal to 30.78 dB. Based on this value, we then calculated the spectrum level of the BBN activator for the younger and older adults for the BBN ART at several durations (12 msec, 100 msec, 200 msec, 300 msec, and 1000 msec). The mean BBN ART at 12 msec was 107 dB SPL in the younger subjects. This BBN ART of 107 dB SPL is divided by the total frequency of the BBN activator delivered by the earphone (30.78 dB) to yield a spectrum level (total energy per cycle) of 76.22 dB.

The same procedure was used to calculate the spectrum level associated with the BBN ART at 12 msec for the older subjects. The mean BBN ART at 12 msec was 105 dB SPL in the older subjects. This BBN ART of 105 dB SPL was divided by the total frequency of the BBN activator delivered by the earphone (30.78 dB) to yiseld a spectrum level of 74.22 dB.

Spectrum levels were then calculated for the BBN ART at 100 msec, 200 msec, 300 msec, and 1000 msec for each group. The results for all durations are summarized below.

Table 21

Analysis of Spectrum Level at Low, Medium, and High Durations for BBN for Younger and Older Subjects

Duration	Age Group	Mean ART	Spectrum Level
12 msec	Younger	107	76.22
	Older	105	74.22
100 msec	Younger	89	58.22
	Older	91	60.22
200 msec	Younger	82	51.22
	Older	87	56.22
300 msec	Younger	76	45.22
	Older	84	53.22
1000 msec	Younger	74	43.22
	Older	83	52.22

The results of this analysis reveal compelling findings, which strongly support our hypothesis with respect to the age-related effect on the BBN ART.

The similarity in BBN ART for the younger and older subjects at durations less than 200 msec, and the subsequent divergence between the two age groups at durations equal to or greater than 200 msec can be explained in terms of spectrum level and IHC vs. OHC involvement. The BBN ARTs are similar and substantially higher at the shorter durations (i.e., 12 msec, 25 msec, 50 msec, and 100 msec) than at the longer durations (>100 msec). At these shorter durations, the spectrum levels for the BBN activator range between 58 and 76 dB; the IHCs contribute to signal processing at these high intensities. Since the IHCs are essentially unaffected by age, the BBN ARTs at these shorter durations do not reveal any age effect. At the longer activator durations ($\geq$ 200 msec), the spectrum levels range between 43 and 56 dB; the OHCs but not IHCs contribute to signal processing at these levels. Since the OHCs are affected by age, the BBN ARTs at these longer durations will be higher for the older than younger subjects.

The mean tonal ART was in the vicinity of 100 dB SPL for both age groups. The spectrum level of this tonal ART was 100 dB per cycle. Thus, the spectrum level was markedly higher for the tonal than BBN ART. A spectrum level of 100 dB reflects the contribution of the IHCs. As mentioned earlier, the IHCs appear to be unaffected by age. The IHCs are affected when the magnitude of hearing impairment exceeds 60 dB HL. Even with total destruction of the OHCs by ototoxic drugs, the IHCs remain completely intact (Pickles, 1988). We can therefore explain the absence of an age effect on the tonal activator in terms of the previous analysis. Since aging will first affect OHCs (Dallos, 1988) before the IHCs, it is unremarkable that no age effect is observed for the tonal ART.

The finding of the absence of an age effect on the tonal ART is in concert with numerous previous investigations for activator duration of 1000 or more msec (Silman *et al.*, 1978; Silman, 1979; Jerger, 1979; Gelfand & Piper, 1981; Wilson, 1979). The tonal activator used in this study (1000 Hz) is one of the few variables unaffected by age (Lynn, 1988 found that the rate of ARA was not significantly affected by age).

Popelka *et al.* (1976) found the difference between the BBN ART and tonal ART to be approximately 20 dB in normal-hearing individuals. This NTD is related to the critical bandwidth for the AR and to the number of components within the bandwidth. The investigators reported that the ART for five or more tonal components equally spaced in log frequency or for a continuous spectrum, is lower than that for only two or three components. Jerger *et al.* (1974), prior to the report by Popelka *et al.* (1976) had noted an identical NTD through clinical observation.

While the SPAR approach developed by Jerger *et al.* (1974) successfully predicts hearing sensitivity in children and young adults, it has poor predictive accuracy in older adults (Jerger *et al.*, 1978; Silman, 1984; Silman *et al.*, 1984a). The poor predictive capability of the SPAR with respect to hearing-loss severity categories in the older adult has been ascribed to the narrowed NTD (as measured at durations of $\geq$ 1000 msec) in the normal-hearing older population. Jerger *et al.* (1978) postulated that the narrowed NTD observed in the older adult results from increased cochlear distortion products. That is, the tonal ARTs decrease as a function of age whereas the BBN ART remains relatively constant with increasing age. Several investigators (Silman, 1979a; Silman *et al.*, 1984; Silverman *et al.*, 1983) attributed the narrowed NTD in the older adult to the elevation (due to age) of the ART for BBN but not tonal activator. Silverman *et al.* (1983) observed that the difference between Jerger *et al.* (1978), on the one hand,

and Silman (1979), on the other hand was related to methodological differences. Jerger used 5-dB steps under clinical conditions, and Silman used 1-dB steps under laboratory conditions. Using 1-dB increments, according to Silverman *et al.* (1983), the BBN ART in the elderly will be elevated as compared to that for the young, but the tonal ARTs will be similar for older and younger adults. This is the case in the current study as well. The elevation of the BBN ART was attributed by Jackimetz *et al.* (1989) to the widening of the critical band for the elderly.

Inspection of Figure 15, which illustrates the tonal and BBN ARTs for the younger adults as a function of duration, reveals that a 20-dB NTD is maintained throughout the three longest durations (i.e., 300 msec, 500 msec and 1000 msec). At shorter durations, the NTD is narrower by about 9-11 dB. Interestingly, the NTD range (7-10 dB) between 12 msec and 100 msec in the younger subjects is similar to that across the span of durations in the older subjects (see Figure 16). It can be concluded that the use of the NTD for the prediction of hearing sensitivity in the young remains a sound technique when it is based upon an activator duration between 300 and 1000 msec. This method cannot be used for prediction of hearing sensitivity in the older population regardless of the activator duration since the NTD is narrowed in this population.

As previously described, prior research revealed large individual variability in temporal integration for the ART for BBN and tonal activators. This variability has long precluded the use of AR temporal integration for diagnostic purposes. In the rationale for the current study, the disparate results were attributed to, among other factors, the lack of control for age and small sample size. When these variables are controlled, as within the current study, the ART temporal integration results reveal small variability both for BBN and tonal activating stimuli.

The results of descriptive statistics (mean, standard error of mean, median, mode, standard deviation, skewness, range, minimum and maximum values) provide normative data for the BBN and 1000-Hz tonal activators at the various durations (i.e., 12 msec, 25 msec, 50 msec, 100 msec, 200 msec, 300 msec, 500 msec, and 1000 msec). These normative data will be useful for comparative purposes when investigating temporal integration for ART in pathological ears.

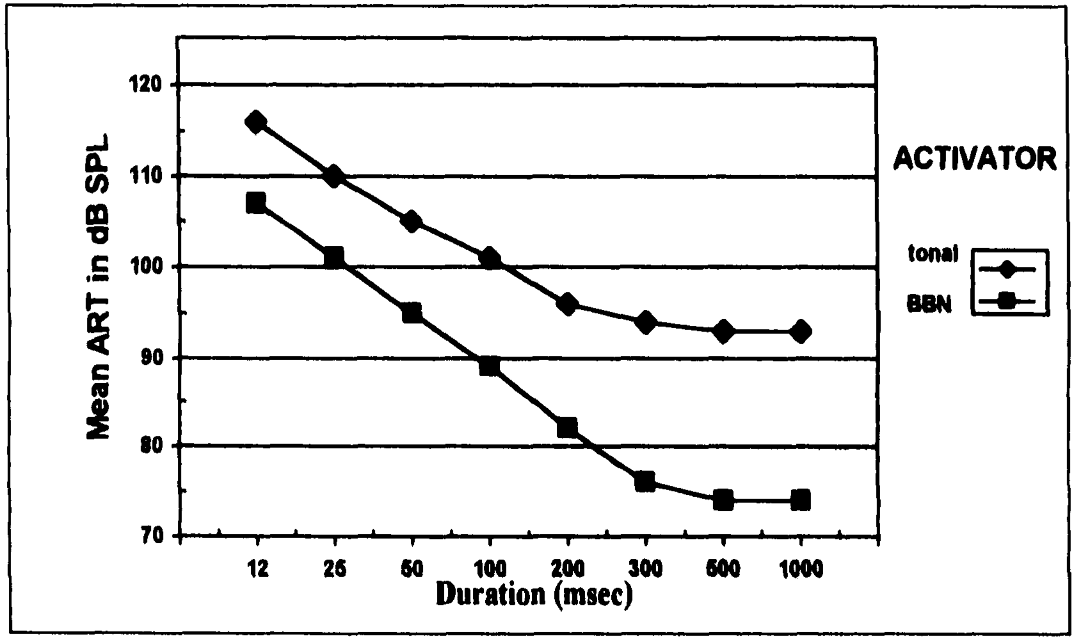


Figure 15. Mean ART for younger adults for tonal and BBN activators.

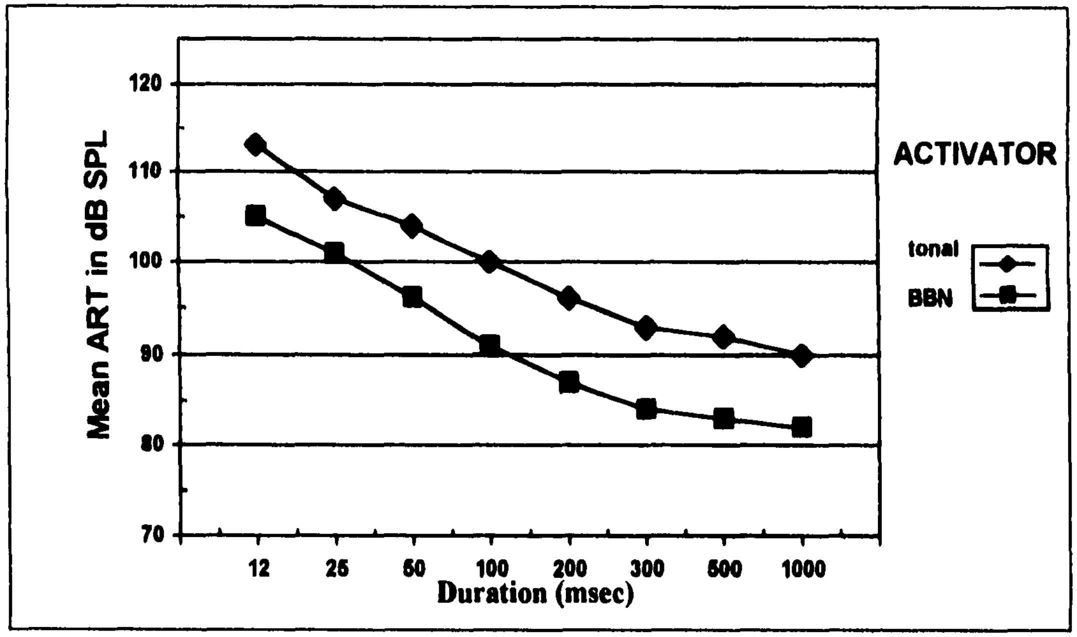


Figure 16. Mean ART for older adults for tonal and BBN activators.

Conclusions

The following conclusions can be drawn from the results of the present study:

(1) An age effect is present for temporal integration for the BBN ART, as evidenced by the significant main effect on the BBN ART and in the interaction between duration and age. An age effect was not observed for the 1000-Hz tonal ART. We presented a theoretical framework for these findings: The effect of age on the BBN ART was hypothesized to relate to a decreased number of OHCs due to the aging process. We believe this reduction in OHCs to be responsible for the elevation of the BBN ART. We also presented a theoretical framework to explain the absence of the age effect for the tonal ART. The tonal ART was substantially higher than the BBN ART, reflecting the contribution of the IHCs rather than OHCs. Since the IHCs are more resistant than the OHCs to the effects of age, the tonal ART was unaffected by the aging process in the normal-hearing individual.

(2) A significant difference in the NTD was observed between the younger and older subjects at the three longest durations (i.e., 300 msec, 500 msec, and 1000 msec). That is, the NTD was significantly larger in the younger subjects (approximately 19 dB) than older subjects (approximately 9 dB) at these longer durations. We also found that the NTDs in the older subjects at all durations were similar to those for the younger adults at the shorter durations (< 200 msec). The implication of this finding is that NTD should not be used to predict hearing impairment in young adults when the

duration is less than 200 msec or in older adults, regardless of the duration. Prediction of hearing sensitivity based on the NTD at durations exceeding 200 msec in the young remains a valid procedure.

(3) The mean BBN and tonal ARTs obtained in this study can be used as normative data. This was made evident by the closeness of the mean, mode, and median, the small standard deviation, and minimal skewness. These data, therefore, could be used for comparative purposes in clinical and research applications of the tonal and BBN ARTs.

Chapter 6

Implications, Limitations, and Recommendations for Future Research

Implications

The results of the current study emphasize the following implications: (a) in order to generate normative data for temporal integration for ART, a large sample of subjects should be used, with adequate control for age; (b) one should bear in mind, when using the ART for clinical purposes, that age must be taken into consideration; (c) it is important that normative data be generated for each signal independently; (d) it is useless to predict hearing sensitivity from the NTD in the older population throughout all durations. The best approach to prediction of hearing loss from ART in the elderly is the combination of tonal ART and BBN ART (see Silman *et al.*, 1984). In that study, the authors suggested that the criterion of a tonal ART exceeding 100 dB HL and BBN ART exceeding 90 dB SPL could be used to separate older individuals with significant SNHL from other older individuals; (e) the presence of inconsistencies in using temporal integration for differential diagnosis was at least partially related to the use of small sample sizes. The feasibility of using temporal integration for the ART in differential diagnosis should be re-examined using large sample sizes.

Limitations of the present study

The results of this study are limited to the following: (a) age groups between 18-29 and 59-75 years; (b) normal-hearing individuals (as defined in this study) in the aforementioned age groups; (c) the BBN and 1000-Hz tonal activators; (d) the instrumentation and methodology used herein; (e) those who demonstrate tonal ARTs (500-, 1000-, and 2000-Hz activators) within the 90th percentiles (Silman & Gelfand, 1981).

Recommendations for Future Research

Based upon the results of the current study we see that there is still much to be accomplished on this topic of temporal integration of the ART. We therefore suggest the following areas for future research: (a) the use of a large sample size to investigate the age effect using 5-dB vs 1-dB steps, to determine clinical applicability of temporal integration of the ART for both tonal and BBN activators; (b) investigation of temporal integration of the ART for other tonal activators (500-, 2000-, and 4000-Hz); (c) investigation of temporal integration of the ART for higher probe-tone frequencies for both tonal and BBN activators (e.g., 660 Hz and 1000 Hz); (d) exploration of a gender effect on temporal integration of the ART for BBN and tonal activators; (e) examination of the effect of SNHL on temporal integration of the ART for tonal and BBN activators; (f) the investigation of whether temporal integration could be used for differential diagnosis of cochlear vs retrochochlear pathology; (g) study of the age effect, decade by decade, on temporal integration of the BBN and tonal activators (newborn through 75 years of age).

Appendix A.1
Individual data for hearing-threshold levels
(Younger subjects are numbered 1-20,
Older subjects are numbered 21-40)

Id	RE_250Hz	RE_500Hz	RE_1000Hz	RE_2000Hz
1	0	0	0	0
2	5	0	0	0
3	0	0	5	0
4	5	0	5	5
5	10	0	5	0
6	0	0	0	0
7	0	0	0	0
8	5	0	5	0
9	0	0	0	0
10	0	5	10	0
11	5	5	0	0
12	0	5	0	0
13	5	5	0	0
14	0	0	0	0
15	10	5	10	5
16	5	0	5	10
17	0	5	0	0
18	5	5	5	0
19	0	0	5	5
20	5	5	0	0
21	15	10	5	10
22	10	10	10	15
23	15	15	5	5
24	10	15	15	20
25	5	10	10	10
26	10	10	5	0
27	10	10	10	10
28	5	5	0	5
29	10	5	5	15
30	5	5	5	10
31	15	20	20	15
32	5	5	5	0
33	20	20	15	15
34	20	15	15	20
35	10	10	5	0
36	5	5	10	10
37	5	5	0	5
38	5	5	5	0
39	15	10	10	10
40	10	10	5	10

Appendix A.1 continued
Individual data for hearing-threshold levels

RE_4000Hz	RE_8000Hz	LE_250Hz	LE_500Hz	LE_1000Hz	LE_2000Hz
0	0	0	5	0	0
5	0	0	0	0	0
5	0	0	0	5	0
0	0	5	5	5	0
0	0	5	0	0	0
0	0	5	0	0	0
0	0	0	0	0	5
5	0	5	5	5	5
0	0	0	0	5	0
5	0	0	5	5	0
0	0	5	10	5	0
0	0	0	0	5	0
0	5	5	5	5	0
0	5	0	0	5	0
0	0	10	0	5	0
0	0	5	0	5	10
0	0	0	5	0	0
0	5	10	10	5	0
0	0	0	0	5	0
0	5	0	0	0	0
10	10	15	15	5	10
15	20	15	15	15	15
10	10	10	10	5	10
20	20	15	10	10	20
10	10	10	10	5	5
0	10	10	5	5	10
15	20	10	10	10	5
20	20	10	0	0	5
20	20	5	5	0	15
5	20	10	10	10	10
5	10	5	20	20	15
15	20	10	0	0	0
10	20	20	20	10	5
10	15	10	15	15	20
10	15	10	10	10	0
5	0	5	0	10	15
5	20	0	0	5	5
5	10	10	10	0	0
20	20	15	10	10	10
10	20	10	10	5	0

Appendix A.1 continued
Individual data for hearing-threshold levels

LE 4000Hz	LE [illegible]Hz
0	0
10	5
0	5
0	0
0	0
0	0
0	0
5	5
0	0
0	5
0	0
0	5
5	5
5	5
5	5
0	0
0	0
0	5
5	0
0	5
15	20
10	20
10	20
20	20
15	5
0	10
10	20
20	20
20	20
10	20
5	5
15	20
15	10
10	15
10	10
5	15
10	20
5	20
20	20
10	15

Appendix A.2
Individual immittance data for younger and older subjects
(MEP = middle-ear peak pressure point Static = static acoustic admittance)

Subject_Id	L_MEP	L_Static	R_MEP	R_Static
1	0	0.8	-5	0.7
2	5	0.4	5	0.4
3	-5	0.7	0	0.6
4	-5	0.7	-5	0.6
5	0	0.5	0	0.4
6	-5	0.6	5	0.7
7	0	0.8	0	1
8	5	0.5	10	0.7
9	5	1.2	10	1
10	0	0.4	5	0.6
11	10	0.6	10	1
12	15	0.8	-20	0.6
13	10	1.6	-5	1.6
14	0	0.4	5	0.5
15	-10	1.1	5	1.1
16	5	0.9	5	1.4
17	5	0.8	5	0.5
18	5	0.4	5	0.5
19	-10	0.8	25	1
20	-15	1	-5	1
21	0	0.6	-15	0.4
22	-20	0.4	-25	0.4
23	-20	0.4	-20	0.4
24	5	1.1	5	1
25	0	0.6	-10	0.7
26	-10	0.4	-15	0.4
27	-5	0.6	15	0.6
28	-5	1.1	-35	0.6
29	5	0.4	5	0.4
30	-10	1.3	20	0.9
31	0	0.4	5	0.4
32	0	0.4	0	0.4
33	45	0.6	5	0.7
34	30	0.8	40	0.9
35	-35	0.6	50	0.7
36	10	0.9	5	0.6
37	0	0.4	0	0.4
38	-15	1.1	5	0.9
39	5	0.7	0	0.8
40	-35	0.6	5	1.6

Appendix A.3
Individual clinical ART data
for younger and older subjects

Id	L_HL_500Hz	L_HL_1000Hz	L_HL_2000Hz	R_HL_500Hz	R_HL_1000Hz	R_HL_2000Hz
1	80	75	80	75	70	75
2	80	85	90	85	85	85
3	80	75	80	90	75	70
4	95	95	90	90	90	90
5	80	75	85	80	80	85
6	80	75	80	70	75	75
7	85	85	85	90	85	90
8	80	80	85	80	80	85
9	80	80	90	90	90	95
10	70	75	80	65	65	75
11	85	75	75	85	75	80
12	80	85	85	75	85	80
13	85	90	95	95	90	95
14	90	80	80	90	80	80
15	85	90	90	90	95	95
16	85	85	90	80	80	85
17	85	80	80	80	75	80
18	75	85	85	80	75	80
19	95	95	95	95	95	95
20	90	85	85	90	85	90
21	95	90	95	95	95	85
22	90	95	95	95	90	95
23	90	85	95	85	90	90
24	65	60	65	80	70	65
25	80	80	70	85	75	75
26	85	80	85	85	85	90
27	90	95	95	95	90	95
28	90	95	90	95	85	90
29	90	75	80	95	70	75
30	85	80	80	70	70	75
31	80	80	70	85	80	80
32	95	95	85	85	80	85
33	85	80	75	85	80	75
34	80	75	80	80	75	80
35	95	80	80	90	80	85
36	70	75	70	90	65	85
37	85	80	75	80	80	80
38	80	75	75	80	75	80
39	85	80	80	80	75	80
40	85	90	85	80	75	70

Appendix A.4

Descriptive Statistics for Younger Subjects for Subproblem 4 for 1000–Hz Activator

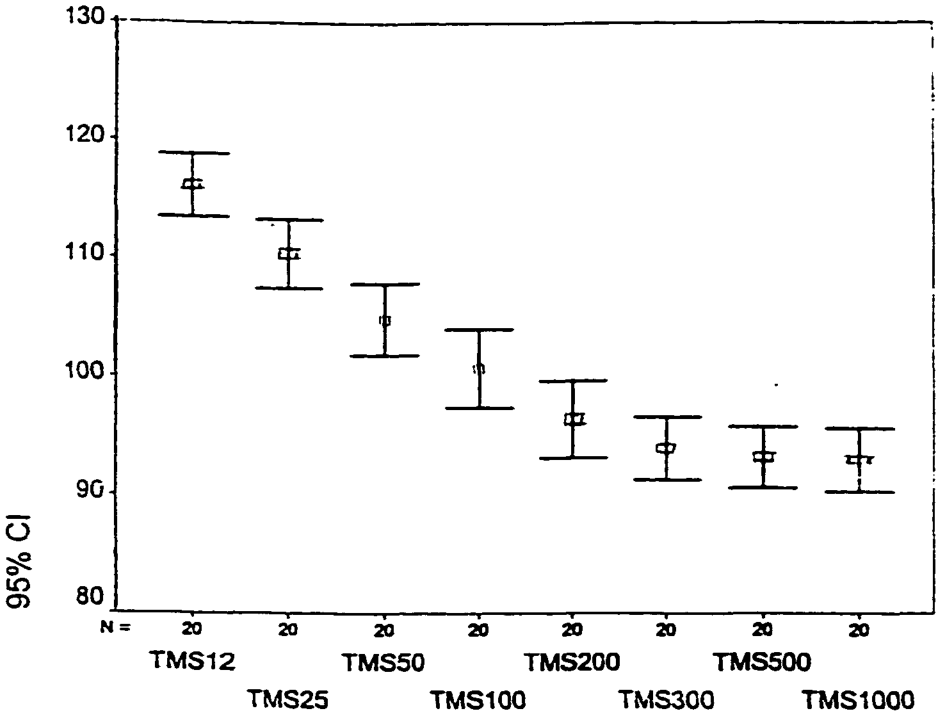
		TMS12	TMS25	TMS50	TMS100	TMS200	TMS300	TMS500	TMS1000
N	Valid	20	20	20	20	20	20	20	20
	Missing	0	0	0	0	0	0	0	0
Mean		116.0750	110.3000	104.7750	100.6500	96.3500	93.9250	93.1750	92.9250
Std. Error of Mean		1.2821	1.3824	1.4516	1.5741	1.5411	1.2614	1.2238	1.2733
Median		117.7500	110.2500	105.5000	100.2500	96.5000	93.5000	93.0000	93.0000
Mode		121.00	114.00	96.00	95.00	97.00	93.00	95.00	93.00
Std. Deviation		5.7337	6.1823	6.4918	7.0395	6.8922	5.6412	5.4731	5.6946
Skewness		-1.841	-.463	-.163	.113	-.297	.108	-.143	-.032
Range		23.00	26.00	25.00	28.00	24.50	19.00	21.00	22.00
Minimum		98.00	95.00	92.00	87.00	81.50	85.00	81.00	81.00
Maximum		121.00	121.00	117.00	115.00	106.00	104.00	102.00	103.00

Appendix A.5

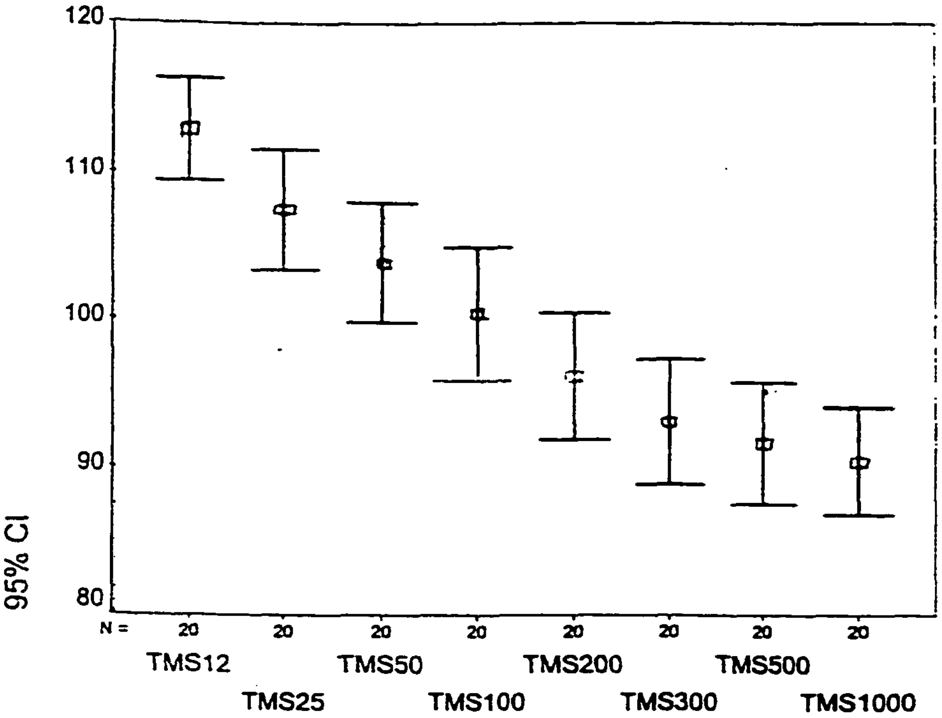
Descriptive Statistics for Older Subjects
for Subproblem 4 for 1000 – Hz Activator

		TMS12	TMS25	TMS50	TMS100	TMS200	TMS300	TMS500	TMS1000
N	Valid	20	20	20	20	20	20	20	20
	Missing	0	0	0	0	0	0	0	0
Mean		112.8500	107.4500	103.8500	100.3500	96.1500	93.0500	91.6000	90.4000
Std. Error of Mean		1.6360	1.9577	1.9561	2.1843	2.0462	2.0095	1.9590	1.7357
Median		114.7500	110.0000	105.2500	101.0000	94.5000	93.5000	91.5000	89.5000
Mode		121.00	108.00	92.00	91.00	109.00	78.00	85.00	87.00
Std. Deviation		7.3163	8.7553	8.7481	9.7685	9.1509	8.9867	8.7609	7.7623
Skewness		-.972	-.577	-.242	-.131	.052	.265	.333	.120
Range		25.00	29.00	28.00	33.00	30.00	33.00	35.00	31.00
Minimum		96.00	92.00	90.00	83.00	80.00	78.00	75.00	75.00
Maximum		121.00	121.00	118.00	116.00	110.00	111.00	110.00	106.00

Appendix A.6
Unpooled 95% Confidence Intervals for Younger Subjects



Appendix A.7
Unpooled 95% Confidence Intervals for Older Subjects



Appendix A.8
Individual data for ART for BBN activator
for younger and older subjects for various durations (in msec)

Id	BBN_12ms	BBN_25ms	BBN_50ms	BBN_100ms	BBN_200ms
1	93	91	82	81	78
2	93	89	83	81	77
3	100	95	90	80	75
4	106	98	93	87	79
5	112	101	95	93	87
6	108	92	82	80	81
7	114	103	101	98	89
8	115	99	93	87	87
9	110	105	98	95	80
10	84	83	79	68	68
11	112	112	94	91	83
12	115	112	104	103	93
13	115	113	105	101	97
14	115	115	101	97	88
15	108	102	100	76	63
16	109	105	104	98	91
17	99	95	94	87	81
18	115	111	104	93	84
19	115	114	108	106	89
20	97	94	97	88	77
21	81	81	74	73	73
22	107	100	92	88	87
23	97	96	95	92	87
24	97	91	82	81	82
25	114	101	97	86	85
26	112	111	111	100	95
27	111	105	100	98	92
28	107	100	98	95	92
29	102	92	89	86	87
30	109	98	92	82	78
31	102	101	88	85	83
32	109	108	104	102	94
33	108	111	103	98	89
34	105	106	102	98	90
35	113	110	107	95	94
36	105	90	89	87	79
37	108	102	99	94	91
38	108	106	98	95	93
39	105	100	101	90	89
40	109	103	101	88	85

BBN_300ms	BBN_500ms	BBN_1000ms
73	74	75
70	70	68
69	70	69
73	66	67
81	83	81
71	70	69
92	74	78
83	83	84
69	65	65
62	62	61
75	75	75
97	89	90
79	79	79
84	76	76
61	64	64
70	72	71
78	76	78
80	77	78
87	78	79
74	76	72
70	72	71
87	83	85
82	84	81
72	72	69
82	81	83
90	89	89
93	92	93
89	86	85
85	84	85
75	75	73
82	82	80
95	92	91
84	83	84
84	83	83
84	82	82
78	78	78
89	88	86
89	89	87
84	84	83
84	82	82

Appendix A.9
Individual data for ART for 1000-Hz (tonal) activator for younger and older subjects for various durations (in msec)

Id	T_12ms	T_25ms	T_50ms	T_100ms
1	114	109	106	99
2	118	111	105	96
3	119	110	102	100
4	121	110	108	105
5	119	106	102	97
6	109	102	97	95
7	121	114	96	95
8	118	114	103	101
9	116	114	109	101
10	98	95	92	87
11	114	107	100	95
12	121	112	106	102
13	121	116	108	106
14	118	110	114	105
15	117	112	109	107
16	116	114	112	111
17	109	103	96	90
18	121	121	117	115
19	121	121	110	109
20	112	107	105	99
21	108	92	90	85
22	110	113	106	102
23	115	117	116	111
24	101	98	91	83
25	121	108	105	101
26	121	117	112	112
27	117	108	107	101
28	121	121	118	116
29	96	92	92	91
30	114	99	98	93
31	119	112	104	100
32	118	114	114	110
33	117	112	111	95
34	116	109	103	103
35	113	111	108	106
36	103	96	93	91
37	113	108	100	96
38	118	114	107	110
39	102	96	92	89
40	115	113	111	113

T_200ms	T_300ms	T_500ms	T_1000ms
95	93	91	92
82	88	91	89
92	86	86	85
101	93	92	93
97	95	94	93
92	91	90	91
93	93	91	91
97	95	95	96
96	93	93	93
86	85	81	81
92	88	90	90
99	94	95	98
106	101	102	103
97	95	95	92
106	102	101	102
105	98	96	96
88	87	87	85
104	102	100	94
105	104	102	102
96	97	93	93
83	80	79	79
101	95	93	93
94	87	87	85
80	78	75	75
99	94	94	93
110	111	110	106
101	97	95	92
109	103	101	100
89	88	85	88
93	91	89	87
91	87	86	87
109	107	100	99
86	85	85	84
95	96	92	90
105	99	99	97
86	82	84	82
94	95	92	91
99	93	91	89
91	89	89	89
109	105	107	102

Appendix B

Research Consent Form

(page 1 of 2)

Subject Name: ______________________________ **Date:** ______________

Title of Study: Age-Related Effects or Changes on Temporal Integration of the Acoustic-Reflex Threshold

Investigator: Michele B. Emmer, M.Phil. **Affiliation:** Brooklyn College, CUNY

Test Site: Brooklyn College, CUNY

DESCRIPTION OF RESEARCH

1. **Purpose of the study and how long it will last.** There is a small muscle in the middle ear as indicated on the attached diagram. This muscle is connected to the bones of the middle ear. The muscle contracts when a sound as loud as normal speech is introduced into the ear. The contraction causes the ear to reject loud sounds. This muscle, therefore, serves a protective function in the human. The determination of whether this muscle is functioning for a given person is part of a routine hearing evaluation. This evaluation is made because if there is a problem in the middle ear, this middle-ear muscle will not function. In this study, we wish to learn about the behavior of this muscle for short-duration sounds (sounds that last less than 1 second) in the younger (18 to 29 years of age) versus older (59 to 75 years of age) population. Previous studies only examined the behavior of this muscle for durations over 1 second. The sounds to be introduced to the ear will be (a) tones and (b) noise - both presented at comfortable levels. Understanding the effect of age on the contraction of the muscle in response to these short-duration sounds may help us clinically both in terms of diagnosis, and for the prediction of hearing loss in the older population. In addition, our knowledge of the function of the middle-ear muscle will be enhanced. The test session will last approximately 1.5 hours.
2. **Description of the study including procedures to be used.** Procedures to be used include (a) conventional hearing testing including hearing for tones through the earphones and (b) routine testing of middle-ear function using a noninvasive instrument which introduces sound and air into your outer ear. (Description of the study is elaborated upon in the section above).
3. **Description of any procedures that may result in discomfort or inconvenience.** The sound will be introduced at a very low level until we see a response. Although it is very unusual, some people will experience a little discomfort. Simply signal us to stop.
4. **Expected risks of the study.** There are no risks.
5. **Expected benefits of the study.** Further knowledge with respect to diagnosis, prediction of hearing loss, and function of the middle-ear muscle.
6. **Other treatment available.** None.

Subject's Initials ______________

Research Consent Form

7. **Use of research results.** Complete confidentiality will be preserved and you will not be identified in any distribution of the findings of this study. Each subject will have his own file that will be kept in the locked office of Dr. Shlomo Silman (faculty advisor). A number will be assigned to each file against the name. The anonymous numbers will also be kept in the lab.
8. **Special circumstances.** None
9. **Payment:** Subjects will be paid $20.00 if they meet the criteria and subsequently participate in the study. If they terminate testing prior to completion, they will still receive $20.00.

RESEARCH SUBJECTS' RIGHTS: I have read or have had read to me all of the above. Michele Emmer has explained the study to me and has answered all of my questions. I have been told of the risks or discomforts and possible benefits of the study.

I understand that I do not have to take part in this study, and my refusal to participate will involve no penalty or loss of services to which I am entitled. I may withdraw from this study at any time without penalty or loss of any services to which I am entitled.

The results of this study may be published, but my records will not be revealed unless required by law.

In case there are any questions, I have been told I can call Professor Michele Emmer at 718 951-4869 during the day and at 718 951-6774 after hours. I may also call Michele Emmer's advisor, Dr. Shlomo Silman at 718 951-4869/5186. I may also call the office of Sponsored Research at 212 642-2059 (contact person: Ms. Hilry Fisher) if I need, or would like to receive, additional information about the study or about my participation as a research subject.

I understand my rights as a research subject, and I voluntarily consent to participate in this study. I understand what the study is about and how and why it is being done. I will receive a signed copy of this consent form.

______________________________	______________________
Subject's Signature	Date
______________________________	______________________
Signature of Investigator	Date

Project approved on ____________________

Use of this form will expire on ____________

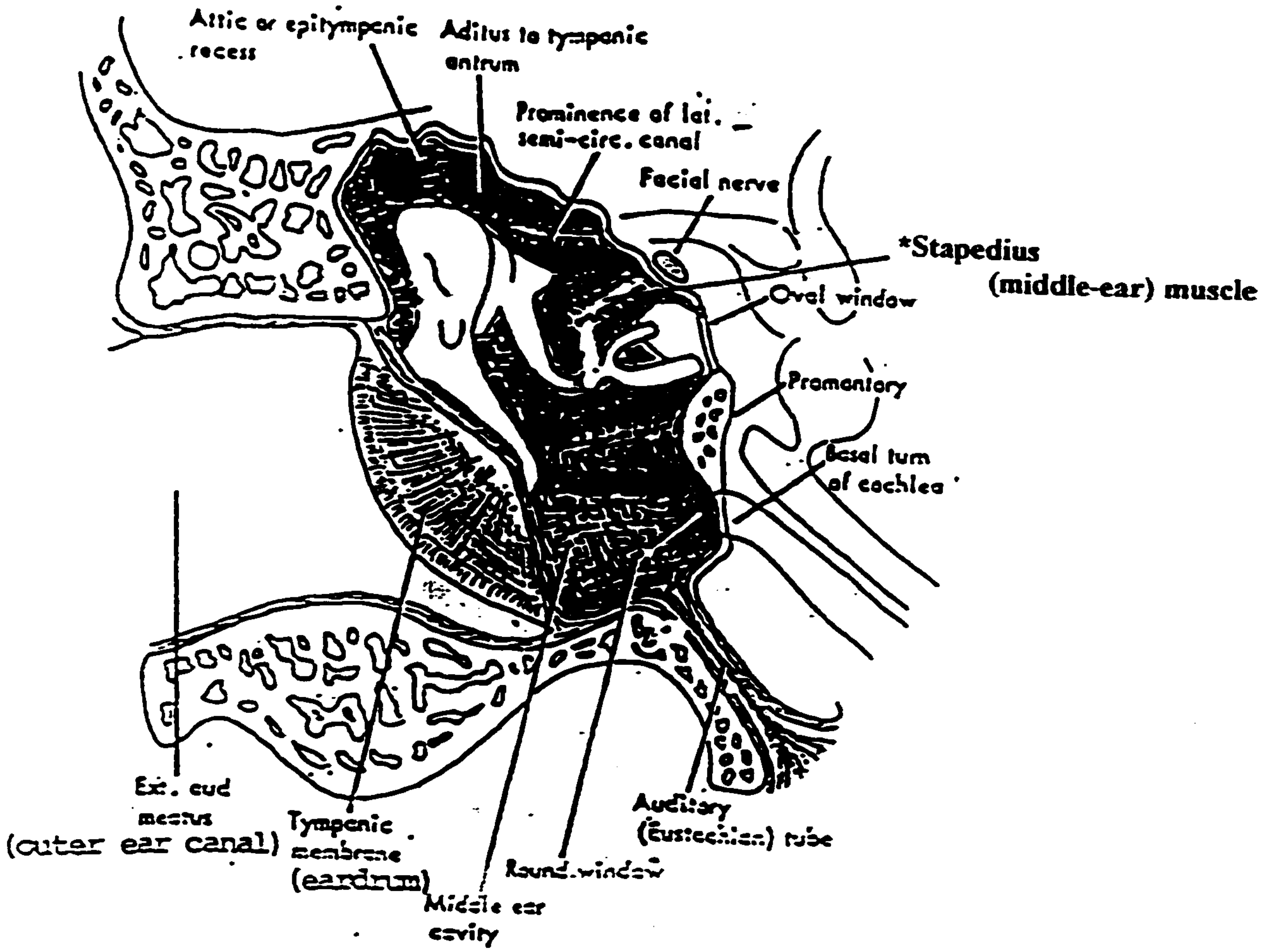


Figure 1. Stapedius muscle as it lies within the middle ear

Appendix C.1

Linear Array Recorders

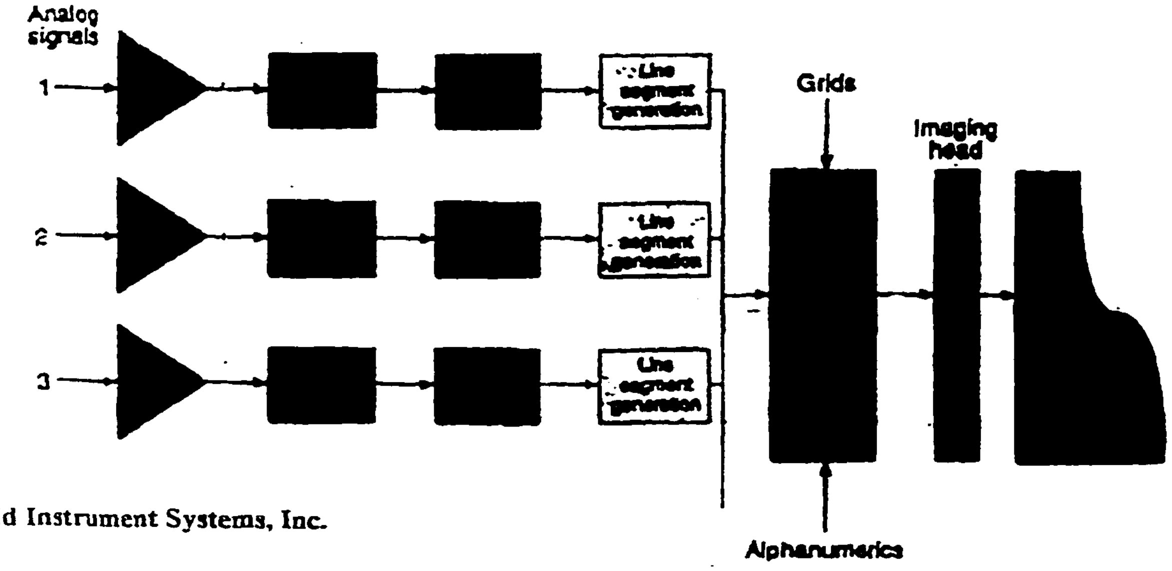
TABLE 1 Comparison of thermal and electrostatic array recorder technologies

	THERMAL ARRAY	ELECTROSTATIC ARRAY
Head Technology	Thin film on substrate	Wires molded in plastic
Max Print Width	384 mm	254 mm
Chart Paper Type	Thermoreactive	Dielectric
Other Consumables	None	Liquid toner
Archivability	Average	Excellent
Paper Cost/Foot	8¢	8¢
Chart Speed Range	1 mm/hr to 200 mm/sec	0.25 mm/sec to 500 mm/sec
Max Print Speed	1800 lines/sec	2000 lines/sec
Energy Consumption	High	Average

Linear array recorders, as the name implies, use a fixed linear array of small recording elements, under which the paper moves. This is in contrast with the conventional recorder that uses a moving pen or stylus. The stylus in the linear array recorder is a large number of fixed "styli," each one of which corresponds to one amplitude of signal to be recorded.

The obvious advantage of a linear array recorder is the absence of moving parts; nothing moves but the paper. The techniques used include:

1. **Thermal elements.**
2. **Electrostatic elements.** □

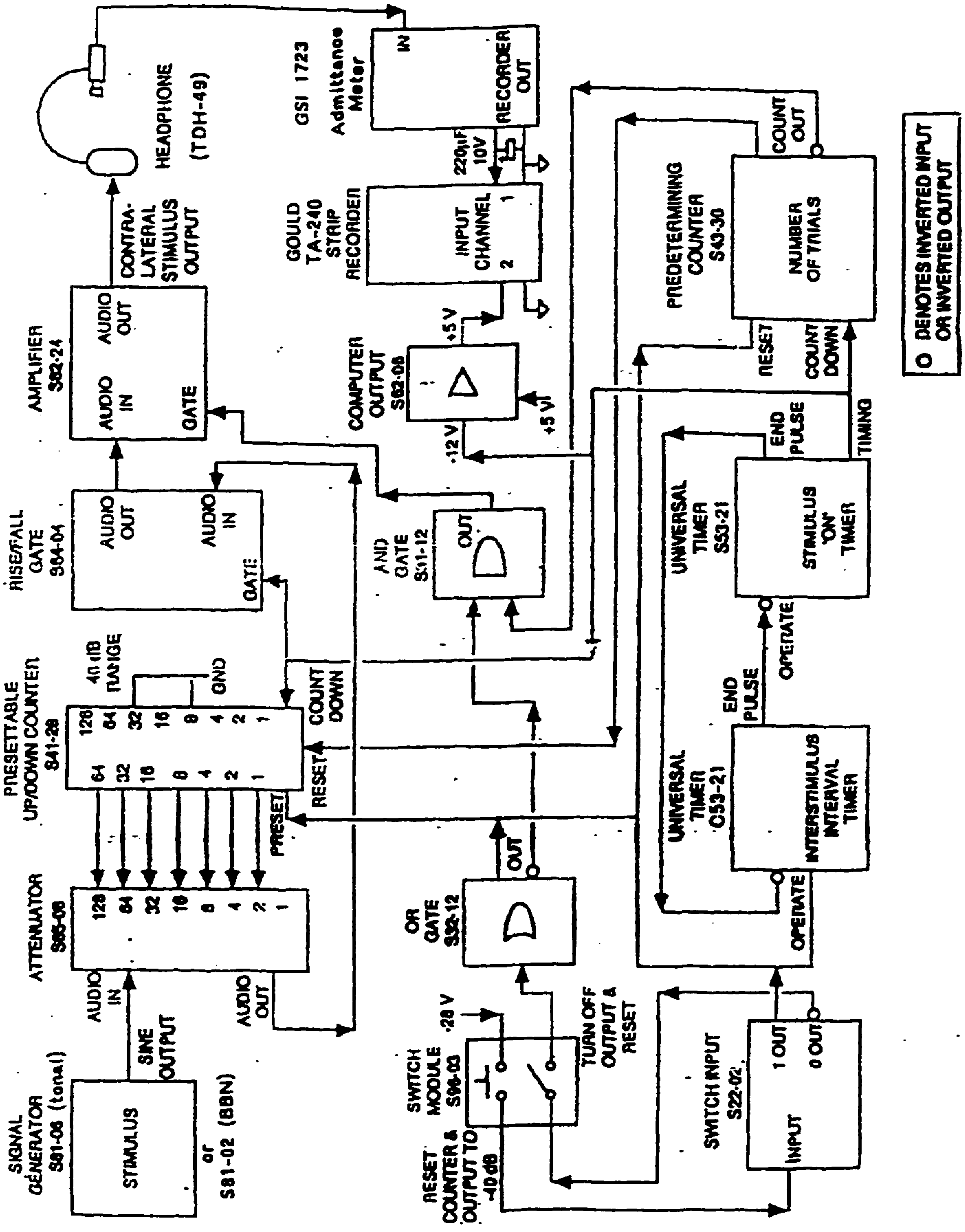


Gould Instrument Systems, Inc.

Principle of operation of array recorder. After conditioning, each signal is digitized at a high rate. Digitized samples are subsequently stored for a fixed period of time — the print cycle time. During this period, the maximum and the minimum of samples are captured and a line segment joining these two values is generated. A composite signal, made of line segments coming from each channel, actuates the imaging head drivers. Grid lines in alphanumeric character generator outputs are added to the composite signal. This signal defines which of the styli will be activated to print the dot pattern forming the elemental portions of alphanumerics, grids and signal traces. This process is repeated for every print cycle and eventually realizes a continuous recording on the chart paper.

Appendix C.2

Block diagram of instrumentation and set up



Appendix D.1

Calibration values for air-conduction signals for left and right TDH-49 earphones. Earphone output check was done at 70 dB HL.

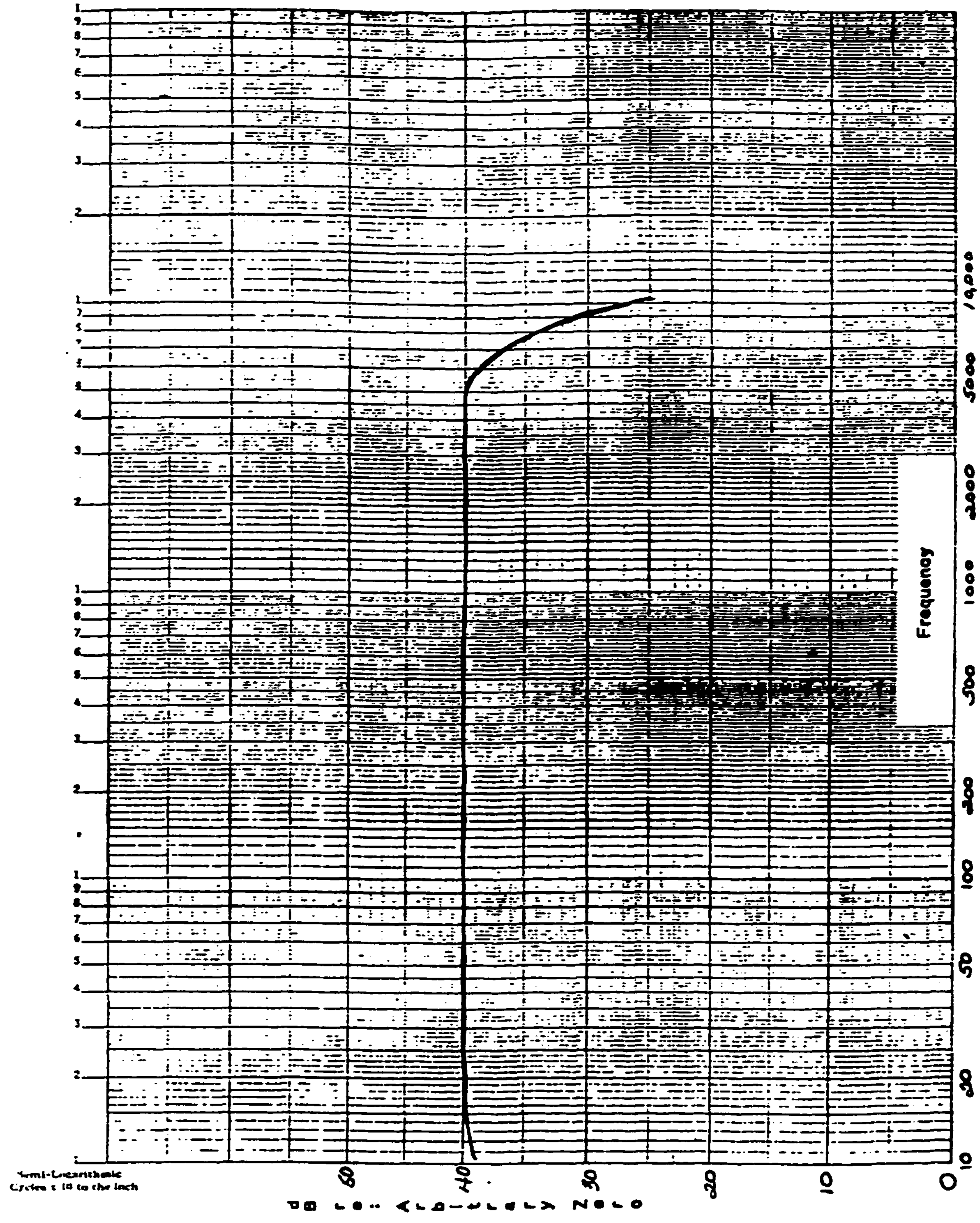
Test Tone Freq. (Hz)	Corrected Calibration Levels - ANSI - TDH-49	Left Earphone - Measured Value	Left Earphone - Variation Error	Correction	Right Earphone - Measured Value	Right Earphone - Variation Error	Correction
250	96.5	96.0	0.5	0	99.6	-3.1	-5.0
500	83.5	83.0	0.5	0	86.6	-3.1	-5.0
1000	77.5	76.7	0.8	0	80.5	-3.0	-5.0
2000	81.0	80.9	0.1	0	84.1	-3.1	-5.0
4000	80.5	81.4	-0.9	0	86.9	-6.4	-5.0
8000	82.5	84.4	-1.9	0	89.6	-7.1	-5.0

Appendix D.2

Calibration of total harmonic distortion as a function of frequency,
rise and fall characteristics of the signal, and measurement of nominal frequency

Nominal Frequency	Right Earphone (TDH-49) Rise	Right Earphone Fall	Right Earphone Frequency Count	Right Earphone Total Harmonic Distortion	Left Earphone (TDH-49) Rise	Left Earphone Fall	Left Earphone Frequency Count	Left Earphone Total Harmonic Distortion
250	38	44	252	-41.3	24	24	253	-55.7
500	22	25	502	-43.2	27	22	503	-58.0
1000	31	18	1000	-38.8	26	18	1000	-52.1
2000	25	26	1992	-62.2	26	26	1992	-56.1
4000	27	27	3982	-51.9	21	21	3981	-56.3
8000	13	16	7936	-39.8	31	34	7929	-45.6

Appendix D.3
Frequency response of TDH-49 earphone



REFERENCES

Abahazi, DA & Greenberg, HJ. (1977). Clinical acoustic reflex threshold measurements in infants. *Journal of Speech and Hearing Research*, 42:515-519.

Anderson, H, Barr, B, & Wedenberg, E. (1969). Intra-aural reflexes in retrocochlear lesions. In CA Hamberger & J. Wersall (Eds.), *Nobel Symposium 10, Disorders of the skull base region, pp. 48-54.* Stockholm: Almquvist & Wikell.

Anderson, H, Barr, B, & Wedenberg, E. (1970). Early diagnosis of VIIIth-nerve tumours by acoustic reflex tests. *Acta Oto-Laryngologica*, 262:232-237.

American National Standards Institute (1977). Criteria for permissible ambient noise during audiometric testing. *ANSI* S3.1-1977. New York: American National Standards Institute.

American National Standards Institute (1981). American national standard for reference equivalent threshold force levels for audiometric bone vibrators. *ANSI* S3.26-1981. New York: American National Standards Institute.

American National Standards Institute (1989). American national standard specification for audiometers. *ANSI* S3.6-1989. New York: American National Standards Institute.

Barry, SJ & Resnick, SB. (1976). Comparison of acoustic reflex and behavioral thresholds as a function of stimulus frequency and duration. *Journal of the American Auditory Society*, 2:35-37.

Baust, W & Berlucchi, G. (1964). Reflex response of cat's tensor tympani during sleep and wakefulness and the influence thereon of the auditory cortex. *Archives Italiennes de Biologic*, 102:686:712.

Bazorov, VG & Moroz, B. (1975). Dependence of the acoustic reflex threshold on the duration of the noise stimulus (in Russian). *Vestnik Otorinolaringoligii*, 3:13-18.

Beattie, RC & Leamy DP. (1975). Otoadmittance: Normative values, procedural variables, and reliability. *Journal of the American Auditory Society*, 1:21-27.

Beedle, RK & Harford, ER. (1973). A comparison of acoustic reflex and loudness growth in normal and pathological ears. *Journal of Speech and Hearing Research,* 16:271-281.

Bennett, MJ. (1975). Acoustic impedance bridge measurements with the neonate. *British Journal of Audiology,* 9:117-124.

Bennett, MJ & Weatherby, LA. (1979). Multiple probe frequency acoustic reflex measurements. *Scandinavian Audiology,* 8:233-239.

Bennett, MJ & Weatherby, LA. (1982). Newborn acoustic reflexes to noise and pure-tone signals. *Journal of Speech and Hearing Research,* 25:383-387.

Bennett, M. (1984). Impedance concepts relating to the acoustic reflex. In S. Silman (ed.), *The Acoustic Reflex: Basic Principles and Clinical Applications,* pp. 35-61. New York: Academic Press.

Block, M & Wightman, F. (1977). A statistically based measure of the acoustic reflex and its relation to stimulus loudness. *Journal of the Acoustical Society of America,* 61:120-125.

Blood, I & Greenberg, HJ. (1977). Acoustic admittance of the ear in the geriatric person. *Journal of the American Auditory Society,* 2:185-187.

Bluestone, CD. (1980). Assessment of eustachian tube function. In. J Jerger & JL Northern (Eds.), *Clinical Impedance Audiometry,* 2nd Ed., pp. 83-108. Acton, MA: American Electromedics Corporation.

Borg, E. (1968). A quantitative study of the effect of the acoustic stapedius reflex on sound transmission through the middle ear of man. *Acta Oto-Laryngologica,* 66:461-472.

Borg, E. (1972). The dynamic properties of the acoustic middle ear reflex in nonanesthetized rabbits. Quantitative aspects of a polysynaptic reflex system. *Acta Physiologica Scandinavica,* 86:366-387.

Borg, E. (1973). On the neuronal organization of the acoustic middle ear reflex: A physiological and anatomical study. *Brain Research,* 49:101-123.

Borg, E, Counter, SA & Rösler, G. (1984). Theories of middle-ear muscle function. In S. Silman (ed.), *The Acoustic Reflex: Basic Principles and Clinical Applications*, pp. (63-99). New York: Academic Press.

Borg, E & Møller, AR. (1975). Effects of central depressants on the acoustic middle ear reflex in rabbits. *Acta Physiologica Scandinavica*, 94:327-338.

Borg, E & Zakrisson, JE. (1975). The activity of the stapedius muscle in man during vocalization. *Acta Oto-Laryngologica*, 79:325-333.

Bosatra, A, Russolo, M & Poli, P. (1976). Oscilloscopic analysis of the stapedius muscle reflex in brain stem lesions. *Archives of Otolaryngology*, 102:284-285.

Bosatra, A, Russolo, M & Silverman, CA. (1984). Acoustic-reflex latency: State of the art. In S. Silman (Ed.), The Acoustic Reflex: Basic Principles and Clinical Applications. New York: Academic Press, pp. 301-328.

Bredberg, C. (1968). Cellular pattern and nerve supply for the human organ of Corti. *Acta Oto-Laryngologica, Supplement*, 236:1-135.

Brooks, DN. (1980). Impedance in screening. In J Jerger & JL Northern (Eds.), *Clinical Impedance Audiometry*, 2nd Ed., pp. 164-182. Acton, MA: American Electromedics Corporation.

Brown, AM, McDowell, B & Forge. (1989). Acoustic distortion products can be used to monitor the effects of chronic gentamicin treatment. *Hearing Research*, 42:143-156.

Brownell, WE. (1990). Outer hair cell electromotility and otoacoustic emissions. *Ear and Hearing*, 11:82-92.

Cacace, AT, Margolis, RH & Relkin, EM. (1991). Threshold and suprathreshold temporal integration effects in the crossed and uncrossed human acoustic stapedius reflex. *Journal of the Acoustical Society of America*, 89:1255-1261.

Clemis, JD, & Sarno, CN. (1980). The acoustic reflex latency test: clinical application. *Laryngoscope*, 90:601-611.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* (2nd edition). New Jersey: Lawrence Erlbaum Associates, Publishers.

Colletti, V, Fiorino, F, Bruni, L & Biasi, D. (1997). Middle ear mechanics in subjects with rheumatoid arthritis. *Audiology*, 36:136-146.

Corso, JF. (1963a). Aging and auditory thresholds in men and women. *Archives of Environmental Health*, 6:350-356.

Corso, JF. (1963b). Age and sex differences in pure-tone thresholds. *Archives of Otolaryngology*, 77:385-405.

Corso, JF. (1971). Sensory processes and age effects in normal adults. *Journal of Gerontology*, 26:90-105.

Courville, J. (1966). Rubrobulbar fibres to the facial nucleus and the lateral reticular nucleus (nucleus of the lateral funiculus). An experimental study in the cat with silver impregnation methods. *Brain Research*, 1:317-337.

Dallos, PJ. (1988). Cochlear neurobiology: Revolutionary developments. *American Speech-Language-Hearing Association*, 30:50-56.

Dallos, PJ. (1964). Dynamics of the acoustic reflex: Phenomenological aspects. *Journal of the Acoustical Society of America*, 36:2175-2183.

Dallos, PJ, Harris, DM, Relkin E, & Cheatham, MMMA. (1980). Two-tone suppression and intermodulation distortion in the cochlea: Effect of outer hair cell lesions. In G van den Brink & FA Blisen (Eds.), *Psychophysical, physiological and behavior studies of hearing* (pp. 242-252). Delft, The Netherlands: Delft University Press.

Deutsch, LJ. (1972). The threshold of the stapedius reflex for pure tone and noise stimuli. *Acta Otolaryngology*, 74:248-251.

Djupesland, G. (1964). Middle ear muscle reflexes elicited by acoustic and nonacoustic stimulation. *Acta Oto-Laryngologica, Supplement*, 188.

Djupesland, G & Zwislocki, JJ. (1971). Effect of temporal integration on the human stapedius reflex. *Acta Oto-Laryngologica*, 71:262-265.

Djupesland, G, Sundby, A & Flottorp, G. (1973). Temporal summation in the acoustic stapedius reflex mechanism. *Acta Oto-Laryngologica*, 76:305-312.

Djupesland, G, Flottorp, G & Winther, FO. (1967). Size and duration of acoustically elicited impedance changes in man. *Acta Oto-Laryngologica, Supplement*, 224:220-228.

Djupesland G, & Zwislocki JJ. (1973). On the critical band in the acoustic stapedius reflex. *Journal of the Acoustical Society of America*, 54:1157-1159

Ekman, E, Berglund G, & Berglund, V. (1966). Loudness as a function of duration of auditory stimulation. *Scandinavian Journal of Psychology*, 7:201-208.

Eliasson, S & Gisselsson, L. (1955). Electromyographic studies of middle ear muscles in the cat. *Electroencepholography and Clinical Neurophysiology*, 7:399-406.

Emmer, MB & Silman, S. Prediction of hearing loss from the acoustic-reflex threshold for the broad-band noise activator in multiply handicapped children. In preparation.

Etholm B & Belal, A, Jr. (1974). Senile changes in the middle ear joints. *Annals of Otology*, 83:49-54.

Evans, EF. (1974). Auditory frequency selectivity and the cochlear nerve. In E Zwicker & E Terhardt (Eds.). *Facts and models in hearing* (118-129). Berlin, Germany: Springer-Verlag.

Feldman, AS. (1975). Acoustic impedance-admittance measurements. In LJ Bradford (ed.), *Physiological Measures of the audiovestibular system*. New York: Academic Press.

Feldman, AS. (1976). Tympanometry-Procedures, interpretation and variables. In AS Feldman & LA Wilber (Eds.), *Acoustic impedance and admittance: The measurement of middle ear function*, pp. 103-155. Baltimore: Williams & Wilkins.

Feldman, AS & Katz, D. (1978). Effects of stimulus duration and stimulus off time on the auditory and acoustic reflex thresholds. *Journal of Speech and Hearing Research*, 21:74-78.

Fiellau-Nikolajsen, M. (1983). Tympanometry and secretory otitis media. *Acta Oto-Laryngologica. Supplement*, 394:1-73.

Flottorp, G, Djupesland, G & Winther, FO. (1971). The acoustic stapedius reflex in relation to critical bandwidth. *The Journal of the Acoustical Society of America*, 49:457-461.

Forquer, BC. (1979). The stability of and the relationship between the acoustic reflex and uncomfortable loudness levels. *Journal of the American Auditory Society*, 5:55-59.

Galambos, R, & Rupert, AL. (1959). Action of the middle-ear muscles in normal cats. *Journal of the Acoustical Society of America*, 31:349-355.

Gates, GA, Cooper, JC, Kannel, WB & Miller, NJ. (1990). Hearing in the elderly: The Framingham cohort, 1983-1985. *Ear and Hearing*, 11:247-256.

Gelfand, SA. (1981). *Hearing: An Introduction to Psychological and Physiological Acoustics.* New York: Marcel Dekker.

Gelfand, SA. (1984). The contralateral acoustic-reflex threshold. In S. Silman (Ed.), *The Acoustic Reflex: Basic Principles and Clinical Applications.* New York: Academic Press, pp. 137-186.

Gelfand, SA & Piper, N. (1981). Acoustic-reflex thresholds in young and elderly subjects with normal hearing. *Journal of the Acoustical Society of America*, 69:295-297.

Gelfand, SA, Piper, N & Silman, S. (1983). Effects of hearing levels at the activator and other frequencies upon the expected levels of the acoustic reflex threshold. *Journal of Speech and Hearing Disorders*, 48:11-17.

Gelfand, SA, Silman, S & Silverman, CA. (1981). Temporal summation in acoustic reflex growth functions. *Acta Oto-Laryngologica*, 91:177-182.

Givens, G & Seidemann, M. (1979). A systematic investigation of measurement parameters of acoustic-reflex adaptation. *Journal of Speech and Hearing Disorders*, 44:534-542.

Goodman, AL & Richards, AM. (1977). Temporal summation of the human acoustic reflex. I. Variabilities. *The Journal of Auditory Research*, 17:191-203.

Gordon-Salant S, & Fitzgibbons, PJ. (1993). Temporal factors and speech recognition performance in young and elderly listeners. *Journal of Speech and Hearing Research*, 36:1276-1285.

Gorga, MP, Neely, ST, Ohlrich, B, Hoover, B, Redner, J & Peters, J. (1997). From laboratory to clinic: A large scale study of distortion product otoacoustic emissions in ears with normal hearing and ears with hearing loss. *Ear and Hearing*, 18(6):440-455.

Green, KW, & Margolis, RH. (1983). Detection of hearing loss with ipsilateral acoustic reflex thresholds. *Audiology*, 22:471-479.

Green, KW & Margolis, RH. (1984). The ipsilateral acoustic reflex. In S. Silman (Ed.), *The Acoustic Reflex: Basic Principles and Clinical Applications*, pp. 275-299. New York: Academic Press.

Hall, JW & Weaver T. (1979). Impedance audiometry in a young population: The effect of age, sex, and tympanometric abnormalities. *Journal of Otolaryngology*, 3:210-221.

Hall, JW. (1978). Predicting hearing level from the acoustic reflex: A comparison of three methods. *Archives of Otolaryngology*, 104:601-605.

Hall, JW. (1979). Effects of age and sex on static compliance. *Archives of Otolaryngology*, 105:601-605.

Handler, SD & Margolis, RH. (1977). Predicting hearing loss from stapedial reflex thresholds in patients with sensorineural impairment. *Transactions of the American Academy of Ophthalmology and Otolaryngology*, 84:425-431.

Hansen, CC & Reske-Nielsen, E. (1965). Pathology studies in presbycusis. *Archives of Otolaryngology*, 83:115-132.

Harty, M. (1953). Elastic tissue in the middle-ear cavity. *Journal of Laryngology and Otology*, 67:723-729.

Himmelfarb, MZ, Shanon, E, Popelka, GR & Margolis, RH. (1978). Acoustic reflex evaluation in neonates. In SE Gerber & GT Mencher (Eds.), *Early Diagnosis of Hearing Loss*, pp. 109-123. New York: Grune & Stratton.

Hirsch, JE, Margolis, RH & Rykken, MA. (1992). A comparison of acoustic reflex and auditory brain stem response screening of high-risk infants. *Ear and Hearing,* 13:181-186.

Holte, L. (1996). Aging effects in multifrequency tympanometry. *Ear and Hearing,* 17:12-18.

Hung, IJ, & Dallos, P. (1972). Study of the acoustic reflex in human beings: I. Dynamic characteristics. *Journal of the Acoustical Society of America,* 52:1168-1180.

Jakimetz, JJ, Silman, S, Miller, MH & Silverman, CA. (1989). Some effects of signal bandwidth and spectral density on the acoustic reflex threshold in the elderly. *Journal of the Acoustical Society of America,* 86:1783-1789.

Jepsen, O. (1955). *Studies on the acoustic stapedius reflex in man.* Aarhus, Denmark: Universitetsforlaget.

Jepsen, O. (1963). Middle-ear muscle reflexes in man. In J. Jerger (Ed.), *Modern Developments in Audiology.* New York: Academic Press. pp. 193-239.

Jerger, J. (1970). Clinical experience with impedance audiometry. *Archives of Otolaryngology,* 92:311-324.

Jerger, J, Jerger, S & Mauldin, L. (1972). Studies in impedance audiometry I. Normal and sensorineural ears. *Archives of Otolaryngology,* 96:513-523.

Jerger, J, Anthony, L, Jerger, S & Mauldin, L. (1974a). Studies in impedance audiometry. III. Middle ear disorders. *Archives of Otolaryngology,* 99:165-171.

Jerger, J, Burney, P, Mauldin, L & Crump, B. (1974b). Predicting hearing loss from the acoustic reflex. *Journal of Speech and Hearing Disorders,* 39:22.

Jerger, J, Harford, E, Clemis, J & Alford, B. (1974). The acoustic reflex in eighth nerve disorders. *Archives of Otolaryngology,* 99:409-413.

Jerger, S, Jerger, J, Mauldin, L & Segal, P. (1974). Studies in impedance audiometry II. Children less than six years old. *Archives of Otolaryngology*, 99:1-9.

Jerger, J. (1975). Diagnostic use of impedance audiometry. In J. Jerger (Ed.), *Handbook of clinical impedance audiometry*. Dobbs Ferry, NY: American Electromedics Corporation, pp. 149-174.

Jerger, S & Jerger, J. (1975). Extra- and intra-axial brain stem auditory disorders. *Audiology*, 14:93-117.

Jerger, J, Hayes, D & Anthony, L. (1978). Effect of age on prediction of sensorineural hearing level from the acoustic reflex. *Archives of Otolaryngology*, 104:393-394.

Jerger, J, Hayes, D, Anthony, L & Mauldin, L (1978). Factors influencing prediction of hearing level from the acoustic reflex. *Maico Monographs in Contemporary Audiology*, 1:1-20.

Jerger, J, Mauldin, L & Lewis, N. (1977). Temporal summation of the acoustic reflex. *Audiology*, 16:177-200.

Jerger, J & Oliver,T. (1987). Interaction of age and intersignal interval on acoustic reflex amplitude. *Ear and Hearing*, 8:322-325.

Jerger, J, Jerger S, Oliver, T & Pirozzolo, F. (1991). Speech understanding in the elderly. *Ear and Hearing*, 10:79-89.

Johansson, B, Kylin, B & Langfy, M. (1967). Acoustic reflex as a test of individual susceptibility to noise. *Acta Oto-Laryngologica*, 64:256-262.

Johnson, NJ & Terkildsen, K. (1980). The normal middle ear reflex thresholds towards white noise and acoustic clicks in young adults. *Scandinavian Audiology*, 9:131-135.

Khanna, SM & Leonard, DGB. (1986). Relationship between basilar membrane tuning and hair cell condition. *Hearing Research*, 23:55-70.

Kaplan, H, Gilman, S & Dirks, DD. (1977). Properties of acoustic reflex adaptation. *Annals of Otology, Rhinology, & Laryngology*,64:256-262.

Keith, RW. (1973). Impedance audiometry with neonates. *Archives of Otolaryngology*, 97:465-467.

Keith, RW. (1975). Middle-ear function in neonates. *Archives of Otolaryngology*, 101:376-379.

Keith, RW. (1977). An evaluation of predicting hearing loss from the acoustic reflex. *Archives of Otolaryngology*, 103:419-424.

Keith, RW & Bench, RJ. (1978). Stapedial reflex in neonates. *Scandinavian Audiology*, 7:188-191.

Keith, RW. (1979). An acoustic reflex technique of establishing hearing aid settings. *Journal of the American Auditory Society*, 5:71-75.

Kelly, JP & Khanna, SM. (1984a). Ultrastructural damage in cochleas used for studies of basilar membrane mechanics. *Hearing Research*, 16:109-126.

Kelly, JP & Khanna, SM. (1984b). The distribution of damage in the cochlea after removal of the round window membrane. *Hearing Research*, 16:109-126.

Kiang, NY-S, Moxon, EC & Levine, RA. (1970). Auditory-nerve activity in cats with normal and abnormal cochleas. In *Sensorineural Hearing Loss* (eds GEW Wolstenholme and J. Knight), pp. 241-268. CIBA Foundation Symposium, Churchill, London.

Kimberley, BP & Nelson, DA. (1989). Distortion product emissions and sensorineural hearing loss. *Journal of Otolaryngology*, 18:365-369.

Kimberley, BP, Hernandi, I, Lee, AM & Brown, DK. (1994a). Predicting pure-tone thresholds in normal and hearing-impaired ears with distortion product emission and age. *Ear and Hearing*, 15:199-209.

Kimberley, BP, Kimberley BM, & Roth, L. (1994b). A neural network approach to the prediction of pure-tone thresholds with distortion product emissions. *ENT Journal*, 73:812-823.

Kirikae, I, Sato T, & Shitara, T. (1964). A study of hearing in advanced age. *Laryngoscope*, 74:205-220.

Klockhoff, I. (1961). Middle ear muscle reflexes in man. *Acta Oto-Laryngologica, Supplement*, 154.

Korabic, EW & Cudahy, EA. (1984). Acoustic reflex temporal summation measured at threshold. *Ear and Hearing,* 5:331-339.

Leonard, DGB & Khanna, SM. (1984). Histological evaluation of damage in cat cochleas used for measurement of basilar membrane mechanics. *Journal of the Acoustical Society of America,* 75:515-527.

Liberman, MC & Dodds, LW. (1984). Single-neuron labeling and chronic cochlear pathology. III. Stereocilia damage and alterations of threshold tuning curves. *Hearing Research,* 16:55-74.

Lilly, D, & Franzen, R. (1970). Threshold of acoustic reflex for pure tones. *ASHA,* 12:435(A).

Liberman, MC & Dodds, LW. (1984). Single-neuron labeling and chronic cochlear pathology. III. Stereocilia damage and alterations of threshold tuning curves. *Hearing Research,* 16:55-74.

Liberman, MC & Kiang, N Y-S. (1978). Acoustic trauma in cats: Cochlear pathology and auditory-nerve activity. *Acta Otolaryngologica Supplement,* 358:1-63.

Lipscomb, DN, Axelsson, A, Vertes, D, Roettger, R & Carroll, S. (1977). The effect of high level sound on hearing sensitivity, cochlear sensorineuroepithelium and vasculature of the chinchilla. *Acta Oto-Laryngologica,* 84:44-56.

Lonsbury-Martin, BL, Cutler, WM & Martin, GK. (1991). Evidence for the influence of aging on distortion-product otoacoustic emissions in humans. *Journal of the Acoustical Society of America,* 89:1749-1759.

Lorente de Nó., R. (1935). The function of the central acoustic nuclei examined by means of the acoustic reflexes. *Laryngoscope,* 45:573-595.

Lutolf, JJ. (1996). The Effects of probe-tone frequency on the acoustic reflex growth function in normal-hearing listeners. *Ph.D. Dissertation.* Columbia University, New York.

Lynn, DJ. (1988). The effects of age on acoustic reflex adaptation. *Ph.D. Dissertation.* Graduate School and University Center, City University of New York.

Mangham, CA, Lindeman, RC & Dawson, WR. (1980). Stapedial reflex quantification in acoustic tumor patients. *Laryngoscope*, 90:242:250.

Margolis, RH. (1981). Fundamentals of acoustic immittance. In GR Popelka (ed.), *Hearing Assessment with the Acoustic Reflex*, (pp. 117-143). New York: Grune & Stratton.

Margolis, RH & Heller, JW. (1987). Screening tympanometry: Criteria for medical referral. *Audiology*, 26:197-208.

Margolis, RH & Popelka, GR. (1975a). Static and dynamic acoustic impedance measurements in infant ears. *Journal of Speech and Hearing Research*, 18:435-443.

Margolis, RH & Popelka, GR. (1975b). Loudness and the acoustic reflex. *Journal of the Acoustical Society of America*, 58:1330-1332.

Margolis, RH & Fox, CM. (1977). A comparison of three methods for predicting hearing loss from acoustic reflex thresholds. *Journal of Speech and Hearing Research*, 20:241-253.

Marshall, L. (1981). Auditory processing in aging listeners. *Journal of Speech and Hearing Disorders*, 46:226-240.

McMillan, PM, Bennett, MJ, Marchant, CD & Shurin, P. (1985). Ipsilateral and contralateral acoustic reflexes in neonates. *Ear and Hearing*, 6:320-324.

Metz, O. (1946). The acoustic impedance measured on normal and pathological ears. *Acta Otolaryngologica, Supplement*, 63:1-254.

Metz, O. (1952). Threshold of reflex contractions of muscles of middle ear and recruitment of loudness. *Archives of Otolaryngology*, 55:536-543.

Miller, GA. (1948). The perception of short bursts of noise. *Journal of the Acoustical Society of America*, 20:160-170.

Møller, AR. (1961). Bilateral contraction of the tympanic muscles in man, examined by measuring acoustic-impedance change. *Annals of Otology, Rhinology & Laryngology*, 70:735-753.

Møller, AR. (1962). Acoustic reflex in man. *Journal of the Acoustic Society of America*, 34:1524-1534.

Møller, AR. (1984). Neurophysiological basis of the acoustic middle-ear reflex. In S Silman (Ed.), *The Acoustic Reflex: Basic Principles and Clinical Applications.* New York: Academic Press, pp. 1-34.

Morgan, DE, Gilman, S & Dirks, D. (1977). Temporal integration at the "threshold" of the acoustic reflex. *Journal of the Acoustical Society of America,* 62:168-176.

Nelson, DA & Kimberley, BP. (1992). Distortion-product emissions and auditory sensitivity in human ears with normal hearing and with cochlear hearing loss. *Journal of Speech and Hearing Research,* 135:1142-1159.

Niemeyer, W & Sesterhenn, G. (1974). Calculating the hearing threshold from the stapedius reflex threshold for different sound stimuli. *Audiology,* 13:421-427.

Nozza, RJ, Bluestone, CD, Kardatzke, D & Bachman, R. (1992). Towards the validation of aural acoustic immittance measures for diagnosis of middle ear effusion in children. *Ear and Hearing, 13:442-453.*

Olsen, WO, Noffsinger D, & Kurdziel, SA. (1975). Acoustic reflex and reflex decay. *Archives of Otolaryngology,* 101:622-625.

Osterhammel, D & Osterhammel, P. (1979). Age and sex variations for the normal stapedial reflex thresholds and tympanometric compliance values. *Scandinavian Audiology,* 8:153-158.

Peterson, JL & Liden, G. (1972). Some static characteristics of the stapedial muscle reflex. *Audiology,* 11:97-114.

Pickles, JA. (1988). *An introduction to the physiology of hearing,* pp. 236-246. San Diego: Academic Press.

Plomp, R & Bouman, MA. (1959). Relation between hearing threshold and duration for pure tones. *Journal of the Acoustical Society of America,* 31:749-758.

Popelka, GR, Margolis, RH & Wiley, TL.(1976). The effect of activating signal bandwidth on acoustic reflex thresholds. *Journal of the Acoustical Society of America,* 59:153-159.

Popelka, GR. (ed). (1981). *Hearing assessment with the acoustic reflex.* New York: Grune and Stratton.

Price, GR. (1963). Middle ear muscle activity in the rabbit. I. The loss threshold. *Journal of Auditory Research,* 3:221-231.

Price, GR. (1966). Middle ear muscle activity in the rabbit. III. Suprathreshold phenomena. *Journal of Auditory Research,* 6:175-180.

Quest Electronics. Model 155 impulse precision sound-level meter & Model OB-145 octave-band filter. Manual.

Rasmussen, GL. (1946). The olivary peduncle and other fiber projections of the superior olivary complex. *Journal of Comparative Neurology,* 84:141-219.

Reger, SN. (1960). Effect of middle-ear muscle action on certain psychophysical measurments. *Annals of Otology, Rhinology, & Laryngology,* 69:1179-1198.

Richards, AM. (1975). Threshold of the acoustic stapedius reflex for short-duration tone bursts. *Journal of Auditory Research,* 15:87-94.

Richards, AM. (1977). Loudness perception for short-duration tones in masking noise. *Journal of Speech and Hearing Research,* 20:684-693.

Ritter, R, Johnson, RM & Northern, JL. (1979). The controversial relationship between loudness discomfort levels and acoustic reflex thresholds. *Journal of the American Auditory Society,* 4:123-131.

Robinette, MS, Rhoads, DP & Marion, MW. (1974). Effects of secobarbitol on impedance and audiometry. *Archives of Otolaryngology,* 100:351-354.

Rosenhall, U, Lidén, G & Nelsson, E. (1979). Stapedius reflex decay in normal hearing subjects. *Journal of the American Auditory Society,* 4:157-163.

Ruth, RA & Niswander, PS. (1976). Acoustic reflex latency as a function of frequency and intensity of eliciting stimulus. *Journal of the American Auditory Society,* 2:54-60.

Saloman, G & Starr, A. (1963). Electromyography of middle ear muscles in man during motor activities. *Acta Neurologica Scandinavia,* 39:161-168

Schow, RL, Christensen, JM, Hutchinson, JM and Nerbonne, MA. (1978). *Communication disorders of the aged.* Baltimore: University Park Press.

Schuknecht, HF. (1955). Presbycusis. *Laryngoscope,* 65:402-419.

Schuknecht, HF. (1964). Further observations on the pathology of presbycusis. *Archives of Otolaryngology,* 80:369-382.

Schuknecht, HF. (1967). The effect of aging on the cochlea. In A Graham Bruce (Ed.), *Sensorineural hearing process and disorders.* Boston: Little & Brown.

Sells, JP, Hurley, RM, Morehouse, CR & Douglas, JE. (1997). Validity of the ipsilateral acoustic reflex as a screening procedure. *Journal of the American Academy of Audiology,* 8:132-136.

Silman, S, Popelka, GR & Gelfand, SA. (1978). Effect of sensorineural hearing loss on acoustic stapedius reflex growth functions. *Journal of the Acoustical Society of America,* 64:1406-1411.

Silman, S. (1979a). The effects of aging on the stapedius reflex thresholds. *Journal of the Acoustical Society of America,* 66:735-738.

Silman, S. (1979b). The acoustic reflex, aging, and the distortion product. *Journal of the Acoustical Society of America,* 66:909-910.

Silman, S & Gelfand, SA. (1979). Prediction of hearing levels from acoustic reflex thresholds in persons with high-frequency hearing losses. *Journal of Speech and Hearing Research,* 22:697-707.

Silman, S, & Gelfand, SA. (1981a). Effect of sensorineural hearing loss on the stapedius reflex growth function in the elderly. *Journal of Acoustical Society of America,* 69:1099-1106.

Silman, S & Gelfand, SA. (1981b). The relationship between magnitude of hearing loss and acoustic reflex threshold levels. *Journal of Speech and Hearing Disorders,* 46:312-316.

Silman, S & Gelfand, SA. (1982). The acoustic reflex in diagnostic audiology - Part 2. *Audiology,* 7:125-138.

Silman, S (Ed.). (1984). *The acoustic reflex: Basic principles and clinical applications.* New York: Academic Press.

Silman, S, Gelfand, SA, Piper, N, Silverman, CA & Van Frank, L. (1984). Prediction of hearing loss from the acoustic-reflex threshold. In S Silman (ed.), *The Acoustic Reflex: Basic Principles and Clinical Applications*, pp. 187-223. New York: Academic Press.

Silman, S & Silverman, CA. (1991). *Auditory diagnosis: Principles and applications.* San Diego: Academic Press.

Silman, S, Silverman, CA, Showers T, & Gelfand, SA. (1984b). The effect of age on prediction of hearing loss with the bivariate plotting procedure. *Journal of Speech & Hearing Research*, 27: 12-19.

Silman, S, Gelfand, SA & Emmer, MB. (1987). Acoustic reflex in hearing loss identification and prediction. *Seminars in Hearing*, 3:379-390.

Silman, S, Silverman, CA & Arick DS. (1992). Acoustic-immittance screening for detection of middle-ear effusion in children. *Journal of the American Academy of Audiology*, 3:262-268.

Silman, S & Emmer, MB. (1995). The ipsilateral acoustic reflex in middle-ear effusion. *Seminars in Hearing*, 16:80-85.

Silverman, CA. (1982). The relation of age and sex to the acoustic reflex threshold. Ph.D. Dissertation, New York University, New York.

Silverman, CA, Silman, S & Miller, MH. (1983). The acoustic reflex threshold in aging ears. *Journal of the Acoustical Society of America*, 73:248-255.

Singh, D & Greenberg, HJ. (1976). Temporal summation of the acoustic reflex in normal and sensorineural hearing-impaired ears. *Journal of the American Auditory Society*,
2:8-14.

Small, AM, Brandt, JF & Cox, PG. (1962). Loudness as a function of signal duration. *Journal of the Acoustical Society of America*, 34:513-514.

Smith, HD. (1943). Audiometric effects of voluntary contraction of the tensor tympani muscles. *Archives of Otolaryngology*, 38:369-372.

Smith, DW, Moody, DB, Stebbins, WC & Norat, MA. (1987). Effects of outer hair cell loss on the frequency selectivity of the patas monkey auditory system. *Hearing Research,* 29:125-138.

Spoor, A. (1967). Presbycusis values in relation to noise induced hearing loss. *International Audiology,* 6:48-57.

Sprague, BH, Wiley, TL & Goldstein, R. (1985). Tympanometric and acoustic-reflex studies in neonates. *Journal of Speech and Hearing Research,* 28:265-272.

Stach, BA & Jerger, JF. (1984). Acoustic reflex averaging. *Ear and Hearing,* 5:289-296.

Statistical Package for the Social Sciences. SPSS, Inc., Chicago, Illinois

Stevens, SS. (1955). The measurement of loudness. *Journal of the Acoustical Society of America,* 27:815-829.

Stover, L, & Norton, (1993). The effects of aging on otoacoustic emissions. *Journal of the Acoustical Society of America,* 94:2670-2681.

Stream, R, Stream, K, Walker, J & Breningstall, G. (1978). Emerging characteristics of the acoustic reflex in the neonate. *Otolaryngology, Head and Neck Surgery,* 86:628-636.

Terkildsen, K, Osterhammel, P & Bertlau, P. (1973). Acoustic middle ear reflexes in patients with otosclerosis. *Archives of Otolaryngology,* 98:152-155.

Thompson, DJ, Sills, JA, Recke, KS & Bui, DM. (1980). Acoustic reflex growth in the aging adult. *Journal of Speech and Hearing Research,* 23:405-418.

Van Camp, KJ, Margolis, RH, Wilson, RH, Creten, WL & Shanks, JE. (1986). Principles of Tympanometry. *ASHA Monograph No. 24.* Rockville, Maryland: American Speech-Language-Hearing Association.

Wallin, A, Mendez-Kurtz, L & Silman, S. (1986). Prediction of hearing loss from acoustic reflex thresholds in the older adult population. *Ear and Hearing,* 7:400-404.

Ward, WD. (1961). Studies on the aural reflex. *Journal of the Acoustical Society of America*, 33:1034-1045.

Weatherby, LA & Bennett, MJ. (1980). The neonatal acoustic reflex. *Scandinavian Audiology*, 9:103-110.

Wersäll, R. (1958). The tympanic muscles and their reflexes. *Acta Oto-Laryngologica, Supplement*, 139:1-112.

Wever, EG & Bray, CW. (1937). The tensor tympani muscle and its relation to sound conduction. *Annals of Otology, Rhinology, & Laryngology*, 46:947-961.

Wever, EG & Bray, CW. (1942). The stapedius muscle in relation to sound conduction. *Journal of Experimental Psychology*, 31:35-43.

Wiley, TL, Cruickshanks, KJ, Nondahl, DM, Tweed, TS, Klein, R & Klein, BEK. (1996). Tympanic measures in older adults. *Journal of the American Academy of Audiology*, 7:260-268.

Wiley, TL & Karlovich, RS (1975). Acoustic reflex response to sustained signals. *Journal of Speech and Hearing Research*, 18:148-157.

Wilson, RH. (1979). Factors influencing the acoustic-immittance characteristics of the acoustic reflex. *Journal of Speech and Hearing Research*, 22:480-499.

Wilson, R. (1981). The effects of aging on the magnitude of the acoustic reflex. *Journal of Speech and Hearing Disorders*, 24:406-414.

Wilson, RH, Shanks, JE & Velde, TM. (1981). Aural acoustic-immittance measurements: Inter-aural differences. *Journal of Speech and Hearing Disorders*, 46:413-421.

Wilson, RH, Steckler, JF, Jones, HC & Margolis, RH. (1978). Adaptation of the acoustic reflex. *Journal of the Acoustical Society of America*, 64:782-791.

Wilson, RH, Shanks, JE & Lilly, DJ. (1984). Acoustic-reflex adaptation. In S Silman (Ed.), *The Acoustic Reflex: Basic Principles and clinical applications*, pp. 329-386. New York: Academic Press.

Woodford, C, Henderson,R, Hamernik, R & Feldman, A. (1975). Threshold-duration function of acoustic reflex in man. *Audiology*, 14:53-62.

Wright, HN. (1972). Temporal summation for tones at threshold. *Journal of the Acoustical Society of America*, 53:313(A).

Zakrisson, JE, Borg, E & Blom, S. (1974). The acoustic impedance change as a measure of stapedius muscle activity in man. A methodological study with electromyography. *Acta Oto-Laryngologica*, 78:357-364.

Zakrisson, JE. (1975). The role of the stapedius reflex in poststimulatory auditory fatigue. *Acta Oto-Laryngologica*, 79:1-10.

Zito, F & Roberto, M. (1980). The acoustic reflex pattern studied by the averaging technique. *Audiology*, 19:395-403.

Zwislocki, JJ. (1960). Theory of temporal auditory summation. *Journal of the Acoustical Society of America*, 32:1046-1060

Zwislocki, JJ. (1969). Temporal summation of loudness. *Journal of the Acoustical Society of America*, 46:431-441.