MIDDLE EAR RESONANT FREQUENCY VALUES IN GERIATRIC SUBJECTS: A MULTIFREQUENCY TYMPANOMETRIC STUDY

By

CATHERINE LOUISE LEBLOND

B.Sc., McGill University, 1988

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

School of Audiology and Speech Sciences

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

December 1990

Department of AUDIOLOGY & SPEECH SCIENCES.

The University of British Columbia
Vancouver, Canada

Date DEC. 11, 1990.

ABSTRACT

Based on anatomical changes known to occur in the middle ear with aging, the purpose of this study was to compare middle ear resonant frequency values of geriatric subjects to those of young adults. Measurements were obtained with two different methods: sweep frequency tympanometry and discrete multifrequency tympanometry. Results from the two methods of measurement were also compared. Furthermore, intra-subject, inter-judge, and longitudinal reliability were examined for each measurement method.

Results showed no significant difference between the two age groups. However, resonant frequency values obtained with the two measurement methods differed significantly ($p < 0.05$). Intra-subject and longitudinal reliability measures were significantly higher for the discrete multifrequency method than for the sweep frequency method. Inter-judge reliability was 95% for both measurement methods.

We therefore concluded that age does not have a significant effect on middle ear resonant frequency values. It follows that normative resonant frequency data can be applied to adults of all age groups. Furthermore, the method used to measure resonant frequency has a significant effect on the values obtained, and comparisons of resonant frequency data should not be made across measurement methods. Although we were unable to determine which measurement method is most valid, the discrete multifrequency method is more reliable within subjects and over time.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to sincerely thank my supervisor, Ellen Levi, for her support, patience, and guidance. Her dedication to this project was complete, and her constant encouragement was of great help.

I also give my appreciation to Dr. Don Greenwood for serving on my committee.

Dr. Ruth McIlrath performed forty otoscopic examinations for the purpose of this study. Her time and enthusiasm were greatly appreciated.

Special thanks to all subjects who volunteered their time to this study.

Finally, I would like to thank my parents for their continual support and optimism throughout my studies.

CHAPTER 1

INTRODUCTION

The average age of Canada's population is increasing at a rapid rate. By the year 2021, it is expected that one-half of the population of Canada will be more than 40 years old, and 17% will be over 65 (Roadburg, 1985). Aging, of course, is not a disease, but rather a continuation of life with a progressive deterioration in physiological function and loss of adaptability to a changing environment (Rowlatt and Franks, 1978). Many theories of aging have been proposed, and the exact cause for the physiological processes that cause senescence remains unclear. Some theories claim that aging is regulated by genetic factors, while others attribute aging to the accumulation of injuries to cells with time (Norwood, 1990). It is known that the absolute number of cells diminishes with age and that many of those which remain do not function properly. These factors affect organs and tissues, and eventually lead to their deterioration and breakdown (Vander et al., 1985).

The rapid increase in average age presents a number of challenging health problems. Hearing loss is one such problem that affects a great majority of geriatric patients. Hearing loss due to aging (that is, presbycusis) is usually caused by cochlear damage and results in sensorineural hearing loss. In addition, there have been reports of age-related structural changes in the middle ear. While it is known that conductive hearing loss does not result from these changes, anatomical changes do affect the physical properties of the middle ear system, and thereby predict a shift in the middle ear resonant frequency with aging. Theoretically, it is of interest to understand how different anatomical changes affect the resonant frequency. Clinically, if resonant frequency values were different in geriatric patients, it would be necessary to establish separate normative data for that population. This would allow differentiation between pathologies that may be treated medically and those related to the normal aging process. Indeed, surgical techniques are improving, and there is less reluctance to perform surgery on older patients. The purpose of this study was to compare resonant frequency values in young adults to those of adults aged 75 years and above.

CHAPTER 2

REVIEW OF THE LITERATURE

In order to understand better the basic theoretical concepts of this study, this chapter will review the relevant literature on the function of the middle ear, tympanometric measures, and how function and its measures are affected by aging.

2.1 The Middle Ear

2.1.1 The Impedance Transformer Function

One function of the middle ear is to direct energy from the external auditory canal to the oval window of the cochlea. The ossicles transmit sound from the tympanic membrane to the oval window; in their absence, the only available sound reaching the round and oval windows does so almost simultaneously, thereby partially cancelling their pressures applied to the two windows.

In order to transmit sound to the cochlea most effectively, the middle ear must make a close match of the impedances seen at the tympanic membrane to that of air. If poorer impedance matching occurred, more of the sound would be reflected at the oval window because cochlear impedance is so much larger than that of the air at the tympanic membrane. Three mechanisms underlie the impedance transformer function of the middle ear (Pickles, 1988). First, because the surface area of the tympanic membrane is larger than that of the oval window, the amount of pressure at the oval window is increased proportionally ($P = F/A$; where P is pressure, F is force, and A is surface area). The second mechanism is the lever action of the ossicles. The long crus of the incus and the longer malleus manubrium form a lever, thereby increasing the force (and decreasing the velocity) at the stapes. Finally, the conical shape of the tympanic membrane and its "buckling" motion also increase the force applied at the oval window. The first factor mentioned is the most significant; the last two contribute much less to the transformer function of the middle ear.

Transformer ratio calculations have shown that the middle ear does not provide a perfect impedance match, especially at higher and lower frequencies. Calculations of the middle ear transfer function for cats (Nedzelnitsky, 1980) have shown bandpass characteristics, with the highest transmission in the vicinity of 1 kHz (see Figure 1). At low frequencies, the elasticity and friction of the ossicles and ligaments reduce energy transmission (Pickles, 1988). The attenuated transmission at high frequencies can be explained by a number of factors. For example, as frequency increases, the effective area of the tympanic membrane decreases, hence pressure increase at the oval window, and subsequent sound transmission, is greatly reduced (Khanna and Tonndorf, 1972). The irregularities in the transfer function at frequencies near 4 kHz are due to acoustic resonances in the middle ear cavity.

To understand better how the middle ear functions as a mechano-vibratory system to transmit sound energy, we must examine its underlying physical concepts.

2.1.2 Physical Concepts

When a force is applied to a physical system, the resulting velocity of movement is dependent on the impedance, or the opposition of the system to the flow of energy (Margolis, 1981). This relation is expressed as $Z = F/V$, where Z is the impedance offered by the system, F is the force applied, and V is the resulting velocity.

The concept of impedance is applicable to mechanical, electrical, acoustical, or thermodynamic systems. It is best understood by taking the example of a mechanical system, where a force is applied to an object, and the resulting velocity is examined. Consider a sinusoidal force with sinusoidal velocity acting on an object; this will result in a sinusoidal output force and velocity that can be compared to the input. Any difference between input and output forces and velocities is due to the impedance of the object. There are three types of oppositions to the flow of energy (Margolis, 1981). First, impedance may take the form of

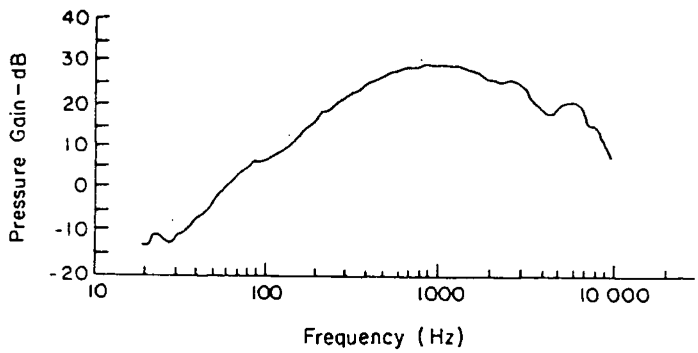


Figure 1. Transfer function of the middle ear for the cat. The pressure gain in the cochlea over that at the tympanic membrane is plotted as a function of frequency (reproduced from Pickles, 1988, with permission).

compliant reactance (X_C) (see Figure 2a). For example, a spring will oppose a sinusoidal force applied to it, so that the resulting sinusoidal velocity leads the force by 90° or 1/4 cycle. Indeed, when the force is maximal, the spring is either maximally compressed or extended, and the velocity is zero. When the force is zero, the spring is expanding or retracting at maximal velocity. The stiffness (or its reciprocal, compliance) of a spring determines its impedance. For example, a very stiff spring will offer large opposition to a force, and result in a reduced velocity. Mathematically, compliant reactance (X_C) is expressed as follows: $-X_C = 1/2\pi fC$, where C is compliance, and f is the frequency of the sinusoid. Impedance, when (ideally) composed only of a compliant reactance, is therefore inversely proportional to frequency. The negative sign indicates the phase lag of force to velocity.

The impedance of a system may be due to its mass reactance (X_m) (Figure 2b). For example, a sinusoidal force applied to a heavy rigid object (in a friction-free environment) will lead the resulting sinusoidal velocity by 90° or 1/4 cycle. Once the object is set into motion by the force, it will continue to move at the same velocity indefinitely without force being applied to it. This is due to the object's inertia. In order to stop the object, an opposite force must be applied to it. Therefore, velocity is maximal when the applied (sinusoidal) force is zero, and velocity becomes nil when such a force is maximal (in either direction). Mass reactance is expressed mathematically as follows: $X_m = 2\pi fM$, where M is the mass. Mass reactance is directly proportional to frequency, and a phase lead of force to velocity prevails.

The last type of mechanical element offering opposition is friction (or resistance, R) (Figure 2c). In a linear system that is characterized by friction only, force and velocity are always in phase. Furthermore, resistance is independent of frequency. Mathematically, resistance is expressed as: $R = b/A^2$, where b is the friction coefficient, and A is the surface area.

Complex physical systems may have impedances composed of two or three of the above elements. In such a case, one must specify impedance mathematically. One way to do so is to use rectangular notation, where for a given sinusoidal force, impedance (Z) is

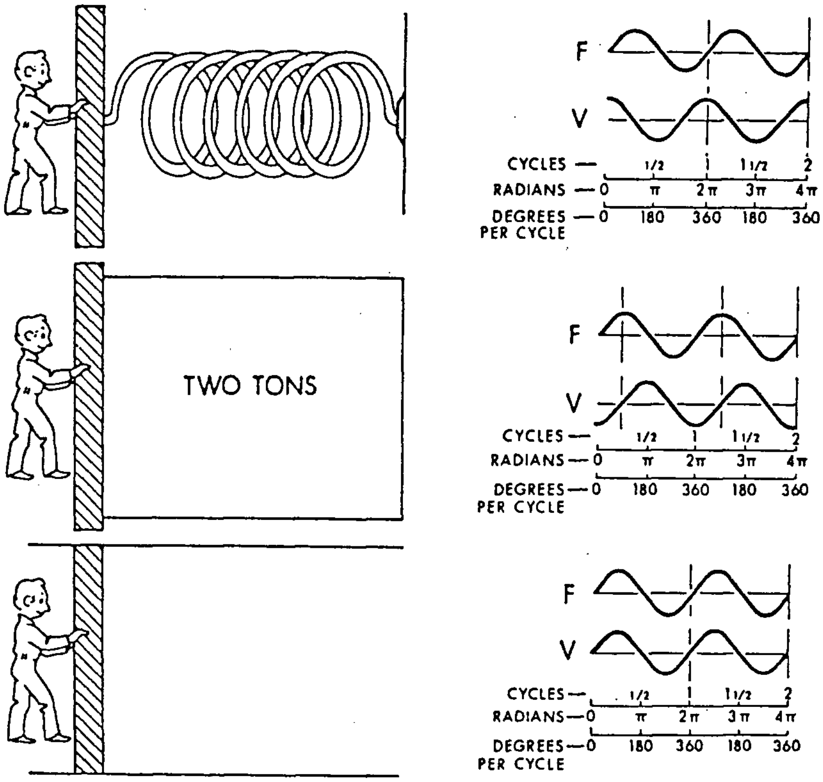


Figure 2. Three types of mechanical systems illustrating impedance elements, and their respective force-velocity relationships: (a) wall with a spring attached to it, corresponding to compliant reactance, (b) wall as part of a heavy object, corresponding to mass reactance, (c) wall with friction, corresponding to resistance (reproduced from Margolis, 1981, with permission).

described on the X-axis as a real component (R) and on the Y-axis as an imaginary component (jX): $Z = \sqrt{R^2 + jX_t^2}$, where $jX_t = j(X_c + X_m)$ (see Figure 3a). Stiffness and mass are opposing elements; that is, the velocity responses of stiffness (-90°) and mass (+90°) components to a sinusoidal force are 180° out of phase. An entire physical system can be characterized as either mass-dominated or stiffness-dominated, depending on which of the two reactance elements is largest. Impedance may also be described using polar notation, in which case the magnitude of impedance ($|Z|$) is specified, as well as the phase angle (Θ_z) of the impedance vector.

The reciprocal of impedance, admittance (Y), can also be used to describe the energy flow of a physical system. The components of admittance are susceptance (B) and conductance (G), which are reciprocally related to their corresponding impedance components, reactance (X) and resistance (R), respectively. Mathematically, $Y = \sqrt{G^2 + jB_t^2}$, where admittance is composed of a real component, G, and an imaginary component, jB_t (see Figure 3b). Similar to reactance, the susceptance component (jB_t) is comprised of two opposing elements, mass and stiffness (or compliance): $jB_t = j(B_m + B_c)$. Figure 3 shows the reciprocal representation of both mass and stiffness elements when comparing impedance (X_m and $-X_c$) and admittance ($-B_m$ and B_c). This results in phase angles (Θ_y) of equal value, but opposite sign. Note that the term "immittance" groups both impedance and admittance.

The middle ear is a complex physical system composed of friction, stiffness, and mass elements. Each component is associated with certain anatomical structures of the ear. Friction is primarily represented by the viscosity of the perilymph of the cochlea, as well as narrow passages and mucous lining within the middle ear (Wiley and Block, 1985). The tympanic membrane, middle ear ligaments and tendons, and air in the ear canal and middle ear collectively compose stiffness (Van Camp et al., 1986). The mass component is associated with the pars flacida of the tympanic membrane, middle ear ossicles, and cochlear perilymph (Van Camp et al., 1986). Energy flow through the middle ear system can be characterized by "acoustical" impedance, Z_a, or admittance, Y_a. In such a case, the sinusoidal force applied to

(a)

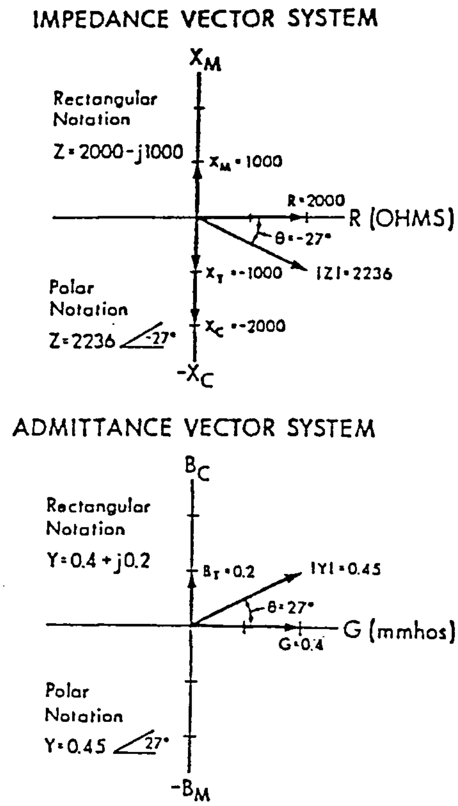


Figure 3. Polar and rectangular notation systems for impedance (a), and admittance (b). For impedance, compliant reactance (X_c), mass reactance (X_m), total reactance (X_t), and resistance (R) are shown, as well as the impedance vector magnitude (|Z|) and its phase angle (Θ). The corresponding elements for admittance illustrated are: compliant susceptance (B_c), mass susceptance (B_m), total susceptance (B_t), and conductance (G), as well as the admittance vector magnitude (|Y|) and its phase angle (Θ) (reproduced from Margolis, 1981, with permission).

the physical system is sound pressure (P), which results in volume velocity (U). Therefore, Z_a = P/U and Y_a = U/P. Acoustical impedance is described with the unit "ohm" (10^5 Pa·sec/m^3); the reciprocal, admittance, uses the arbitrary unit "mho" (m^3 x 10^{-5}/Pa·sec) (Margolis, 1981).

The measurement of acoustical immittance as a clinical means of evaluating middle ear function is relatively new. The next section will discuss the evolution and theory of "tympanometric" measures.

2.2 Tympanometric Measurements

2.2.1 Foundations

Long before tympanometry was accepted as a clinically useful procedure, researchers became interested in applying the concept of acoustical impedance to the middle ear. Metz, in 1946, was the first to construct a mechanical acoustic impedance bridge. The basic principle of any such bridge is to direct , from a probe tip, a signal of a specific sound pressure level and frequency at the tympanic membrane. Depending on the impedance of the tympanic membrane and middle ear structures behind it, some sound energy is reflected, some is transmitted, and a small amount is absorbed. The higher the impedance, the more sound energy is reflected back to the probe, where it is received by a small microphone (see Figure 4). Thus, the microphone voltage is directly proportional to impedance at the plane of the probe tip. In 1960, Terkildsen and Scott-Nielsen developed the first commercially available electroacoustic impedance bridge.

Instruments were further refined so that air pressure could be changed within the external ear canal. This enabled researchers to measure middle ear impedance at different ear canal pressures, and thereby plot "tympanograms" (impedance as a function of ear canal pressure) (see Figure 5). At very negative and very positive canal pressures, the tympanic membrane is maximally extended laterally and medially, respectively. At these extremes, the tympanic membrane is very stiff (its impedance is high). Consequently, most of the sound

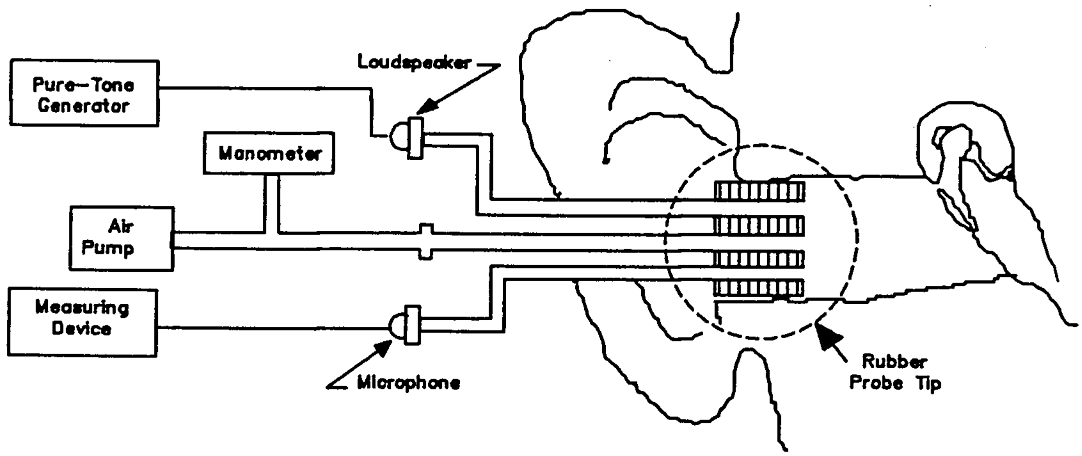


Figure 4. Diagram of an electroacoustic impedance bridge (reproduced from Bess and Humes, 1990, with permission).

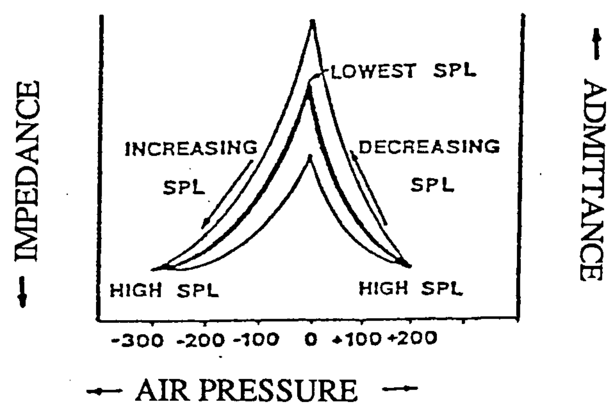


Figure 5. Tympanogram: graph of middle ear impedance and admittance as a function of pressure change within the ear canal. Also shown are the relative levels of sound pressure (SPL) in the ear canal as pressure is varied. Note that 0 daPa is equivalent to ambient pressure (adapted from Northern and Grimes, 1978, with permission).

energy directed into the ear canal is reflected off the tympanic membrane and recorded by the microphone. Subjectively, the sound is quite faint, because very little sound energy is transmitted to the middle ear. As the canal pressure becomes more nearly equal to the middle ear pressure, the tympanic membrane becomes more mobile, and more sound energy is transmitted. When the air pressure in the ear canal equals the ear pressure in the middle ear, impedance reaches a minimum and admittance is at a maximum; minimal sound energy is reflected off the tympanic membrane, and consequently, relatively little sound is recorded at the probe microphone. Subjectively, the tone is perceived as "loudest". In the presence of normal middle ear and eustachian tube function, minimum impedance occurs at barometric pressure (0 daPa - see figure 5). That is, the air pressure in both the ear canal and middle ear corresponds to ambient room pressure.

In sum, at very negative and positive pressures, the impedance of the tympanic membrane is high, therefore the reflected sound pressure level recorded is also high, and transmission of sound energy is low. Conversely, the canal pressure that corresponds to the value of middle ear pressure will yield low impedance values, low sound pressure levels at the microphone, and high transmission of sound energy.

2.2.2 Static Tympanometric Measurements

The addition of a manometer to acoustic impedance bridges also permits elimination of inter-subject differences in impedance values due to ear canal volume. Impedance measured at the probe must be transformed to reflect the value at the tympanic membrane. A first measure taken at very high or low canal pressures (re: ambient pressure) yields impedance measures approximating ear canal impedance (Z_{ec}) alone. A second impedance measure taken at the impedance minimum approximates the impedance of the entire system (Z_i); that is, the ear canal and the middle ear together. Based on a model of electrical parallel circuitry, static acoustic impedance of the middle ear (Z_{me}) can be calculated using the following equation: $Z_{me} = Z_{ec}Z_i/(Z_{ec}-Z_i)$ (Margolis and Shanks, 1991). The reciprocal measure, static acoustic admittance of the middle ear (Y_{me}), is more easily calculated in parallel networks: ear canal admittance (Y_{ec}) is simply subtracted from admittance of the entire system (Y_i); that is, $Y_{me} = Y_i - Y_{ec}$ (Margolis and Shanks, 1991). This calculation has been termed the "MAX/MIN method". In normal ears, static acoustic admittance reflects middle ear admittance (Y_{me}) in its resting position (that is, admittance maximum occurs at canal pressure equal to 0 daPa, re: ambient pressure).

Note that the MAX/MIN method may only be used to determine static admittance if the middle ear and ear canal are parallel elements; that is, the MAX/MIN method is valid only so long as the magnitude and phase of sound pressure at the probe tip are equivalent to those of sound pressure at the tympanic membrane (Van Camp et al., 1986). This is the case only for probe tone frequencies below 1000 Hz. Thus, above 1000 Hz, the MAX/MIN method is not a satisfactory method for calculating static admittance. Alternatively, if one uses the MAX/MIN method to calculate static susceptance and static conductance ($B_{me} = B_i - B_{ec}$; $G_{me} = G_i - G_{ec}$, respectively), then static admittance can be calculated from its individual components: $|Y_{me}| = \sqrt{B_{me}^2 + G_{me}^2}$ (Margolis and Shanks, 1991).

The probe frequency dictates whether static acoustic admittance is most influenced by stiffness or mass components of the middle ear (Van Camp et al., 1976, 1986; Shanks et al., 1988). At lower probe frequencies, the middle ear is said to be 'stiffness-controlled' because the stiffness component of susceptance (jB_c) is larger than its mass component ($-jB_m$), resulting in an overall positive susceptance (jB) value. Moreover, the susceptance magnitude B is greater than that of conductance G, thus the admittance phase angle (Θ_y) falls between 45° and 90° (see Figure 6 - diagram for 220 Hz probe frequency). In other words, when the magnitude ratio of susceptance to conductance (B:G) is greater than one, the admittance phase angle will fall between 45° and 90°.

As probe tone frequency increases, the magnitude ratio of susceptance to conductance decreases, and consequently the admittance phase angle decreases. For example, when

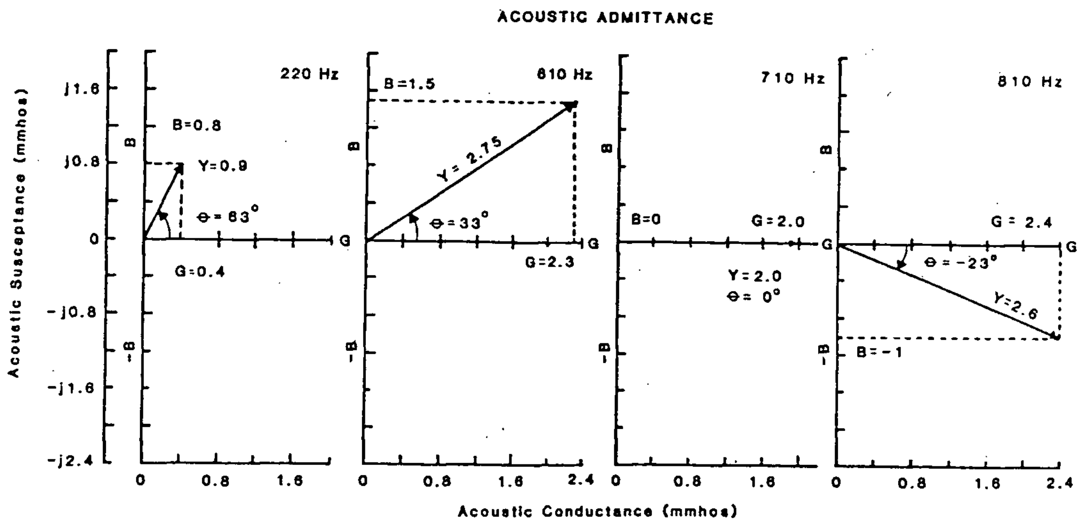


Figure 6. Normal peak compensated static admittance at 220, 610, 710, and 810 Hz. Rectangular notation components: susceptance (B) and conductance (G). Polar notation components: admittance (Y) and phase angle (Θ) (reproduced from Shanks et al., 1988, with permission).

susceptance and conductance are equal (magnitude ratio equal to one), the admittance phase angle is 45°; when conductance is greater than susceptance (magnitude ratio less than one), the admittance phase angle is less than 45° (see Figure 6 - 610 Hz). As long as overall susceptance remains positive, the stiffness component of susceptance is larger than its mass component, and admittance is controlled by the stiffness properties of the middle ear.

When the probe frequency is equal to the resonant frequency of the middle ear, the magnitude of the conductance component is high and that of susceptance is zero. At resonance, the mass and stiffness components of susceptance are equal and opposite, resulting in an overall susceptance value of zero. It follows, therefore, that in this condition, admittance phase angle equals 0° (see Figure 6 - 710 Hz).

As probe frequency is increased above resonance, overall susceptance becomes negative because the mass component is larger than its stiffness component. The middle ear is said to be 'mass-controlled' at such frequencies. The admittance phase angle also becomes negative (see Figure 6 - 810 Hz). Moreover, the magnitude ratio of susceptance to conductance (B:G) becomes negative, and continually decreases (i.e., becomes increasingly positive) with increasing probe frequency. Thus, admittance phase angle rotates from 0° to -90°.

2.2.3 Dynamic Tympanometric Measurements

Tympanometry is used to measure acoustic admittance components of the middle ear system (|Y|, B, and G) as a function of ear canal pressure, as well. The shape of admittance tympanograms is independent of ear canal volume (Shanks et al., 1988). As ear canal volume increases, admittance tympanograms are shifted linearly. In contrast, the effect of ear canal volume on the shape of impedance tympanograms is nonlinear (see Figure 7): as ear canal volume increases, the impedance tympanogram broadens and becomes more shallow. Since the shapes of admittance tympanograms do not change with changes in ear canal volume, admittance tympanograms better represent middle ear function than impedance tympanograms

(a)

(b)

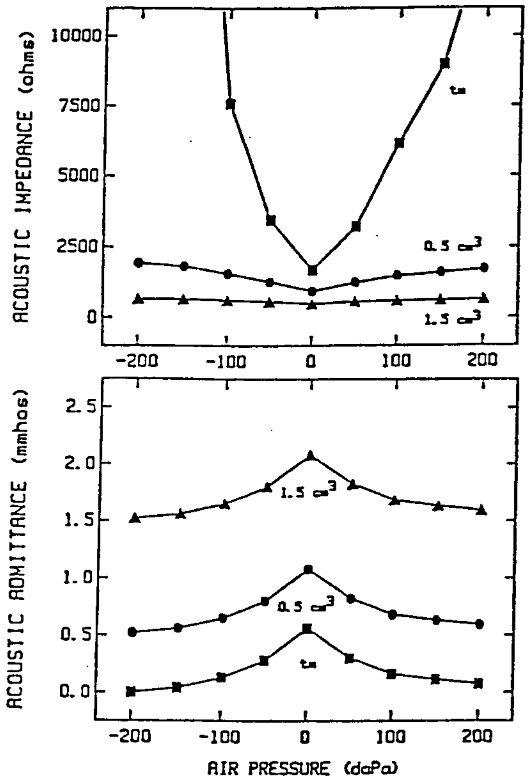


Figure 7. Impedance (a), and admittance (b) tympanograms plotted for different ear canal volumes (reproduced from Shanks et al., 1988, with permission).

(Shanks et al., 1988). For this reason, and because of the simplicity of the static acoustic admittance calculation (see above), most commercially available instruments measure admittance and its parameters. From this point, we will restrict further discussion to admittance (instead of impedance).

Dynamic measures of admittance (tympanograms) are affected by a number of procedural variables (Van Camp et al., 1986; Shanks et al., 1988). First, the direction of pressure change in the ear canal (negative to positive: ascending, or positive to negative: descending) affects tympanometric amplitude and shape. Ascending pressure change, in contrast to descending pressure change, results in higher admittance values for single-peaked tympanograms (Creten and Van Camp, 1974), and more complex tympanometric shapes (i.e., more notching) due to overall reactance becoming more positive (see Vanhuyse model, section 2.2.4) (Margolis et al., 1985). The starting pressure used when recording tympanograms relates to the direction of pressure change and can also affect tympanograms. Although a pressure of +200 daPa is commonly used, it has been shown that a starting pressure of -400 daPa yields more accurate ear canal volume estimates, therefore resulting in more accurate admittance values (Shanks and Lilly, 1981). The effect of the rate of pressure change on tympanograms can be compared to that of the direction of pressure change. A relatively low rate of pressure change results in lower admittance values (Creten and Van Camp, 1974), and less complex tympanometric shapes due to overall reactance taking on more negative values (Van Camp et al., 1986). Another procedural variable is the number of successive tympanometric measurements. This will be further discussed in section 2.2.6.

Probe tone frequency can also be considered as a procedural variable that affects admittance tympanograms. The previous section showed that probe tone frequency influences the relationship between static acoustic parameters. The next section will examine how probe tone frequency directly influences the morphology of admittance, susceptance, and conductance tympanograms.

2.2.4 The Vanhuyse Model

Vanhuyse et al., in 1975, proposed a mathematical model to account for susceptance and conductance tympanometric shapes. His model is based on the frequency-dependent relationship between middle ear reactance (X) and resistance (R) tympanograms, and the mathematical relations between impedance and admittance components (Margolis and Shanks, 1990):

$$G = R/(R^2 + X^2) \quad \text{(equation 1)}$$

$$B = -X/(R^2 + X^2) \quad \text{(equation 2)}$$

$$|Y| = \sqrt{B^2 + G^2} \quad \text{(equation 3)}$$

$$\Theta_y = \arctan (B/G) \quad \text{(equation 4)}$$

In general, the model assumes that middle ear acoustic resistance as a function of increasing ear canal pressure is a slightly decreasing monotonic function and is independent of probe frequency. Middle ear acoustic reactance is modeled as an inverted V-shaped symmetrical function with respect to the zero pressure point, which shifts to more positive values with increasing probe frequency. These assumptions correspond quite well to empirical measurements of middle ear resistance and reactance as a function of ear canal pressure (Møller, 1965; Margolis and Popelka, 1977). Using this model, Vanhuyse et al. (1975) demonstrated that simple linear shifts in the reactance tympanogram can account for the observed changes in the shapes of admittance, susceptance, and conductance tympanograms as a function of probe frequency.

According to Vanhuyse et al. (1975), the relationship shown in Figure 8a between reactance and resistance as a function of ear canal pressure, can be assumed for low probe frequencies. Note that the absolute value of the reactance tympanogram is greater than that of resistance for any given pressure value. In this case, reactance is always negative, and the middle ear is therefore stiffness-controlled. The reactance-resistance relationship, in combination with equations 1 to 4, indeed predicts: 1) the peak amplitude of the susceptance tympanogram to be approximately twice that of the conductance tympanogram (see Figure 9 -

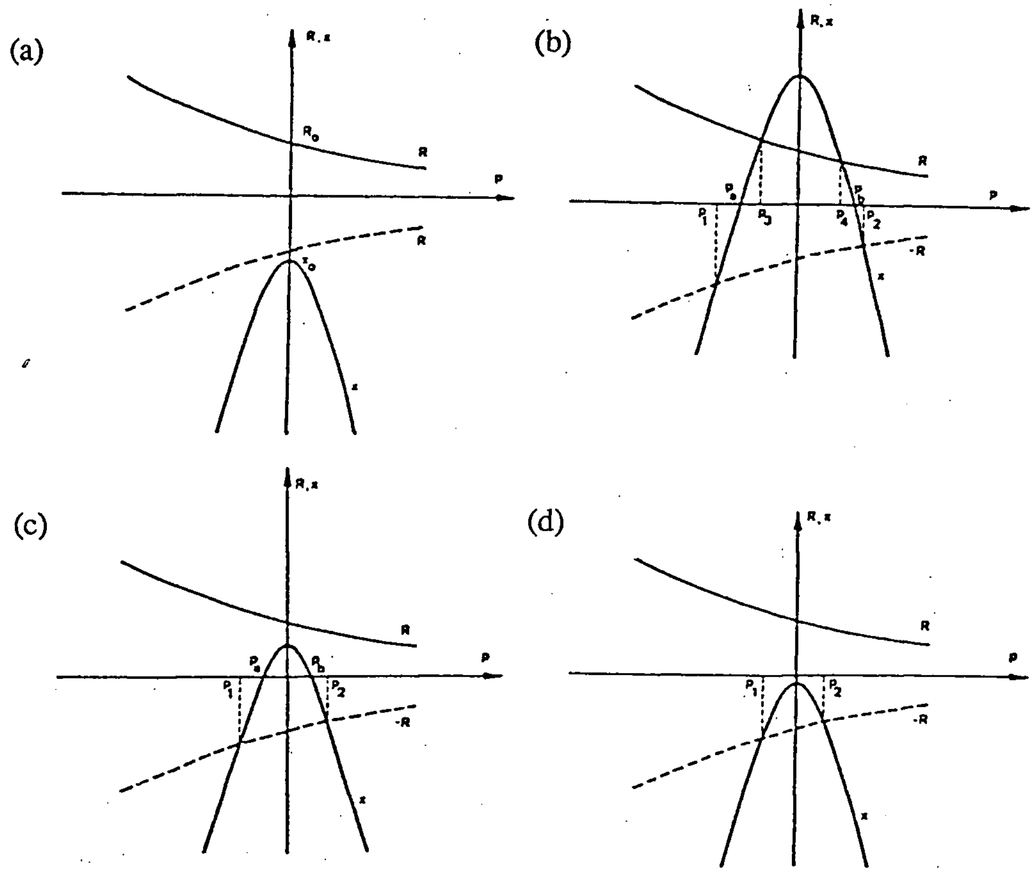


Figure 8. Vanhuyse model of tympanometric shapes. Hypothetical middle ear reactance (x) and resistance (R) tympanograms plotted for increasing probe frequencies: (a) lowest frequency, to (d) highest frequency. Ear canal pressure (P) is represented on the abscissa (reproduced from Van Camp et al., 1986, with permission).

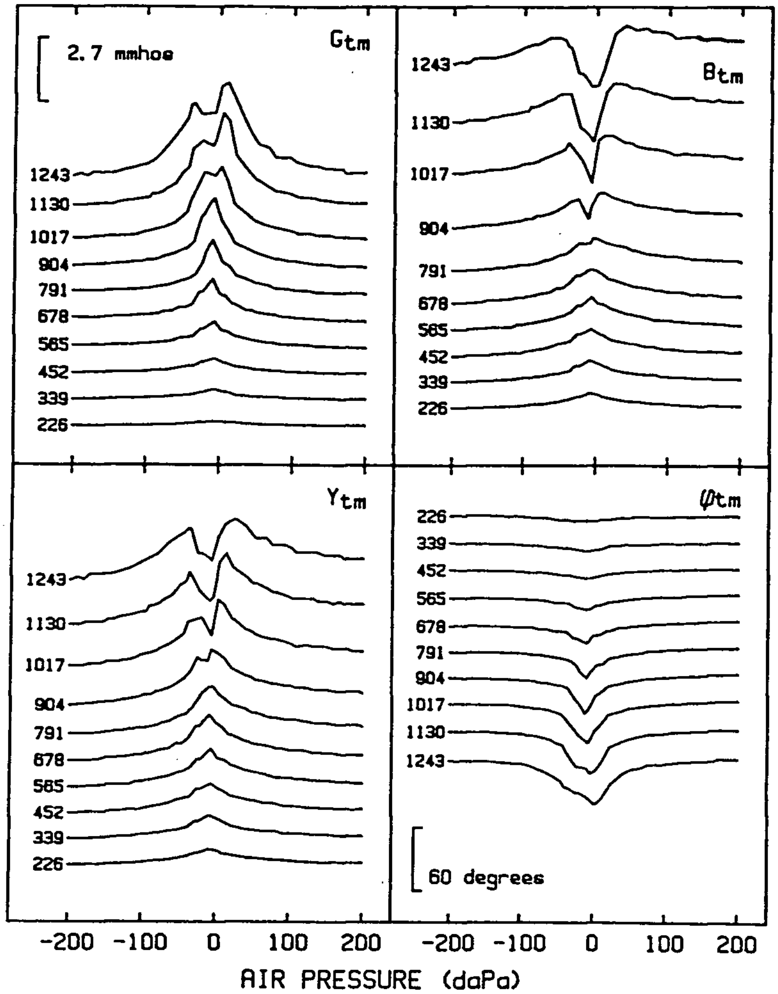


Figure 9. Conductance (G), susceptance (B), admittance (Y), and phase angle (Θ) tympanograms plotted for probe tone frequencies between 226 and 1243 Hz (reproduced from Margolis and Shanks, 1991, with permission).

tympanograms at 339 Hz), 2) the single peaked admittance tympanogram, 3) and the resultant admittance phase angle of approximately 60° (at pressure equal to 0 daPa; see figure 10 - 339 Hz).

As probe tone frequency increases, the reactance tympanogram shifts to more positive values, which corresponds to a decrease in the absolute value of reactance at any given pressure value (see Figure 8b). The Vanhuyse model predicts that the susceptance tympanogram begins to notch when the absolute values of reactance and resistance are equal at pressure equal to 0 daPa. Further increase in probe frequency results in increased deepening of the notch in the susceptance tympanogram. For example, Figure 8b shows the case in which the absolute value of reactance is smaller than resistance at low canal pressures (i.e., near pressure equal to 0 daPa), and larger than resistance at high (positive or negative) pressures. Reactance is negative at all pressures as well, thus the middle ear system is stiffness-controlled. This relationship between reactance and resistance predicts: 1) increased peak amplitude of the conductance tympanogram (see Figure 9 - 791 Hz), 2) notching of the susceptance tympanogram at low canal pressures where the absolute value of reactance is smaller than resistance, 3) the single peaked admittance tympanogram, 4) and a smaller admittance phase angle (at pressure equal to 0 daPa; see Figure 10 - 791 Hz).

At resonance, the reactance tympanogram has a value of 0 ohm at pressure equal to 0 daPa; for all other canal pressures reactance is negative. Thus, the resulting susceptance tympanogram shows a notch that dips to the value of its tails (see Figure 9 - resonant frequency between 904 and 1017 Hz)[1]; the notch minimum equals the tail rather than 0 mmho because the measured susceptance at the tail reflects the susceptance of the ear canal. Since at middle ear resonance the mass and stiffness components are equal and opposite, the resulting

---

[1] Recall that when determining the static acoustic susceptance of the middle ear (B_{me}), susceptance of the ear canal (B_{ec}) must be subtracted from the susceptance of the entire system (B_i), that is, $B_{me} = B_i - B_{ec}$ (Margolis and Shanks, 1990). Likewise, in dynamic measures of susceptance, to establish middle ear susceptance at a given ear canal pressure, ear canal susceptance (measured at high ear canal pressure, or the tympanogram tail) must be subtracted from the overall measure of susceptance.

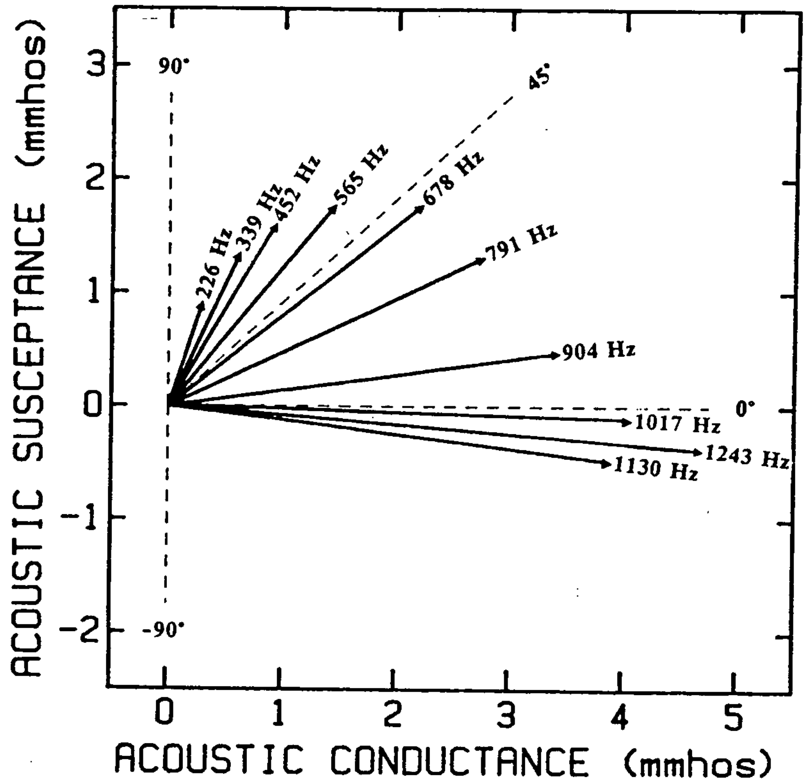


Figure 10. Acoustic admittance vectors when ear canal pressure equals ambient pressure (0 daPa) for probe tone frequencies between 226 and 1243 Hz (reproduced from Margolis and Shanks, 1991, with permission).

admittance phase angle is 0° (at pressure equal to 0 daPa; see Figure 10 - between 904 and 1017 Hz). The very high peak amplitude of the conductance tympanogram and the single peaked admittance tympanogram are also predictable by the relationship between resistance and reactance tympanograms at resonance.

At frequencies above resonance, reactance is positive and smaller than resistance at low canal pressures (Figure 8c). At higher (positive or negative) canal pressures, reactance is negative and its absolute value is smaller than resistance. And, at even higher (positive or negative) canal pressures, reactance is still negative but its absolute value is larger than resistance. Thus, the middle ear system is mass-controlled at low canal pressures and stiffness-controlled at high canal pressures. In this case, 1) the susceptance notch dips below the value of its tails (see Figure 9 - 1130 Hz), 2) the conductance tympanogram shows a notch between the pressure values where reactance is positive, 3) and the admittance phase angle becomes negative (at pressure equal to 0 daPa; Figure 10 - 1130 Hz). The model assumes that further increases in probe frequency result in increasingly positive reactance, which becomes larger than resistance at pressures near the tympanometric peak (see Figure 8d). The resulting susceptance tympanogram will show a notch that dips to values well below its tail values. Both conductance and admittance tympanograms will show a deeper notch, and the admittance phase angle will be more negative.

Lastly, note the increased widening of the notch peaks in the 791 to 1243 Hz susceptance tympanograms (see Figure 9). This is predicted by the Vanhuyse model since: 1) reactance is modeled as an inverted V-shaped function which shifts toward more positive values with increasing probe frequency, 2) and notching occurs between the negative and positive ear canal pressures where the absolute values of reactance and resistance are equal.

2.2.5 Probe Tone Frequencies Used in Tympanometric Measurements

Early tympanometric measurements were performed using only one low probe frequency; only later did investigators begin experimenting with higher probe frequencies.

Lidén and his colleagues (1974a, 1974b, 1977) were among the first to investigate the clinical utility of higher frequency probe tones. Using an 800-Hz probe tone, they found two impedance tympanogram patterns to be added to the three described by Jerger in 1970 (see Figure 11; note the ordinate in relation to the impedance tympanogram plotted in Figure 5 is reversed). Using a low frequency probe tone, Jerger identified normal type A tympanograms, flat type B tympanograms associated with increased stiffness due to middle ear fluid, and type C tympanograms demonstrating negative middle ear pressure. Using a 800-Hz probe tone, Lidén et al. (1974a, 1974b, 1977) identified narrow undulating W-shaped impedance tympanograms (type D) in subjects with scarred and/or flaccid tympanic membranes. In subjects with ossicular discontinuities, they found a broad undulating W-shaped tympanogram which was termed type E, indicating a hypermobile tympanic membrane. Additionally, a 220-Hz probe tone in such subjects (that is, those with ossicular discontinuities) yielded normal V-shaped tympanograms, and a 625-Hz tone produced normal and abnormal tympanograms unpredictably. They concluded that the 800-Hz probe tone was more reliable in identifying ossicular discontinuities.

2.2.6 Middle Ear Resonant Frequency Measurements

Measurements of middle ear resonant frequency provide information about the relationship between mass and stiffness. Although the effect of the tympanic membrane and associated structures cannot be ignored, it seems that such measures are very sensitive to changes of the ossicular system (Funasaka et al., 1984). For example, resonance is shifted to higher values in cases of ossicular fixation, and to lower values with ossicular disruption (Funasaka et al., 1984; Funasaka and Kumakawa, 1988).

There is some disagreement in the literature on normal resonant frequency values of the middle ear. Van Camp et al. (1976) based on a report by Zwislocki (1962), suggest that the first resonant peak is between 750 and 900 Hz, which concurs with Lidén et al.'s (1974a) observation of approximately 800 Hz. Others have found a much wider range, extending into

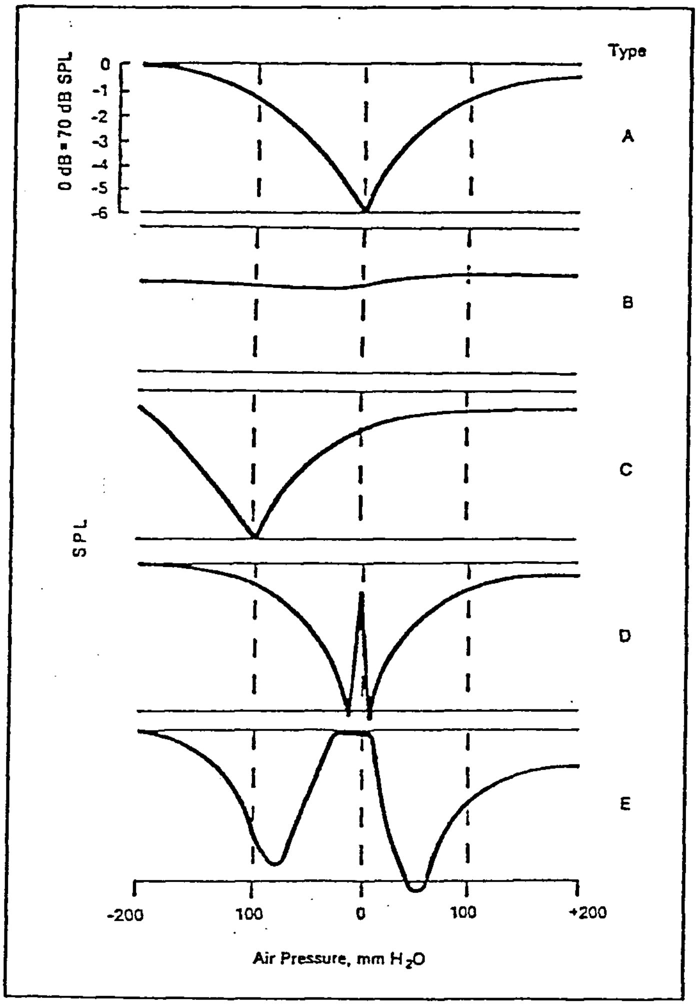


Figure 11. Five tympanogram types for low frequency probe tones. (A) normal middle ear , (B) middle ear fluid, (C) negative middle ear pressure, (D) scarred and/or flaccid tympanic membrane, (E) hypermobile tympanic membrane (reproduced from Lidén et al., 1974b, with permission).

higher frequencies: 800 to 1200 Hz (Shanks and Lilly, 1981; Shanks, 1984), 650 to 1400 Hz (Colletti, 1975), and 720 to 1880 Hz (Funasaka et al., 1984). Differences in methodology may explain some discrepancies; different methods of measurement were used across studies, on either models or human subjects.

One method for determining middle ear resonant frequency is to analyze tympanometric shapes obtained at discrete probe frequencies. Colletti (1975, 1976, 1977) identified three different shape patterns (see Figure 12; note, as before, the reverse plotting of impedance tympanograms relative to Figure 5): the first occurs at low frequencies below resonance (ear is stiffness controlled), resulting in a V-shaped impedance tympanogram. As the probe frequency increases to that of the middle ear resonance, the tympanogram becomes W-shaped. Above resonance, where the ear is mass-controlled, the tympanogram assumes the shape of an inverted V. Middle ear abnormalities cause a shift in the frequencies at which the different patterns occur. In particular, a shift in the frequency range characterized by the W shaped impedance tympanogram has been observed in the presence of middle ear pathology (Colletti, 1975, 1976, 1977). While Colletti's reports are based on impedance tympanograms, Shanks et al. (1988) have found that susceptance tympanograms are more sensitive to changes in probe tone frequency. As described previously (see section 2.2.4), the relationship of the conductance and susceptance magnitude vectors, at pressure equal to 0 daPa, can be used to predict the morphology of admittance, susceptance, and conductance tympanograms at different probe tone frequencies. Resonant frequency is defined as the frequency at which the static measure (at pressure equal to 0 daPa) of the susceptance vector is equal to 0 mmho, and that of the conductance vector is high. This corresponds best to the dynamic measure (tympanogram) of susceptance notching to the value of its tail; the lowest frequency at which this occurs is identified as resonance (Shanks et al., 1988). The conductance and admittance tympanograms do not become multipeaked until resonant frequency is exceeded. Therefore, the susceptance tympanogram shape is indeed more sensitive to changes in probe frequency (Van Camp et al., 1986; Shanks et al., 1988).

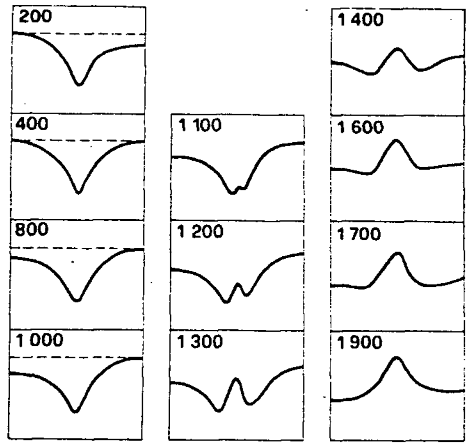


Figure 12. Impedance tympanograms plotted for probe tone frequencies ranging from 200 to 1900 Hz (reproduced from Colletti, 1976, with permission).

The effects of successive tympanometric measurements cannot be ignored in methods that obtain tympanograms at discrete frequencies to determine resonance (Wilson et al., 1984). Indeed, the amplitude of tympanometric peaks obtained using lower probe frequencies (226 and 678 Hz) has been shown to increase, especially during the first three to five measurements. Furthermore, the number of tympanometric peaks, or notching of the tympanogram, increases with the number of tympanometric runs. These effects can be explained by reactance values becoming more positive, which (recall from the above discussion of the Vanhuyse model) increases the complexity of susceptance tympanograms (Wilson et al., 1984), and therefore lowers the resonant frequency measured. No clear physiological explanation for this outcome has been given, although some have suggested changes in the viscoelastic properties of the tympanic membrane (Wilson et al., 1984). One way to eliminate this effect is to sweep probe frequency at discrete ear canal pressures (Berg, 1980, as reported by Lilly, 1984). For examples, Berg reported sweeping probe tone frequency (from 200 to 2000 Hz) at discrete ear canal pressures (in 25 daPa intervals, between -275 and +275 daPa), and recording admittance values, in normal subjects. A three-dimensional array of pressure vs frequency vs admittance was obtained, and the effects of canal pressure and probe frequency on the value of admittance were examined (see Figure 13). Others have used this method to obtain multifrequency admittance, susceptance, and conductance tympanograms (e.g., Shanks et al., 1987).

Alternatively, sweep frequency tympanometric measures at only two ear canal pressures also have been used to identify the middle ear resonant frequency (Funasaka et al., 1984; Funasaka and Kumakawa, 1988). Similar to the protocol reported by Berg (1980), in this method, frequency is changed while ear canal pressure is held constant. Measurements are obtained, however, at only two canal pressures, 0 and -200 daPa; both the difference between reflected sound pressures (or impedance), and the difference between phase angles at the two canal pressures are examined. These results are then plotted: sound pressure difference ($SPL_{0\ daPa}$ - $SPL_{-200\ daPa}$) as a function of frequency, and phase difference

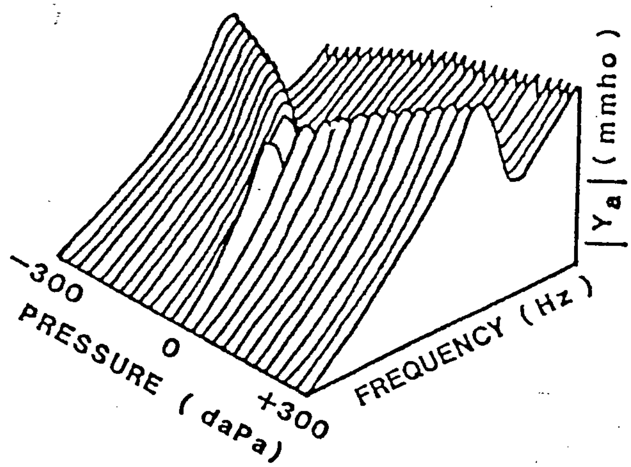


Figure 13. Three-dimensional representation of admittance (|Y|) tympanograms obtained with different probe tone frequencies (reproduced from Lilly, 1984, with permission).

($\Theta_{0\ daPa}$ - $\Theta_{-200\ daPa}$), as a function of frequency (see Figure 14). Resonant frequency is identified as the point at which the sound pressure difference curve crosses the 0-dB line. Some commercially available instruments calculate admittance or one of its two components instead of reporting sound pressure differences. As above, susceptance more accurately estimates resonant frequency than admittance (or impedance)[2].

Note that the MAX/MIN method of calculating static acoustic admittance is similar to the sweep frequency calculation. In both cases, the value of admittance (or susceptance) at high (positive or negative) pressure is subtracted from the value of admittance (or susceptance) at peak pressure (0 daPa in normal ears). Recall, from section 2.2.2, that the admittance (or susceptance) value obtained at peak pressure is a measurement of the entire middle ear system (ear canal and middle ear), while that obtained at high pressure is a measurement of the ear canal alone. The subtraction therefore yields a value of admittance (or susceptance) representing the middle ear alone.

The underlying principle of the sweep frequency measure can also be understood by drawing parallels with discrete multifrequency tympanometric measures (see susceptance tympanograms - Figure 9). At low probe tone frequencies, the difference between the susceptance tympanogram tip and tail values (corresponding to 0 and -200 daPa, respectively), is large and positive, as the tympanogram has an inverted V shape. The tip (or notch) to tail difference becomes smaller as probe tone frequency approaches resonance since the susceptance tympanogram begins to notch. At resonance, the notch of the tympanogram reaches the value of the tail, and the difference is zero. As frequency is increased further, the notch dips below the tail value, and the tip to tail difference becomes negative.

The phase difference curve in the sweep frequency method corresponds to the

---

[2] Recall that the difference between admittance at low and high ear canal pressures does not reach zero until the probe frequency is well above the resonant frequency of the middle ear. Therefore, resonant frequency obtained from the admittance (or sound pressure level) difference curve will be higher than the actual middle ear resonant frequency, or that obtained from the susceptance difference curve.

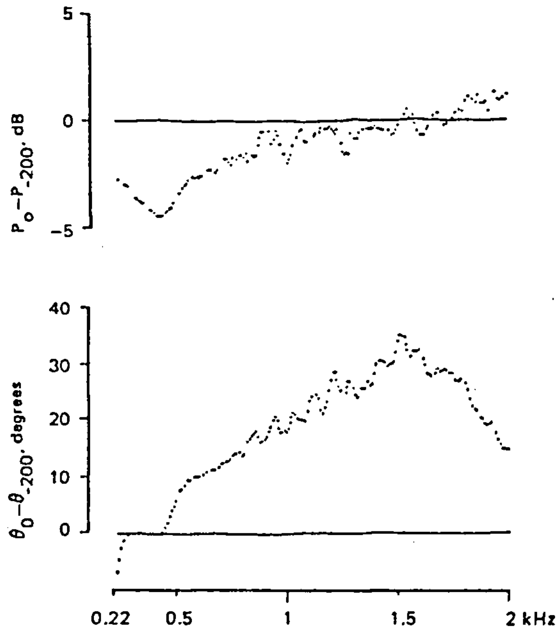


Figure 14. Sound pressure difference (P_0 - P_{-200}) curve and phase angle difference (Θ_0 - Θ_{-200}) curve, for a normal subject. (reproduced from Funasaka et al., 1984, with permission).

difference between the phase angle at 0 daPa and at -200 daPa (see phase angle tympanograms in Figure 9). At low probe frequencies, no such difference exists, so that the result is zero. As probe frequency increases, the phase angle at 0 daPa becomes larger than that at -200 daPa, yielding a positive difference. According to Funasaka and Kumakawa (1988), the maximum phase angle difference occurs at resonance (Figure 14). Beyond the resonant frequency, the phase angle difference, although still positive, decreases gradually back to pre-resonance values. But in reality, the maximum phase angle difference occurs when the magnitude of reactance at 0 daPa is equal, but opposite, to that at -200 daPa[3]. Using the phase angle curve to obtain absolute resonant frequency is not as valid as using the sound pressure curve because the former is more susceptible to procedural factors (Funasaka and Kumakawa, 1988).

2.3 Aging and Tympanometry

Anatomical and physiological changes are known to occur in the aging middle ear system. For example, middle ear muscle atrophy, changes in connective tissue, and/or lax ossicular joints have been observed with aging (Marshall et al., 1983; Gilad and Glorig, 1979). Other studies have shown calcification and arthritic joints in the ossicular chain with aging (Etholm and Belal, 1974; Rosenwasser, 1964). Earlier investigators associated such physiological changes with the phenomenon of "conductive presbycusis", that is, the presence of a high frequency air-bone gap in some older subjects (Marshall et al., 1983; Gilad and Glorig, 1979). This now has been dismissed as having been due to the imprecision of early experimental techniques and equipment, and it is generally agreed that the middle ear is not involved in hearing loss due to aging (Anderson and Meyerhoff, 1982; Marshall et al., 1983).

Other investigations on age-related changes in stiffness properties of the middle ear

---

[3] That is, note in the phase angle tympanograms in Figure 9, that the difference in phase angle between -200 and 0 daPa continues to increase above resonant frequency, which occurs between 904 and 1017 Hz. Therefore, using the peak of the phase angle difference curve to identify resonant frequency will result in a value that is higher than the actual resonant frequency of the middle ear.

have used acoustic immittance measurements. Conflicting results confound this area of research (Jerger et al., 1972; Beattie and Leamy, 1975; Blood and Greenberg, 1975; Nerbonne et al., 1978; Thompson et al., 1979; Gates et al., 1990). For example, Jerger et al. (1972) measured static admittance in subjects aged 6 years and older, with either normal hearing or sensorineural hearing loss. While sensorineural hearing loss had no significant effect on static admittance, a significant age effect was observed; static admittance increased with age, to a maximum at 30 to 39 years of age, then decreased with increasing age. A stiffer middle ear system in the young and elderly was implied. Other investigators (Blood and Greenberg, 1975; Nerbonne et al., 1978; Gates et al., 1990) have concluded that the middle ear system becomes stiffer in elderly.subjects. In contrast, Beattie and Leamy (1975) concluded that the stiffness characteristics of the middle ear decrease with age. They compared peak admittance values between younger and older adults, and found that admittance was higher for the older subject group. Thompson et al. (1979) reported a similar tendency. To date, all studies investigating age-related changes in tympanometric measures have used relatively low frequency probe tones (220 or 660 Hz). Therefore, the observed changes in admittance with aging most likely resulted from anatomical change in structures which are known to underlie the stiffness properties of the middle ear (see above)[4]. Alternatively, it remains unclear whether these studies examined stiffness- or mass-related properties of the middle ear until resonant frequency norms are established for the elderly. No study has investigated age-related changes in the middle ear using probe frequencies above 660 Hz.

In theory, anatomical structures associated with the mass characteristics of the middle ear can be studied using high probe frequencies during tympanometry. Therefore, mass-related changes with aging, for example, should cause changes in high frequency immittance measurements (Van Camp et al., 1986). In fact, clinical reports have shown that high

---

[4] Recall that in the normal population, 660 Hz is below middle ear resonance, and that acoustic immittance is "stiffness-controlled" at frequencies below resonance.

frequency probe tones are preferable for examining mass-related changes of the ossicular chain such as otosclerosis (Lidén et al., 1974b; Van Camp et al., 1976; Feldman, 1977).

2.4 Statement of Purpose

We propose to investigate the effect of age on the middle ear system. Using the two methods described above (sweep frequency tympanometry and discrete multifrequency tympanometry), this study will examine if changes occur in the resonant frequency of the middle ear with aging. If the middle ear system becomes stiffer with age, we expect resonant frequency values to be higher for elderly subjects. Conversely, a less stiff middle ear system in geriatric subjects should yield lower resonant frequency values.

Pathologies lateral to the middle ear will be ruled out by otoscopic examination. Scarring of the tympanic membrane, monomeres, and/or tympanosclerosis, can affect tympanometric measurements. These conditions can either increase or decrease the tympanic membrane impedance, causing the resonant frequency to shift to higher or lower values. Low impedance conditions of the tympanic membrane have been shown to mask high impedance pathologies located more medially (Feldman, 1976). Cerumen in the ear canal can also affect tympanometric results by completely or partially blocking the probe tip (Feldman, 1976). Thus, otoscopic examination will ensure that our results represent changes in middle ear structures medial to the tympanic membrane.

Specifically, this study proposes to answer the following questions. Is there a significant difference in the resonant frequency values obtained in older adults (75 years and above) and in young adults, as measured by sweep frequency tympanometry and discrete multifrequency tympanometry? Do the two methods for identifying the resonant frequency, sweep frequency tympanometry and discrete multifrequency tympanometry, yield significantly different results?

CHAPTER 3

METHOD

The goal of this study was to compare middle ear resonant frequency values of geriatric subjects and young adults, using two experimental methods (sweep frequency measure and discrete multifrequency tympanometry). Sections 3.1, 3.2, and 3.3 outline the experimental protocol. Interpretation of experimental findings required that a follow-up study be completed. This sub-study is described in section 3.4.

3.1 Subjects

The experimental group consisted of 11 persons aged 75 years and above. Each subject included had normal tympanic membranes and ear canals as judged by an otolaryngologist upon otoscopic examination. Air conduction thresholds at octave intervals between 250 and 4000 Hz, and at 6000 Hz fell within the bone conduction limits at each respective frequency. Bone conduction thresholds were within 10 dB of the corresponding air conduction thresholds. Absence of an air-bone gap ruled out conductive pathologies that influence tympanometric results. Subjects had no history of chronic middle ear problems. They were mobile and mentally alert.

Normal hearing young adults between the ages of 20 and 25 years served as controls. Previous studies have shown that larger differences in age between the experimental and control groups yield more significant results (Blood and Greenberg, 1977; Nerbonne et al., 1978). The criteria for selection were similar to the experimental group, except that their air conduction thresholds were lower than 20 dB HL at the above indicated frequencies.

3.2 Procedures

To eliminate subjects with a history of middle ear problems, a screening interview was first conducted (see Appendix A). Subsequently, an otolaryngologist performed an otoscopic examination, and removed any cerumen from the ear canal. Bilateral pure tone air and bone conduction thresholds were obtained using the GSI 16 audiometer, in a sound-treated booth. Threshold procedures followed those recommended by ASHA (1978); subjects were required to raise their hand each time a sound was heard. Audiometric calibration met the standards specified by ANSI (1969).

Multifrequency immittance measurements were obtained using the GSI 33 Middle Ear Analyzer. A daily calibration check of the system was performed according to the manufacturer's recommendations. Hard-walled calibration cavities (0.5, 2.0, and 5.0 cm^3) were used to check admittance (Y) and its two components (B and G), at 226, 678 and 1000 Hz. A biological check of the multifrequency mode was also performed. Calibration of the immittance system, as specified by ANSI (1987), was performed before and after the study. The two calibrations were done six weeks apart, and all parameters measured were found to be within tolerance limits. These calibrations examined the immittance measurement system and the probe signal (Shanks et al., 1988). The immittance measurement system was calibrated as described above. Calibration of the probe signal involved measuring the accuracy of its frequency and sound pressure level. Using an HA-1 (2 cm^3) coupler and a sound level meter, the above features were measured to ensure that they complied with the specified standards. The pneumatic system was calibrated prior to data collection. An external manometer was used to measure air pressure accuracy. The rate of pressure change, as well as its range, were also measured.

Immittance measurements were obtained from one ear only for each subject. The number of right and left ears tested was kept as nearly equal as possible within each age group, and across age groups. The ear canal was hermetically sealed with a probe tip, and the probe tone level was held constant at 70 dB HL across frequencies. The immittance component measured was susceptance (B).

Middle ear resonant frequency was measured using two methods: sweep frequency tympanometry and discrete multifrequency tympanometry. Before any measurements were obtained, the ear canal pressure was swept between -400 and +200 daPa three times, in order to reduce the effect of consecutive tympanometric runs (Van Camp and Vogeleer, 1986). Sweep frequency tympanometry was performed initially; the probe tone frequency automatically increased in 50 Hz steps from 200 to 2000 Hz while the ear canal pressure was held constant at -400 daPa. An admittance tympanogram was then obtained at 226 Hz, and a similar frequency sweep was completed at the peak pressure identified by the tympanogram. The differences between susceptances at the two canal pressures were then plotted against probe tone frequency, and a hard copy of the data was obtained. The point at which the susceptance difference (ΔB) curve crossed the 0-mmho line was automatically identified by the tympanometer's cursor as the resonant frequency.

Susceptance tympanograms were then obtained at discrete frequencies close to the resonant frequency (discrete multifrequency tympanometry). Pressure in the ear canal was changed from -400 to +200 daPa, at a rate of 12.5 daPa/s. A starting pressure of -400 daPa yields a more accurate estimate of ear canal volume (Shanks and Lilly, 1981), but the ascending (negative to positive) ear canal pressure change results in more complex tympanogram shapes (Van Camp et al., 1986)[5]. The rate of ear canal pressure change used (12.5 daPa/s) is best suited for analyzing tympanometric shapes at discrete frequencies. A low rate of pressure change results in lower admittance values, and less complex tympanometric patterns (Creten and Van Camp, 1974).

---

5 Ideally, pressure in the ear canal should be changed from +200 to -400 daPa. However, at the time of data collection, it was thought that equipment limitations required ascending pressure changes. Only subsequently was it realized that start frequency could have be changed to a positive pressure value after the sweep frequency measure. Discrete multifrequency measures therefore could have been obtained using descending pressure changes.

For the discrete multifrequency method, the first tympanogram was recorded at the resonant frequency indicated by the sweep frequency method. If the initial tympanogram showed a notch that did not dip to its -400 daPa tail value, or if no notch was apparent, subsequent tympanograms were obtained in 50 Hz steps above the resonant frequency value. Such tympanograms were recorded until the notch reached the value of the tail. The lowest frequency at which this occurred was identified as the resonant frequency (Shanks et al., 1988). If the tympanogram recorded at the sweep frequency resonance showed a notch dipping to values equal to or lower than the tail, tympanograms were obtained in 50 Hz steps below the value of the resonant frequency. Resonant frequency was identified as in the first case. Studies that have recorded successive tympanograms using discrete probe tone frequencies have done so from low to high frequencies (Margolis et al., 1985; Van Camp and Vogeleer, 1986). Pilot data indicated that no difference existed in recording tympanograms from high to low frequencies or from low to high frequencies.

A repeated resonant frequency measure was obtained from each subject; half of the subjects in each age group were assigned the sweep frequency method, while the remaining subjects were assigned the discrete multifrequency method. This second measure of the resonant frequency served as a reliability measure.

Finally, since identification of resonant frequency in both methods required subjective judgements, a second interpretation of the data was obtained. The second judge was not involved in the data collection of this study.

3.3 Data Analysis

The goal of this study was to investigate the effect of age on the resonant frequency of the middle ear.

Resonant frequency was measured using two different tympanometric methods. A two-way analysis of variance was performed to determine if the independent variables of age and measurement method significantly affect the dependent variable, that is, resonant frequency. This also permitted us to identify if an interaction between the two independent variables (age and method) exists. Where main effects were found significant, further statistical analysis was completed using t-tests.

For each method, intra-subject reliability was analyzed by calculating the mean difference between repeated measurements of resonant frequency. A t-test was performed on the mean difference values to compare the reliability of the two methods of measurement.

The two measurement methods were also compared using the longitudinal data. First, a paired t-test comparing mean resonant frequency values obtained with each measurement method was performed to determine if the method used had a significant effect on resonant frequency values. Second, resonant frequency values obtained for each method were subtracted from the mean of all values obtained with that method. The mean difference values calculated for each method were compared using a t-test to determine whether or not one measurement method is more reliable than the other, over time.

3.4 Sub-Study Method

Interpretation of the results from the main study was found to be constrained by possible order effects of the resonant frequency measurements. Because of equipment limitations (see section 3.4.2), the sweep frequency method of measurement was always performed before that of the discrete multifrequency method. Conclusions regarding the significant main effect of method on the dependent variable (resonant frequency) were limited because the observed difference may have been influenced, or even directly caused, by the order of measurement. A potential source of measurement error is repeated ear canal pressure changes which can increase the complexity of tympanograms by shifting the reactance tympanogram to more positive values (Wilson et al., 1984). This type of error would theoretically result in the discrete multifrequency (second) method yielding lower resonant frequency values than the sweep frequency method (first), suggesting a more compliant (less stiff) middle ear system in the second measurement. Such results were indeed obtained.

Therefore, it was important to determine whether or not the observed method effect was the result of measurement order. Recall that before any measurements were obtained from each subject, ear canal pressure was swept at least three times between -400 and +200 daPa. This procedure should have reduced effects of repeated pressure changes (Van Camp and Vogeleer, 1986), but we must nevertheless determine if there was a true order effect. A sub-study was devised to evaluate the effect of method order on resonant frequency values.

3.4.1 Subjects

Ten subjects between the ages of 20 and 25 were tested. The selection criteria were identical to those used for the control group of the main study (see section 3.1).

3.4.2 Procedures

As in the main study, a screening interview, an otological examination, and a hearing test were followed by multifrequency immittance testing. Daily calibration checks, including biological checks of the multifrequency mode, were performed (see section 3.2). As before, ear canal pressure was initially swept three times between -400 and +200 daPa to reduce the effects of repeated tympanometric measures. For five subjects, the sweep frequency measure of middle ear resonant frequency was completed before the discrete multifrequency measure, as in the previous study.

For the alternate five subjects, the discrete multifrequency measure was completed first, prior to the sweep frequency measure. The GSI 33, when set to its multifrequency mode, requires that the sweep frequency measure be completed before obtaining tympanograms at specific frequencies. Therefore, in subjects receiving the discrete multifrequency treatment first, the non-test ear was used initially to obtain a sweep frequency measurement. The discrete multifrequency measurement could then be obtained first on the subject's test ear. In this subject group, the starting probe tone frequency was set at 1000 Hz; this frequency was chosen based on the average resonant frequency obtained in the main study. The shape of the

1000 Hz susceptance tympanogram determined whether to decrease or increase the probe tone frequency for subsequent tympanograms. The sweep frequency measurement procedures followed those outlined in section 3.2.

3.4.3 Data Analysis

Results from the sub-study were statistically analyzed using a two-way analysis of variance. The main effects of order and method of measurement on resonant frequency values were evaluated.

CHAPTER 4

RESULTS

4.1 Population Description

Twenty-six subjects were evaluated in this study. Of those, four were eliminated because of unacceptable air-bone gaps bilaterally, hearing losses greater than permitted, or otoscopic abnormalities (retracted tympanic membranes). Therefore, results were considered for twenty-two subjects. As can be seen in Tables Ia and Ib, each age group contained eleven subjects. Older subjects ranged in age from 75 to 81 years, with a mean of 77.7 years. Young adults ranged in age from 21 to 25 years, with a mean of 23 years. Although gender was not considered in this study, it has been shown that static compliance values are lower in females than in males (Jerger et al., 1972; Blood and Greenberg, 1975; Nerbonne et al., 1978). The number of males and females was kept as nearly equal as possible across groups. Geriatric subjects were composed of seven (64%) females and four (36%) males, whereas the young adults were eight (73%) females and three (23%) males. Middle ear resonant frequency values were obtained from one ear only for each subject. In each age group, equal numbers of right and left ears were strived for, since the significance of ear laterality remains unknown. We were forced to use one ear for most geriatric subjects, primarily because of unacceptable air-bone gaps but due also to monomeric tympanic membranes or excessive cerumen. Eight (73%) right ears and three (27%) left ears were tested for geriatric adults. This was matched as closely as possible for young adults: six (54%) right ears and four (46%) left ears.

4.2 Middle Ear Resonant Frequency

4.2.1 Descriptive Statistics

Tables IIa and IIb contain individual and group middle ear resonant frequency values obtained for the two different methods of measurement: sweep frequency and discrete

Table I. Description of subject population; age, gender, and ear tested in determining middle ear resonant frequency, for geriatric subjects (a) and young adults (b).

Subject number	Age (years)	Gender	Ear tested
(a) *Geriatric adults*			
1G	76	M	R
2G	76	F	R
3G	80	F	R
4G	80	M	R
5G	75	F	R
6G	77	F	L
7G	75	F	R
8G	80	F	L
9G	81	M	R
10G	79	M	L
11G	76	F	R
	Mean = 77.7 Range=75 to 81 N = 11	Ratio M:F = 4:7	Ratio R:L = 8:3
(b) *Young adults*			
1Y	25	F	L
2Y	21	M	L
3Y	23	M	R
4Y	21	M	L
5Y	24	F	R
6Y	22	F	R
7Y	21	F	L
8Y	24	F	L
9Y	23	F	R
10Y	24	F	R
11Y	25	F	R
	Mean = 23.0 Range=21 to 25 N = 11	Ratio M:F = 3:7	Ratio R:L = 6:5

Table II. Individual and group resonant frequency values obtained using two methods of measurement: sweep frequency and discrete multifrequency. Results shown for geriatric subjects (a) and young adults (b).

Subject number	Resonant frequency-sweep (in Hz)	Resonant frequency-discrete (in Hz)	Difference between resonant frequency values: sweep-discrete (in Hz)
(a) *Geriatric adults*			
1G	1100	900	200
2G	800	700	100
3G	1100	1050	50
4G	1200	1200	0
5G	1250	1050	200
6G	1150	750	400
7G	1200	1200	0
8G	1000	1000	0
9G	>2000*	1950	-
10G	1200	1200	0
11G	1500	900	600
	Mean=1150.0 S.D.=179.51 N = 10	Mean=1081.82 S.D.=335.61 N = 11	Mean=155.0 S.D.=203.37 N = 10
(b) *Young adults*			
1Y	1200	1000	200
2Y	>2000*	800	-
3Y	1250	1000	250
4Y	1600	1300	300
5Y	1300	1050	250
6Y	1050	800	250
7Y	1200	950	250
8Y	1250	1000	250
9Y	1500	1050	450
10Y	1350	850	500
11Y	1850	1400	450
	Mean=1355.0 S.D.=233.87 N = 10	Mean=1018.18 S.D.=188.78 N = 11	Mean=315.0 S.D.=108.14 N = 10

* Values beyond 2000 Hz limit of equipment.

multifrequency. In two cases, subjects #9G and #2Y, the ΔB (susceptance difference) sweep frequency curve did not cross the 0-mmho line. It is assumed, therefore, that resonant frequency exceeded the maximum frequency measure of 2000 Hz. In such cases, it was not possible to estimate the exact resonant frequency value, thus these two subjects were not included in any statistical analyses pertaining to resonant frequency values obtained using the sweep frequency method. Geriatric mean resonant frequency was 1150 Hz (S.D. = 179.5 Hz) for the sweep frequency measure, and 1082 Hz (S.D. = 335.6 Hz) for the discrete multifrequency measure. For young adults, these values were 1355 Hz (S.D. = 233.9 Hz) and 1018 Hz (S.D. = 188.8 Hz), respectively. Figures 15a and 15b compare individual middle ear resonant frequency values obtained with the two measurement methods, for old and young adults, respectively. Figures 16a and 16b illustrate frequency distributions of resonant frequency values across age groups for sweep frequency and discrete multifrequency methods, respectively.

Also note in Table II the individual differences between resonant frequency values obtained with each method; for every subject, the resonant frequency value obtained with the sweep frequency method was always equal to or higher than that obtained with the discrete multifrequency method. The positive resonant frequency difference values are therefore those obtained by subtracting the value of the discrete multifrequency method from that of the sweep frequency method. For older subjects, the mean difference in resonant frequency values was 155 Hz (S.D. = 203.4 Hz). The mean difference value for young adults was 315 Hz (S.D. = 108.1 Hz). Figure 17 represents frequency distributions of the difference in resonant frequency obtained for sweep frequency and discrete multifrequency methods, across age groups.

4.2.2 Inferential Statistics

To determine if the independent variables of age and measurement method significantly affect the dependent variable of resonant frequency, a two-way analysis of variance (ANOVA),

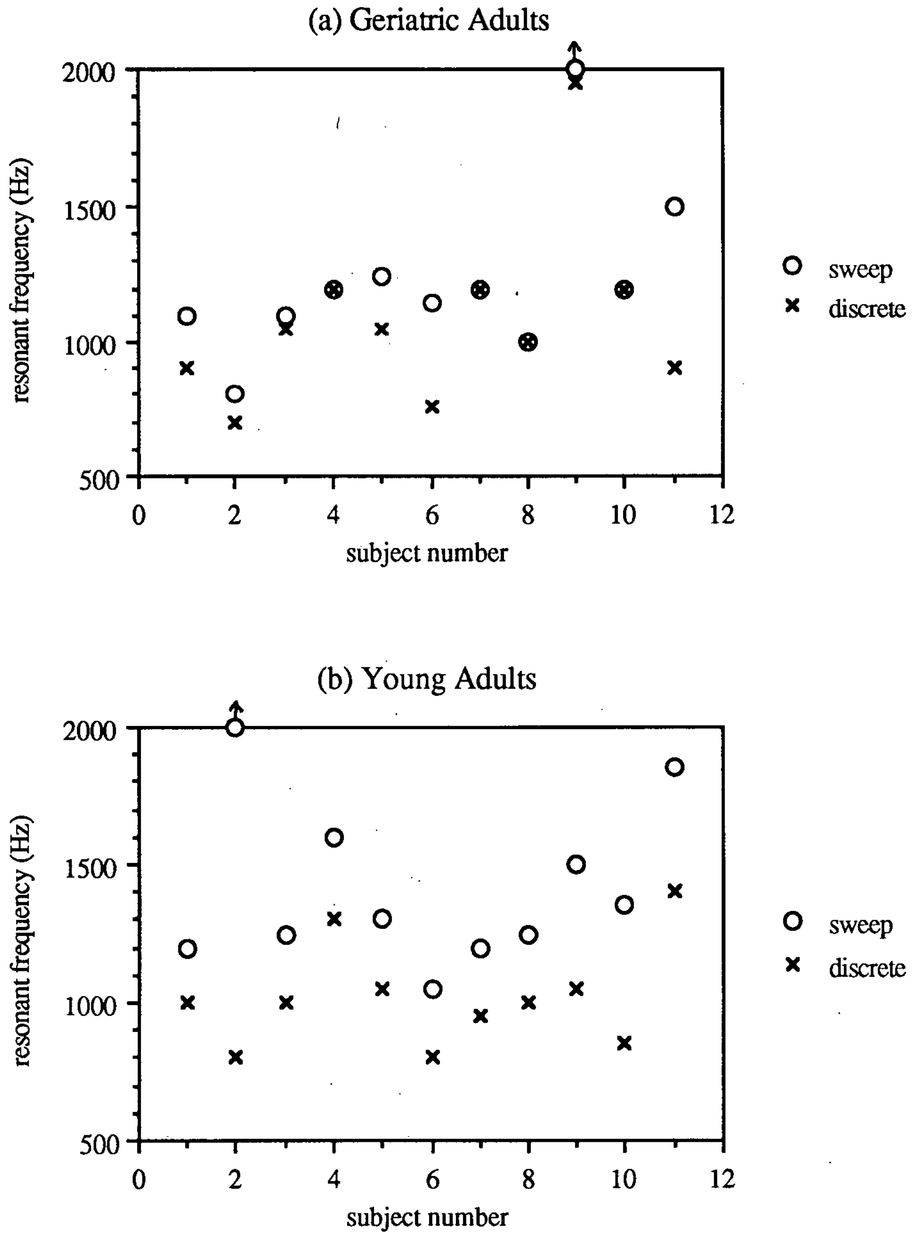
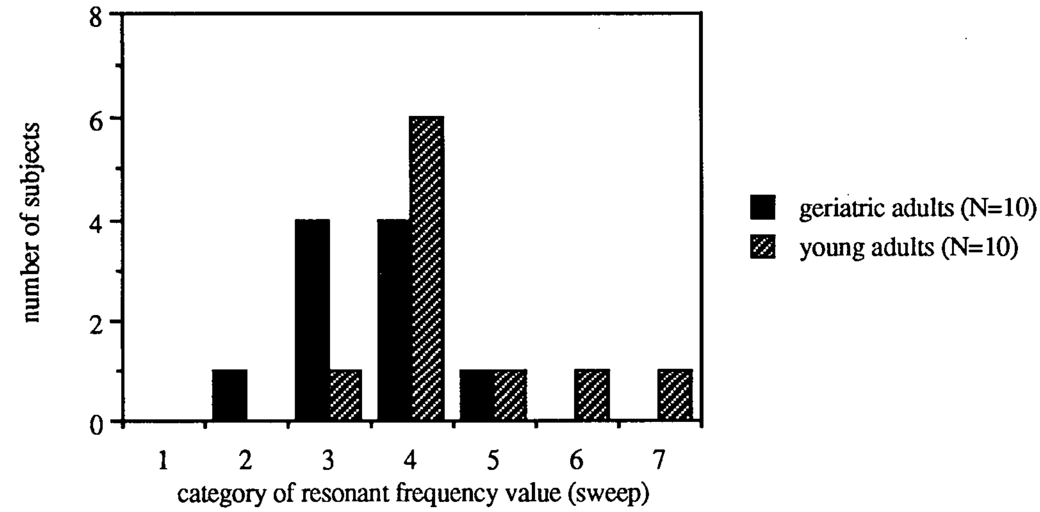


Figure 15. Resonant frequency values (in Hz) measured using two different methods: sweep frequency and discrete multifrequency. Results are shown for eleven geriatric adults (a), and eleven young adults (b).

(a) Sweep Frequency Method



Categories:

1 = 600 to 799 Hz
2 = 800 to 999 Hz
3 = 1000 to 1199 Hz
4 = 1200 to 1399 Hz
5 = 1400 to 1599 Hz
6 = 1600 to 1799 Hz
7 = 1800 to 1999 Hz

(b) Discrete Multifrequency Method

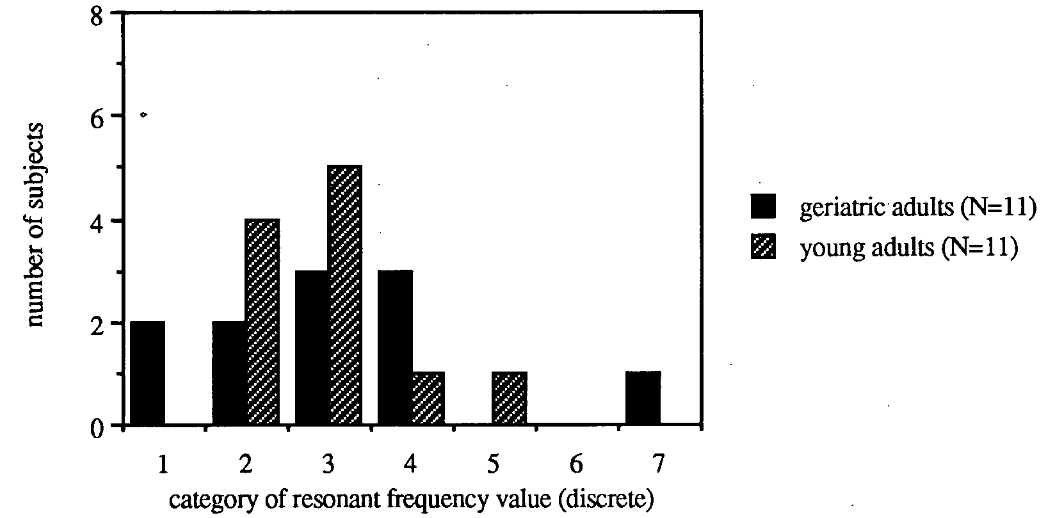
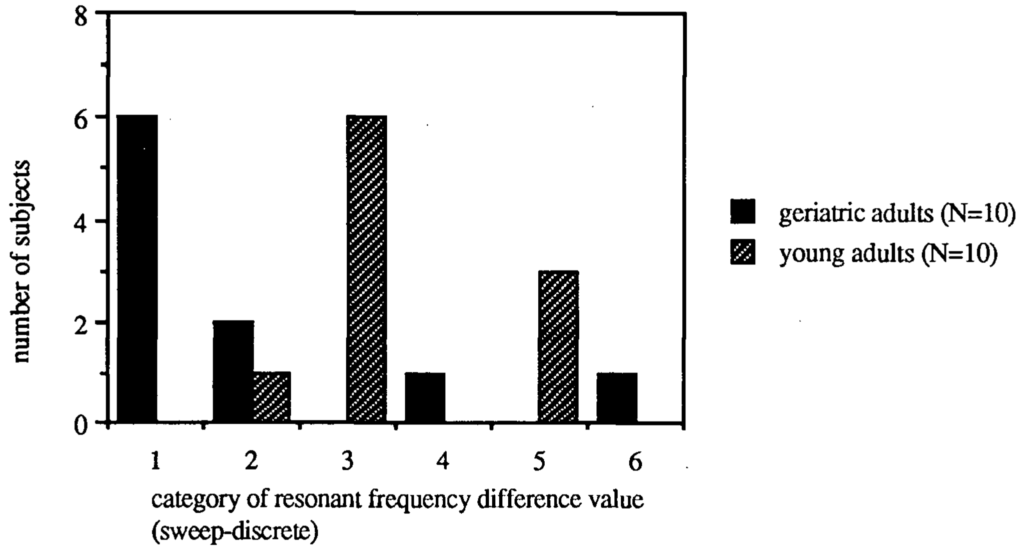


Figure 16. Frequency distributions of resonant frequency values obtained from geriatric and young adults, as measured by the sweep frequency method (a), and the discrete multifrequency method (b).



Categories:

1 = 0 to 100 Hz
2 = 101 to 200 Hz
3 = 201 to 300 Hz
4 = 301 to 400 Hz
5 = 401 to 500 Hz
6 = 501 to 600 Hz

Figure 17. Frequency distributions of differences between resonant frequency values obtained with the sweep frequency measure and the discrete multifrequency measure (sweep-discrete). Data shown for geriatric and young adults.

with repeated measures on the method variable, was performed. Significance was set at the level of $p < 0.05$. Table III contains the results of the two-way ANOVA. First, the age variable did not have a significant effect on middle ear resonant frequency values ($F = 2.457$, d.f. = 1, $p > 0.05$). Second, the main effect of measurement method used to determine resonant frequency was significant ($F = 41.636$, d.f. = 1, $p < 0.05$). Finally, the interaction of the two variables, age and method, was significant ($F = 4.825$, d.f. = 1, $p < 0.05$). Figure 18 shows mean resonant frequency values obtained with the two measurement methods, for each age group. In addition, this representation illustrates the interaction of the two variables. That is, the effects of method and age do not behave independently of one another. Further, for each age group, paired t-tests were completed to compare the two methods of measurement (see Table IV). For both old and young adults, there was a significant difference between resonant frequency values obtained using the sweep frequency and discrete multifrequency methods (respective values being: $t = 2.410$, d.f. = 9, $p < 0.05$; $t = 9.211$, d.f. = 9, $p < 0.05$).

4.3 Measurement Reliability

4.3.1 Intra-Subject Reliability

For each subject, middle ear resonant frequency was measured a second time using only one of the two methods. For each age group, 55% of subjects were retested using the sweep frequency method, and 45% percent using the discrete multifrequency method. Since the main effect of age was not significant, subject groups were pooled for this analysis. Table V shows both initial and repeated measures of resonant frequency by measurement method. The absolute difference between the first and second trials is also shown in the last column. This difference represents a measure of the intra-subject variability of each method. For the sweep frequency method, the mean within-subject difference was 170 Hz (S.D. = 176.7 Hz); the mean difference for the discrete multifrequency method was 15 Hz (S.D. = 24.2 Hz).

Table III. Results from a two-way ANOVA that examined the effects of age and method of measurement on mean middle ear resonant frequency values.

Source	*d.f.*	*M.S.*	*F*	*p*
Between subjects:				
age	1	156250.0	2.457	0.134
error	18	63597.222	-	-
Within subjects:				
method	1	552250.0	41.636	0.000
ageXmethod	1	64000.0	4.825	0.041
error	18	13263.889	-	-

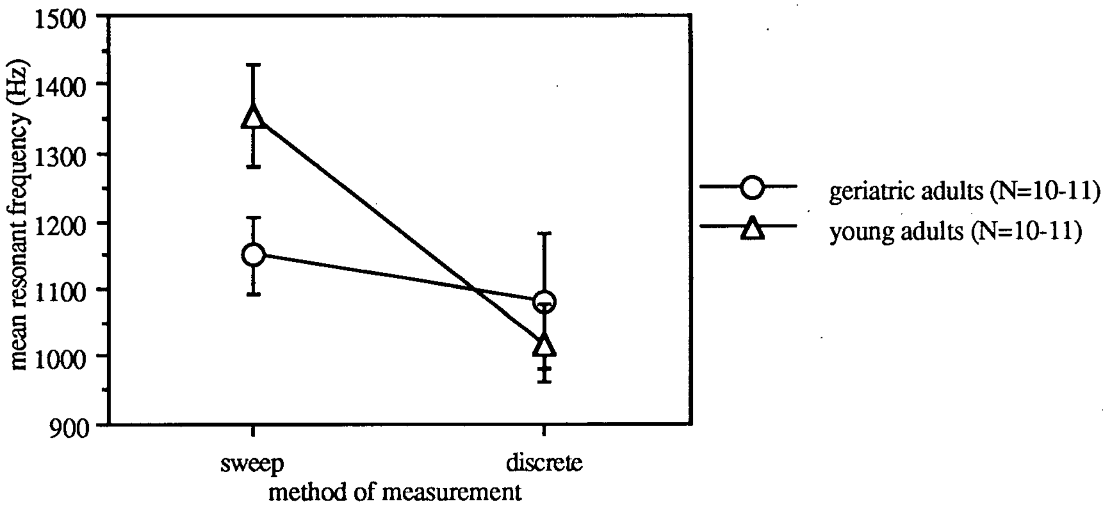


Figure 18. Mean resonant frequency values, with corresponding standard errors of the mean, as a function of measurement method. Data shown for geriatric and young adults.

Table IV. Results of paired t-tests comparing the two methods of measurement, for each age group.

Group	*N*	*Mean (Hz)*	*S.D. (Hz)*	*t*	*d.f.*	*p*
geriatric adults:						
sweep	10	1150.0	179.51	2.410	9	0.039
discrete	11	1081.82	335.61			
young adults:						
sweep	10	1355.0	233.87	9.211	9	0.000
discrete	11	1018.18	188.78			

Table V. Intra-subject reliability of resonant frequency values for two methods of measurement; sweep frequency (a) and discrete multifrequency (b).

Subject number	Resonant frequency value from trial #1 (in Hz)	Resonant frequency value from trial #2 (in Hz)	Absolute difference between 1st and 2nd trials (in Hz)
(a) *Sweep frequency method*			
1Y	1200	1300	100
3G	1100	1100	0
2Y	>2000	800	-
6G	1150	850	300
5Y	1300	1200	100
7G	1200	1200	0
7Y	1200	1000	200
9G	>2000	1900	-
10G	1200	1300	100
9Y	1500	1300	200
10Y	1350	1250	100
11G	1500	900	600
	Mean = 1270.0 S.D. = 139.84 N = 10	Mean = 1175.0 S.D. = 291.94 N = 11	Mean = 170.0 S.D. = 176.70 N = 10
(b) *Discrete multifrequency method*			
1G	900	900	0
2G	700	650	50
4G	1200	1200	0
5G	1050	1050	0
3Y	1000	1000	0
4Y	1300	1250	50
6Y	800	800	0
8G	1000	1000	0
8Y	1000	950	50
11Y	1400	1400	0
	Mean =1035.0 S.D. = 216.09 N = 10	Mean = 1020.0 S.D. = 220.10 N = 11	Mean = 15.0 S.D. = 24.15 N = 10

Table VI. Independent t-test comparing intra-subject differences obtained with each method of measurement.

Group	*N*	*Mean (Hz)*	*S.D. (Hz)*	*t*	*d.f.*	*p*
sweep	10	170	176.70	2.748	18	0.013
discrete	10	15	24.15			

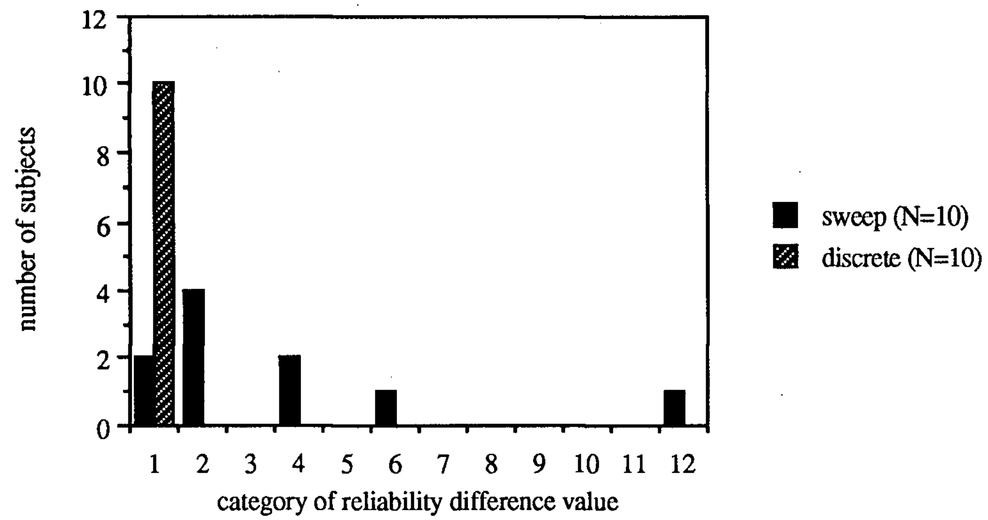
Results of an independent t-test showed a significant difference between within-subject differences obtained for each method of measurement ($t = 2.748$, d.f. = 18, $p < 0.05$) (see Table VI). In Figure 19, the frequency distributions of within-subject difference values for each method are shown. All the subjects retested with the discrete multifrequency method produced resonant frequency values within 50 Hz of the first measure. Alternatively, within-subject differences were as high as 600 Hz for subjects retested with the sweep frequency measure.

4.3.2 Inter-Examiner Reliability

Results from the interpretation of resonant frequency data by a second judge were equivalent to the first interpretation for 95% of the measures. Table VII shows results for the two subjects in which interpretations differed. For each of the two exceptions, interpretations differed by only 50 Hz. In these two cases, a consensus between the two judges determined the final value used in calculations. For subject 2Y, the first judge's value of 800 Hz was kept; whereas for subject 8G, the second judge's value was used.

4.3.3 Longitudinal Reliability

Middle ear resonant frequency values were obtained using both measurement methods on the examiner's right ear, every day of testing. The results are recorded in Table VIII and illustrated in Figure 20. Table IX shows the results of a paired t-test comparing the longitudinal mean resonant frequency value of the sweep frequency method to that of the discrete multifrequency method ($t = 5.193$, d.f. = 12, $p < 0.05$). As observed in the experimental data, a significant difference between the two measurement methods was obtained. Further calculations were made to determine if the variability of the two methods over time was significantly different. Table X contains absolute difference values which were obtained by subtracting individual resonant frequency values measured, from the mean resonant frequency of the respective method used; mean (mean) difference values obtained



Categories:		
	1 = 0 to 50 Hz	7 = 301 to 350 Hz
	2 = 51 to 100 Hz	8 = 351 to 400 Hz
	3 = 101 to 150 Hz	9 = 401 to 450 Hz
	4 = 151 to 200 Hz	10 = 451 to 500 Hz
	5 = 201 to 250 Hz	11 = 501 to 550 Hz
	6 = 251 to 300 Hz	12 = 551 to 600 Hz

Figure 19. Frequency distributions of reliability difference values: absolute difference between two measures of resonant frequency from the same subject. Results are shown for the sweep frequency method, and the discrete multifrequency method.

Table VII. Results from the two subjects for which inter-judge interpretations of resonant frequency measures differed.

Subject number	Method	Examiner's interpretation of resonant frequency value (in Hz)	Second interpretation of resonant frequency value (in Hz)	Difference between 1st and 2nd interpretations: (2-1) (in Hz)
2Y	discrete	800	850	+50
8G	sweep	1050	1000	-50

Table VIII. Longitudinal reliability of resonant frequency values measured by two different methods.

Date	Resonant frequency value-sweep measure (in Hz)	Resonant frequency value-discrete measure (in Hz)
Sept.26'90	800	600
Sept.27'90	850	550
Oct.1'90	700	550
Oct.3'90	1200	550
Oct.4'90	800	600
Oct.5'90	700	600
Oct.10'90	800	600
Oct.11'90	800	550
Oct.12'90	850	550
Oct.15'90	650	550
Oct.17'90	900	600
Oct.18'90	900	600
Oct.19'90	1400	600
	Mean = 873.08 S.D. = 207.78 N = 13	Mean = 576.92 S.D. = 25.94 N = 13

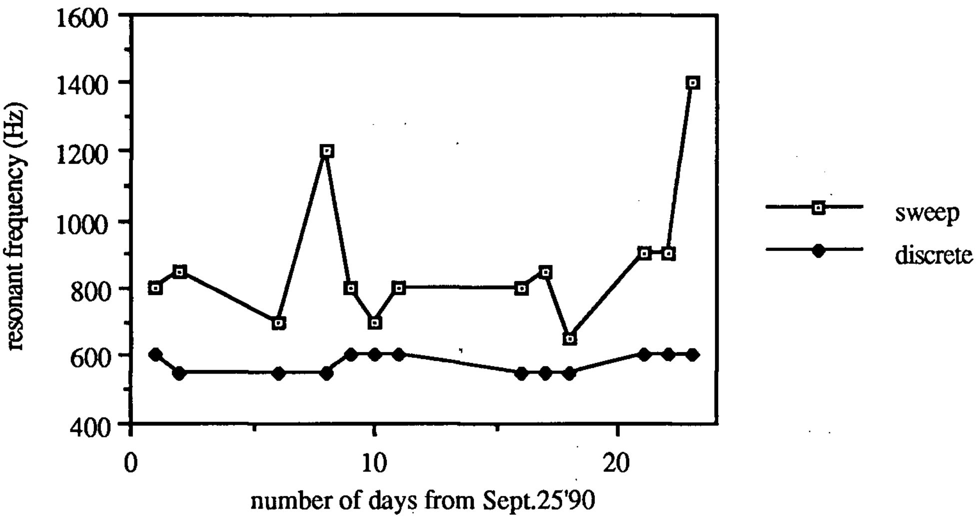


Figure 20. Longitudinal reliability. Resonant frequency values obtained with the sweep frequency measure and the discrete multifrequency measure from the same ear of the experimenter, on different days of testing.

Table IX. Paired t-test comparing resonant frequency values obtained with each method of measurement, over several days.

Group	*N*	*Mean (Hz)*	*S.D. (Hz)*	*t*	*d.f.*	*p*
sweep	13	873.08	207.78	5.193	12	0.000
discrete	13	576.92	25.94			

Table X. Absolute differences from the median(mean) of resonant frequency values obtained with each measurement method, as part of the longitudinal reliability.

Date	Absolute differences from mean resonant frequency values (in Hz)	
	sweep frequency	*discrete multifrequency*
Sept.26'90	73	23
Sept.27'90	23	27
Oct.1'90	173	27
Oct.3'90	327	27
Oct.4'90	73	23
Oct.5'90	173	23
Oct.10'90	73	23
Oct.11'90	73	27
Oct.12'90	23	27
Oct.15'90	223	27
Oct.17'90	27	23
Oct.18'90	27	23
Oct.19'90	527	23
	Mean = 139.62 S.D. = 148.51 N = 13	Mean = 24.85 S.D. = 2.08 N = 13

were 140 Hz (S.D. = 148.5 Hz) for the sweep frequency method, and 25 Hz (S.D. = 2.1 Hz) for the discrete multifrequency method. Figure 21 compares the frequency distributions of the difference from the mean values for the two measurement methods. Difference values calculated for the discrete multifrequency method data appear lower overall, and less variable. A paired t-test was performed to compare the mean (mean) difference values for each method. The results of the t-test (see Table XI) indicate that the discrete multifrequency is significantly more reliable over time than the sweep analysis ($t = 2.786$, d.f. = 12, $p < 0.05$).

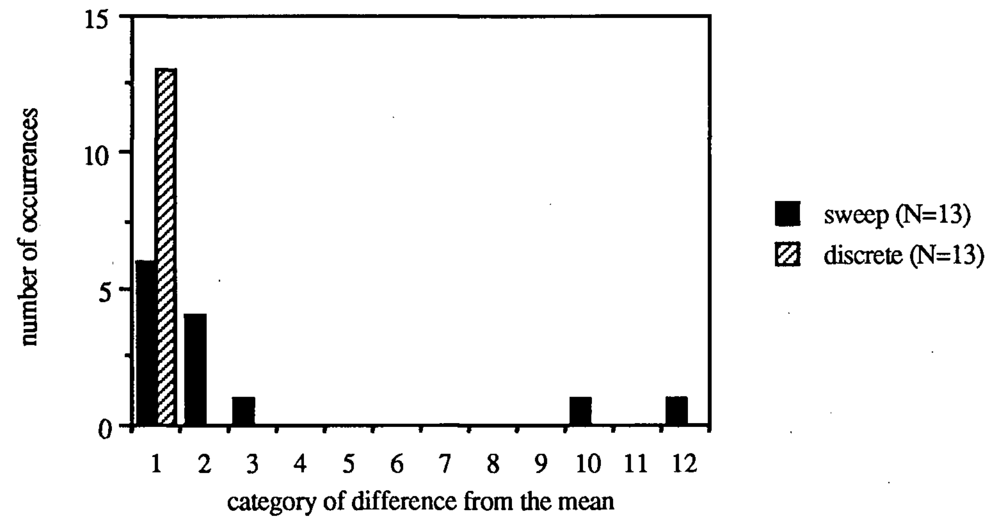
4.4 Results of Sub-Study

4.4.1 Population Description

Tables XIIa and XIIb describe the ten subjects in the sub-study; five additional subjects were eliminated because of excessive cerumen or poor health. Subjects were divided into two groups corresponding to the order in which resonant frequency measurements were made (see section 3.4.2). For order 1, the subjects' ages ranged from 23 to 25 years, with a mean of 24.2 years. For order 2, the age range was 21 to 25 years, with a mean of 23.6 years. One male and four females were tested in order 1; two males and three females were tested in order 2. The ratio of right to left ears from which resonant frequency values were obtained, was 2 to 3 for order 1, and 3 to 2 for order 2.

4.4.2 Middle Ear Resonant Frequency

Tables XIIIa and XIIIb show individual and group resonant frequency data. In order 1, resonant frequency values were obtained with the sweep frequency method first, followed by the discrete multifrequency method. This was the order used throughout the main study. In order 2, resonant frequency was determined using the discrete multifrequency method before the sweep frequency method. For order 1, the mean resonant frequency values obtained were 1280 Hz (S.D. = 236.1 Hz) with the sweep frequency measure, and 1060 Hz



Categories:		
	1 = 0 to 50 Hz	7 = 301 to 350 Hz
	2 = 51 to 100 Hz	8 = 351 to 400 Hz
	3 = 101 to 150 Hz	9 = 401 to 450 Hz
	4 = 151 to 200 Hz	10 = 451 to 500 Hz
	5 = 201 to 250 Hz	11 = 501 to 550 Hz
	6 = 251 to 300 Hz	12 = 551 to 600 Hz

Figure 21 . Frequency distributions of absolute difference from the mean values calculated for the sweep frequency method and the discrete multifrequency method.

Table XI. Paired t-test comparing difference from the mean values calculated for each method of measurement.

Group	*N*	*Mean (Hz)*	*S.D. (Hz)*	*t*	*d.f.*	*p*
sweep	13	139.62	148.51	2.786	12	0.016
discrete	13	24.85	2.08			

Table XII. Description of population used in sub-study; age, gender, and ear used in resonant frequency testing.

Subject number	Age (years)	Gender	Ear tested
(a) *Order 1 (sweep 1st; discrete 2nd)*			
B	23	F	L
D	24	F	L
F	25	F	R
G	25	F	L
J	24	M	R
	Mean = 24.2 Range = 23 to 25 N = 5	Ratio M:F = 1:4	Ratio R:L = 2:3
(b) *Order 2 (discrete 1st; sweep 2nd)*			
A	25	M	L
C	24	F	R
E	21	M	L
H	23	F	R
I	25	F	R
	Mean = 23.6 Range = 21 to 25 N = 5	Ratio M:F = 2:3	Ratio R:L = 3:2

Table XIII. Resonant frequency values obtained in the sub-study. Results shown for the two orders of measurement; sweep frequency first (a), and discrete multifrequency first (b).

Subject number	Resonant frequency-sweep (in Hz)	Resonant frequency-discrete (in Hz)	Difference between resonant frequency values: sweep-discrete (in Hz)
(a) *Order 1 (sweep 1st; discrete 2nd)*			
B	1200	1000	250
D	1150	950	250
F	1000	900	100
G	1500	1300	200
J	1550	1150	400
	Mean = 1280.0 S.D. = 236.11 N = 5	Mean = 1060.0 S.D. = 163.55 N = 5	Mean = 240.0 S.D. = 108.40 N = 5
(b) *Order 2 (discrete 1st; sweep 2nd)*			
A	1100	1000	100
C	1200	850	350
E	950	750	200
H	1150	800	350
I	1750	1400	350
	Mean = 1230.0 S.D. = 305.37 N = 5	Mean = 960.0 S.D. = 263.15 N = 5	Mean = 270.0 S.D. = 115.11 N = 5

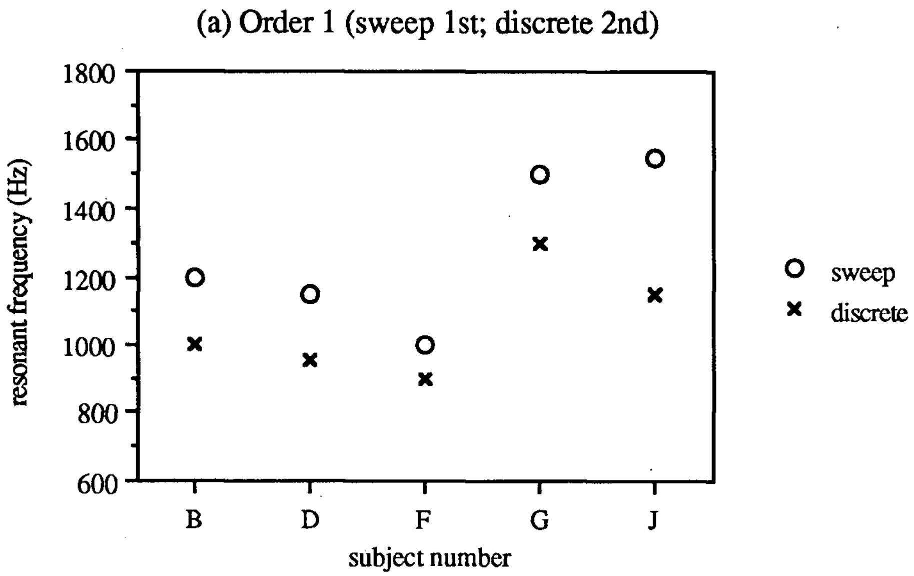
(S.D. = 163.6 Hz) with the discrete multifrequency measure. For order 2, mean resonant frequency values for the sweep frequency measure and the discrete multifrequency measure were, 1230 Hz (S.D. = 305.4 Hz) and 960 Hz (S.D. = 263.2 Hz), respectively. Individual middle ear resonant frequency values obtained with each measurement method, are shown in Figures 22a and 22b, for measurement order 1 and order 2, respectively.

Individual differences between values obtained with each measurement method were also calculated by subtracting the value obtained with discrete multifrequency from the value obtained from sweep frequency (see Tables XIIIa and XIIIb). For order 1, the mean difference value was 240 Hz (S.D. = 108.4 Hz); for order 2, the mean difference was 270 Hz (S.D. = 115.1 Hz). Figure 23 contains frequency distributions of resonant frequency difference values for each order of measurement.

Table XIV, as well as Figure 24, illustrate the mean resonant frequency values (and standard deviations) calculated for each measurement method in young adult subjects from the main study and the sub-study. Independent t-tests comparing resonant frequency means from the two studies were performed for each measurement method; no significant differences were found between studies, for either method (sweep: $t = 0.907$, d.f. = 18, $p > 0.05$; discrete: $t = 0.093$, d.f. =19, $p > 0.05$).

4.4.3 <u>Inferential Statistics</u>

A two-way analysis of variance (ANOVA) was performed to determine if the independent variables of order and method of measurement had an effect on the dependent variable of resonant frequency. Results are shown in Table XV. First, the measurement order did not show a significant effect on resonant frequency values ($F = 0.242$, d.f. = 1, $p > 0.05$). As in the main study, the effect of the measurement method used to obtain resonant frequency was significant ($F = 47.545$, d.f. = 1, $p < 0.05$). Finally, the interaction of the order and method variables was not significant ($F = 0.495$, d.f. = 1, $p > 0.05$). Figure 25 represents mean resonant frequency values obtained with each measurement method, for each order of



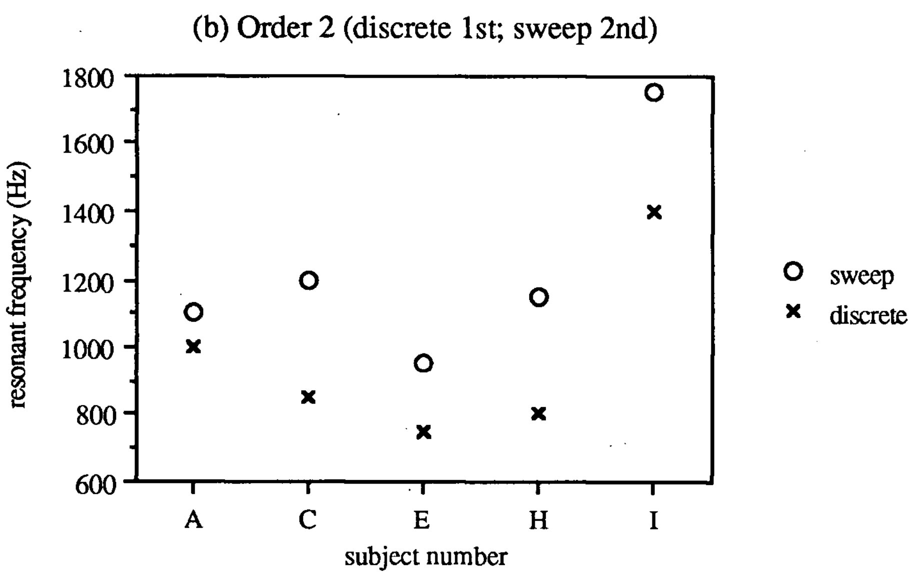
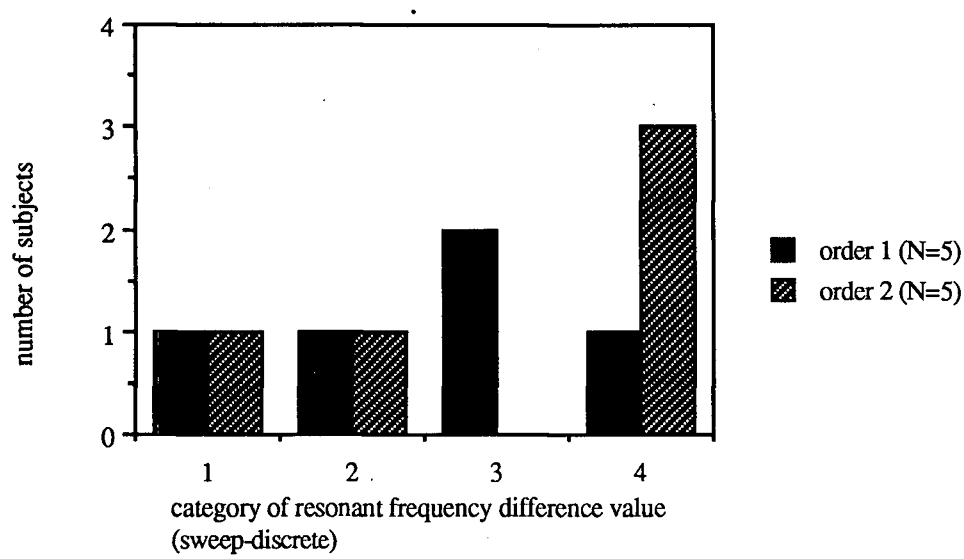


Figure 22. Resonant frequency values (in Hz) measured using two different methods: sweep frequency and discrete multifrequency. Results are shown for young adults tested in order 1 (sweep 1st; discrete 2nd) (a), and in order 2 (discrete 1st; sweep 2nd) (b).



Categories: 1 = 0 to 100 Hz
2 = 101 to 200 Hz
3 = 201 to 300 Hz
4 = 301 to 400 Hz

Figure 23. Frequency distributions for differences between resonant frequency values obtained with the sweep frequency method and the discrete multifrequency method (sweep-discrete). Data shown for two orders of measurement: order 1 (sweep 1st; discrete 2nd), and order 2 (discrete 1st; sweep 2nd).

Table XIV. Young adult group resonant frequency data for both measurement methods, as obtained in the main study (young adults) and the sub-study.

	sweep frequency	*discrete multifrequency*
(a) *main study* *(young adults)*	Mean = 1355.0 Hz S.D. = 233.87 Hz N = 11	Mean = 1018.18 Hz S.D. = 188.78 Hz N = 11
(b) *sub-study*	Mean = 1255.0 Hz S.D. = 258.68 Hz N = 10	Mean = 1010.0 Hz S.D. = 213.18 Hz N = 10

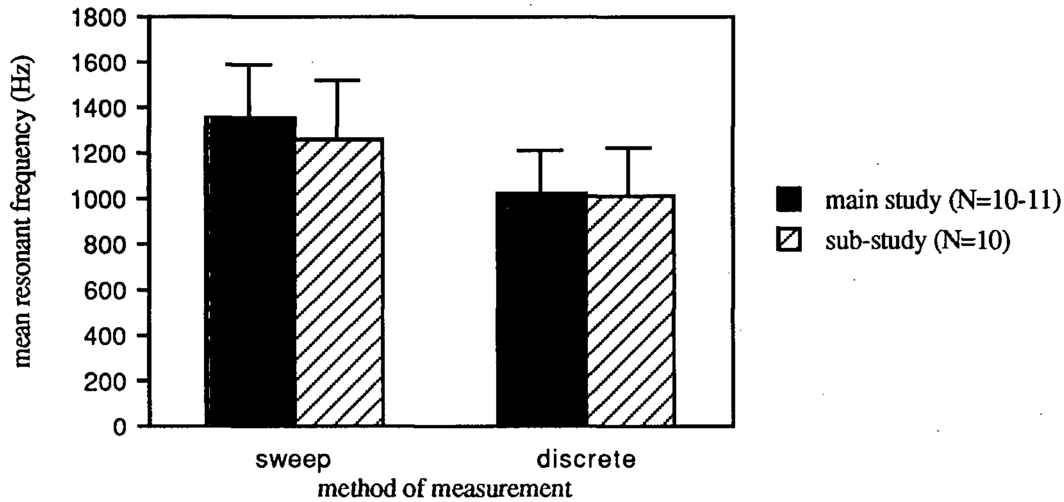


Figure 24. Mean resonant frequency values and standard deviations for the sweep frequency and discrete multifrequency methods, as measured in the main study (young adults) and the sub-study.

Table XV. Results from a two-way ANOVA testing for effects of order and method of measurement on mean middle ear resonant frequency values.

Source	*d.f.*	*M.S.*	*F*	*p*
Between subjects:				
order	1	28125.0	0.242	0.636
error	8	116187.5	-	-
Within subjects:				
method	1	300125.0	47.545	0.000
orderXmethod	1	3125.0	0.495	0.502
error	8	6312.5	-	-

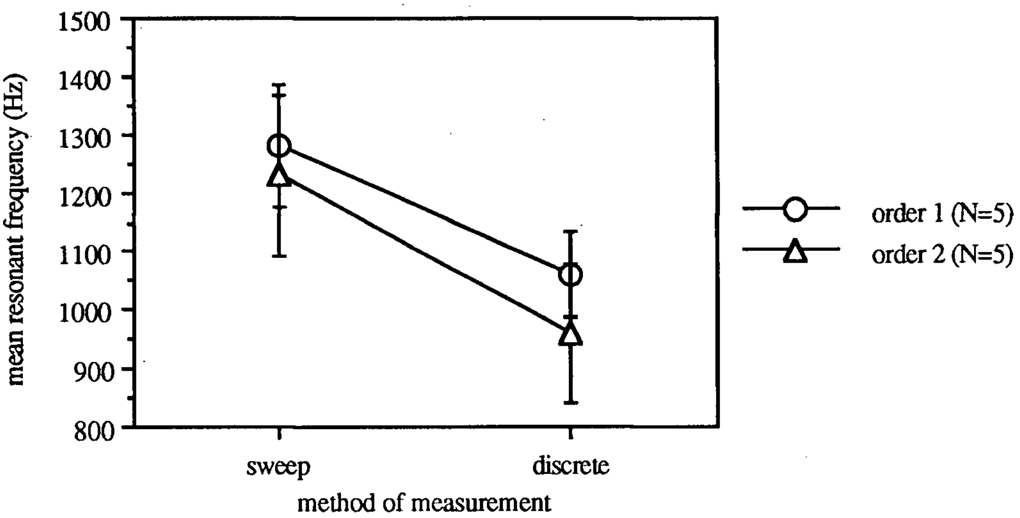


Figure 25 . Mean resonant frequency values, with corresponding standard errors of the mean, as a function of measurement method. Data shown for two orders of measurement: order 1 (sweep 1st; discrete 2nd), and order 2 (discrete 1st; sweep 2nd).

measurement (standard errors of the mean are also represented). The parallel relationship between the two functions suggests that both independent variables act independently of one another. For each order of measurement, a paired t-test was performed to compare the two measurement methods (see Table XVI). For both orders of measurement, there was a significant difference between resonant frequency values obtained with the sweep frequency and the multifrequency methods (order 1: $t = 4.491$, d.f. = 4, $p < 0.05$; order 2: $t = 5.245$, d.f. = 4, $p < 0.05$).

Table XVI. Results of paired t-tests comparing the two methods of measurement, for each order of measurement (order 1: sweep 1st, discrete 2nd; order 2: discrete 1st, sweep 2nd).

Group	*N*	*Mean (Hz)*	*S.D. (Hz)*	*t*	*d.f.*	*p*
order 1:						
sweep	5	1280.0	236.11	4.491	4	0.011
discrete	5	1060.0	163.55			
order 2:						
sweep	5	1230.0	305.37	5.245	4	0.006
discrete	5	960.0	263.15			

CHAPTER 5

DISCUSSION

The purpose of this study was to examine the effect of age on resonant values of the middle ear. We also compared two methods of resonant frequency measurement; sweep frequency and discrete multifrequency. Results obtained show that age does not significantly affect resonant frequency values. Conversely, the experimental method used to measure resonant frequency did have a significant effect on values obtained.

5.1 Normal Resonant Frequency Values

Resonant frequency values obtained from our measures were quite variable and covered a wide range: 700 Hz to over 2000 Hz (see Table II). These values are higher than the normal range of 750 to 900 Hz reported by Van Camp et al. (1976), based on research by Zwislocki (1962). Zwislocki used an electrical analog model of the middle ear which can only be an approximation of human middle ears. Comparisons are difficult to make with studies that do not specify the methodology in which the normal values were obtained. Such is the case for Shanks (1984) reporting a normal resonant frequency range of 800 to 1200 Hz, and Lidén et al. (1974a) who report an average value of 800 Hz.

Because our study found an effect of the method of measurement, it may well be best to compare ranges of values only between studies that employed similar measurement techniques. For example, Colletti (1975) used a discrete multifrequency method similar to ours, and found that resonant frequency values from normal middle ears were between 650 and 1400 Hz. Values obtained with the discrete multifrequency method in our study were all between 700 and 1400 Hz, with a single exception of one at 1950 Hz. Using the sweep frequency method, Funasaka et al. (1984) found a slightly wider and higher range of normal resonant frequency values: 720 to 1880 Hz. Again, this corresponds well to our results;

sweep frequency values were between 800 and 1850 Hz, except for two cases in which resonant frequency exceeded the equipment limits (>2000 Hz). If we closely examine the three exceptions above, we find that they involve two subjects: 9G (sweep and shape) and 2Y (sweep) (see Table II). It is possible that subject 9G had an undetected pathology that caused the exceptionally high resonant frequency values obtained with both methods. Note that the sweep frequency method was repeated in his case as a reliability measure (see Table V): at 1900 Hz, the value was still above the normal range reported by Funasaka et al. (1984). Subject 2Y had an exceptionally high resonant frequency value as measured by the sweep frequency method (>2000 Hz), but the discrete multifrequency method yielded a value of 800 Hz. Such a difference between the two resonant frequency methods is well beyond the maximum of 600 Hz found in other subjects. Furthermore, the second sweep frequency measure (reliability measurement) obtained from subject 2Y yielded a resonant frequency value of 800 Hz (see Table V). This test-retest difference (>2000 Hz vs 800 Hz) is considerably above the maximum of that found in other subjects (also 600 Hz). One explanation may be that the first sweep frequency measure was invalid, either due to equipment malfunction, or subject effects (swallowing, coughing, vocalizing, probe movements) of which the examiner was not aware.

We can therefore conclude that middle ear resonant frequency measurements obtained in this study are in agreement with values reported by other investigators, using similar measurement methods. However, such good agreement is somewhat unexpected, considering that in this study the susceptance component of admittance was used to identify resonant frequency, whereas both Funasaka et al. (1984) and Colletti (1975) measured impedance. Recall from our discussion of the Vanhuyse model (section 2.2.4), that admittance (and impedance) tympanograms begin to notch at higher probe tone frequencies than susceptance tympanograms. Therefore, resonant frequency, or the frequency at which the minimum notch value (at peak pressure) equals the tail value (at -400 daPa), is expected to be higher for impedance measures than for susceptance measures.

5.2 Effect of Age

Middle ear resonant frequency values obtained from old and young adults were not significantly different in this study. As discussed previously, middle ear resonant frequency is directly affected by the anatomy of the middle ear, more specifically, by the relationship between mass and stiffness properties of the middle ear. Previous studies have found age-related anatomical changes suggesting an increase in middle ear stiffness (Etholm and Belal, 1974), whereas others suggest a decrease in stiffness (Gilad and Glorig, 1979). One interpretation of the results of this study is that anatomical changes with opposite effects may be simultaneously occurring with aging, thereby not significantly affecting the overall mean resonant frequency. Another related possibility is that changes occurring in the middle ear of geriatric subjects are unpredictable and differ among individuals. Finally, it is possible that anatomical changes in older middle ear systems are not significant enough to affect resonant frequency.

Previous studies that have examined age-related changes in middle ear stiffness properties using immittance measures, have found conflicting results (Jerger et al, 1972; Beattie and Leamy, 1975; Blood and Greenberg, 1975; Nerbonne et al., 1978; Thompson et al., 1979; Gates et al., 1990). Those studies used low probe tone frequencies, and therefore were more sensitive to stiffness-related changes. In contrast, by measuring resonant frequency, our study was more concerned with the interaction of mass and stiffness properties of the middle ear. That is, our measures were more representative of the entire middle ear system, and of overall changes occurring with age. We can therefore conclude that age does not affect measurements of middle ear resonant frequency.

5.3 Effect of Measurement Method

Our study found a significant difference between resonant frequency values obtained with the sweep frequency method and the discrete multifrequency method. Values obtained with the sweep frequency measure were systematically higher than those from the discrete multifrequency measure. While our study measured susceptance values, and both Funasaka et al. (1984) and Colletti (1975) measured impedance values, the normal resonant frequency range reported by Funasaka using a sweep frequency measure was nonetheless slightly higher than that reported by Colletti, who used a discrete multifrequency measure.

The effect of measurement method could have been due to the order in which the measurements were obtained. As described previously, the effect of successive tympanometric measures can produce results suggesting a less stiff system. Because the discrete multifrequency measurements were always obtained after the sweep frequency measurements, and yielded lower resonant frequency values (consistent with the above effect), we devised a sub-study to investigate the effect of order. As reported, order of measurement did not have a significant effect on resonant frequency values obtained. Therefore, the order of measurement cannot explain differences obtained between methods.

We must therefore closely examine the two measurement methods. Recall that the two methods measure the same parameter, susceptance, based on the same principle of comparing susceptance values at -400 daPa and peak pressure. In one case, frequency is varied as pressure is held constant (sweep frequency method); in the other, pressure is varied as frequency is held constant (discrete multifrequency method). Because of the difference in results from the two methods, we must question the validity of resonant frequency values obtained with both methods. One of the two methods presumably yields more valid results than the other. Which one, and why?

Intuitively, we can propose that the sweep frequency method may yield more valid results because it covers a very wide range of probe tone frequencies. The discrete multifrequency method used in this study only examined a subset of frequencies. The start frequency was either determined by the sweep frequency result, or set at 1000 Hz (for one group of subjects in the sub-study). This may have biased the discrete multifrequency results. A more thorough, but time-consuming, procedure would be to obtain tympanograms at the 36 frequencies used in the sweep frequency method. We would not expect the above effect to be significant if we recall that the Vanhuyse model predicts an orderly sequence of tympanometric shapes with probe frequency changes (Vanhuyse et al., 1975). Regardless of the start frequency, the tympanometric shape obtained at a specific frequency should always be the same.

Procedural variables that affect tympanogram amplitude and morphology were described in section 2.2.3. The ascending pressure change used in this study (-400 to +200 daPa), yields higher admittance (and susceptance) values (Creten and Van Camp, 1974) and more complex tympanometric shapes (Margolis et al., 1985), than a descending pressure change. The ascending pressure change would lead to lower resonant frequency values suggesting a less stiff middle ear system. The slow rate of pressure change (12.5 daPa/s) has opposite effects (Creten and Van Camp, 1974; Van Camp et al., 1986): lower susceptance values and less complex tympanometric shapes result in resonant frequency values that are higher than those obtained with a faster rate of pressure change. Because of the opposing effects of the above two procedural variables, the overall effect on resonant frequency values obtained was likely minimal. A third variable is the effect of consecutive tympanometric measurements. Such measurements lead to high susceptance values and more complex tympanometric shapes (Wilson et al., 1984), suggesting a less stiff middle ear system, as evidenced by lower resonant frequency value. This last variable was controlled for by changing the pressure between -400 and +200 daPa at least three times before any tympanometric measurements were obtained. Although this procedure certainly reduced the effect of consecutive tympanometric measurements, we cannot rule out a small residual effect (Van Camp and Vogeleer, 1986).

The validity of resonant frequency values obtained with the sweep frequency method could be reduced by subject effects such as swallowing, coughing, vocalizing, and probe movements caused by body shifting. These variables would affect the sweep frequency measure more than the discrete multifrequency measure. Each sample recorded during the sweep frequency procedure is taken into account in the calculation of resonant frequency, whereas tympanograms recorded for the discrete multifrequency method allow more variations; the two most important points are -400 daPa and the pressure range around the notch. So long as variations do not occur at those two locations, they do not influence the resonant frequency value obtained. As discussed in the next section, the reliability of the discrete multifrequency method is better than that of the sweep frequency method.

5.4 Reliability of Measurement Methods

The overall reliability of the discrete multifrequency method was found to be higher than for the sweep frequency method. Test-retest reliability, both within the same session (across subjects), and over several days (for a single subject), was better for the discrete multifrequency measure than the sweep frequency measure.

One might argue that the order of measurement could account for these findings. That is, since the reliability measurement (either sweep frequency or discrete multifrequency) always followed the discrete multifrequency measure, then consecutive measurements (sweep-discrete-discrete) would yield lower test-retest differences than nonconsecutive measurements (sweep-discrete-sweep). We reject this argument for two reasons: 1) as was shown in the sub-study, the effect of measurement order on resonant frequency is not significant; and 2) the longitudinal reliability data also demonstrates that the sweep frequency measurement of resonant frequency is significantly more variable than that of the discrete multifrequency measurement.

Subject effects described in the previous section could explain, in part, the reliability differences obtained. And as above, limitations inherent to the equipment could cause across trial variation; this remains to be investigated. Examiner bias was reduced by having a second judge interpret the data. High inter-judge agreement eliminates this factor as a plausible explanation.

Note that although the reliability of the discrete multifrequency method is better than that of the sweep frequency method, we cannot draw conclusions regarding the validity of resonant frequency values obtained with either method.

5.5 Clinical Implications of the Findings

Age was not found to have a significant effect on resonant frequency values. Therefore, normative resonant frequency data obtained from young adults is applicable to geriatric adults as well. Note that these results should not be extended to other special age groups, such as children or infants.

The method of measurement of middle ear resonant frequency was found to have a significant effect on values obtained. The method of measurement used should therefore always be taken into account when comparing sets of resonant frequency data of different sources.

5.6 Conclusions

Conclusions from this study can be summarized as follows:

(1) The equipment used (Grason-Stadler GSI 33 Middle Ear Analyzer), yielded middle ear resonant frequency values comparable to those obtained by other investigators using similar measurement methods, but different equipment.

(2) Advanced age does not have a significant effect on middle ear resonant frequency values, suggesting that anatomical changes which occur in the middle ear with aging are either unpredictable and variable, are not significant enough to be measured, or are a combination of these factors.

(3) Clinically, normative middle ear resonant frequency values from young adults can be applied to geriatric patients as well.

(4) Sweep frequency tympanometry and discrete multifrequency tympanometry yield significantly different middle ear resonant frequency values, and therefore data obtained with one method cannot be compared with data obtained with the other.

(5) Both test-retest reliability within a single session , and over several days (longitudinal), were found to be significantly better for the discrete multifrequency method than the sweep frequency method.

5.7 Implications for Future Research

A similar study targeting other special age groups would be of interest. Infants and young children, as separate subject populations, should be compared to available middle ear resonant frequency data obtained from young adults. Valuable developmental information regarding the middle ear would be gained.

Repeating this study using a descending (positive to negative) ear canal pressure change in the discrete multifrequency method would determine if the method effect found in this study can be accounted for by the procedural variable, direction of pressure change.

BIBLIOGRAPHY

American National Standards Institute (1969) Specifications for audiometers (ANSI S3.6-1969). New York.

American National Standards Institute (1987) American national standard specifications for instruments to measure aural acoustic impedance and admittance (aural acoustic immittance) (ANSI S3.39-1987). New York.

American Speech and Hearing Association, Committee on Audiometric Evaluation (1978) Guidelines for manual pure-tone threshold audiometry. Asha 20, 297-301.

Anderson, R.G. and W.L. Meyerhoff (1982) Otologic manifestations of aging. Otolaryngol. Clinics N. Amer. 15, 353-370.

Beattie, R.C. and D.P. Leamy (1975) Otoadmittance: normative values, procedural variables, and reliability. J. Am. Audiol. Soc. 1, 21-27.

Bess, F.H. and L.E. Humes (1990) Audiology: The Fundamentals, F.H. Bess and L.E. Humes (Eds.), Williams & Wilkins, Baltimore.

Blood, I. and H.J. Greenberg (1977) Acoustic admittance of the ear in the geriatric person. J. Am. Audiol. Soc. 2, 185-187.

Colletti, V. (1975) Methodologic observations on tympanometry with regard to the probe tone frequency. Acta Oto-Laryngol. 80, 54-60.

Colletti, V. (1976) Tympanometry from 200 to 2000 Hz probe tone. Audiology 15, 106-119.

Colletti, V. (1977) Multifrequency tympanometry. Audiology 16, 278-287.

Creten, W.L. and K.J. Van Camp (1974) Transient and quasi-static tympanometry. Scand. Audiol. 3, 39-42.

Etholm, B. and A. Belal (1974) Senile changes in the middle ear joints. Ann. Otol. 83, 49-54.

Feldman, A.S. (1976) Tympanometry. In Acoustic Impedance and Admittance: The Measurement of Middle Ear Function, A.S. Feldman and L. Wilber (Eds.), Williams & Wilkins, Baltimore. 103-155.

Feldman, A.S. (1977) Diagnostic implication and interpretation of tympanometry and the acoustic reflex. Audiology 16, 294-306.

Funasaka, S. and K. Kumakawa (1988) Tympanometry using a sweep-frequency probe tone and its clinical evaluation. Audiology 27, 99-108.

Funasaka, S., H. Funai, and K. Kumakawa (1984) Sweep-frequency tympanometry: its development and diagnostic value. Audiology 23, 366-379.

Gates, G.A., J.C. Cooper, W. B. Kannel, and N.J. Miller (1990) Hearing in the elderly: the Framingham cohort, 1983-1985. Part I. Basic audiometric test results. Ear Hear. 11, 247-256.

Gilad, O. and A. Glorig (1979) Presbycusis: the aging ear, part I. J. Am. Audiol. Soc. 4, 195-206.

Jerger, J. (1970) Clinical experience with impedance audiometry. Arch. Otolaryngol. 92, 311-324.

Jerger, J., S. Jerger, and L. Mauldin (1972) Studies in impedance audiometry. I. Normal and sensorineural ears. Arch. Otolaryng. 96, 513-523.

Khanna, S.M. and J. Tornndof (1972) Tympanic membrane vibrations in cats studied by time-averaged holography. J. Amer. Soc. Amer. 51, 1904-1920.

Lidén, G., G. Bjorkman, H. Nyman, and H. Kunov (1977) Tympanometry and acoustic impedance. Acta Oto-Laryngol. 83, 140-145.

Lidén, G., E. Harford, and O. Hallen (1974a) Automatic tympanometry in clinical practice. Audiology 13, 126-139.

Lidén, G., E. Harford, and O. Hallen (1974b) Tympanometry for the diagnosis of ossicular disruption. Arch. Otolaryngol. 99, 23-29.

Lilly, D.J. (1984) Multiple frequency, multiple component tympanometry: new approaches to an old diagnostic problem. Ear Hear. 5, 300-308.

Margolis, R.H. (1981) Fundamentals of acoustic immittance. In Hearing Assesment with the Acoustic Reflex, G.R. Popelka (Ed.), Grune & Stratton, New York. 117-143.

Margolis, R.H. and G.R. Popelka (1977) Interactions among tympanometric variables. J. Speech Hear. Res. 20, 447-462.

Margolis, R.H. and J.E. Shanks (1991) Tympanometry: Basic principles and clinical applications. In Hearing Assessment (ed.2), W.F. Rintelmann (Ed.), Pro-ed, Austin, Texas. 179-245.

Margolis, R.H., K.J. Van Camp, R.H. Wilson, and W.L. Creten (1985) Multifrequency tympanometry in normal ears. Audiology 24, 44-53.

Marshall, L., S.A. Martinez, and M.E. Schlaman (1983) Reassessment of high-frequency air-bone gaps in older adults. Arch. Otolaryngol. 109, 601-606.

Metz, O. (1946) The acoustic impedance measured on normal and pathological ears. Acta Otolaryngol. Suppl. 63.

Møller, A. (1965) An experimental study of the acoustic impedance of the middle ear and its transmission properties. Acta Oto-Laryngol. 60, 129-149.

Nedzelnitsky, V. (1980) Sound pressures in the basal turn of the cat cochlea. J. Acoust. Soc. Amer. 68, 1676-1689.

Nerbonne, M.A., A.T. Bliss, and R.L. Schow (1978) Acoustic impedance values in the elderly. J. Am. Audiol. Soc. 4, 57-59.

Northern, J.L. and A.M. Grimes (1978) Introduction to acoustic impedance. In, Handbook of Clinical Audiology (ed.2), J. Katz (Ed.), Williams & Wilkins, Baltimore. 344-355.

Norwood, T.H. (1990) Cellular aging. In Geriatric Medicine (ed.2), C.K. Cassel et al. (Eds.), Springer-Verlag, New York. 1-15.

Pickles, J.O. (1988) The outer and middle ears. In An Introduction to the Physiology of Hearing (ed.2), J.O. Pickles (Ed.), Academic Press, London. 12-35.

Roadburg, A. (1985) Aging: retirement, leisure and work in Canada. Methuen, Agincourt, Ontario.

Rosenwasser, H. (1964) Otitic problems in the aged. Geriatrics 19, 11-17.

Rowlatt, C. and L.M. Franks (1978) Aging in tissues and cells. In Textbook of Geriatric Medicine and Gerontology (ed.2), J.C. Brocklehurst (Ed.), Churchill Linvingstone, Edinburgh. 3-17.

Shanks, J.E. (1984) Tympanometry. Ear Hear. 5, 268-280.

Shanks, J.E. and D.J. Lilly (1981) An evaluation of tympanometric estimates of ear canal volume. J. Speech Hear. Res. 24, 557-566.

Shanks, J.E., D.J. Lilly, R.H. Margolis, T.L. Wiley, and R.H. Wilson (1988) Tympanometry. ASHA working group on aural acoustic-immittance measurements. Committee on audiologic evaluation. J. Speech Hear. Dis. 53, 354-377.

Shanks, J.E., R.H. Wilson, and C. Palmer (1987) Multiple frequency tympanometry. Asha 29, 131.

Terkildsen, K. and S. Scott-Nielsen (1960) An electroacoustic impedance measuring bridge for clinical use. Acta Oto-Laryngol. 72, 339-346.

Thompson, D.J., J.A. Sills, K.S. Recke, and D.M. Bui (1979) Acoustic admittance and the aging ear. J. Speech Hear. Res. 22, 29-36.

Van Camp, K.J., E.R. Raman, and W.L. Creten (1976) Two-component versus admittance tympanometry. Audiology 15, 120-127.

Van Camp, K.J., R. Margolis, R. Wilson, W. Creten, and J. Shanks (1986) Principles of tympanometry. ASHA Monographs 24.

Van Camp, K.J. and M. Vogeleer (1986) Normative multifrequency tympanometric data on otosclerosis. Scand. Audiol. 15, 187-190.

Vander, A.J., J.H. Sherman, and D.S. Luciano (1985) Homeostatic mechanisms. In Human Physiology: The Mechanisms of Body Function (ed.4), A.J. Vander et al. (Eds.), McGraw-Hill, New York. 147-171.

Vanhuyse, V.J., W.L. Creten, and K.J. Van Camp (1975) On the W-notching of tympanograms. Scand. Audiol. 4, 45-50.

Wiley, T.L. and M.G. Block (1985) Overview and basic principles of acoustic immittance measurements. In Handbook of Clinical Audiology (ed. 3), J. Katz (Ed.), Williams & Wilkins, Baltimore. 423-437.

Wilson, R., J. Shanks, and S. Kaplan (1984) Tympanometric changes at 226 Hz and 678 Hz across ten trials and for two directions of ear-canal pressure change. J. Speech Hear. Res. 27, 257-266.

Zwislocki, J.J. (1962) Analysis of the middle-ear function. Part I: Input impedance. J. Acoust. Soc. Amer. 34, 1514-1523.

APPENDIX A

UNIVERSITY OF BRITISH COLUMBIA
SCHOOL OF AUDIOLOGY AND SPEECH SCIENCES

SCREENING INTERVIEW (to be given orally)

Subject number: _________ Date: ___________________
Date of birth: ____________

Physical health

1. Do you now have a cold? yes ___ no ___
2. Have you been physically ill in the past six months?
   yes ___ no ___ if yes, please explain:
3. How would you describe your recent health?
   excellent ___ good ___ fair ___ poor ___
4. Are you now taking any medication?
   yes ___ no ___ if yes, please explain:

Hearing status

1. Do you now, or have you ever had a hearing problem?
   yes ___ no ___ if yes, please explain:
2. Have you ever been medically treated for a hearing problem?
   yes ___ no ___ if yes, please explain:
3. Have you ever had ear infections?
   yes ___ no ___ if yes, please explain (how many, when, how were they treated, etc.)
4. Have you ever perforated your eardrum(s)?
   yes ___ no ___ if yes, please explain:
5. Is there a history of hearing loss in your family?
   yes ___ no ___ if yes, please explain: