WIDEBAND REFLECTANCE IN ADULTS: NORMATIVE DATA AND A CASE SERIES OF OTOSCLEROSIS

by

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B.Sc., The University of Alberta, 2001

A THESIS SUBMITTED IN PARTIAL FULFILMENT
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

October 2004

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Title of Thesis: Wideband Reflectance in Adults: Normative data and a case series of otosclerosis.

Degree: M.Sc. Year: 2004

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Abstract

For years immittance has been used in order to help diagnose middle ear pathologies. Specifically, multi-frequency tympanometry is able to relate information to clinicians regarding the mechano-acoustical characteristics of the middle ear system. In the past two decades a new method of middle ear measurement, wideband reflectance (WBR), has been discovered. Wideband reflectance is the ratio of energy reflected from the surfaces of the ear canal and middle ear on its way to the cochlea in relation to the energy that reaches the surface, or incident energy. This ratio is known as energy reflectance and can be manipulated to give values of power absorption, admittance, susceptance, and conductance. There are numerous advantages to WBR over multi-frequency tympanometry, including its objectiveness, speed, and wide frequency range. However, as of yet, few normative studies have been published to guide clinicians in the practical uses of WBR and their ability to assess middle ear pathologies, such as otosclerosis.

In this regard, this thesis adds to the limited normative data available, as well as explores whether these normative data have a clinical utility in the diagnosis of otosclerosis. Taking into consideration possible gender and race differences, normative data were collected for both genders in Chinese and Caucasian populations. Mean, 5th, and 95th percentiles were gathered from 128 subjects (240 ears) for these groups as well as in seven patients (seven ears) with otosclerosis. The four WBR parameters assessed were power absorption, admittance, susceptance, and conductance. Analysis consisted of: (1) a repeated measures analysis of variance including the within subject factor of level of frequency and the between subject factors of gender, race, and ear, and (2) a visual comparison of graphically presented normative group data, as well as individual patient data graphically compared with appropriate normative values. Combining statistical analysis and visual observations, this study strongly suggests the need for

implementation of gender and race specific normative values for WBR. Differences in graphic representation of patient data plotted against normative values are found for some WBR measures. Further research is needed in this area.

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List of Abbreviations

Abbreviation	Definition
AGC	Automatic gain control
B	Susceptance (admittance)
B_m	Mass susceptance (admittance)
B_s	Stiffness susceptance (admittance)
B_t	Total susceptance (admittance)
daPa	dekaPascal
ECV	Ear canal volume
ER	Energy reflectance
F45°	Frequency corresponding to an admittance phase angle of 45°
G	Conductance (admittance)
HL	Hearing level
Hz	Hertz
mmhos	millimhos
MFT	Multi-frequency tympanometry
PA	Power absorption
R	Resistance (impedance)
RF	Resonant frequency
TW	Tympanometric width
TEOAE	Transient evoked otoacoustic emission
SA	Static admittance
SF	Sweep frequency
SP	Sweep pressure
SPL	Sound pressure level
Y	Admittance
Z	Impedance
+B	Positive compensated susceptance
-B	Negative compensated susceptance

Acknowledgements

Completing a thesis is not to be taken lightly, as is evident by the weight of this book. It takes countless hours of procedural set up, data collection, analysis, and writing, not to mention editing. None of these tasks can be accomplished alone.

I would like to thank my thesis supervisor, Dr. Navid Shahnaz, for his vision of extensive middle ear studies that made my thesis possible. His willingness to share new knowledge and his enthusiasm for cutting edge discoveries gave me the drive to continue. I greatly appreciate the time and effort he devoted to my thesis.

I would also like to thank my thesis committee, Drs. Sipke Pijl and Brian Westerberg, for their insightful comments and excellent advice. I particularly wish to thank Dr. Westerberg and Marleen for their organization of patient assessment, making it possible for me to obtain clinical data.

I also wish to thank Drs. M. P. Feeney and C. A. Sanford for providing normative data for comparison, as well as, Drs. J. Meyer and J. Allen for their expertise in the interpretation of the data.

And last, but definitely not least, I would like to thank my family and friends, without whom this thesis would never have been completed. Their many hours of patient listening to my concerns of the day were sincerely appreciated.

Chapter I Introduction

Wideband reflectance (WBR) is a relatively new measure for middle ear evaluation. It uses a wide range of sound frequencies to establish a ratio of sound energy reflected on its way to the cochlea in relation to the sound that reaches the cochlea. Wideband reflectance has the potential to exceed the clinical utility of commonly used tympanometric measures for the diagnosis of middle ear pathologies. In addition to expanding the understanding of middle ear conditions through the use of WBR, examination of pathological middle ear systems will add to the knowledge about WBR. One of the common middle ear pathologies that could benefit from the examination by a sound stimulus of a wide range of frequencies is that of otosclerosis. Examination of this common disorder with tympanometric measures has lead to the improved understanding of the relative contributions of mass, stiffness, and resistance to middle ear pathologies (Shahnaz & Polka, 2002). By further examining otosclerotic ears with WBR, significant advancement of the audiologists' ability to diagnose and monitor middle ear disease is expected.

In the fifth edition of the *Handbook of Clinical Audiology* (Rappaport and Provençal, 2002), otosclerosis, a disorder of the otic capsule leading to symptoms of progressive hearing loss, is described as "the most intriguing of all otologic diseases" (p. 21). Descriptions of this common disorder have been in the literature for almost 300 years. In 1735, Valsalva reported that ankylosis or fixation of the stapes could cause hearing loss (Ginsberg & White, 1985). This observation was repeated by others and by 1893, Adam Politzer of Vienna, determined that this ankylosis was due to a disease of the bone that is responsible for forming the otic capsule and the surrounding area and not due to chronic middle ear catarrh as had been previously thought (Ginsberg & White, 1985). Over time, the understanding of the pathophysiology of otosclerosis

has evolved. It is now understood as a fixation of the stapedial footplate (Gelfand, 2001). This fixation results in reduced ability of the ossicular chain to transmit signals to the cochlea.

Audiological techniques for the diagnosis and assessment of otosclerosis are based on the concepts that otosclerosis typically increases the stiffness of the middle ear system (Shahnaz & Polka, 2002). Therefore, it is classed as a high impedance (low admittance) pathology (Shahnaz & Polka, 2002). The most effective measures for diagnosing otosclerosis are those that evaluate the relative contributions of mass, stiffness, and resistance (Shahnaz & Polka, 2002; Shanks & Shelton, 1991). For some time, clinical audiologists have relied upon traditional single component, low frequency tympanometry mainly static admittance (SA) in diagnosis of otosclerosis (Alberti, & Kristensen, 1970; Browning, Swan, & Gatehouse, 1985; Dempsey, 1975; Jerger, 1970; Jerger, Anthony, Jerger, & Mauldin, 1974; Liden, Peterson, & Bjorkman, 1970; and Muchnik, Hildesheimer, Rubinstein, & Glettman, 1989). There have also been suggestions that otosclerosis is associated with narrower tympanometric width (TW) (Dieroff, 1978; Ivey, 1975; Koebsell, Shanks, Cone-Wesson, & Wilson, 1988; Shahnaz & Polka, 1997). In recent years multi-frequency tympanometry (MFT) has shown diagnostic utility in otosclerosis (Shahnaz & Polka, 2002), as described in chapter two in the following literature review. However, there is still a significant overlap between healthy and otosclerotic ears on all measures obtained by tympanometry. More information is needed about middle ear characteristics in patients with otosclerosis.

This study will provide a more detailed picture of the mechano-acoustical properties of the middle ear using WBR. By charting how much energy is transferred into the system across a wide range of frequencies, WBR can evaluate the relative contribution of mass, stiffness, and resistance. Ultimately, the study hopes to show that WBR can provide an objective means of predicting the conductive involvement in otosclerosis. If this is accomplished, the study will

confirm Keefe, Bulen, Arehart, & Burns (1993) study that WBR expands the presently available measure of MFT. Thus, WBR can potentially be used both to diagnose otosclerosis and to evaluate different surgical procedures and the efficiency of various prosthetic devices for the treatment of otosclerosis. Wideband reflectance provides this potential as it measures how the middle ear reflects or absorbs sounds across a range of frequencies much greater than that of MFT.

Surgical techniques for otosclerosis have been in the literature for more than 125 years. Currently, there are two techniques in use: stapedectomy (the removal of the ankylosed stapes and footplate) and stapedotomy (where a hole is bored in the footplate rather than removing it). Surgery is discussed further in the following literature review (Chapter II).

Research about otosclerosis is active today on many fronts. Audiologists, otolaryngologists, genetists, histologists, epidemiologists, and others, are exploring ways to advance understanding of the causes, varying population distributions, audiological evaluation, and treatments of otosclerosis. The aspect of critical concern for audiologists and otolaryngologists alike is the advancement of audiological techniques to improve diagnostic accuracy of otosclerosis prior to surgery and to explore objective means to assess and advance treatment options. This can be achieved by a series of steps, some of which are addressed in this study. The steps include: (1) understanding the limitations of current clinical measures of middle ear pathology and investigating new technologies that may improve the understanding of both normal and pathological middle ear dynamic characteristics, (2) obtaining normative values for new measures of middle ear function in accordance with the confounding variables that can affect normative data, such as, age, gender, and race, (3) testing subjects with otosclerosis on these new measures and compare results with normative values, and (4) using audiometric, operative, and histological descriptions of otosclerosis to establish grading systems for

comparison with the measurements in order to expand knowledge both of the pathophysiology of otosclerosis and the clinical utility of the new diagnostic tests.

This study focuses on establishing adult normative values for WBR including the examination of gender and race effects to see whether gender and race specific normative data should be used. The second stage is an exploratory study to investigate the potential clinical utility of WBR in otosclerosis. This is the first research to address the effect of race on WBR.

This thesis follows standard format of literature review of otosclerosis, current diagnostic testing methods, WBR testing; details of subjects, methods and procedure, and results; discussion, summary, implications, and applications and ideas for future research.

Searches for the literature review were conducted through PubMed. The keywords entered were tympanometry, multi-frequency tympanometry, and wideband reflectance. These were later combined with otosclerosis. Well-known authors were also searched for by name, such as Margolis, Feeney, and Keefe. Search results were then limited to the English language and human subjects. References were also found by visually scanning articles available in the Reference Library of the Middle Ear Laboratory, located on the University of British Columbia campus.

Chapter II Literature Review

2.1 Clinical issues of otosclerosis

Otosclerosis is a term used to describe "a disease of the temporal bone in which normal bone is progressively reabsorbed and replaced with *spongy* bone that may harden to become sclerotic" (Gelfand, 2001, p. 196). While otosclerosis develops at isolated locations, hearing loss occurs when it involves the oval window and the stapedial footplate, commonly called *stapedial otosclerosis* (Gelfand, 2001). This may result in complete ankylosis or fixation of the stapedial footplate (Gelfand, 2001). As the ossicular chain can no longer transmit signals as efficiently to the cochlea a progressive conductive hearing loss develops, causing *clinical otosclerosis* (Gelfand, 2001). Should the pathological process be observed at surgery to obliterate the footplate, the term *obliterated otosclerosis* is used (Lippy, et al., 1999). When the disease process involves the inner ear, sensorineural hearing loss may occur which is called *cochlear otosclerosis* (Gelfand, 2001). Otosclerosis and its associated disabilities of tinnitus (Gros, Vatovec, Šereg-Bahar, 2003), conductive hearing loss (Gros, et al., 2003), and eventually sensorineural hearing loss (Gros, et al., 2003), with or without vestibular symptoms (Gros, et al., 2003) are common and strike healthy adolescents and adults in their prime. The disease has a large personal, societal and economic cost, making early, accurate diagnosis and effective treatment important to patients.

Otosclerosis is the single most common cause of hearing impairment amongst Caucasians, regardless of their geographic distribution with a calculated clinical probability using histological information from autopsy data of 0.3% (Declau, Van Spaendonck, Tommermons, Liang, Qiu, & van de Heyning, 2001). The estimated prevalence of clinical otosclerosis among Caucasians is two to ten per 1000 (Chen, Campbell, Green, et al., 2002). It is twice as common among females as males (Ginsberg & White, 1985). Clinical otosclerosis

with the onset or progression of otosclerosis in or just following pregnancy has been linked to increased estrogen stimulatory effect of osteocytic activity resulting in greater ossification of osteosclerotic foci (Menger & Tange, 2003). The average age of onset of hearing loss is 36 years (Ginsberg & White, 1985), with the age range including children as young as 12 years (Gros, et al., 2003). About 50% of persons with otosclerosis have a known affected family member (Wang, Merchant, McKenna, Glynn, & Nadol, 1999). While causal factors such as metabolic, vascular, and infectious have been considered, today's research focuses on the genetics of otosclerosis. Epidemiological studies suggest autosomal dominant inheritance with incomplete penetrance (Chen, et al., 2002) of approximately 40% (Menger & Tange, 2003). Discoveries of genome loci for hearing loss are rapidly progressing. At least three loci have been mapped for otosclerosis (Chen, et al., 2002). These include, OTSC1 on chromosome 15q26.1 as described in 1998 in an Indian family, OTSC2 on chromosome 7q34-q36 as described in 2001 in Belgian and Dutch families where 25% of otosclerosis is linked to this gene, and OTSC3 on chromosome 6p21.3-t22.3 as described in 2000 in Cyprus (Chen, et al., 2002). Among Caucasians there is no indication that the prevalence of otosclerosis and its complications will decrease.

Once diagnosed, otosclerosis may be treated with amplification, sodium fluoride, or surgery. Although the use of amplification (i.e. hearing aids) does not alter the progression of the disease, there is also no chance of damaging hearing as a result of surgery. Another alternative is sodium fluoride, an oral medication which may arrest the progression in 80% of patients, but is unlikely to improve hearing loss already present (Gelfand, 2001). Surgery is effective in improving hearing in 90-95% of patients (Rappaport & Provençal, 2002). Surgery is the treatment of choice for otosclerosis (Gelfand, 2001). Stapedectomy was developed by Shea in 1956. Stapedectomy removes the ankylosed stapes and footplate and seals the oval window

with connective tissue or vein graft (Gelfand, 2001). The stapes may be replaced with various prostheses of wire, strut, or piston of various materials (Gelfand, 2001). A partial stapedectomy removes the anterior footplate leaving the posterior crus to transmit signals to the cochlea (Gelfand, 2001). Stapedotomy, where a hole is bored through the stapedial footplate with a drill or laser came to the forefront in the 1980s (Lippy, Berenholz, Burkey, 1999). Stapedotomy has been considered to give similar results to the stapedectomy (Levy, Shvero, & Hadar, 1990), and to have similar long-term pure tone average improvement (Aarnisalo, Vasama, Hopsu, & Ramsay, 2003). Today this is the preferred method. Several authors have now reported that stapedotomy gives less risk of profound hearing loss and is more effective in preserving high frequency hearing than stapedectomy (House, Hansen, Al Dakhail, & House, 2002; Kursten, Schneider, & Zrunek, 1994; and Moller, 1992). There may be a slight, but progressive loss of hearing after surgery and revision stapedectomies may be needed (Gelfand, 2001). Long-term post-surgical outcomes are affected not only by the surgical procedure but by the choice of prostheses (deBruijn, Tange, & Dreschler, 1999).

Evaluation of the treatments of otosclerosis has been strongly recommended (Monsell, Balkany, Gates, Goldenberg, Meyerhoff, & House, 1995), and the importance of the choice of outcome measures reinforced (Goldenberg & Berliner, 1995). Recommended outcome measures included four frequency pure-tone average, and the closure of air-bone gap (Monsell, et al., 1995; deBruijn, Tange, & Dreschler, 2001) as well as word recognition scores (Lippy, Burkey, & Arkis, 1998). Functional outcome measures and satisfaction questionnaires are also recommended (Aarnisalo, et al., 2003; Stewart, Jenkins, Coker, Jerger, & Loiselle, 1997). There is potential to expand the evaluation of treatments for otosclerosis through the use of new, objective, and easy to use measures, such as WBR, as experience with this measure increases.

2.2 Diagnostic approach to otosclerosis

Audiologists or otolaryngologists are generally the first medical professionals to suspect the diagnosis of clinical otosclerosis. Generally patients, in their third or fourth decade of life, often women, complain of a slowly progressive hearing loss, often accompanied by tinnitus, or an abnormal perception of sounds for which there is no external stimulus (Gelfand, 2001). From the patient, the audiologist seeks family history, unilateral or bilateral involvement and suggestions of conductive loss. In conductive disorders, patients often complain of a loss of intensity, not clarity. That is, they may say that speech is too quiet. "Relatively intense sounds are generally less bothersome to patients with conductive hearing losses because these sounds are reduced in level before entering the cochlea" (Gelfand, p.176). Good word recognition suggests the hearing loss is conductive and not yet sensorineural. Otoscopic examination may reveal Schwartze's sign, a reddish or pinkish discolouration seen through the tympanic membrane and reflective of vascularization of the cochlear promontory seen in otosclerosis (Gelfand, 2001).

Occasionally radiological imaging is considered in the diagnosis of otosclerosis. High resolution computerized tomography is the gold standard diagnostic imaging test for otosclerosis (Shin, Calvas, Deguine, Charlet, Cognard, & Fraysse, 2001). This allows for determination of the presence of bilateral disease with clinical otosclerosis only on one side, for completing familial studies, and examining the size of the thickened footplate (Shin, et al., 2001). It should be mentioned that the detection of otosclerosis using imaging techniques is dependent on the quality of the scans, thickness of the sections, and experience of the radiologist. Familial otosclerosis tends to be more extensive within the otic capsule than that which does not occur in families. In familial otosclerosis there is an increased association between anterior foci, a thickened footplate, and pericochlear foci (Shin, et al., 2001). While confirmation of the

diagnosis could be accomplished by this testing, it is expensive, contains irradiation, and is unnecessary in most cases. It is possible that with the correct diagnostic audiological battery the presence of bilateral disease with clinical otosclerosis on one side could be diagnosed, and familial studies could be done without imaging.

Pure tone audiometric testing with air- and bone-conduction is the main test usually performed by audiologists when otosclerosis is suspected. The size of the hearing loss depends on the progression of the disease at the time of testing and may be mild to severe (Gelfand, 2001). Initially, the loss is worse in the lower frequencies, but becomes flatter with disease progression. This is because the disease increases the stiffness effect which is more evident at low frequencies. The degree of conductive hearing loss appears to be determined by the stage of pathological changes at the stapes footplate (Cherukupally, Merchange, & Rosowski, 1998). An air-bone gap is usually greatest in the lower frequencies and may decrease at 2000 Hz to about 30 dB HL and increases again at 4000 Hz. This finding is called Carhart's notch and is not a true sensorineural component. It is "thought to occur because the mechanical advantage provided by the 2000-Hz resonance of the ossicular chain is altered by the ankylosis, which prevents the ossicles from vibrating normally" (Gelfand, 2001, p. 197). If the disease has progressed to include sensorineural hearing loss, this latter component is not reversed by surgery.

Information provided by a standard 226 Hz tympanogram is typically inadequate for distinguishing a normal middle ear from an ear with otosclerosis (Browning, et al. 1985; Colletti, 1976; Shahnaz & Polka, 1997; Shahnaz & Polka, 2002). Standard tympanometry often fails to distinguish otosclerosis because the status of the tympanic membrane dominates the tympanogram and overshadows conditions of more medial structures (Shahnaz & Polka, 1997). Also, low frequency tympanometry forces the middle ear to behave as a stiffness dominated

system (Shahnaz & Polka, 1997). Two parameters from standard low-frequency tympanometry have been found to be somewhat different in otosclerosis than normal subjects. The first of these, and the one still commonly used, is static admittance (SA). Studies have shown a trend for lower SA in patients with stapes fixation, although there is overlap with normal subjects (Alberti & Kristensen, 1970; Browning, et al., 1985; Jerger, 1970; Liden, et al., 1970; Shahnaz & Polka, 1997). The second is tympanometric width (TW) as an index for quantifying steepness of the tympanometric peak. A narrower TW in ears with otosclerosis as compared with normal ears has been reported (Koebsell, et al., 1988; Shahnaz & Polka, 1997). In current audiologic practice both for diagnosis and follow-up of otosclerosis, standard tympanometry could be used more effectively when used in combination with other parameters, such as, MFT.

In recent years, MFT has been shown to have diagnostic utility in surgically proven otosclerosis (Shahnaz & Polka, 1997; 2002). In their paper, Shahnaz and Polka (2002) confirmed the advantages of higher probe tone frequencies over standard low probe tone frequency in distinguishing otosclerotic ears from normal ears. The receiver operating characteristic curves obtained at the higher probe tone frequencies of 630 Hz and 710 Hz were statistically better in distinguishing otosclerotic ears than the standard low probe tone frequency which was operating at a chance level (Shahnaz & Polka, 2002). High-frequency tympanometry is not yet routinely used by audiologists when testing patients suspected of having otosclerosis. Shahnaz and Polka (1997) have shown that optimal test performance to improve the diagnostic utility of tests distinguishing otosclerotic patients was achieved by combining F45° derived from sweep frequency recordings and TW. They did this by combining standard tympanometry results of SA and TW with MFT results including resonant frequency (RF) and frequency corresponding to admittance phase angle of 45° (F45°). Routine practice has not yet included these tests in the diagnosis of otosclerosis, in part related to their shortcomings. Multi-frequency

tympanometry cannot test beyond 2000 Hz, although it does provide testing of a much wider range than standard low frequency tympanometry. However, tests that improve the diagnostic accuracy for otosclerosis are being developed. More specifically, it is thought that the success of acoustic ear canal tests (i.e. OAEs) in predicting cochlear hearing loss can be extended to acoustic immittance tests to predict conductive hearing losses (Piskorski, Keefe, Simmons, & Gorga, 1999).

In addition to the use of MFT for the diagnosis of otosclerosis, WBR may be helpful to distinguish between normal-hearing ears and those with otosclerosis. Wideband reflectance is a relatively new middle ear analysis technique involving the use of ambient static pressure across a much wider frequency range than MFT (Jeng, Levitt, Lee, & Gravel, 1999; Keefe, Folsom, Gorga, Vohr, Bulen, & Norton, 2000). Advantages of WBR are that the location of the probe in the ear canal is no longer as critical, for both standing waves and ear canal compliance; recent studies have shown WBR to be a fast, sensitive, and non-invasive test for middle ear disease (Jeng, et al., 1999; Keefe, et al., 2000); and WBR can measure more than one resonant frequency allowing for further analysis of middle ear function. Using multivariate analysis, Piskorski, et al. (1999) showed admittance reflectance at 2 and 4 kHz increased sensitivity to 90% and specificity to 94% when predicting conductive hearing loss in children. In 2003, Keefe and Simmons reported the test performance of a wideband acoustic transfer function to give greater sensitivity in predicting the presence of conductive hearing loss; with pressurized wideband acoustic transfer function sensitivity reached 94%.

Presently, there are few studies giving normative data on WBR and none reporting on the effect of gender and race. There are no published studies focusing on the results of WBR in otosclerosis. Scattered reports on patients with middle ear disease have included some patients with otosclerosis. Feeney, Grant, & Marryott (2003) reported on two patients with otosclerosis.

They found that WBR, as measured in energy reflectance (ER), was more sensitive than a standard probe tone of 226 Hz to the presence of otosclerosis. These clinical case histories are outlined in section 2.3.4.

2.3 Theory and clinical use of middle ear assessment measures

The following sections provide a brief description of immittance terminology and principles as well as a brief overview of standard low probe tone frequency tympanometry and MFT. This will assist in the interpretation of the results of the otosclerotic case studies and increase the understanding of the underlying principles of WBR. This background will also assist in the interpretation of collected WBR normative data.

2.3.1 Immittance

The term immittance includes admittance and impedance. Admittance (Y) is measured in acoustic millimhos (mmhos) and is defined by the ease of energy flow into the middle ear system. Reciprocally, impedance (Z) is measured in acoustic ohms (ohms) and is defined by the opposition of energy flow into the middle ear system. Modern immittance audiometry machines measure energy flow in admittance; hence, for the purpose of this study admittance will be used whenever possible.

Within the term admittance there are three elements: stiffness, mass, and friction. In the middle ear system these elements each work along a specific vector to determine admittance. The stiffness component is referred to as stiffness susceptance (B_s) and works along the positive vertical vector. The mass component is referred to as mass susceptance (B_m) and works along the negative vertical vector. Together stiffness susceptance and mass susceptance are referred to as total susceptance (B_t). That is:

$$(B_t) = (B_s) + (B_m) \qquad (1)$$

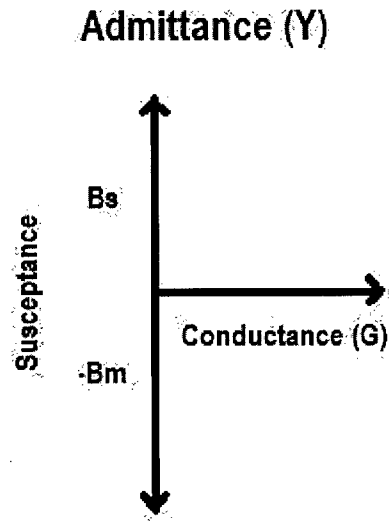

Figure 2.1: Graphical representation of admittance terminology.

When B_t is positive the middle ear system is stiffness dominated. When B_t is negative the middle ear system is mass dominated. The third element of admittance is friction which either dissipates or absorbs acoustical energy. This component is referred to as conductance (G) and works along the positive horizontal vector.

In MFT it is important to understand the relationship between these admittance components and frequency in the normal middle ear system. The frictional component or acoustic conductance is independent of frequency, whereas the stiffness component, or B_s is inversely proportional to frequency, and the mass component, or B_m is directly proportional to frequency. That is, with increasing frequency the total susceptance (B_t) moves from being positive or stiffness dominated (+B), toward zero or resonance, to negative or mass dominated (-B). When stiffness susceptance and mass susceptance are equal, resonance of the middle ear system is reached (B_t = 0 mmhos). At RF the only component that contributes to admittance is conductance. Using MFT, it has been found that the RF in a normal adult ear varies from 630

Hz to 2000 Hz (Margolis & Goycoolea, 1993), and in various pathologies shifts lower (mass dominating pathologies, e.g. ossicular discontinuity; Feeney, et al., 2003) or higher (stiffness dominating pathologies e.g. otosclerosis; Shahnaz & Polka, 1997). These shifts result from the relationship between RF and middle ear mechanical properties. Thus, RF is directly proportional to stiffness and inversely proportional to mass within the middle ear system. This results in a higher RF in a stiffness dominated middle ear system.

Another important measure occurs when, as the frequency increases, susceptance decreases and conductance increases. Figure 2.2 depicts these concepts.

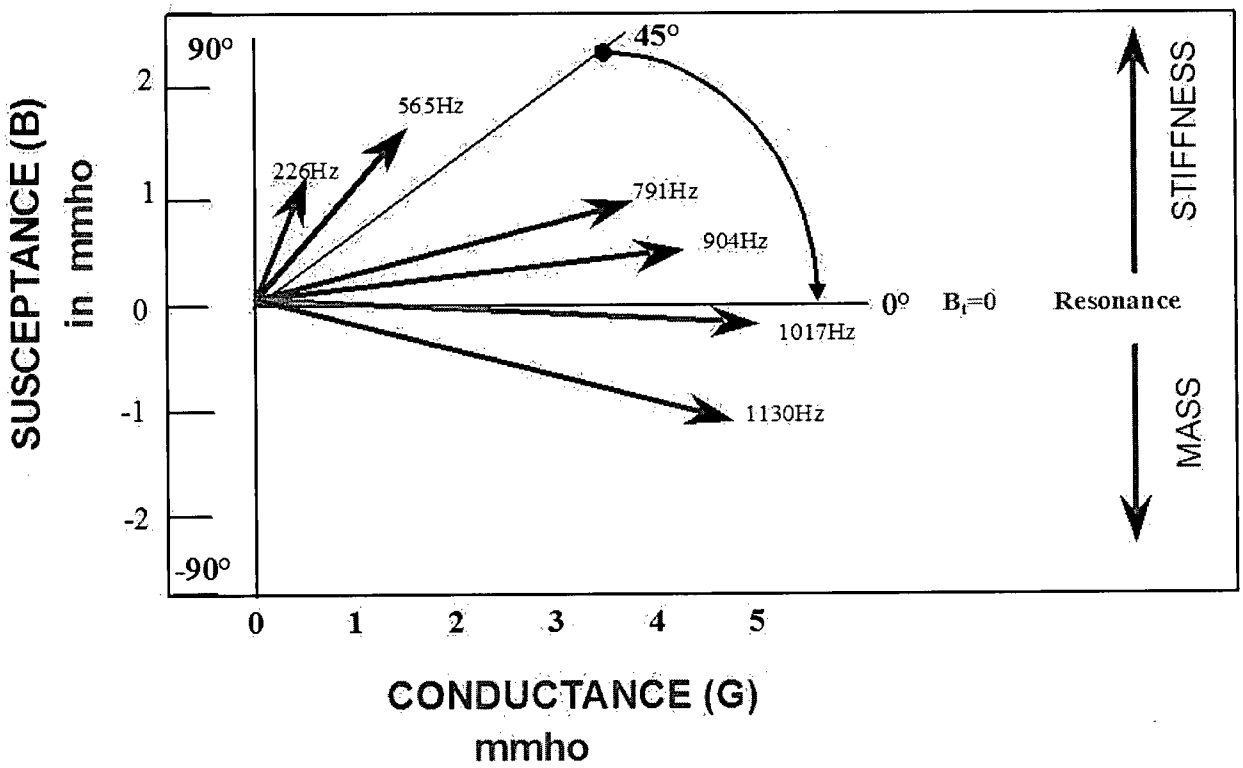

Figure 2.2: Compensated admittance vectors in relation to frequency. Adapted from Margolis & Shanks, 1991.

2.3.2 Low frequency tympanometry

Clinical measurement of admittance of the middle ear system is ordinarily done using standard low probe tone tympanometry. By presenting a tone at either 220 or 226 Hz and measuring admittance magnitude as a function of the ear canal pressure, a graphical representation of the middle ear system is formed.

There is one major problem with standard tympanometry. By using a low probe tone frequency, the middle ear system in normal individuals is stiffness dominated and thus the stiffness component contributes a much greater part to the admittance measurement than the conductance, or frictional component. This, in effect, often conceals pathological middle ears from detection, especially in ossicular chain abnormalities (Colletti, 1975, 1976; Lilly, 1984). As seen in figure 2.2, probe tone frequency increase relates directly to a reduction in stiffness dominated middle ear systems. This is particularly relevant to WBR as a larger frequency range allows for better detection of middle ear pathologies.

This difficulty of detecting some middle ear pathologies may lie with the anatomy of the middle ear as the structures involved are medial to the tympanic membrane, or with our lack of understanding about such ossicular dysfunctions on tympanometric results. Knowing this and understanding how different ossicular chain pathologies affect the stiffness or mass of the middle ear system leading to an increase or decrease in the RF of the middle ear, researchers have realized that using higher probe tone frequencies, closer to the RF of the middle ear will be more likely to distinguish normal and pathological middle ears (Colletti, 1977; Feldman, 1976; Shahnaz & Polka, 2002). This is particularly true of those affecting the ossicular chain (Shanks, 1984). This leads to an explanation of why tympanometry using higher probe tone frequencies, especially those frequencies close to resonant frequencies of the middle ear, are thought to give a

greater distinction between normal and abnormal middle ears, such as those with stapes fixation (Colletti, 1977; Liden, et al., 1974).

2.3.3 Multi-frequency tympanometry

Historically, low probe tone frequency of 220 or 226 Hz was used due to its ease of calibration (Terkildsen & Thomson, 1959; Margolis & Shanks, 1995). With the advancement of technology related to higher probe tone frequencies, it is realized that more clinically useful information can be collected when using multiple frequencies (226-2000 Hz).

Resonant frequency can be defined as the frequency at which total susceptance is zero. Resonance is directly proportional to the stiffness and inversely proportional to the mass of the middle ear system. For example, in otosclerosis there is an increased stiffness in the system which correspondingly relates to an increase in RF (Figure 2.2). The MFT have become useful tools in assisting clinicians and researchers alike in their understanding of middle ear pathologies; however, there are disadvantages to MFT as well. A pressure seal is needed for MFT to be functional. Multi-frequency tympanometry is also limited in its ability to measure frequencies above 2000 Hz leading to a restricted view of the middle ear system.

2.3.4 Wideband reflectance

A new measure of middle ear evaluation has been developed called WBR. In order for humans to hear, sound must pass through the external ear canal, the tympanic membrane, the middle ear, and into the cochlea. In doing so, some of this sound is absorbed by these structures and some is reflected back out of the ear canal. Wideband reflectance is the ratio of energy reflected from the surfaces on its way to the cochlea in relation to the energy that reaches the surface, or incident energy. This ratio is called energy reflectance (ER) and varies from zero, where all sound energy is absorbed, to one, where all sound energy is reflected.

$$\text{Energy Reflectance} = \frac{\text{Reflected Energy}}{\text{Incident Energy}} \qquad (2)$$

Energy reflectance is derived from wideband impedance measures using a chirp as a probe stimulus. In general, when a middle ear pathology is present that increases the susceptance (i.e. stiffness) of the middle ear, ER at lower frequencies should increase, i.e. more energy is reflected. With middle ear pathologies, such as tympanic membrane perforation, that decrease the stiffness susceptance of the middle ear, ER at low frequencies should decrease, i.e. more energy is absorbed (Jeng, et al., 1999). Following this conclusion, ER at lower frequencies should increase in otosclerosis due to increased stiffness. It has been shown (Shahnaz & Polka, 2002) that otosclerosis affects conductance (i.e. resistance) more than stiffness. In a mechanical system this resistance will result in a rapid decay of vibration.

Another measure used in WBR is power absorption (PA). This measure is the reciprocal of ER in that PA is a ratio of incident energy to reflected energy. Power absorption varies from zero, where all sound energy is reflected, to one, where all sound energy is absorbed.

$$\text{Power Absorption} = \frac{\text{Incident Energy}}{\text{Reflected Energy}} \qquad (3)$$

Contrary to measures using tympanometry, WBR uses a measure of acoustical immittance as a function of frequency at a constant pressure, usually ambient pressure. The components of both tympanometry and WBR, however, are similar:

$$Y(f) = G(f) + jB(f) \qquad (4)$$

where Y or complex acoustic admittance is equal to G or conductance (real part) plus B or susceptance (imaginary part, j), at a specific frequency. Piskorski, et al. (1999) chose the three variables of conductance, equivalent volume, and energy reflectance to represent the acoustic response of the ears they tested. Conductance, as defined in Piskorski, et al. (1999) by power absorption (Π), is expressed as follows:

$$\Pi(f) = \tfrac{1}{2}G(f)|p(f)|^2 \qquad (5)$$

where $|p(f)|^2$ represents the squared magnitude of pressure at frequency f. Equivalent volume (V), in terms of susceptance, is expressed as follows:

$$V_{(f)} = \rho c^2 \frac{B_{(f)}}{2\pi f} \qquad (6)$$

where ρ is the density of air, c is the phase velocity of sound, B is susceptance, and f is frequency. The third variable, energy reflectance, is defined here in terms of admittance (Y) as follows:

$$\left|R_{(f)}\right|^2 = \left|\frac{1 - Z_c Y_{(f)}}{1 + Z_c Y_{(f)}}\right|^2 \qquad (7)$$

where $Z_c = \rho c/S$ and Z_c represents the characteristic impedance of a cylindrical tube of area S (i.e. an estimate of the ear canal area). All constants are shown in Table 2.1.

It is important to note that in WBR machines a normalization factor is implemented, i.e. the characteristic impedance of the ear canal. Due to this normalization factor, admittance values are dimensionless (Shahnaz, 2004). This is discussed further in methods section (3.5.3).

As well, WBR instrumentation does not yet compensate for the effect of the ear canal; thus, results are a combined measure of the ear canal, middle ear, and inner ear (Shahnaz, 2004). Researchers are currently working on ways of compensating for the ear canal.

Name	Constant	Value	Units
Speed of sound	c	33480	cm/s
Density of air	ρ	0.001223	g/cm^3
Ear canal diameter	d	0.75	cm
Ear canal area	S	0.43	cm^2
Specific impedance	ρc	40.946	$g/s \cdot cm^2$
Characteristic impedance	$Z_c = \frac{\rho c}{S}$	95.2	$g/s \cdot cm^4$

Table 2.1: Constants used for admittance-reflection formula calculations. Adapted from Voss and Allen (1994).

The WBR instrumentation consists of a probe system, signal processing board, a compatible laptop computer, and a calibration device. More information about the instrumentation for WBR is given in the Methods section (3.5.3). A probe stimulus is presented from low, usually 250 Hz, to high, usually 8000 to 10 000 Hz and measures are obtained seconds later using computer averaging.

Although research on WBR is limited, early studies have been promising. Keefe, et al. (1993) and Voss and Allen (1994) have studied normal middle ear function in adults using WBR. Among adult patients with middle ear pathologies, research is beginning to discover the diagnostic applications of using WBR to assist in distinguishing middle ear pathologies from

normal middle ears and other middle ear pathologies (Feeney, et al., 2003). With regard to children, WBR shows promising results in discriminating children with otitis media from normal hearing children (Jeng, et al., 1999; Piskorski, et al., 1999).

Results of WBR measures for middle ear pathologies in adults are scarce. An article by Feeney, et al. (2003) studied ER in ten adult participants with ages ranging from 21 to 65 years (mean of 42 years) who had a variety of hearing impairments. They compared the ER results of these ten participants to 40 normal hearing individuals with ages ranging from 19 to 24 years (mean of 22 years). In this article, normative data were presented graphically; hence, the mean, SD, and 90% range values were not published. Data have also been obtained from Feeney & Sanford (2004) and is referred to in section 2.4.3.

Figure 2.3 shows the group mean data averaged across 75 ears of the 40 normal hearing participants in Feeney, et al.'s (2003) study. Estimate comparisons are also made to normative data from Keefe, et al. (1993) and Margolis, Saly, & Keefe (1999). The general shape is consistent with that seen in children (Jeng, et al., 1999), albeit reciprocal to Jeng, et al.'s (1999) power absorption curve due to the y-axis variable. That is, ER is high in the low frequencies and decreases as a function of frequency to a minimum near 4.0 kHz, and then increases once again until 8.0 kHz.

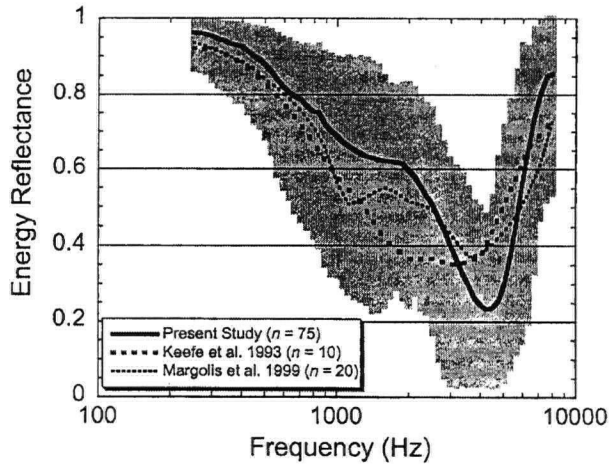

Figure 2.3: Comparison of adult normative data of energy reflectance (ER) as a function of frequency in three different studies. Data are given as one-twelfth octave ER. Full authors are as follow: Feeney, Grant, and Marryott (2003; Present Study); Keefe, Bulen, Arehart, and Burns (1993); and Margolis, Saly, and Keefe (1999). From Feeney, Grant, and Marryott (2003).

Of the participants with hearing impairments (Feeney, et al. 2003), two patients had otosclerosis. One subject, P5, a 49-year-old woman had an eight-year history of right ear mixed hearing loss. Air conduction demonstrated a moderate loss (40-50 dB HL) from 250-8000 Hz. Bone conduction showed a loss at 2000 Hz of 40 dB HL. Using 226 Hz tympanometry, her SA was 0.4 mmhos and TW was 65 daPa. Wideband ER exceeded the 95th percentile from 250 to 944 Hz but results were within normative values at higher frequencies (Feeney, et al., 2003) as seen in Figure 2.4.

The second patient, P6, a 26-year-old woman with bilateral otosclerosis had had previous otosclerotic surgery with slipped prosthesis and disarticulation on the left. The right, non-operated ear, had air conduction from 25 to 50 dB HL, greater in the lower frequencies, and a slight sensorineural hearing loss notch at 1000 and 2000 Hz. The 226 Hz tympanogram was characterized by an abnormally low SA of 0.2 mmhos and a TW of 110 daPa at the high end of

the normal range. Compared with normative values, the wideband ER was above the 95th percentile from 250 to 1189 Hz and 5993 to 7551 Hz and lower than the 5th percentile at 4757 Hz as seen in Figure 2.4.

Together these cases suggest a higher than normal ER for frequencies below 1000 Hz for the otosclerotic ears. As this occurred in both cases, while 226 Hz tympanometry was abnormal in only one patient, this suggests increased sensitivity of wideband ER in the presence of otosclerosis (Feeney, et al., 2003). While Feeney, et al. (2003) present just two cases of otosclerosis, their results are very informative. While these are only case studies, not lending themselves to statistical analysis, these results suggest more research should be done in this area.

These two cases of otosclerosis as seen in Figure 2.4 are of special interest to this thesis. For the right ear of P5 (P5R) the tympanometric findings were within the normal limits. Wideband reflectance results, however, picked up a difference, where the ER data exceeded the 95th percentile between 250 and 944 Hz. For the right ear of P6 (P6R) the tympanometric results show an abnormally low SA and a TW approaching the high end of the normal range. Similar WBR results of P5 show that ER exceeds the 95th percentile between 250 and 1189 Hz. In addition, ER for "higher frequencies was mostly within the normal range except for higher than normal ER between 5993 and 7551 Hz, and lower than normal ER at the one-twelfth octave centered at 4757 Hz. Figure 2.4 depicts these results of higher than normal ER at frequencies below 1000 Hz. Due to the fact that tympanometric results for P5 were considered within normal limits, it has been suggested that the "ER pattern … was more sensitive to the presence of otosclerosis than was the 226-Hz tympanometry" (Feeney, et al, 2003, p. 900). As previously mentioned, the low sample size detracts from the accuracy of these results, but the overall patterns will likely remain the same, which will hopefully lead to greater diagnostic accuracy for

otosclerosis. Feeney, et al. (2003) also point out that the large difference in mean age between the participant groups may be a confounding variable.

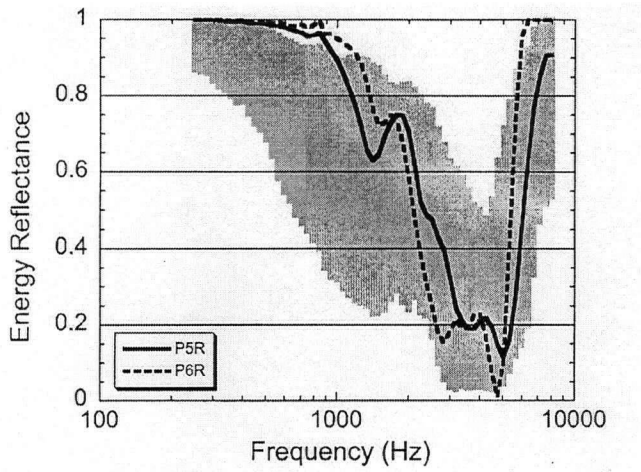

Figure 2.4: Energy reflectance as a function of frequency for two ears with otosclerosis. P5R represents the right ear of one participant. P6R represents the right ear of a second participant. The shaded area represents the 5th to 95th percentile range of normal hearing sensitivity participants. From Feeney, Grant, and Marryott (2003).

While Feeney, et al. (2003) focus on measures of ER, Jeng, et al. (1999) and Voss and Allen (1994) show measures using PA. The results obtained for ER are the reciprocal of those for PA. Thus, the normal pattern of graphed data expected for PA would increase in the lower frequencies and decrease in the higher frequencies, i.e. the peak corresponds to the range that energy is most effectively transmitted to the middle ear.

Jeng, et al. (1999), studying children, and Voss and Allen (1994), studying adults, have come to similar conclusions. Only a small amount of acoustic power is absorbed by the ear at low frequencies due to eardrum stiffness, but as frequency increases, the power absorption also increases "such that at 1.0 kHz, just over half of the acoustic power entering the ear canal is absorbed by the middle ear and cochlea" (Jeng, et al., 1999, pp 195-96) and by 3.0 to 5.0 kHz

almost all of the acoustic power is absorbed (Jeng, et al., 1999; Voss & Allen, 1994). That is, the location of the peak corresponds to the range that energy is most effectively transmitted to the middle ear. Although there are large variations among subjects, Figure 2.5 shows that a general shape is clearly present in the power absorption curve. Other researchers have also observed this pattern in normal middle ears of adults (Keefe, Ling, & Bulen, 1992; Keefe, et al., 1993; and Voss & Allen, 1994).

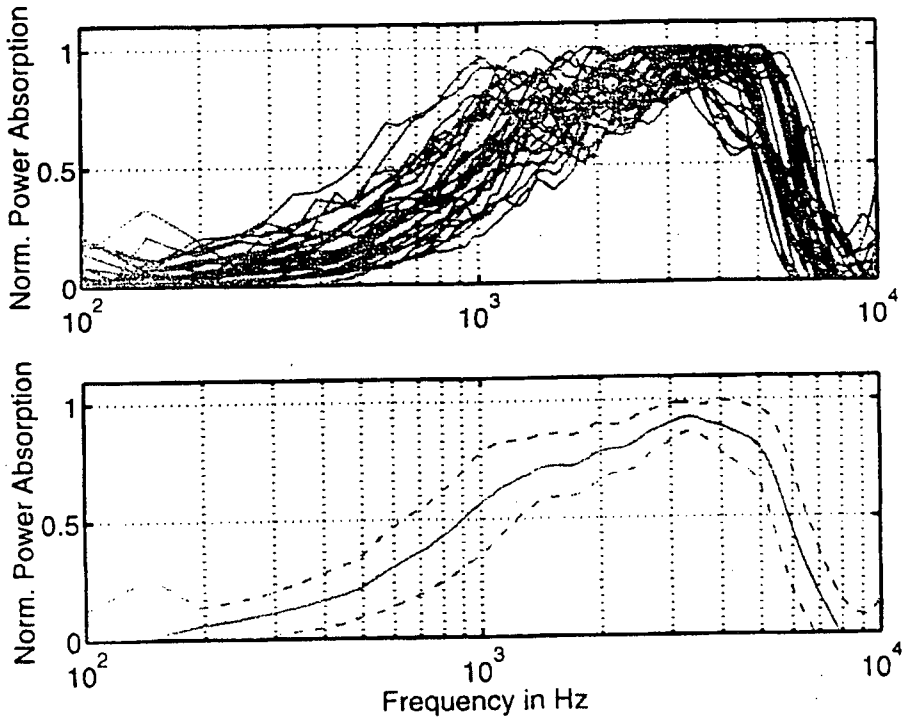

Figure 2.5: Normalized power absorption curves for 30 normal middle ears of children ages 2.5 to 5 years (upper panel). Mean normalized power absorption curve from the above panel with ± 1 standard deviation (dotted lines; lower panel). From Jeng, Levitt, Lee, & Gravel, 1999.

Piskorski, et al. (1999) conducted a study using clinical decision theory to discover whether results from acoustic ear canal responses can predict conductive hearing loss. Using 161 ears from children two to 10 years of age, they classified the ears as normal or impaired with

air-bone gap measurements as a 'gold standard'. A multivariate analysis of YR responses proved that the presence of conductive hearing loss can be predicted, with areas under the response operating curve of up to 0.97 (Piskorski, et al, 1999). Also, they confirmed that the 2.0 to 4.0 kHz frequency range is a "particularly sensitive indicator of middle-ear status" (Piskorski, et al., 1999, p. 1749) and agree with Keefe, et al. (1993) that WBR is a useful clinical tool.

Wideband reflectance has a number of advantages and limitations. First, WBR is fast, objective, and non-invasive. Second, contrary to MFT, WBR can measure frequencies exceeding 2000 Hz which allows a better 'view' of the middle ear system. Third, with this increased frequency range, WBR provides more precise frequency specific information about the conductive portion of the peripheral auditory system. Fourth, again with relation to the increased frequency range, information can be related from the type of hearing loss to the frequency response of speech. Fifth, when measures of acoustic power flow are used, the problem of standing waves in the ear canal is eliminated (Jeng, et al, 1999). That is, WBR measurements are not "critically dependent on the location of the probe in the ear canal as is the case with pressure measurements" (Jeng, et al., 1999). Sixth, the lack of need for a pressure seal allows for diagnostic use when other measures may harm, or interfere with a middle ear or inner ear disorder. Because of this lack of need of a pressure seal, WBR should be a safe measure to use after surgery for otosclerosis or ossicular discontinuity. As well, WBR reduces the concern over ear canal compliance in infants (Keefe, et al, 2000). Seventh, there is a possibility to measure more than one resonant frequency in the middle ear system.

There are three limitations of WBR. First, WBR is not yet in clinical use. Second, few clinical norms have yet been published for either normal or pathological ears. Third, WBR results must correlate to surgical findings in order for WBR to be deemed diagnostically accurate. All of these above limitations may be overcome given time. Research is increasing in

this field which can only lead to a better understanding of WBR and a broader usage of this measure.

From information known about WBR this should be a very useful measure to diagnose and evaluate treatment in otosclerosis. It is known that otosclerosis increases stiffness of the middle ear system and is classed as a high impedance pathology (Shahnaz & Polka, 2002; Shanks & Shelton, 1991). As ER drops in the range of 4000 to 6000 Hz indicating a stiffness system, then WBR should be abnormal in otosclerosis below 6000 Hz. The only published study available using WBR with otosclerotic patients is the two case studies by Feeney, et al. (2003) as described above. Since this study only contained two ears from two different subjects, this author does not believe it justified to try to look beyond a basic pattern for such a limited sample size. Patients of Feeney, et al. (2003), as seen in Figure 2.4, show a basic pattern of higher than normal ER at frequencies below 1000 Hz. Wideband reflectance patterns may vary with the degree of otosclerosis; however, there is currently no data to support this premise.

2.4 Normative data

Unfortunately, there are no tables available from published studies on WBR to extract precise normative values; thus, estimates taken from published graphs showing normative data are used for comparison purposes. Published normative values are presented mainly as ER graphic data. Graphic presentation of normative data for adults are not given for Y, B, and G in the literature. Recording the data in various formats, e.g. PA, Y, B, and G, allows a more complete view of the data. This may enhance available information when comparing groups or make the data more comparable to MFT results for further analysis.

2.4.1 Justification for developing gender and race specific normative data based upon previous middle ear studies

The effect of gender on normative values obtained from standard low probe tone tympanometry has been evaluated by a number of authors with conflicting results. Comments below are limited to those used in this study as background and supporting measures. While the differences outlined below are marginal, they are sufficient for the current recommendation to be that gender specific normative values be used when completing tympanometric measurements in adults (Shahnaz & Davies, 2004).

Margolis and Heller (1987) using a Welch Allen microtymp machine with a pump speed of 200 daPa/s and a pressure range of +200 to -300 daPa found no gender differences for SA or TW. However, Roup, et al. (1998) using a GSI 37 machine with a pump speed of 600/200 daPa/s and a pressure range of +200 to -300 daPa and Wiley, et al. (1996) using a Virtual 310 and pressure range of +250 to -300 daPa found males to have a larger mean SA than females, but with similar lower margins of the 90% range. Shahnaz and Davies (2004), using the Virtual 310, pump speed of 125 daPa/s and pressure range of +250 to -300 daPa found no gender effect for SA, but the lower margin of the 90% range was 0.30 mmhos for males and 0.36 mmhos for females. Both Shahnaz and Davies (2004) and Wan and Wong (2002); using a GSI 33 machine, with a pump speed of 600/200 daPa/s and pressure range of +200 to -200 daPa, showed no significant statistical difference between mean or 90% range results for SA among Chinese males and females. While there were differences in procedure from study to study, each used the same procedure for males and females within an individual study. Some differences in SA according to gender appear to be present.

Fewer authors have studied gender effect for MFT. The measures of particular interest for this study are RF. Margolis & Goycoolea (1993) and Shahnaz & Polka (1997) demonstrated a trend for higher RF in Caucasian males over females, whereas Wiley, et al. (1999) found female results to be higher. Shahnaz and Davies (2004) found no differences for RF by either

recording method or compensation method in either Caucasians or Chinese. However, the 90% range differed regardless of the method used suggesting the need for male and female normative values.

Most published normative data for middle ear measures do not mention the racial background of their subjects. To accomplish such studies definitions of race are necessary. Shahnaz and Davies (2004) used the following definitions that are also used in this study. Chinese participants were primarily immigrants from mainland China, Hong Kong, and Taiwan, i.e. both grandparents and parents were from these areas. This is similar to the definition of Wan and Wong (2002) for tympanometric measurements. Their Chinese youth were descendants of immigrants from mainland China without traceable foreign decent. Using the Statistics Canada (2002) definition, Shahnaz & Davies (2004) defined Caucasian as non-Hispanic, non-Aboriginal, non-Arab/West Arab, non-Black, non-East/South/South-East Asian, with white or light skin and of European descent. Race was determined by self report.

From low frequency tympanometric measures, Chinese subjects were found to have lower SA than Caucasians (Shahnaz & Davies, 2004). Similarly, from MFT measures, Chinese subjects have higher mean RF than Caucasians thought to be associated with increased stiffness in the middle ear transmission system (Shahnaz & Davies, 2004). These findings lead Shahnaz and Davies (2004) to recommend race specific normative data for all tympanometric measures. The results are convincing and future studies and clinical work should consider race specific normative data. As yet there are no data specifically linking SA and RF measurement results to those of WBR. However, in view of the gender and racial differences just discussed, these variables must be taken into consideration in this study.

2.4.2 Normative values for wideband reflectance

Normative values for WBR are few and there are significant difficulties in comparing them. As seen in Table 2.2, instrumentation and procedures differ among the studies available giving normative values for adults. In addition, normative information is given graphically. This is likely due to the complexity of addressing the numerous frequencies tested. The numbers of subjects in each study are relatively few. As described by Voss and Allen (1994) considerable variability is noted. While there are a number of ways that WBR measures can be expressed, most studies report ER or PA. Race is not mentioned in these papers.

Investigator	Machine	No. of Adults (ears)	Age (years)	M/F	Chirp signal	Frequency	Measure recorded
Voss & Allen (1994)	Brüel and Kjaer 4157 and Industrial Research Products, Inc. DB-100	10	18-24	N/A	1024-point, 12.8 ms	100-15000 Hz	ER, impedance
Keefe, et al. (1993)	custom made*	10	N/A	N/A	2048-point, 40 ms	125-10700 Hz	One-third octave averaged ER
Margolis, et al. (1999)	custom made*	20	20-53	10/10	40 ms at 12.5/s	125-11310 Hz	ER at 0, +300 and -300 daPa
Feeney, et al. (2003)	custom made*	40 (75)	19-24	20/20	40 ms at 12.5/s	200-10000 Hz	One-twelfth octave ER

Table 2.2: Procedural variables for measuring wideband reflectance in published studies. N/A = information not available. Full investigator names include: Feeney, Grant, & Marryott (2003); Keefe, Bulen, Arehart, & Burns (1993); and Margolis, Saly, & Keefe (1999).

* Custom-made wideband reflectance machine by Keefe, Ling, Bulen (1992); modified and used by Keefe, et al. (1993); used by Margolis, et al. (1999) and Feeney, et al. (2003).

In their 1994 paper, Voss and Allen present case study data of 10 normal adult subjects, 18-24 years. Their work establishes ER and impedance patterns. Graphical representation of means and standard deviations is shown for reflectance. The series of graphs show considerable

variability. The variability was believed to be due to subject cochlear and middle ear impedance differences. Voss and Allen (1994) replicated their own individual subject data. Static air pressure was not measured. They found the reflectance patterns to be highest in the lower frequencies, dropping at 2000 to 4000 Hz and then rising. Similar ER patterns have been since found.

In their 1993 paper, Keefe, et al. examined young children as well as healthy adults. For this study only information from the 10 healthy adults is reviewed. The instrument was custom made based on earlier work by Allen (1985) used to measure eardrum impedance of cats. This instrument differs from Voss and Allen (1994), but is used or modified by the three authors with published normative values, i.e. Keefe, et al., 1993; Margolis, et al., 1999; and Feeney, et al., 2003. The results of Keefe, et al. (1993) were reported as third-octave averaged ER with a pattern similar to those of Voss and Allen (1994). For the 10 adult subjects the mean and standard deviation for the minimum value of ER was 0.35 ± 0.20 at 3200 Hz, and a maximum value of 0.73 ± 0.18 at 8000 Hz. Variations between subjects were noted. To a lesser extent than subject variability, measurement errors of ER related to ear canal volume and were noted mainly under 2000-3000 Hz.

In 1999, Margolis, et al. studied 20 normal subjects using WBR tympanometry, with the majority of the data collected above or below ambient pressure, but not at static ambient pressure. The results as published are not strictly comparable to other results. Gender differences were noted for middle ear impedance, but not mentioned for ER. Reflectance as a function of frequency at 0 daPa is given in Fig 2.6, (Margolis, et al, 1999, Figure 6c, p. 273). The curve of this graph is in standard numeric format, decreasing from the low frequencies to about 3000 Hz and then increasing. This is the same pattern of the normal ER as previously described.

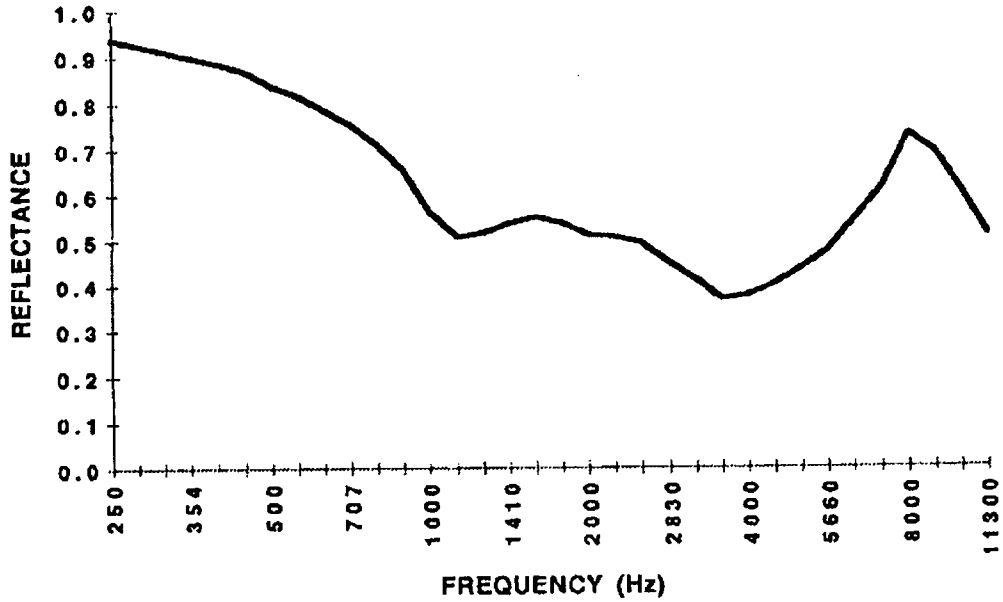

Figure 2.6: Average energy reflectance as a function of frequency. Adapted from Margolis, Saly, & Keefe, 1999, Figure 6c, p. 273.

As seen in Figure 2.3, Feeney, et al. (2003) incorporate their own data and those of Keefe, et al. (1993) and Margolis, et al. (1999) each on their own curve, now using logarithmic x-axis. The latter has the effect of accentuating the values for the higher frequencies. It is likely that Feeney, et al. (2003) used the raw data from these authors to construct the figure. Feeney, et al. (2003) had 75 ears obtained from 40 young adults subjects. Data were derived from wideband impedance measures at ambient pressure. The normative values, including graphing presentation of the mean and 5th and 95th percentile, are presented as ER. Subsequently, individual data from Feeney, et al.'s (2003) series of case studies were superimposed on the 90% range graphic data. Data from individual cases falling outside this range or cutoff were considered abnormal.

Only one paper, Piskorski, et al., (1999) gives normal data on conductance in children, confirming high resistance in the lower frequencies with a gradual decline to 8000 Hz.

With regard to gender and ear differences using WBR, the only study found to statistically account for these variables was by Keefe, et al. (2000). Findings from neonatal ears state that the "left ear was acoustically stiffer than the right ear, and that the female ear was acoustically stiffer than the male ear" (Keefe, et al., 2000, p. 461). This was thought to be related to neonatal specific factors, i.e. vernix fluid. As such, WBR ear differences would be unlikely among adults.

Normative data accompanying the Mimosa Acoustics RMS-System v4.0.4.4, that is the instrument used for this study, is shown graphically below in Figure 2.7 as PA. (The reciprocal, ER, is also available by Mimosa.) Mimosa literature does not give the race, gender, age, or number of subjects used to obtain this normative data. It is assumed that this Mimosa data combines the genders. Normative values from this study will be visually compared with these normative values and differences discussed in the results section.

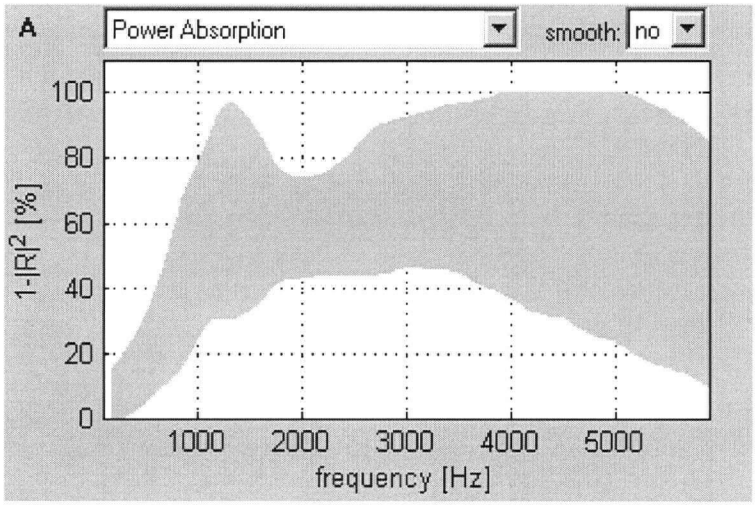

Figure 2.7: Power absorption graph as seen before testing begins. The shaded area represents normative adult values provided by Mimosa Acoustics. From Mimosa Acoustics RMS system version 4.0.4.4.

The above descriptions demonstrate how little normative data for adults tested using WBR are available. The primary concern is a lack of consistency or known comparability among studies in the instrumentation. This concern is extended to the present study where the Mimosa Acoustics RMS-System v4.0.4.4 differs from Keefe, et al.'s (1992) custom machine and its successor used by Feeney, et al. (2003). Other concerns include small sample sizes, not to mention lack of stratification by race and gender. In addition, the primary mode of publication is by graphing which does not lend itself to comparison with the present data. Another problem is the lack of detailed description of the subjects of the normative database of Mimosa Acoustics and a failure of information regarding gender.

Some corrections could make up for the deficits of the published normative data on WBR. To attempt to overcome this, data from Feeney and Sanford (2004) were obtained and are discussed in section 2.4.3. The most important correction this study can make to this literature is to describe the collected normative data clearly by gender and race. Given the differences found in tympanometric data as described in 2.4.1 and the recommendations by Shahnaz and Davies (2004), failure to analyze this normative data by the important variables of gender and race would diminish its value for both research and clinical purposes.

2.4.3 Normative data obtained from unpublished data

As raw data values, and actual mean, standard deviation, or 90% range are not given in the previously mentioned publications of Feeney, et al. (2003), Margolis, et al. (1999), or Keefe, et al. (1993), a request was made to Dr. M.P. Feeney for more information. Data prepared for a soon to be published paper by Feeney and Sanford (2004) were received for WBR consisting of 15 frequencies representative of the test frequencies between 250 to 6000 Hz. Data were from 40 subjects (20 males and 20 females), with a mean age of 21 years. The race of the subjects is unknown. No gender specific data are given. Data were received for four variables, ER, Y, B,

and G presented as mean, 5th, and 95th percentile. These data are presented in Tables A1, A2, A3, and A4 in Appendix I.

Data for the variable of ER were transformed into its reciprocal PA. The mean and 90% range of this PA data can be found in the results section (Figure 4.1) presented with the data from this study on the same graph. As expected from the previously mentioned graphic normative data, a steep rise in percent PA is noted in the lower frequencies under about 1200 Hz and a decline in percent PA after 4000 Hz. In frequencies around 2000 Hz a flattening effect is seen.

2.5 Goals of this thesis

2.5.1 Underlying hypothesis of the total project

Differences between normal and otosclerotic ears are more evident at frequencies above 226 Hz which are rarely tested in routine clinical practice. Wideband reflectance will provide a more detailed picture of the mechano-acoustical properties of normal and otosclerotic middle-ears across a much wider frequency range than standard middle ear analysis techniques.

2.5.2 Objectives of this thesis

The primary objective objective of this study is to determine gender and racial differences within the normative values for power absorption, admittance, susceptance, and conductance of WBR measures measures in Chinese and Caucasian adults. The second objective is to explore if WBR is clinically useful in measuring predictable differences from normative population data in a group of patients with surgically confirmed otosclerosis.

2.5.3 Specific research questions addressed by this thesis

There are three specific research questions addressed by this thesis. They are as follow:

1. Are there differences in collected normative WBR data in relation to gender and race?

2. How does the normative data collected on WBR measures compare with those in the literature?

3. How does the collected data on otosclerotic ears compare with normative WBR data collected for this thesis?

Chapter III Methods

3.1 Research design

The study was a cross-sectional, group comparison study of a sample of normal hearing subjects and a consecutive group of patients with surgically confirmed otosclerosis. This was exploratory, such that, the number of study subjects with otosclerosis is inadequate for definitive statistical comparison of audiological parameters with those of the normal subjects; however, it will provide significant contribution with regard to potential clinical applicability of WBR.

3.2 Subjects

3.2.1 Inclusion criteria for normal subjects.

1. Chinese or Caucasian as defined in section 2.4.1.
2. Age of between 18 to 34 years.
3. Normal otoscopic examination.
4. Pure tone audiometric thresholds lower than 25 dB HL at octave frequencies between 250-8000 Hz with no air-bone gap greater than 10 dB at any frequency.
5. Normal hearing status as determined by passing a transient-evoked otoacoustic emissions (TEOAE). TEOAEs provide a screening for normal middle ear and cochlear function and are quite sensitive to conductive hearing loss (Koivunen, Uhari, Laitakari, Alho, & Luotonen, 2000).

3.2.2 Inclusion criteria for study subjects.

1. Normal otoscopic examination with the exception of Schwartze's sign.
2. Pure tone audiometric thresholds assessed, but there no cut-off limit for abnormal functioning.
3. TEOAEs used to verify pure tone results in otosclerotic patients. No criteria set.

4. Otosclerosis confirmed at surgery.

5. Able to give informed consent.

3.2.3 Exclusion criteria for normal subjects

1. Evidence of eardrum abnormalities excludes a subject. The exclusion of subjects with tympanic membrane abnormalities is necessary because the associated low impedance masks the more medially significant high impedance pathology of otosclerosis (Feldman, 1974).
2. If more than one-third of the tympanic membrane could not be seen, the ear was excluded.
3. A history of head trauma or recurrent otitis media.

3.2.4 Exclusion criteria for study subjects

1. If any evidence of eardrum abnormalities (with the exception of Schwartze's sign) is present, the subject's results were excluded.
2. If more than one-third of the tympanic membrane could not be seen, then ears were cleaned by an otolaryngologist before testing, or results were excluded.
3. A history of head trauma or recurrent otitis media.
4. Known previous ear surgery, including surgery for otosclerosis in the ear under study.

3.2.5 Description of normal subjects

Two populations were used for the collection of normative data for a total of 128 subjects (240 ears).

3.2.5.1 Caucasian normal subjects

As otosclerosis occurs more frequently in Caucasian subjects, Caucasian normative data were collected. Sixty-two subjects volunteered. Twenty-eight Caucasian male subjects (51 ears)

with a mean age of 27.3 ± 4.7 years participated in this study. Thirty-four Caucasian female subjects (64 ears) with a mean age of 24.4 ± 3.9 years participated in this study. Data from another nine Caucasian ears were omitted due to wax, failure to meet TEOAE inclusion criteria, or incompletion of testing.

3.2.5.2 Chinese normal subjects

Racial differences in normative data were sought in this study. Chinese make up a significant proportion of the population of Greater Vancouver. Of note, otosclerosis is infrequent among Chinese (Declau, et al., 2001). Sixty-six subjects volunteered. Twenty-four Chinese male subjects (46 ears) with a mean age of 24.1 ± 4.5 years participated in this study. Forty-two Chinese female subjects (79 ears) with a mean age of 23.4 ± 4.6 years participated in this study. Seven ears were omitted due to wax, failure to meet TEOAE inclusion criteria, or incompletion of testing.

3.2.6 Description of study subjects

Ten study subjects volunteered. Data from one subject was excluded due to previous ear surgery. One other subject volunteered but was not tested because she had had previous otosclerotic surgery on the ear to be studied. Another subject of Chinese background was fully tested, but data were excluded due to extreme negative middle ear pressure.

Seven study subjects (one male, six females, seven ears) with otosclerosis were tested from June 15 to August 25, 2004. Otosclerosis has been surgically confirmed in two of these subjects to date (Appendix II). While both ears of these seven subjects were fully tested, only results from the ears with otosclerosis were used. The mean age of the study subjects was 41.4 ± 11.4 years (range 24 to 56 years).

3.3 Recruitment

3.3.1 Recruitment of normal subjects

Subjects were recruited through advertising on the University of British Columbia campus. Potential subjects were contacted by the investigator and a brief interview was conducted to determine eligibility. See Appendix III for the telephone questionnaire and Appendix IV for the email questionnaire. Appointments were made at the Middle Ear Laboratory where subjects were tested. Informed consent was obtained before testing.

3.3.2 Recruitment of study subjects

Patients with otosclerosis were recruited from consecutive patients awaiting surgery for their ear condition at St. Paul's Hospital (Vancouver). They were recruited through an introductory letter describing the study some months prior to their surgery date. This letter provided details of how to contact the principal investigator should potential subjects have further questions. Patients who agreed to participate in this project were required to remain for approximately 15 minutes longer at an otherwise regularly scheduled pre-operative evaluation in order to complete the additional testing.

The purpose and procedures of this project were discussed in lay terms with those subjects who indicated that they wished to participate. This was done prior to the commencement of the already established pre-operative audiological evaluation which took place at St. Paul's Hospital. This investigator discussed the project and consent form with the subjects and addressed concerns. Informed consent was obtained. A copy of the consent form is found in Appendix V.

3.4 Ethics approval

3.4.1 Ethics approval

Ethics Board approvals were obtained from the University of British Columbia (REB File number C04-0098) and the University of British Columbia/Providence Health Care Office of Research – Research Ethics Board at St. Paul's (REB File number P04-0059).

3.4.2 Consent retention

All signed consent forms are locked in a filing cabinet in the Middle Ear Laboratory.

3.5 Instrumentation

3.5.1 Inspection, audiometry, and transient-evoked otoacoustic emissions

Otoscopy was conducted with a Welch-Allyn clinical otoscope with disposable tips. For pure tone audiometry, an OB 802 audiometer was used for the normative subjects and a GSI 10 audiometer was used for the subjects with otosclerosis, both calibrated to ANSI standards (re: S3.6.1989). Supra-aural earphones (TDH-39) were used to test hearing levels in a sound booth.

Transient-evoked otoacoustic emissions were tested using an ILO-292 Analyzer (Otodynamics, Ltd., Hatfield, England) calibrated based on the operators manual from the manufacturer. Transient-evoked otoacoustic emissions are used widely within the clinical field and are safe, non-invasive, and risk free for young children, adults (Robinette & Glattke, 2002), as well as newborns (NIH, 1993). A hypoallergenic probe tip containing a microphone was inserted into the outer ear canal. A series of clicks at approximately the loudness of conversational speech (80 dB pe) were presented to each ear. Emissions from the cochlea were measured and averaged by a computer.

3.5.2 Tympanometry

The Virtual 310 digital immittance instrument, commercially available and routinely used to test newborn through geriatric patients, was used for this study. This instrument which

contains an extended high frequency option, was calibrated before each data collection session using three standard cavities (0.5, 2.0, and 5.0 cm^3) as specified in the operation manual provided by the manufacturer. Data obtained through tympanometry is not part of the normative data for this study, but will be used for a larger study and provides background for testing patients with otosclerosis.

3.5.3 Wideband reflectance

Wideband reflectance is safe, non-invasive, and extremely efficient, taking only two to three seconds to measure each ear. A Mimosa Acoustics (RMS-system v4.0.4.4) wideband reflectance machine was used for this study. The instruments consist of an IBM compatible laptop or desktop computer with a Type II PCMCIA slot for audio data acquisition and delivering and for digital signal processing, a probe interface cable which connects the probe to the PC board and functions as the pre-amplifier for the probe, and an ER-10CP probe (acoustical probe) with two output transducers and one input transducer (microphone). A four-cavity calibration device which is supplied with the WBR instrument is also required. The computer should be placed at least one and one-half meters from the subject while testing occurs. The DSP-Card, with the "Mimosa Acoustics" label up, is inserted into the PCMCIA slot of the computer. The Probe Interface Cable (PIC) then joins the DSP-Card to the probe.

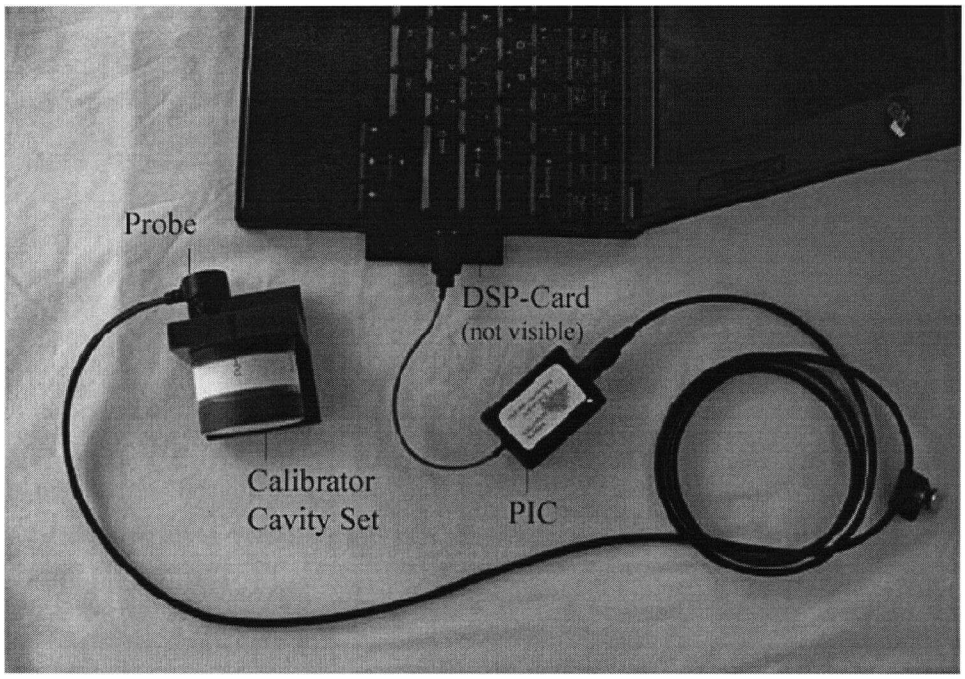

Figure 3.1: Components of the Mimosa Acoustics (RMS-system v4.0.4.4) wideband reflectance machine.

In order to ensure that there is a proper probe fit for both calibration and testing, it is important to keep the plastic tube of the ear tip flush with the front edge of the ear tip, to properly align the ear tip with the probe, and to roll the ear tip evenly prior to insertion to decrease the diameter of the tip and prevent leakage. The appropriate ear tip size should also be selected for each subject. Both plastic and foam ear tips are available in a variety of sizes for the Mimosa Acoustics instrument. Foam ear tips were used in this study and were calibrated appropriately.

Calibration of the WBR machine was completed using the four-cavity calibration device prior to each subject. Once the appropriate ear tip size had been selected and each of the four calibration cavities had been measured individually, an overall calibration was completed. A value of at least 91% was required for testing to proceed. All subjects in this study passed with the calibration at or above 91%.

The Mimosa WBR machine used in this study, collected data using impedance (i.e. the reciprocal of admittance). Data were then mathematically altered by the instrument to present the other variables. Power absorption was presented automatically in percent; hence, the ratio value from zero to one was multiplied by 100. The admittance variables of Y, B, and G were presented in unitless values as they were normalized by the characteristic impedance of the ear canal. Using an average adult ear canal size of 0.75 cm, the characteristic impedance can be calculated.

$$Z_c = \frac{\rho c}{S} \tag{8}$$

Formula (8) defines Z_c as the characteristic impedance of the ear canal, ρ as the density of air, c as the speed of sound, and S as the area of the ear canal. Impedance, as measured by the instrument, was then divided by the characteristic impedance in order to obtain the normalized values and attempt to compensate for the effect of the ear canal.

Four data graphs were available for each patient. Each of these data graphs can be set up to show one of fourteen different y-axis variables: Sound pressure level, Sound pressure level (Group Delay), Power Reflectance, Reflectance (Group Delay), Power Absorption, Impedance (Real Part), Impedance (Imaginary Part), Admittance (Real Part), Admittance (Imaginary Part), Impedance (Magnitude), Impedance (Group Delay), Admittance (Magnitude), Admittance (Group Delay), and Sound intensity level. The variables chosen in this study, as already discussed, are Power Absorption, Admittance (Magnitude), Admittance (Imaginary Part), and Admittance (Real Part), previously referred to as PA, Y, B, and G, respectively. The three admittance variables were chosen because they best approximate tympanometric admittance data to be more comparable for future research. As well, by evaluating these components, the

underlying mechanism of difference between races and normal and diseased groups may be observed.

During testing two of the four data graphs were set to power absorption as a function of frequency and the other two were set to power reflectance as a function of frequency. See Figure 3.2. This was done so that the Mimosa Acoustics normative values could be visualized while testing. It was not necessary to run tests for all the variables used in this study as the Mimosa software automatically calculates values for the other variables if they are chosen from the menu. See Figure 3.3.

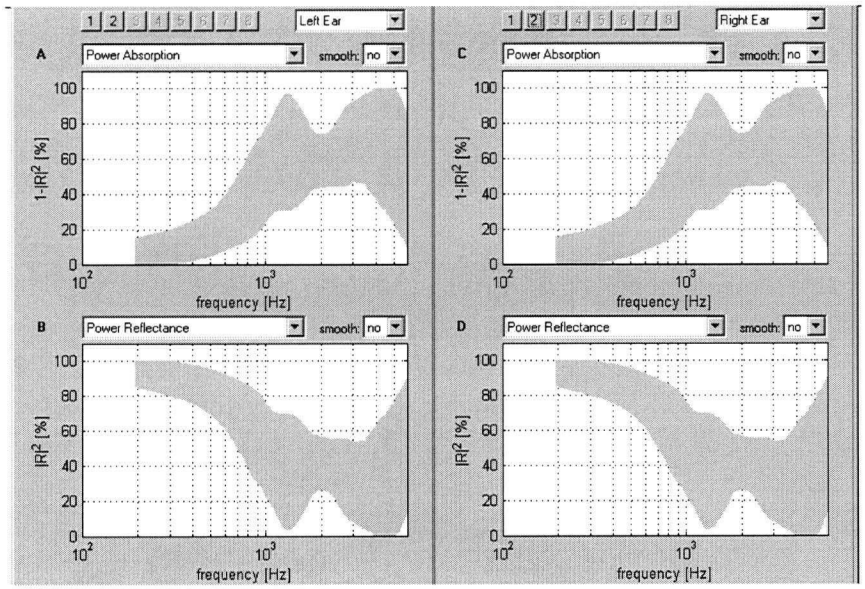

Figure 3.2: Organization of data graphs during testing using the Mimosa Acoustics (RMS-system v4.0.4.4) wideband reflectance machine. The shaded area represents normative data provided by Mimosa Acoustics.

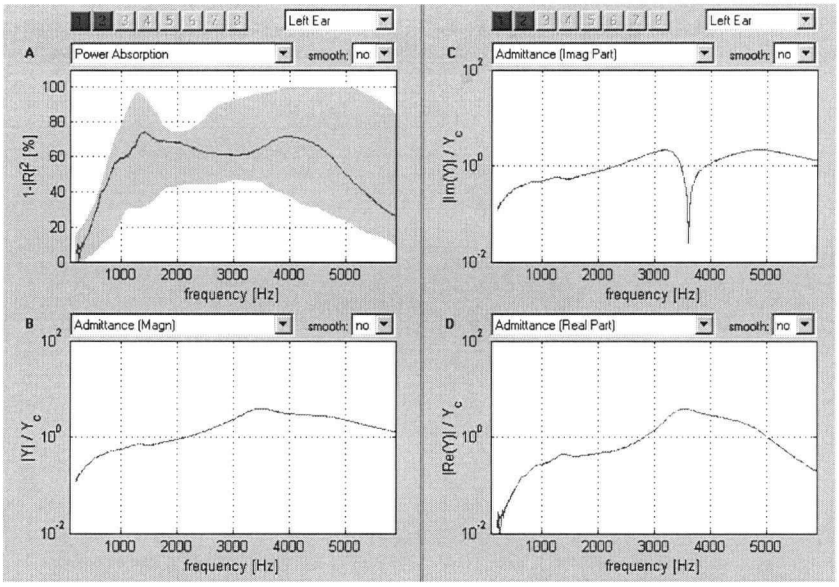

Figure 3.3: Graphical view of the four variables used in this study: Power absorption, Admittance (Magn), Admittance (Imag Part), and Admittance (Real Part). The shaded area refers to normative data provided by Mimosa Acoustics. Of these, only the power absorption curve was visualized during testing. The admittance variables were calculated automatically by the Mimosa software after testing was completed. Frequency is represented in linear format.

The test is then run by selecting the correct type of ear tip used for the subject, the ear to be measured, and the Reflectance Measurement System (RMS) icon. A new window then opens which allows for a single measurement to occur (Figure 3.4). The result can then be accepted or re-measured depending on whether the signal-to-noise ratio is adequate across all frequencies tested. Measurements were accepted only if the signal was visible clearly above the noise value at the lowest measured frequency. The input spectrum should also be as smooth as possible. Up to eight individual measurements can be taken during one testing session.

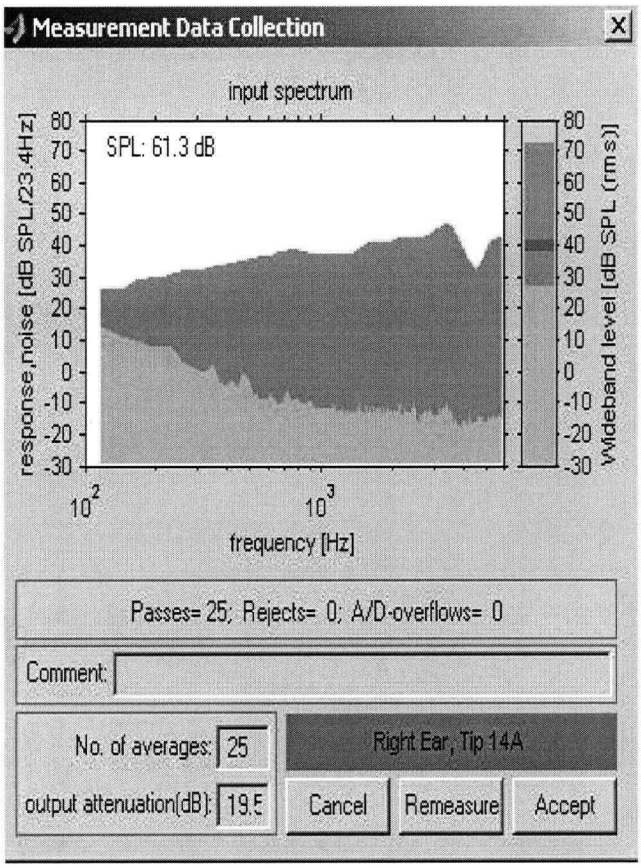

Figure 3.4: Measurement data collection screen used to acquire subject results from Mimosa Acoustics (RMS-system v4.0.4.4) wideband reflectance machine. The above shaded region represents the signal level, while the below shaded region the noise level.

For each ear, at least two individual measurements were taken in order to judge test-retest reliability. In order to check the test-retest reliability of the measures, at least two of the measures taken must visually approximate the other using the PA curve. This can be seen in Figure 3.5.

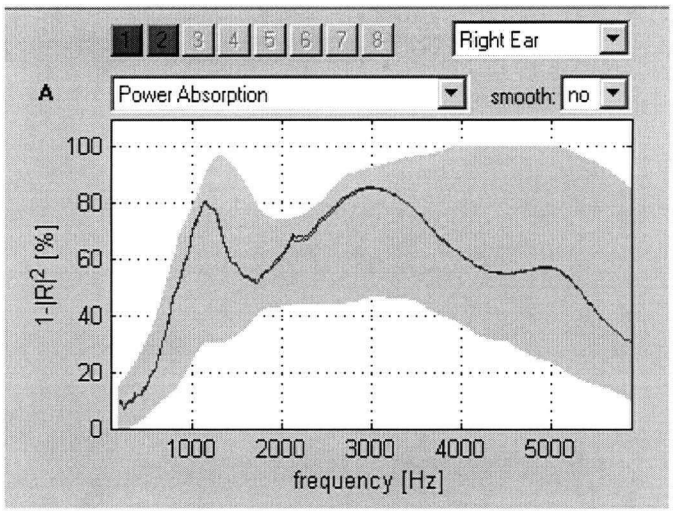

Figure 3.5: Visual measure of test-retest reliability using the power absorption curve.

Once testing was complete, data could be viewed graphically as any of the 14 y-axis variables listed above. See Figure 3.3 for a visualization of the variables used in this study. In order to obtain the numerical results, each saved graph was exported separately from the Mimosa Acoustics software into a text file and then into a Microsoft Excel file where it could be analyzed further.

3.6 Procedure

3.6.1 Testing done prior to subject inclusion in this study

Otoscopy was performed on all subjects to rule out excessive cerumen, discharge, or gross tympanometric abnormalities. Appropriate referrals were made when necessary. Pure tone audiometry was performed in a standard sound booth using a 10 dB HL down, 5 dB HL up bracketing technique. Behavioural responses were recorded for the softest tones heard. These above tests are part of the regular pre-operative evaluation for otosclerotic patients and were mandatory; further testing proceeded only with the written consent of the patient.

The TEOAE test was conducted in a quiet room using a laptop computer. Results indicate status of the middle ear and cochlea. Testing of TEOAEs was completed after pure tone

audiometry in order to avoid researcher bias with prior knowledge of middle ear or cochlear status. Measurements were considered unreliable when the stimulus level in the closed ear canal was less than 71 dB pe. Each of the five frequencies, 1000, 1500, 2000, 3000, and 4000 Hz, were estimated separately. Transient-evoked otoacoustic emissions were considered to be present when the amplitude of the emission was greater than, or equal to 3 dB relative to the noise (i.e. ≥3 dB signal-to-noise ratio) from frequencies 1000 to 3000 Hz.

3.6.2 Testing done after subject inclusion in this study

If the subject met the inclusion criteria, as described in section 3.2, tympanometry was performed. Subjects were tested using both standard tympanometry and MFT. For the normal subjects, as both ears were being used, alternate ears were tested first to prevent order effects. For the study subjects, the otosclerotic ear was tested first.

For WBR, four parameters were computed: power absorption (PA), admittance magnitude (Y), susceptance (B), and conductance (G). The data were recorded in PA and then exported into text format for the four variables of PA, Y, B, and G. The data from each subject were then imported into a Microsoft Excel spreadsheet. All the data from each subject were then transposed and compiled into a database based on variable (i.e. PA, Y, B, and G). In total, data from 248 frequencies, dispersed evenly from 211 to 6000 Hz, were collected.

These measurements allowed the researcher to evaluate subtle mechano-acoustical changes of the middle ear across a wide range of frequencies. Each of the WBR variables was analyzed across the entire frequency range.

3.6.3 Background tympanometric testing used in this study

The data obtained using the Virtual 310 system was not analyzed in this study as it was collected in lieu of larger study which is not relevant to the scope this paper. However, both

standard tympanometric and multi-frequency tympanometric results were used as background information for the otosclerotic subjects.

3.7 Data handling

Graphics give data as mean and 90% range. This range includes those values falling between the 5th and 95th percentiles. Values beyond the 90% range were considered abnormal. The value of the 90% range was useful as it provides cutoff points for differential diagnosis.

Normative data from the literature were limited to some variables (i.e. PA and ER) and were provided in graphic forms showing the 90% range. Similarly normative data from the Mimosa Acoustics machine were provided showing 90% range for PA.

Gender and race specific normative data were generated by this study for PA, Y, B, and G. These were given in graphic format using Microsoft Excel to show mean and 90% range. Graphic comparisons between normal subject groups were made. Comparison between otosclerotic subjects as a group and normative data were problematic due to a sample size of seven. Thus, data from a series of otosclerotic case studies were individually plotted alongside appropriate normative data showing the mean and 90% range. This allowed visual determination of the frequencies or ranges of frequencies where the data of the subjects were beyond the cutoff values.

3.8 Data analysis

Prior to repeated measures analysis of variance (ANOVA), the data from normal subjects for each of the four variables of the WBR measure was explored using box-plots. The data were observed for asymmetry in empirical distribution and outliers were identified. Square root transformation was done to identify only the extreme outliers. These extreme outliers due to measurement errors were excluded from further analysis e.g. negative values using the PA variable which is measured in percent.

For each of the 248 frequencies from 211 to 6000 Hz, four variables were recorded, PA, Y, B, and G. Under these circumstances, repeated measures ANOVA was advantageous as error variance is reduced by decreasing variability among subjects. In repeated measures ANOVA each subject was considered as a block and thus variability among blocks was taken away from the error variance, making the test of significance more sensitive. Another advantage of repeated measures design was that as the subjects are measured repeatedly, fewer subjects were required for the study to detect a significant difference between groups.

Level of frequency, a continuous variable, was considered to be the within subject factor. Between subject factors for the categorical variables of gender (male and female), race (Chinese and Caucasian), and ear (right and left) were established. Significant effects were further explored using 95% confidence intervals (CI) at each frequency level for the four variables. Significance was determined in two ways: (1) by comparison of means with values of $p < .05$ considered significant, and (2) by clear separation of the 95% CI plots.

Chapter IV Results and Discussion

This study evaluates the effect of gender and race, Chinese compared with Caucasian, on normative values for four wideband reflectance (WBR) measures and presents the pre-operative test results using WBR for seven cases of otosclerosis. These WBR measures include power absorption (PA), admittance (Y), susceptance (B), and conductance (G). In order to effectively use WBR in clinical practice, all sources of subject variability that can affect the outcome of measurement should be considered. These currently known sources of variability include: age, gender, and race. As age is limited for the normal subjects of this study to healthy young adults and is similar to that of the subjects of Feeney, et al. (2003), age is not evaluated. There are no age-specific normative values for WBR from older adults at this time.

The two variables considered as sources of variation for normative values in this study are gender and race. This variation is considered for three reasons. First, it allows for the creation of gender specific or race specific normative data. Second, previous reports for other measures of middle ear function have suggested gender or racial differences. Margolis, et al. (1987), Roup, et al. (1998), Wiley, et al. (1996), Shahnaz and Davies (2004), and Wan and Wong (2002) have reported differences in normative tympanometric data either by gender or race or both. (See section 2.4). Based on their recent study, Shahnaz and Davies (2004) recommended the use of gender specific and race specific (Chinese and Caucasian) normative data for both low frequency tympanometry and MFT. Third, this method helps to answer the question whether data by gender and race should be collapsed when normative data are compared with that of different middle ear pathologies.

For WBR measures there are seven ears from seven otosclerotic subjects and 240 ears from 128 normal subjects (51 ears from 28 Caucasian males; 64 ears from 34 Caucasian females; 46 ears from 24 Chinese males; and 79 ears from 42 Chinese females). Analyses for gender and

racial differences were completed for each of the four measures of WBR for normal subjects. All seven otosclerotic subjects were Caucasian. Comparisons were made with Caucasian normal subjects, using gender specific data as appropriate.

The organization of this chapter is by section, first according to each of the four measures given above, then by case histories. For each of the four measures, subsections are as follows: (1) procedure, (2) between gender and race statistical analysis for normal subjects to justify whether race and gender specific normative values should be used, (3) graphed normative data by race and gender, and (4) discussion of normative data. Within the subsection on PA, normative data from this study is plotted alongside normative data from Feeney and Sanford (2004, Figure 4.1).

The second section of the results gives the case histories of the seven otosclerotic subjects with their individual data presented graphically relative to normative data. As statistical analysis would be problematic due to the small sample size, this method allows for interpretation of the data and formulation of future recommendations.

4.1 Power Absorption

4.1.1 Procedure

A commercially available WBR machine developed by Mimosa Acoustics was used for this study. Calibration of the WBR machine was completed prior to each subject using the four-cavity calibration device. A value of at least 91% must be obtained in order for testing to proceed. All subjects in this study passed with the calibration at or above 91%. Each of the four variables used as part of the WBR measure in this study were chosen from 14 possible variables within the Mimosa Acoustics WBR machine's software. Power absorption was chosen as the measure that would be visible on the screen while testing was in progress so that each subject's results could be readily compared with Mimosa's normative data collected by Voss and Allen.

A broadband chirp stimulus of between 200-6000 Hz was presented and data from 248 frequencies (at approximately a 23.3 Hz interval) between 211-6000 Hz were collected. Once testing was completed, data were saved and exported to a Microsoft Excel spreadsheet where further analysis took place. Each ear took approximately 2-3 seconds to test.

Prior to graphing the data by gender and race, the 90% range for 15 frequencies of the combined Caucasian and Chinese groups of this study was compared with the requested unpublished normative values by Feeney and Sanford (2004). Feeney and Sanford's (2004) data were equally divided by gender and were of unknown race. It was thus assumed that no selection criteria were made for race when establishing the normative values. As such, data from this study were averaged across gender and race, and combined for overall mean, 5th, and 95th percentile values. The data, as received, were then transformed into PA. Knowing that ER and PA are reciprocal ratios, Feeney and Sanford's (2004) ER ratio data were converted using simple subtraction from one and then multiplied by 100 in order to gain percent values to be compatible with results from this study. Table A1 (Appendix I) gives the ER mean, 5th, and 95th percentile data from Feeney and Sanford (2004). As seen below in Figure 4.1, the mean and percentile data from Feeney and Sanford (2004) and the combined gender and race data from our study show a fairly steep increase in the percent of PA until about 1200 Hz. The values from this study were all substantially higher from 250 to approximately 3500 Hz where there was a reversal. These differences may be due to the WBR machine used, race, units of presentation, or some other, yet unexplained factor. Further comparisons can be done when more specific information from Feeney and Sanford's (2004) data are available.

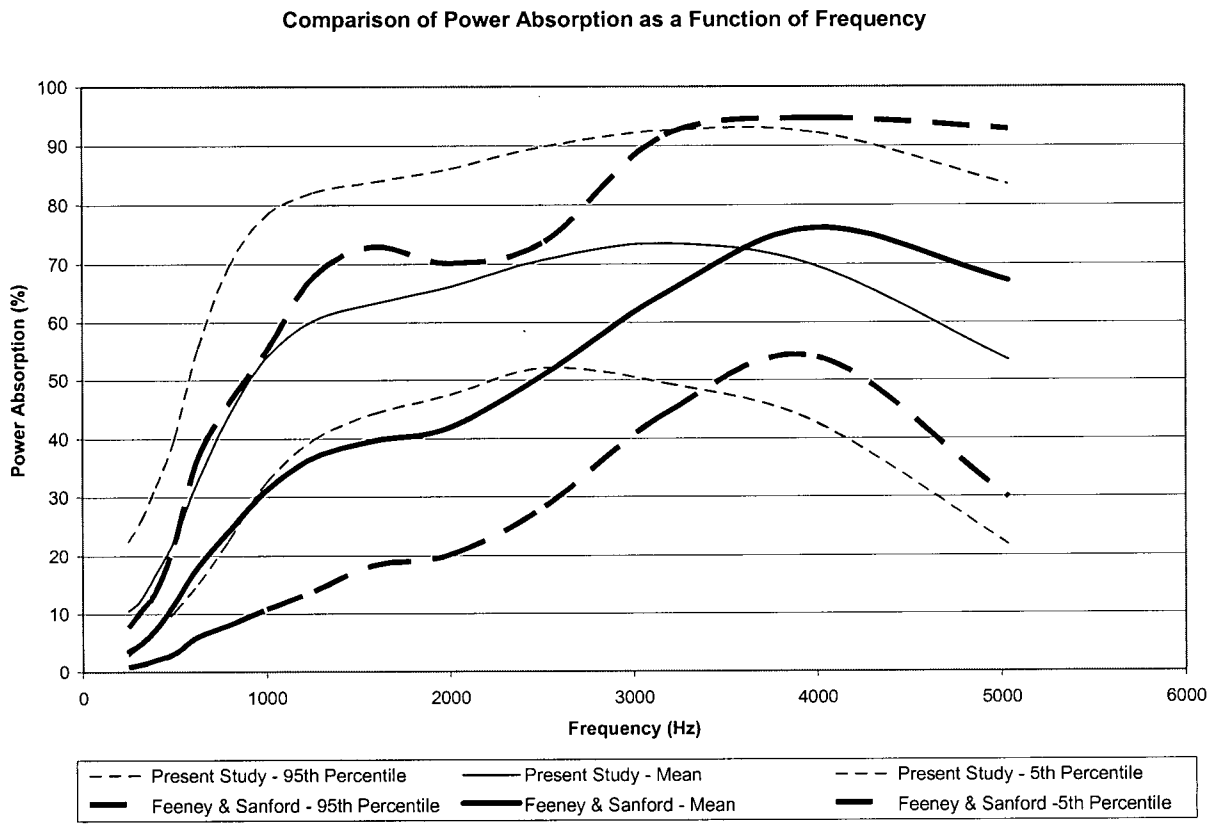

Figure 4.1: Comparison of power absorption as a function of frequency. Mean, 5th, and 95th percentile values are plotted. Data are from Feeney and Sanford (2004) and combined race and gender normative values from this study.

4.1.2 Between gender and race statistical analysis

The data for the variable PA were explored using repeated measures ANOVA. The variables of interest for this analysis were the between subject factors of gender (male or female), race (Chinese or Caucasian), and ear (right or left). The within subject factor was level of frequency. Preliminary box-plots showed that the distribution of PA was symmetrical except for very few outliers. Six extreme outlier observations (ear outliers) of three subjects, defined by negative values, were eliminated. As the empirical distribution of the PA data was symmetrical, no transformation was needed. Had this distribution been asymmetrical, a transformation, such

as, square root transformation, would have been used to allow for a more normal distribution and to define the most extreme outliers. Table A6 (Appendix V) shows the ANOVA summary table. The main effect of race was significant [$F(1, 235) = 12.45$, $p = .001$]; however, the effect of gender and ear were not significant [$F(1, 235) = 1.53$, $p = .218$], and [$F(1, 235) = 0.78$, $p = .377$], respectively. There were no significant interactions. Gender differences were not observed within either race.

To find at which frequency differences occurred between different races of the same gender, 95% CI plots were observed. As confirmed by 95% CI plots, Chinese and Caucasian females differed at frequencies 422-1805 Hz and 4313-6000 Hz. Caucasian values were higher in the lower frequencies and lower in the higher frequencies. Similarly Chinese and Caucasian males differed. In the lower frequencies, 352-1266 Hz, Caucasian males had higher averages than Chinese males, but at 3891-6000 Hz the reverse is true. There were no ear differences.

A possible explanation for the above findings is that higher PA in lower frequencies reflects more efficiency within the system. Caucasian males and females demonstrated higher values, suggesting greater efficiency, at lower frequencies. This is presumably due to the anatomical differences of larger middle ear cavities. At higher frequencies, the Chinese male and female data demonstrated more efficiency than Caucasians. This might be explained by the smaller size of the middle ear of Chinese, as smaller cavities have higher resonant frequencies.

4.1.3 Collected normative values

Given that differences have been found between races for tympanometric measures, two normative groups were established. Chinese and Caucasian normative values were also separated by gender. As discussed earlier, both the 5th and 95th percentiles were calculated and plotted alongside their corresponding mean value. The range between the 5th and 95th

percentile lines, or the 90% range, is often used clinically as a cutoff between normal and abnormal results.

4.1.3.1 Normative data comparing Chinese males and females

As seen in Figure 4.2, the mean, 5th, and 95th percentile lines of the graph showed PA between Chinese males and females did not directly overlap. As just discussed in section 4.1.2, mean statistical differences in gender data were not seen among Chinese. Despite the lack of statistical differences, plotting of the 90% range was used to compare whether these cutoffs are the same or different between the two genders within a race. Observed differences between males and females suggest that gender specific data is needed. In this graph (Figure 4.2) the 5th percentile lines for Chinese males and females up to about 1400 Hz are very close. This may be important as this is the area Feeney, et al. (2003) suggested would be abnormal in otosclerosis. From about 1400 Hz to 2350 Hz Chinese female scores fall below 5th percentile for males. The reverse is true with Chinese females having greater PA at the 95th percentile than males for frequencies between 2836-5000 Hz. In general, visual inspection suggests Chinese females have values above Chinese males in the higher frequencies at the 5th and 95th percentiles and males have higher values in the lower frequencies. These observations suggest that the female Chinese middle ear may be less efficient at lower frequencies and thus is stiffer at those frequencies, as less energy is absorbed compared with the Chinese male middle ear. The data also suggest that at higher frequencies, the middle ears of Chinese females may be more efficient. These differences may be anatomical, related to middle ear size. Studies have shown that there is a correlation between head size and middle ear size in humans (Huang, et al., 2000). Based on this argument, if female middle ears are, on average, smaller than male middle ears, then female middle ears should have a higher RF. This higher RF value can be translated into better efficiency of energy transfer at higher frequencies. This argument is supported by evidence

from Shahnaz & Davies (2004) as ear canal volume was found to be significantly different between male and females. Overall, differences noted in the cutoff levels appear sufficient to require gender specific normative data for Chinese adults.

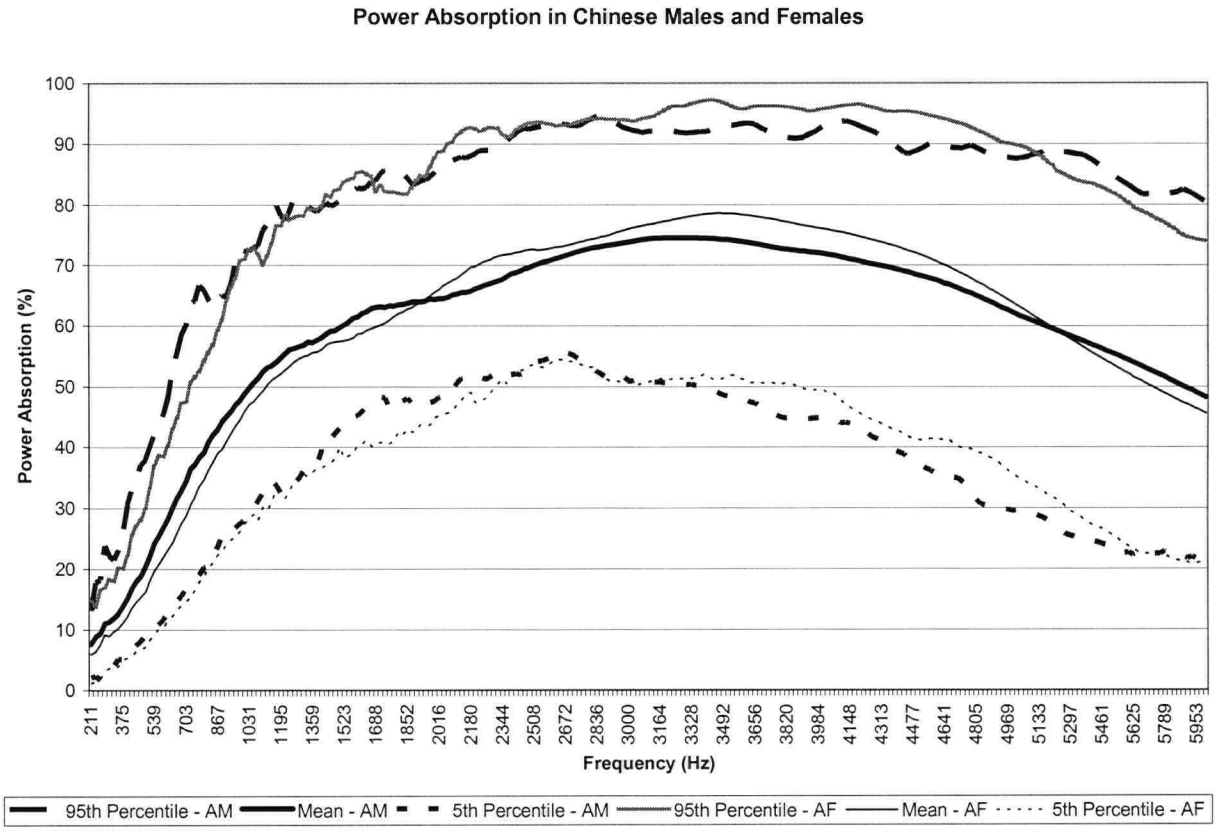

Figure 4.2: Power absorption as a function of frequency comparing normative data from Chinese males and females. AM refers to Chinese males; AF refers to Chinese females.

Compared with the Mimosa normative values (Figure 2.8), there is no peak around 1250 Hz for the 90% range. As well, there is no drop in the 95th percentile at around 2000 Hz. The values from this study continue to gradually increase throughout the lower frequencies. Visual inspection of Chinese normative values for PA for both genders compared with those of Feeney and Sanford (2004) as seen in Figure 4.1 suggests Chinese data curves do not reveal a relative

flattening at approximately 1200-1900 Hz and show an overall pattern more like that of the combined normative data of this study (Figure 4.1).

4.1.3.2 Normative data comparing Caucasian males and females

Figure 4.3 displays PA graphic data for Caucasian males and females. As stated in 4.1.2, gender differences were not statistically significant. However, plotting of the 90% range showed differences in the cutoff values. As with the Chinese, Caucasian females had lower scores at the 5th and 95th percentile range in lower frequencies than males and higher scores in the frequencies exceeding about 1200 Hz. As mentioned for the Chinese population, this PA data suggests greater stiffness among females than males at lower frequencies and less stiffness at higher frequencies. The Caucasian male middle ear may be more efficient at lower frequencies than the female ear. Anatomical middle ear size likely accounts for much of this difference. This graphic data strongly suggests gender specific data are needed.

With the exception of the large 90% range in the low frequencies, the Caucasian group had a more similar overall pattern to the Mimosa normative values of Voss and Allen than the Chinese group. The pattern of the Caucasian gender combined data was more similar to that of Feeney and Sanford (2004) data than to the Chinese data of this study.

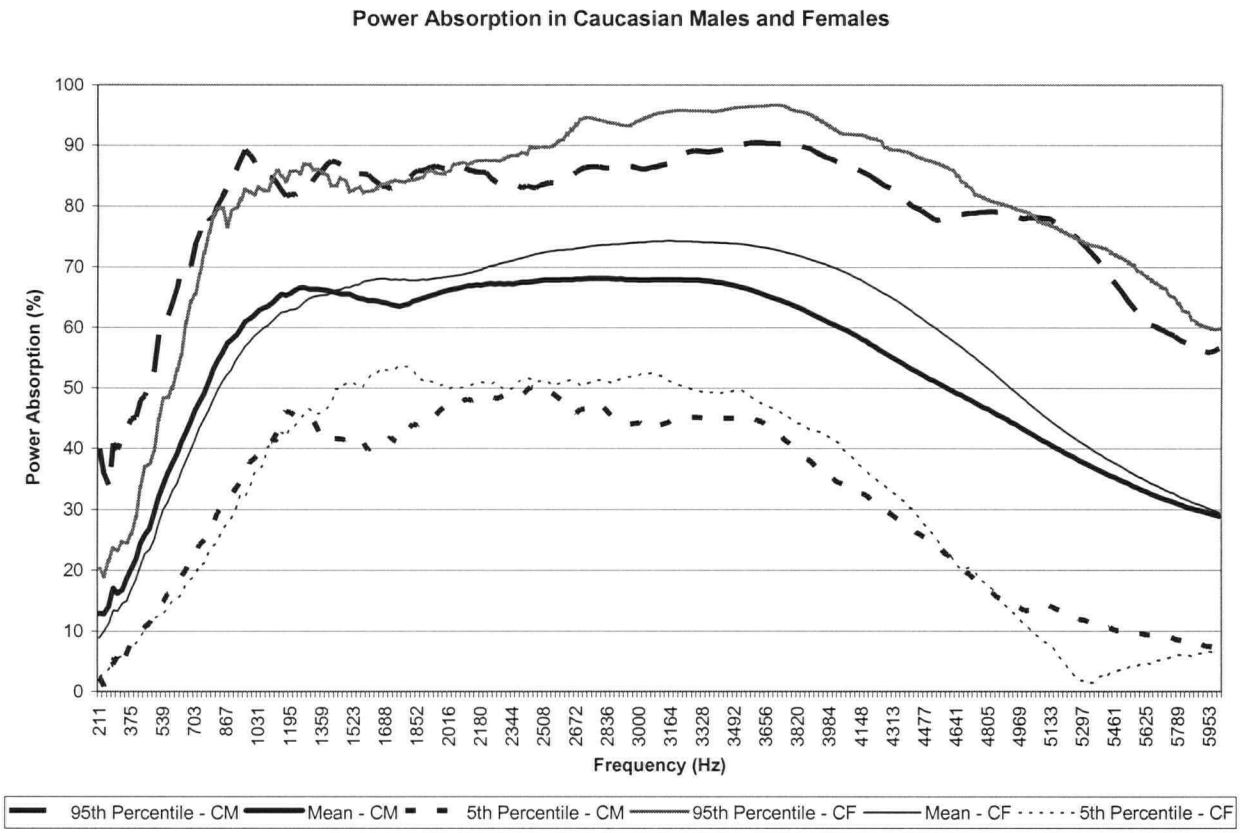

Figure 4.3: Power absorption as a function of frequency comparing normative data from Caucasian males and females. CM refers to Caucasian male; CF refers to Caucasian female.

4.1.3.3 Normative data comparing Chinese and Caucasian males

When values of Chinese and Caucasian males were compared, as seen in Figure 4.4, there were significant differences in the patterns of the curves. As just seen in 4.1.2, there were statistical differences in Chinese and Caucasian male values. Visually, Caucasian males had higher mean, 5th and 95th percentiles in the low frequencies than Chinese males. This reversed at higher frequencies. Mean differences were separated by about 15% at approximately 1100 Hz and by a full 20% at 5000 Hz.

These results are consistent with statistical findings; hence, it is clear that separate racial normative values are needed for males. Compared with Chinese males, the Caucasian male

middle ear is more efficient in transferring power at low frequencies; the Chinese middle ear is better at higher frequencies. Possible reasons for these differences are discussed in section 4.1.4. It is interesting to note that compared with Chinese males, Caucasian males have a larger variation at frequencies below 500 Hz.

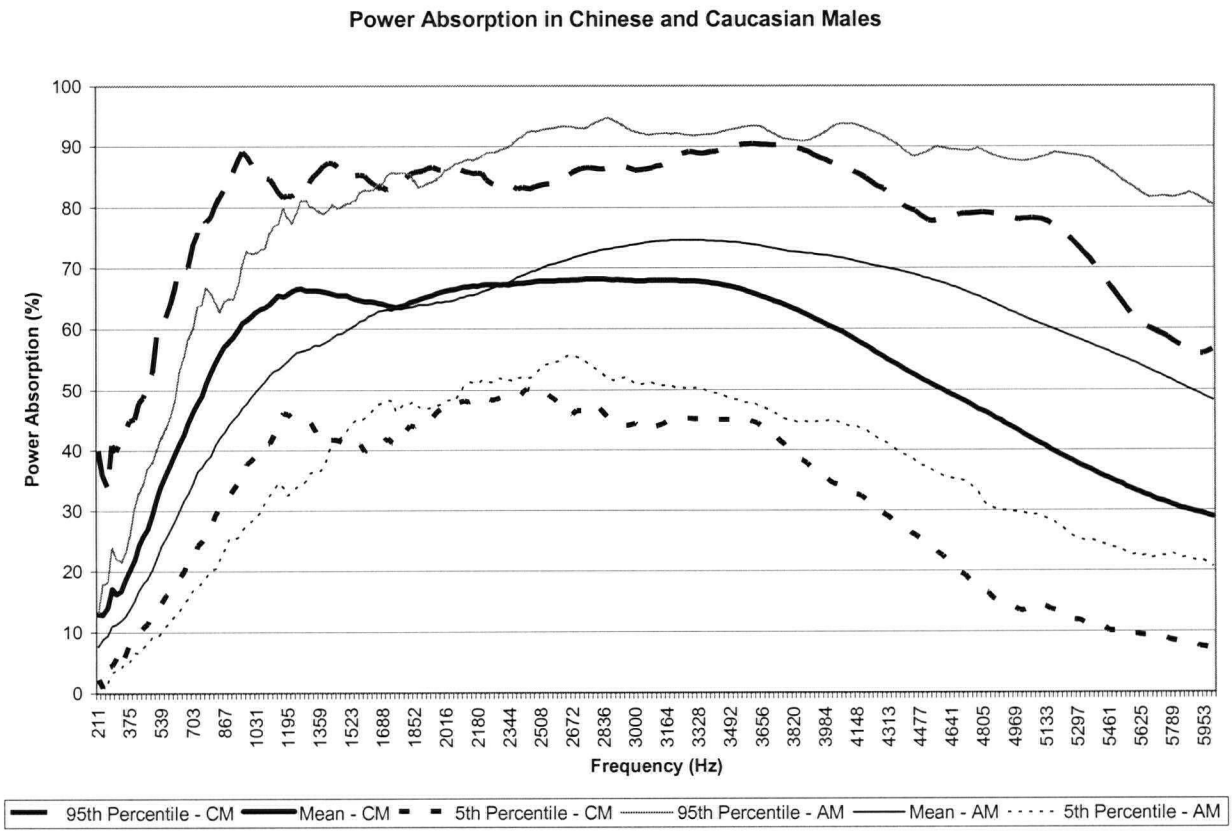

Figure 4.4: Power absorption as a function of frequency comparing normative data from Chinese and Caucasian males. CM refers to Caucasian males; AM refers to Chinese males.

When compared with the Mimosa normative values by Voss and Allen, the overall pattern for the Caucasian males was more similar to these normative values than those of the Chinese males. Mimosa values showed a peak in the low frequencies for the 95th percentile values. This contrasted with the gently sloping Chinese male pattern. As mentioned previously, the rapid acceleration and peak of the percent PA at 1000 Hz for Caucasian males revealed a

pattern similar to that of Feeney and Sanford (2004). Both Caucasian and Chinese mean values were higher than those in Feeney and Sanford (2004). Such apparent variations may be due to different calibration, or other such factor, between the different machines used.

4.1.3.4 Normative data comparing Chinese and Caucasian females

As seen in Figure 4.5, the differences observed between Chinese and Caucasian males persist with females. Statistical differences between mean values have been shown (section 4.1.2). Visually, Caucasians had higher mean, 5th, and 95th percentile scores in low frequencies. As described earlier, the Caucasian middle ear has greater percentage of PA at lower frequencies than the Chinese middle ear and is more efficient. This may relate to increased stiffness in the lower frequencies due to size of the middle ear cavity, or physiological aspects of the annular ligament as is discussed in section 4.1.4.

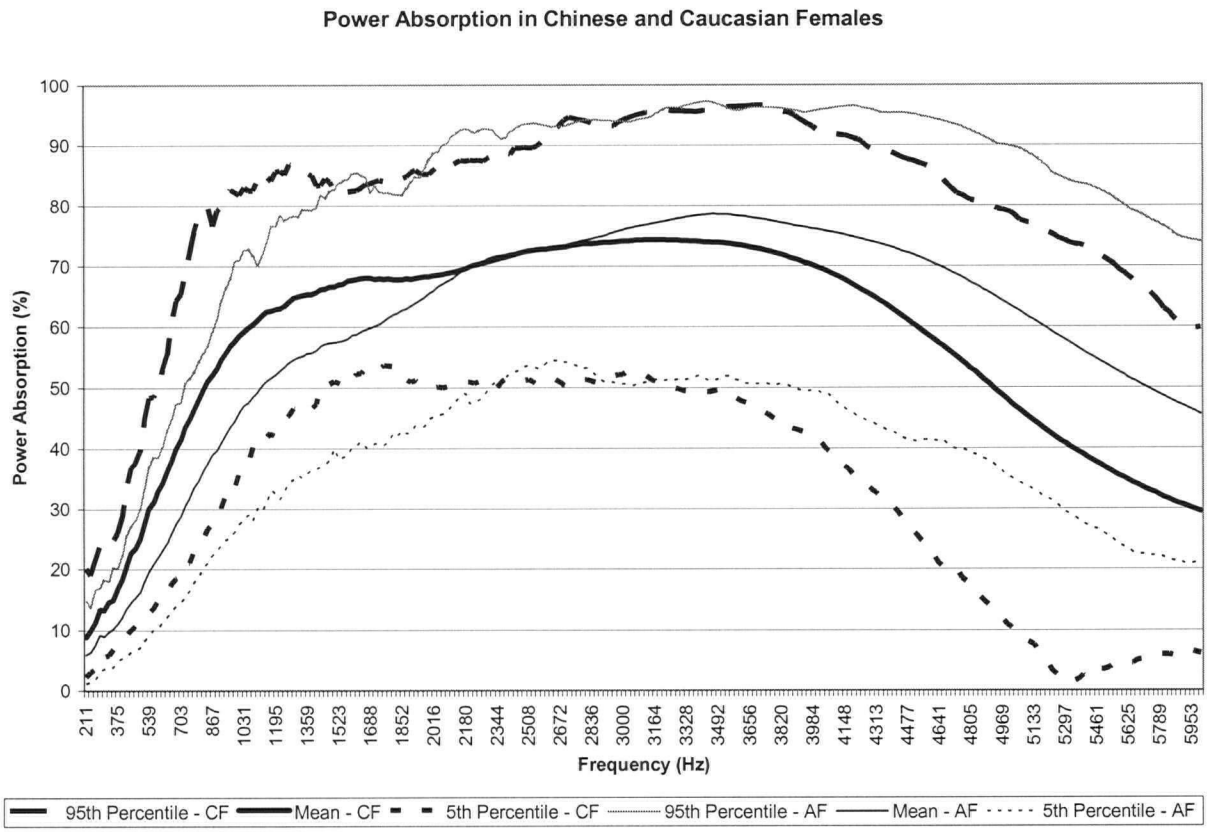

Figure 4.5: Power absorption as a function of frequency comparing normative data from Chinese and Caucasian females. CF refers to Caucasian females; AF refers to Chinese females.

Compared with the Mimosa normative values by Voss and Allen, the results showed a higher power absorption level at 2000 Hz. This can also be said of the other normative values collected in this study. The mean score for Chinese females paralleled most closely the mean scores of Feeney and Sanford (2004). However, unlike the Chinese females, the Caucasian females have a slight peak in PA at approximately 1200 Hz in the 95th percentile curve which is similar to Feeney and Sanford's (2004) combined data under the 95th percentile curve. Thus, the pattern of the curve in Feeney and Sanford's data suggested that they had mainly Caucasian normative subjects. This remains to be seen as Feeney and Sanford's (2004) data have not yet been published; thus, race is unknown.

4.1.4 Discussion of power absorption results

Power absorption was chosen as a WBR variable since the 90% range from Mimosa normative data, obtained by Voss and Allen, was available in PA and provided a framework to readily compare the data. Power absorption can also be compared, albeit reciprocally to some published data. This was the first attempt to determine if gender plays a role in the results for either race. No statistical differences were found in means for gender for either Caucasian or Chinese subjects. However, differences can be seen in the 90% range cutoffs of the graphic data. Differences in the 90% range between genders are important as these cutoffs are used to separate diseased from non-diseased ears. This suggests that gender specific normative values should be used.

Statistical differences in means were found between races for each gender. In addition, 90% range differences were found between Chinese and Caucasian males and Chinese and Caucasian females. Again, these cutoffs were important in separating diseased from healthy ears. Power absorption data showed more efficiency of the middle ear at lower frequencies for the males compared with females and Caucasians compared with Chinese. As discussed above, differences in percentage of PA by gender and race are likely related to differences in size of the middle ear cavity among these groups. Keefe, et al. (1993) studied cross-sectional area of the adult ear canal in relation to ER and showed greater variation of results in frequencies below 3000 Hz.

Another reason that has been postulated as a cause of the variation in low frequencies is due to the physiological response of the annular ligament. The annular ligament is located around the oval window and footplate and in normal hearing individuals assists in reducing low frequency sounds. If this physiological response is different among groups, this could result in a variation in low frequency efficiency as showed by the percentage of PA. There is ongoing

debate over the cause of high frequency differences. Based on the results found in this study, race specific normative values are required.

4.2 Admittance

4.2.1 Procedure

Admittance was chosen as a measure as it was thought to be comparable to tympanometric admittance; thus, future studies would have a base of comparison. Once testing was completed, data were saved and the admittance values exported to a spreadsheet where further analysis took place. All admittance variables are in normalized units as discussed in 3.5.3. The normalization factor given by Mimosa Acoustics relates to the characteristic impedance of the ear canal. Due to this normalization process, admittance is dimensionless.

4.2.2 Between gender and race statistical analysis

Exploratory analysis using box-plots was completed. Results showed asymmetry of the distribution of admittance data. Thus, square root transformation was used to make the data more symmetrical. This resulted in the exclusion of six observations (ear outliers) from three separate subjects.

In order to evaluate the effects of race, gender, and ear, a repeated measure ANOVA was performed. The within subject factor was level of frequency, while the between subject factors were gender (male or female), race (Chinese or Caucasian), and ear (right or left). These ANOVA results are summarized in Table A7 (Appendix V). The main effect of race was significant [$F(1, 234) = 12.89$, $p = .000$]. Gender effect was also significant [$F(1, 234) = 4.64$, $p = .032$], but ear effect was not significant. Race-gender interaction was not significant [$F(1, 234) = 1.8$, $p = .18$]. The 95% CI plots of male and female values within each racial group were examined. For Y, Caucasian males have higher values than females from 1781 to 2367 Hz. Similar 95% CI plots for Chinese show no difference between males and females.

Between race-group analysis confirmed a significant statistical difference in means as given above. The 95% CI plots confirmed differences between Caucasian and Chinese male mean values from 281 to 1125 Hz with Caucasians having higher values. Similarly, for females, the 95% CI plots showed differences between mean values for Chinese and Caucasian females from 211 to 1313 Hz. Caucasian values were higher. These findings were clinically significant. No differences were found by ear as seen in Table A7 Appendix V.

4.2.3 Collected normative values

4.2.3.1 Normative data comparing Chinese males and females

As seen in Figure 4.6, showing the mean, 5th, and 95th percentiles of admittance across frequencies from 211 to 6000 Hz, Asian males generally have higher results than females. With the exception of the 5th percentile curve, from about 2500 to 2800 Hz, males had a lower cutoff level than females. No statistical differences were found between genders for Chinese values. However, observation of the 90% range values support the need for separate cutoff levels for Chinese males and females.

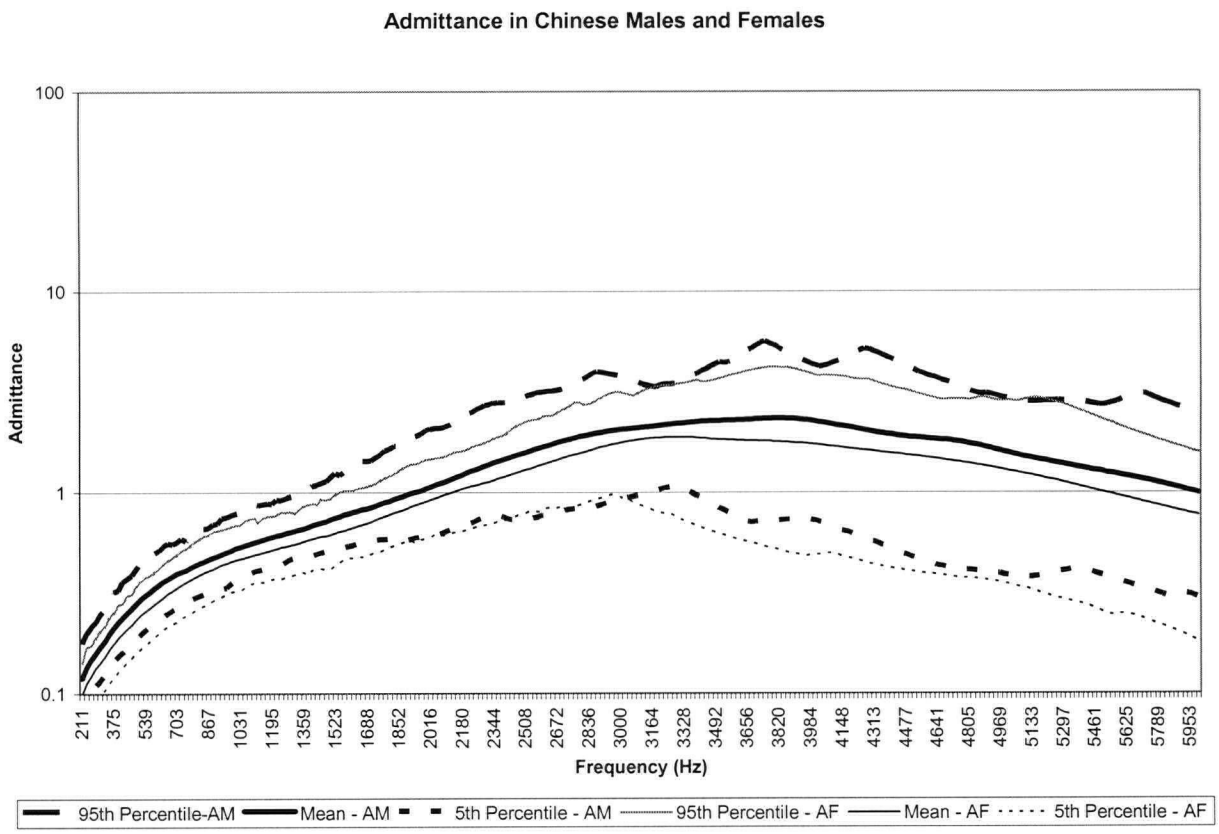

Figure 4.6: Admittance as a function of frequency comparing normative data from Chinese males and females. AM refers to Chinese males; AF refers to Chinese females. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.2.3.2 Normative data comparing Caucasian males and females

Similar to Chinese males and females for admittance results, there are visual differences in the 90% range between Caucasian males and females (Figure 4.7). Males have higher 5th and 95th percentile values until about 4000 Hz; however, for higher frequencies the mean, 5th and 95th percentile scores all dropped below those of females. As shown in Figure 4.7, it is easier for energy in males (i.e. higher admittance values) to enter the middle ear in lower frequencies than in females. This can be explained by the possible size difference of the middle ear as males have a larger volume behind the eardrum; hence, their middle ear is more compliant in the low

frequencies. These Y results support conclusions noted for PA, that at least in the lower frequencies, there is more absorption for Caucasians than Chinese; among Caucasians, there is more absorption among males. This could be due to larger middle ear cavities in these groups which allow less energy reflectance and less stiffness based on the principles of the Helmholtz resonator (Durrant & Lovrinic, 1995). Contrary to Caucasians, Chinese males continue to have higher admittance values across all of the frequencies tested. Perhaps there is a difference in the susceptance and/or conductance at the higher frequencies in Chinese middle ears.

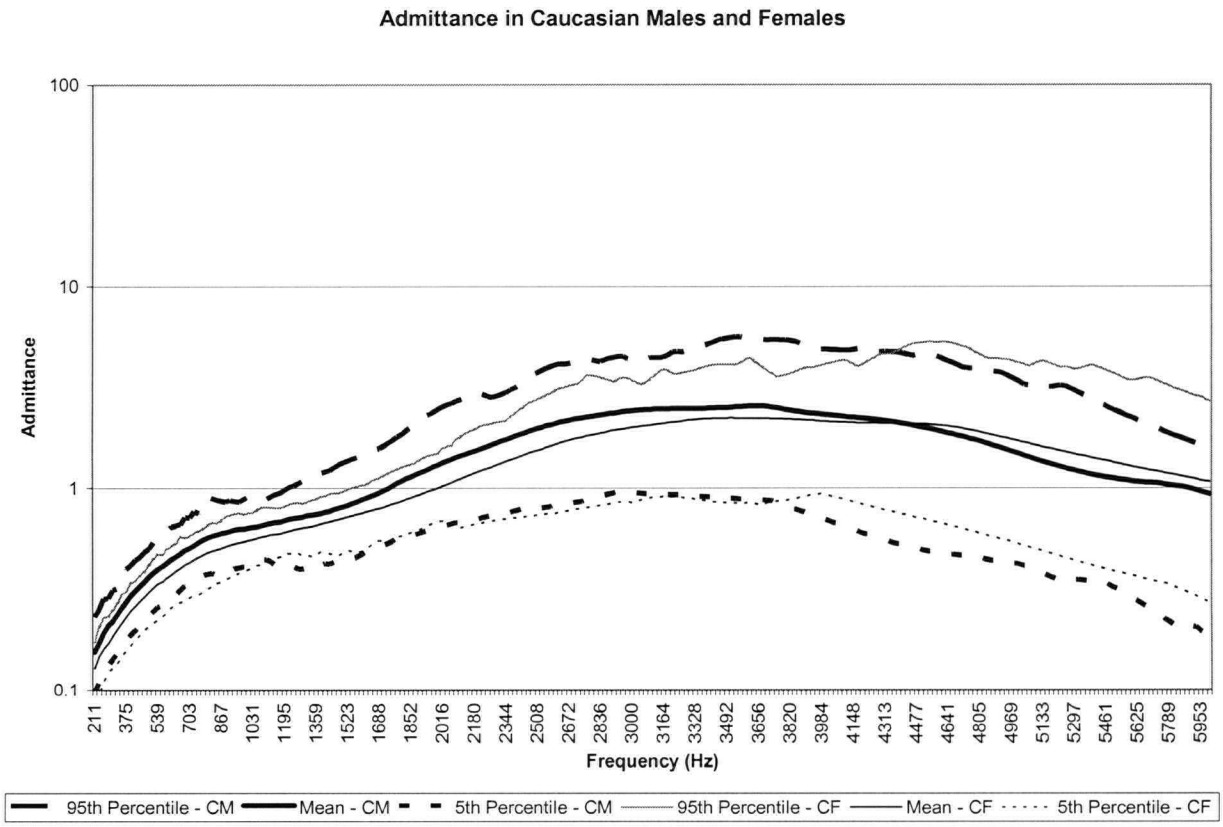

Figure 4.7: Admittance as a function of frequency comparing normative data from Caucasian males and females. CM refers to Caucasian males; CF refers to Caucasian females. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.2.3.3 Normative data comparing Chinese and Caucasian males

As seen in Figure 4.8, Caucasian males had observed higher scores for 95th percentiles for frequencies below about 5200 Hz, higher mean values to about 3600 Hz, and higher 5th percentile values below about 1200 Hz. This suggests that the Caucasian ear is more compliant in the lower frequencies, as with PA data, but is not found for Y across frequencies.

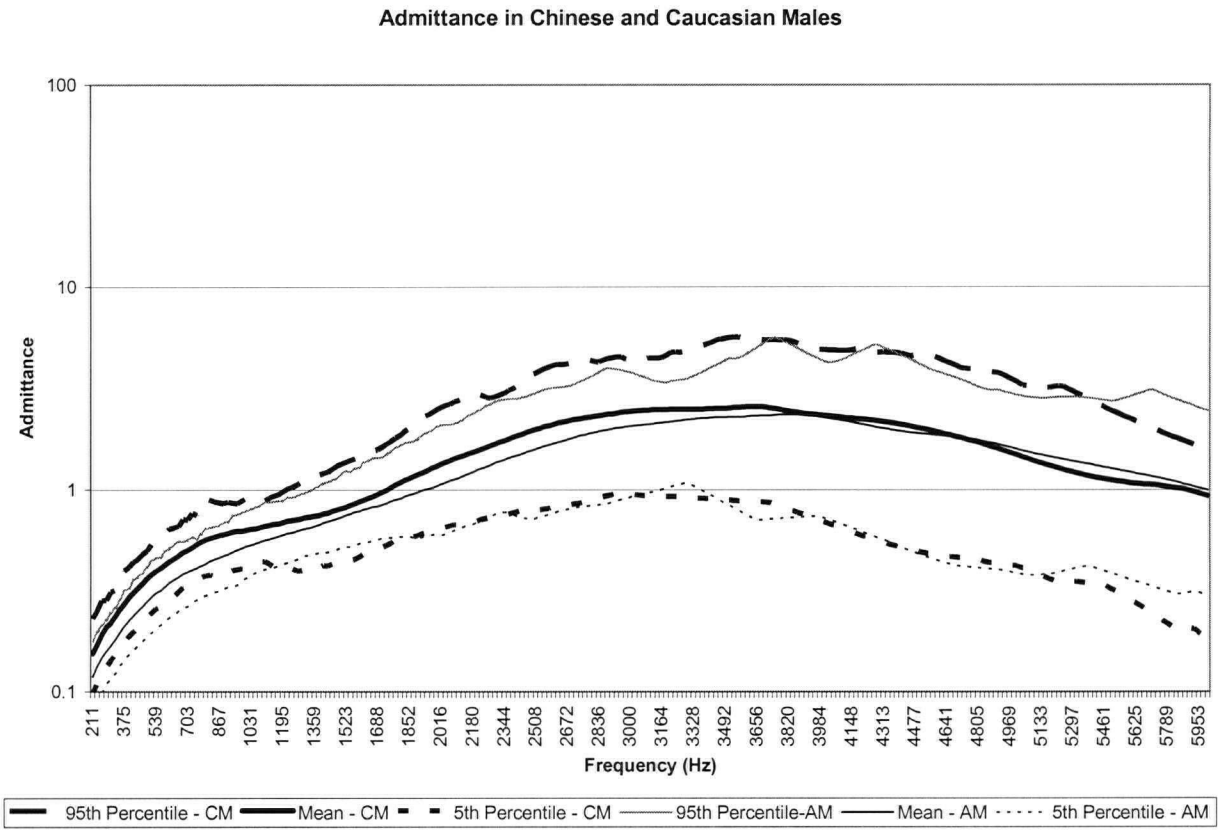

Figure 4.8: Admittance as a function of frequency comparing normative data from Chinese and Caucasian males. CM refers to Caucasian males; AM refers to Chinese males. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.2.3.4 Normative data comparing Chinese and Caucasian females

As seen in Figure 4.9, Caucasian females had higher mean and 95th percentile values across all frequencies than Chinese females. Caucasian 5th percentile values were higher in the

low frequencies to about 1500 Hz. In the lowest frequencies under about 550 Hz, the mean for Caucasian females approached the 95th percentile for Chinese females. Chinese female scores dropped well below Caucasian females at about 4000 Hz for the 95th percentile curve and 3000 Hz for the 5th percentile curve. Admittance observations for Caucasian and Chinese females in the low frequencies supported the PA observations of more efficiency. It can now be said that this increased efficiency is due to the increased ease of energy when entering the Caucasian middle ear, compared to the Chinese middle ear. It is possible that these differences are due to size of the middle ear cavity. Unlike, the PA findings, however, Caucasians continue to have greater admittance across the frequency range. This may be due to differences in stiffness, possibly imposed by the annular ligament.

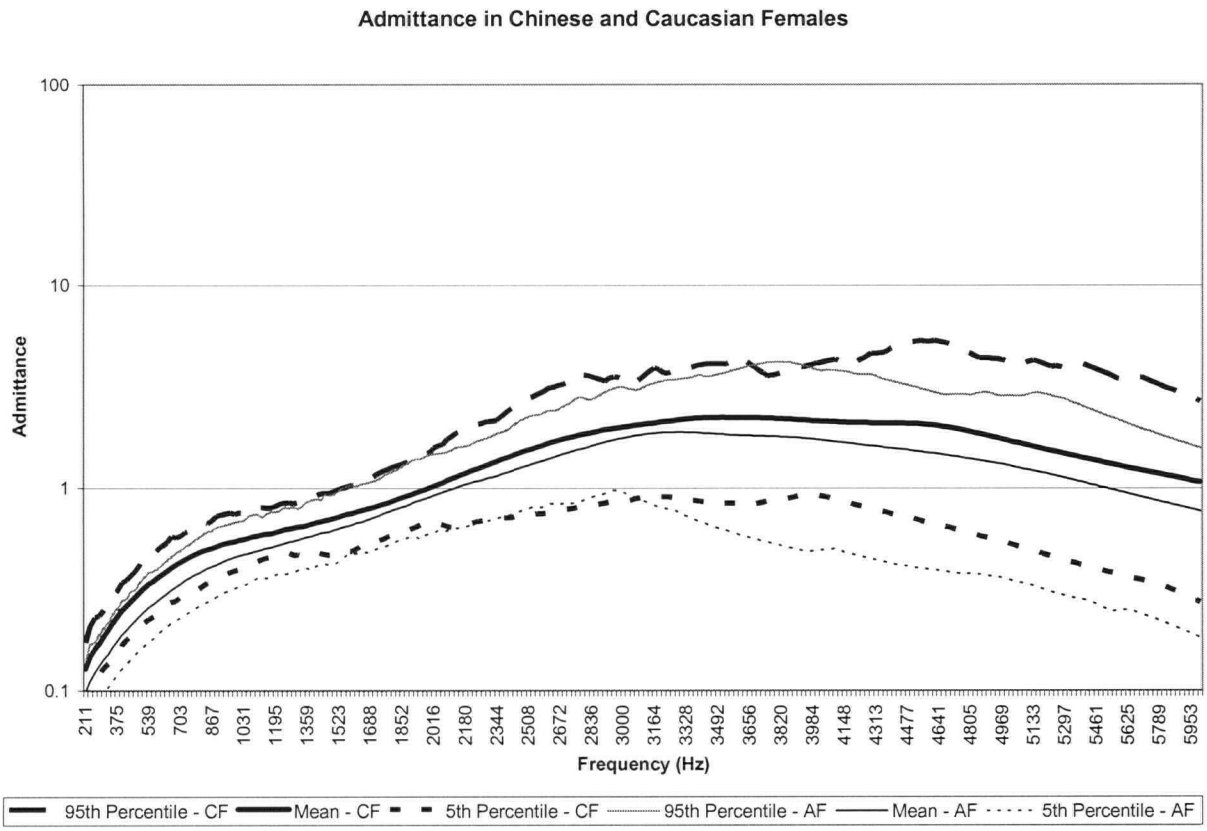

Figure 4.9: Admittance as a function of frequency comparing normative data from Chinese and Caucasian females. AF refers to Chinese females; CF refers to Caucasian females. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.2.4 Discussion of admittance results

For Y, repeated measures ANOVA confirmed gender differences within the Caucasian race; however, analysis did not confirm gender differences within the Chinese race. Statistical analysis confirmed racial differences within each gender. This is supported by 95% CI plots with Caucasian and Chinese subjects separated across some frequencies for both males and females. There is no doubt that for Y, race specific normative values should be used. Gender specific normative data are suggested for Caucasians. In general, Y data supports the concept of

greater efficiency of the middle ear system in low frequencies for Caucasians over Chinese and Caucasian males over Caucasian females.

4.3 Susceptance

4.3.1 Procedure

Susceptance was chosen as a measure as it was thought that it would be most comparable to tympanometric susceptance. Once testing was completed, data were saved and the susceptance values were exported to a spreadsheet where further analysis took place. As susceptance is one of the elements of admittance, it is also in normalized units; hence, susceptance is dimensionless (section 3.5.3).

4.3.2 Between gender and race statistical analysis

Exploratory box-plots of within subject effect of level of frequency showed a symmetrical empirical distribution of the data for the variable B. Five outliers were noted and excluded. No transformation of the data was required.

Table A8 (Appendix V) shows the results of the repeated measures ANOVA regarding the parameter of B. As for the previous analysis, the between subject factors are gender, race, and ear. The main effect of race was significant [$F(1, 235) = 17.27$, $p = .000$]. The effect of gender was significant [$F(1, 235) = 10.35$, $p = .001$], but the effect of ear was not significant [$F(1, 235) = 0.11$, $p = .918$]. The interaction effects were not significant.

The 95% CI plots for gender interaction with Caucasian males have higher values at frequencies at 1945-1992 Hz. Differences between 95% CI plots for Chinese by gender, with males having higher values, were at frequencies 4172 to 4383 Hz. These short segments of frequencies showed statistically significant differences by gender within races.

Between gender and race group analyses showed significant differences in means as given above [$F(1, 235) = 10.35$, $p = .001$]. The 95% CI plots for Caucasian and Chinese females

showed statistical differences from 211 to 867 Hz and from 3844 to 5203 Hz. This is seen graphically by a widening between means of Chinese and Caucasian females with Caucasians having higher scores. Repeated measures ANOVA did not find differences between races within male gender. No differences were found by ear.

4.3.3 Collected normative values

The 5th percentile curve for the race and gender graphs appeared irregular for frequencies from about 2500 to 6000 Hz. It is unlikely that smoothing would improve these curves. One possible explanation for these findings is the use of a logarithmic scale for the dependent variable.

4.3.3.1 Normative data comparing Chinese males and females

For frequencies to about 2500 Hz, male Chinese had higher 95th percentile and mean curves than females. For a mid-frequency range, 2800-3100 Hz, values were similar and again for high frequency males had higher values. For the lowest frequencies to about 750 Hz, Chinese males values were above females, however from about 750-1050 Hz males and females had similar scores. It is not possible to determine whether male or female Chinese scores were higher for the 5th percentile from 2500 Hz to 5000 Hz (Figure 4.10). However, as reported above, mean differences are highly significant with Chinese males having higher values than females. This suggests that the male middle ear system in less stiff than the female middle ear system. Physiological differences likely result in this decreased stiffness.

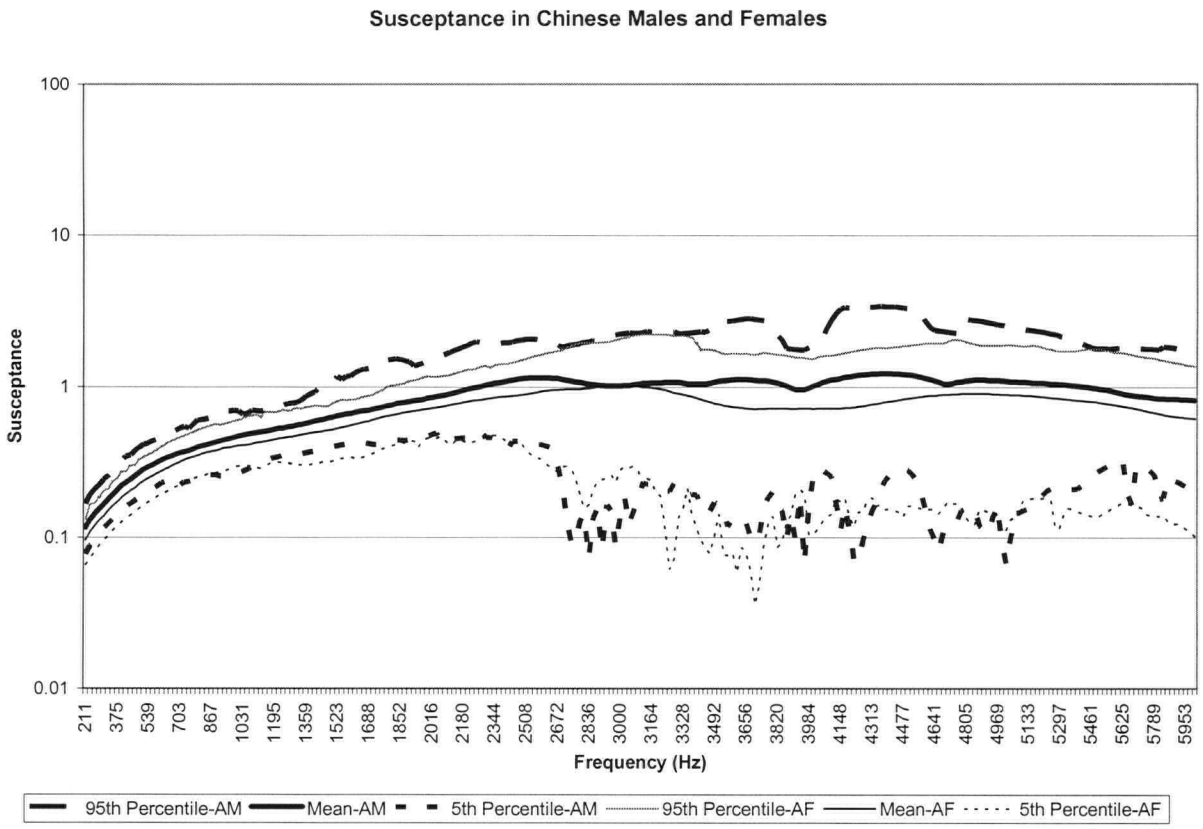

Figure 4.10: Susceptance as a function of frequency comparing normative data from Chinese males and females. AM refers to Chinese males; AF refers to Chinese females. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.3.3.2 Normative data comparing Caucasian males and females

As seen in Figure 4.11, for the 95th percentiles and mean curves, Caucasian male values exceeded female values throughout the low frequencies and up to about 5000 Hz. Values were similar in higher frequencies. For the lower range cutoff, male values appeared above female until 700 Hz. Although this 5th percentile curve was irregular from about 2100- 5000 Hz, male values appeared higher than female.

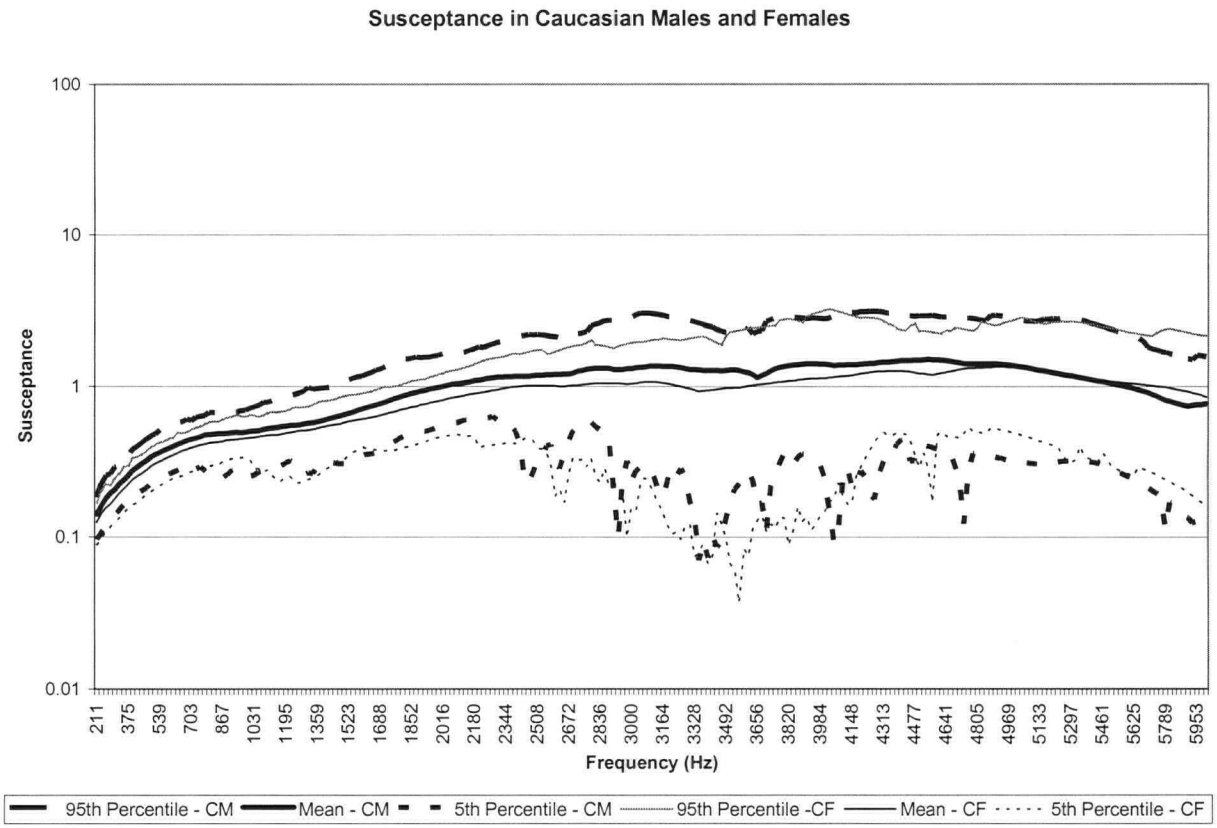

Figure 4.11: Susceptance as a function of frequency comparing normative data from Caucasian males and females. CM refers to Caucasian males; CF refers to Caucasian females. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.3.3.3 Normative data comparing Chinese and Caucasian males

Figure 4.12 displays data for males, comparing Chinese and Caucasian values. In general, the 95th percentile scores overlapped. There were minor differences in mid-frequencies with Caucasian males having higher values. For the lowest frequencies up to 800 Hz, Caucasian males had higher values than Chinese. From about 2000 Hz, Caucasian males had higher values on the 5th percentile curve than Chinese, dropping below Chinese by about 4500 Hz.

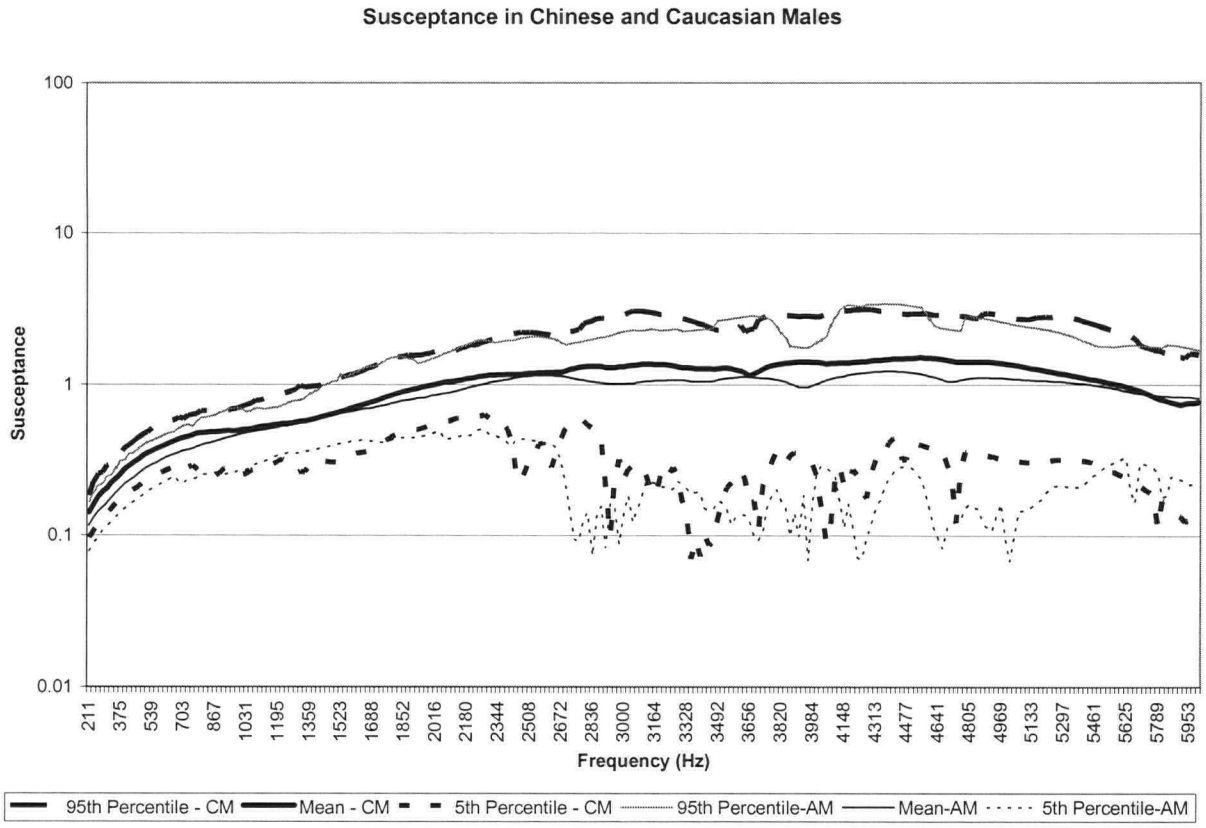

Figure 4.12: Susceptance as a function of frequency comparing normative data from Chinese and Caucasian males. AM refers to Chinese males; CM refers to Caucasian males. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.3.3.4 Normative data comparing Chinese and Caucasian females

The pattern shown in Figure 4.13 is similar to that of Figure 4.12. Caucasian and Chinese females had similar mean and 95th percentile scores for frequencies below about 3200 Hz. At higher frequencies Caucasian females had higher scores. For frequencies below about 900 Hz Caucasian females had values higher than Chinese females. At frequencies from about 2500-5500 Hz, Caucasian females had values above Chinese females. These differences are likely due to the size of the middle ear cavity with smaller middle ears promoting more

reflectance; hence, the middle ear of Chinese females is stiffer. At higher frequencies, the Caucasian mean values were statistically significant, above those of the Chinese females.

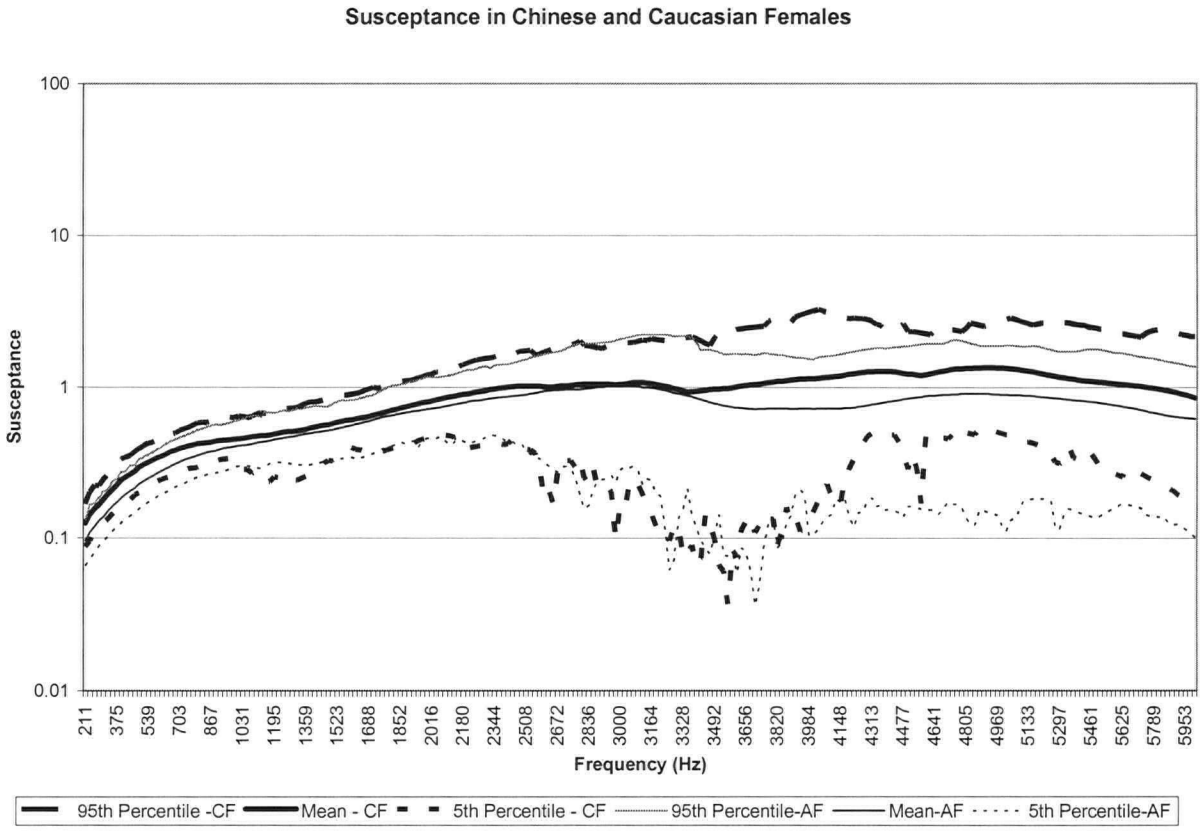

Figure 4.13: Susceptance as a function of frequency comparing normative data from Chinese and Caucasian females. AF refers to Chinese females; CF refers to Caucasian females. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.3.4 Discussion of susceptance results

The data for susceptance varies from that expected along the 5th percentile curve. This curve is highly irregular after about 2500 Hz. It should be noted that when individual normal subjects were graphed, they had a deep dip or reverse spike within this frequency range. This increased irregularity may reflect more variation at the lower cutoff. There are sufficient differences in the mean and 95th percentile curves to suggest that gender and race specific

normative data curves should be established for B. However, the variation of the 5th percentile B values over 2500 Hz would make cutoff level determination difficult.

Statistical analysis showed significant differences between means for Caucasian and Chinese females in both lower and higher frequencies with the Caucasians having higher values. This low frequency difference suggests less stiffness among Caucasian females compared with Chinese, thus greater efficiency. The findings for Caucasians compared with Chinese males are similar, but without reaching statistical significance. The smaller middle ear of Chinese, whether male or female, may give smaller volume which then increases stiffness. This is similar to the increased stiffness and reduced percentage of PA in Caucasians compared with Chinese already described. The annular ligament may also impose stiffness in the lower frequencies.

4.4 Conductance

4.4.1 Procedure

Conductance, as with admittance and susceptance, was chosen as a measure as it was thought that it would be most comparable to its tympanometric equivalent. Once testing was completed, data were saved and the conductance component was exported to a spreadsheet where further analysis took place. For further information, please refer to section 3.5.3. Conductance, as it is an element of admittance, is dimensionless due to Mimosa Acoustic's normalization procedure. Unfortunately, until further research can be done, these dimensionless variables cannot be compared with tympanometric values.

4.4.2 Between gender and race statistical analysis

Exploratory box-plots of the within subject effect of level of frequency showed the empirical distribution of data to be symmetrical except for three observations on two subjects, thus classed as outliers.

With respect to differences between means for the between subject effect for gender, race, and ear, a repeated measures ANOVA was performed. Results were summarized in Table A9 (Appendix V). The effect of race was not significant [$F(1, 237) = 2.58$, $p = .110$]; gender effect was significant [$F(1, 237) = 4.23$, $p = .041$]. There was no significant ear effect. Race-gender interaction was significant [$F(1, 237) = 5.79$, $p = .017$]. No other interactions were significant.

To find out the frequencies where the males and females differed within races, 95% CI plots for each frequency were explored. For the Caucasian race, mean gender differences were found at 2016 to 2297 Hz with males having higher values. There were no differences between males and females among Chinese. In 95% CI plots, Caucasian females had a higher mean value than Chinese females shown at frequencies 422-1758 Hz. This difference in means is seen in Figure 4.15. Caucasian males had higher mean values than Chinese male values as seen in 95% CI plots for frequencies 539 to 1430 Hz, 2063-2250 Hz, and 5227-6000 Hz. This is reflected in Figure 4.16. There were no significant ear effects found.

4.4.3 Collected normative values

4.4.3.1 Normative data comparing Chinese males and females

As seen in Figure 4.14, Chinese males had higher cutoff levels and higher mean values than females on conductance. Given the consistency across frequencies of males having higher conductance values than females, anatomical considerations may be contributing to the observed difference. On average, males have a larger ear canal cavity and middle ear space (Huang, et al. 2000); thus, resistance is less and conductance is higher. It is important to note that conductance is somewhat different from resistance as conductance is the product of both reactance and resistance.

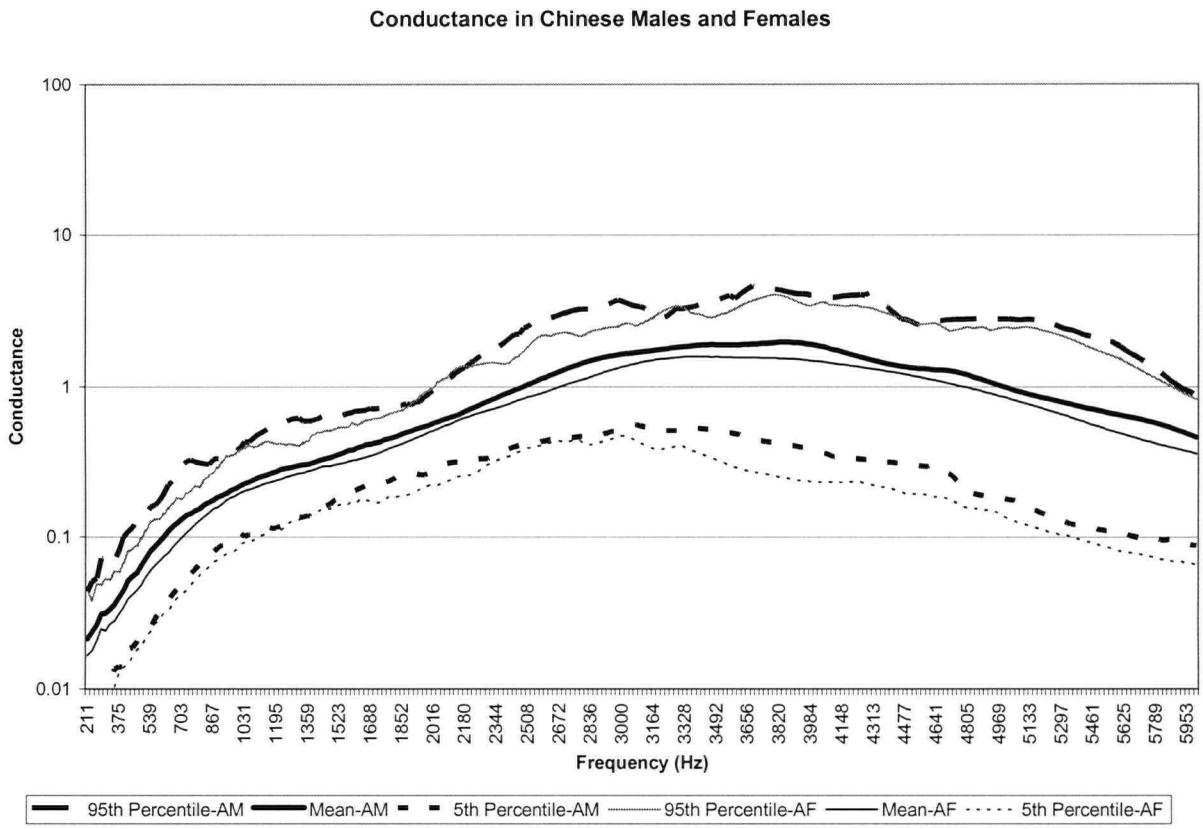

Figure 4.14: Conductance as a function of frequency comparing normative data from Chinese males and females. AM refers to Chinese males; AF refers to Chinese females. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.4.3.2 Normative data comparing Caucasian males and females

As seen in Figure 4.15, males had higher values than females for the 95th percentiles for all frequencies up to about 4350 Hz, values then dropped well below female values. By 6000 Hz, male and female mean values were the same as each other and the same as the 95th percentile for males. Mean scores for males exceeded females from about 3800 Hz and below, then dropped below mean values for females. The 90% range was much greater at higher than lower frequencies for females. For the 5th percentile curve, males and females had similar values to about 2400 Hz, then males dropped below females until about 4800 Hz.

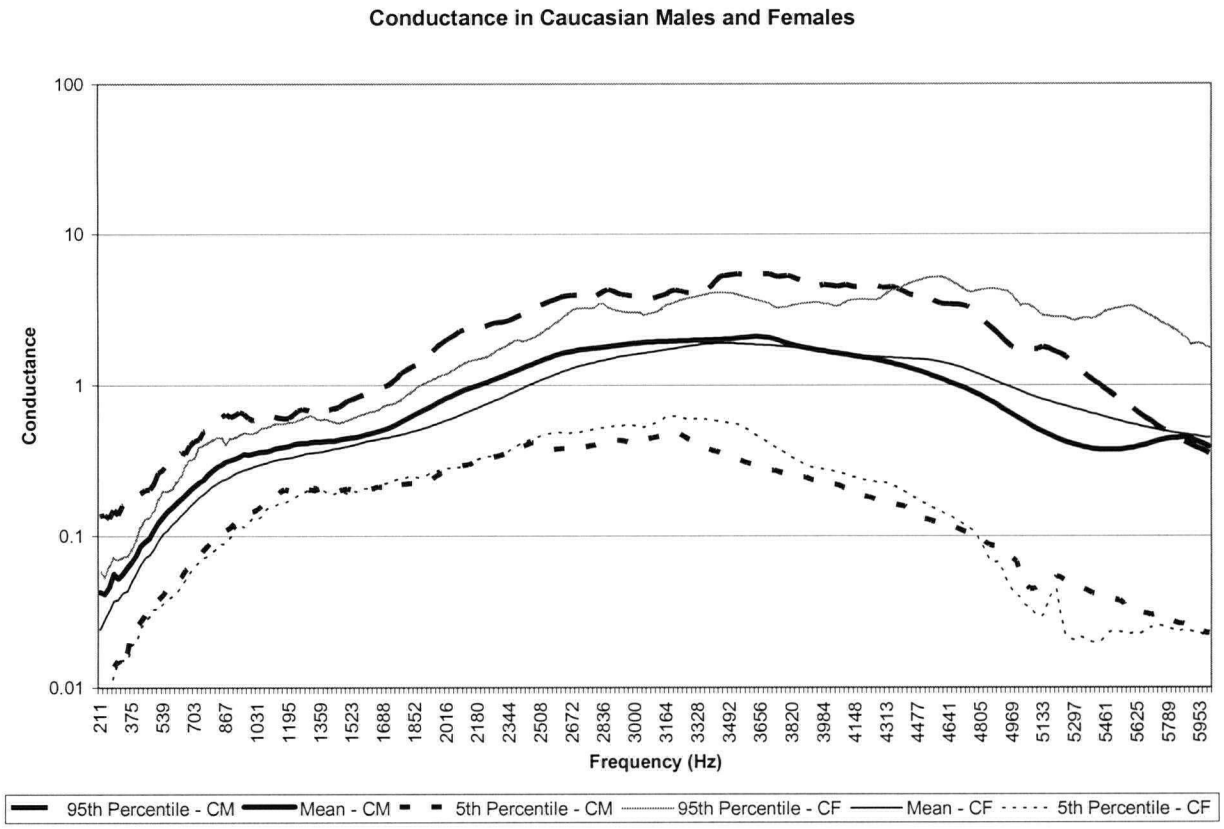

Figure 4.15: Conductance as a function of frequency comparing normative data from Caucasian males and females. CM refers to Caucasian males; CF refers to Caucasian females. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.4.3.3 Normative data comparing Chinese and Caucasian males

Figure 4.16 shows significant shifts with the 90% range being smaller in lower frequencies compared with higher frequencies. In lower frequencies to about 1600 Hz male values for mean, 5th and 95th percentile for Caucasians exceeded Chinese. For frequencies less than 900 Hz, the mean for Caucasian males was approximately the same as the 95th percentile for Chinese males. For the 5th percentile curve, Caucasian males had higher values than Chinese males until about 1600 Hz. By about 3200 Hz the 5th percentile values for the

Caucasian males dropped well below Chinese. Indeed, the 95th percentile for Caucasian males approached the mean and the 5th percentile values dropped greatly.

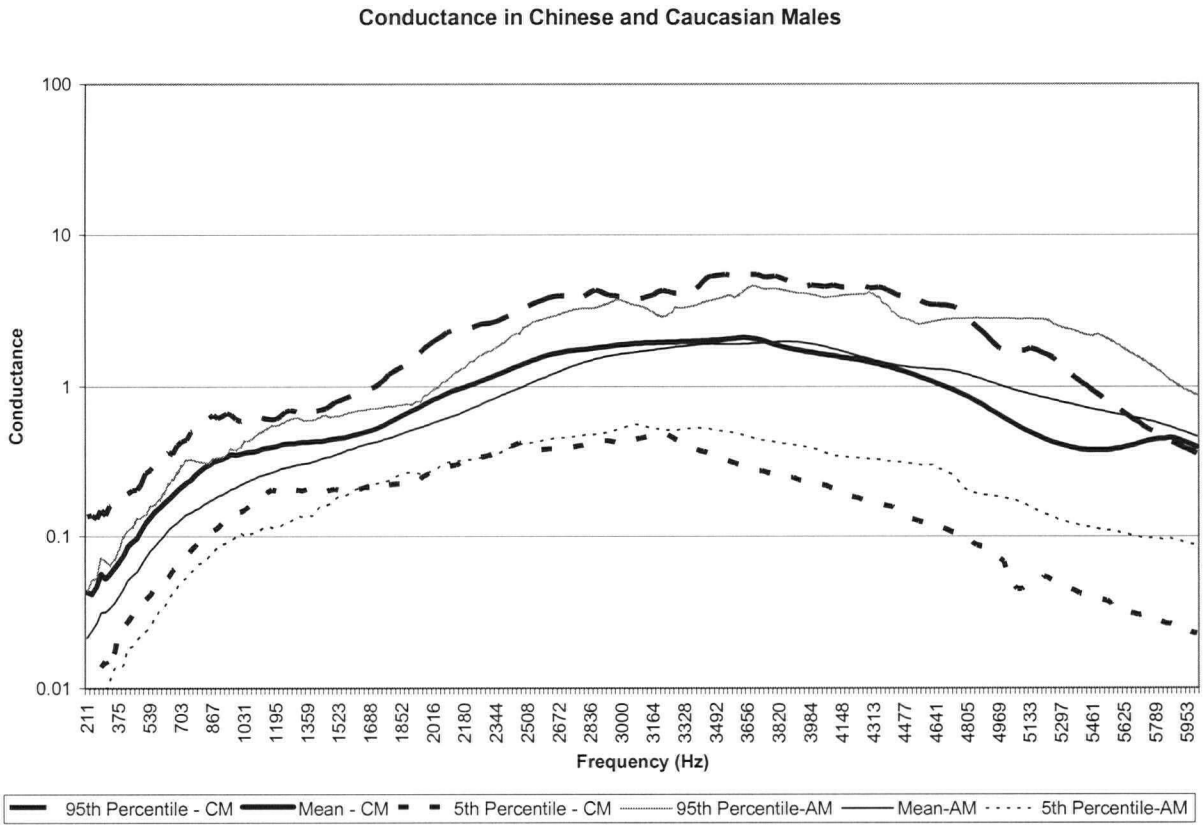

Figure 4.16: Conductance as a function of frequency comparing normative data from Chinese and Caucasian males. AM refers to Chinese males; CM refers to Caucasian males. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.4.3.4 Normative data comparing Chinese and Caucasian females

Figure 4.17 shows a pattern similar to that of Figure 4.16, in the lower frequencies. That is, as for males, female values showed the mean of Caucasians approximating the 95th percentile for Chinese. The 5th percentile for Caucasian females was significantly above that of Chinese until about 4300 Hz. As for males, the 5th percentile curve for Caucasian females dropped below the Chinese values in higher frequencies.

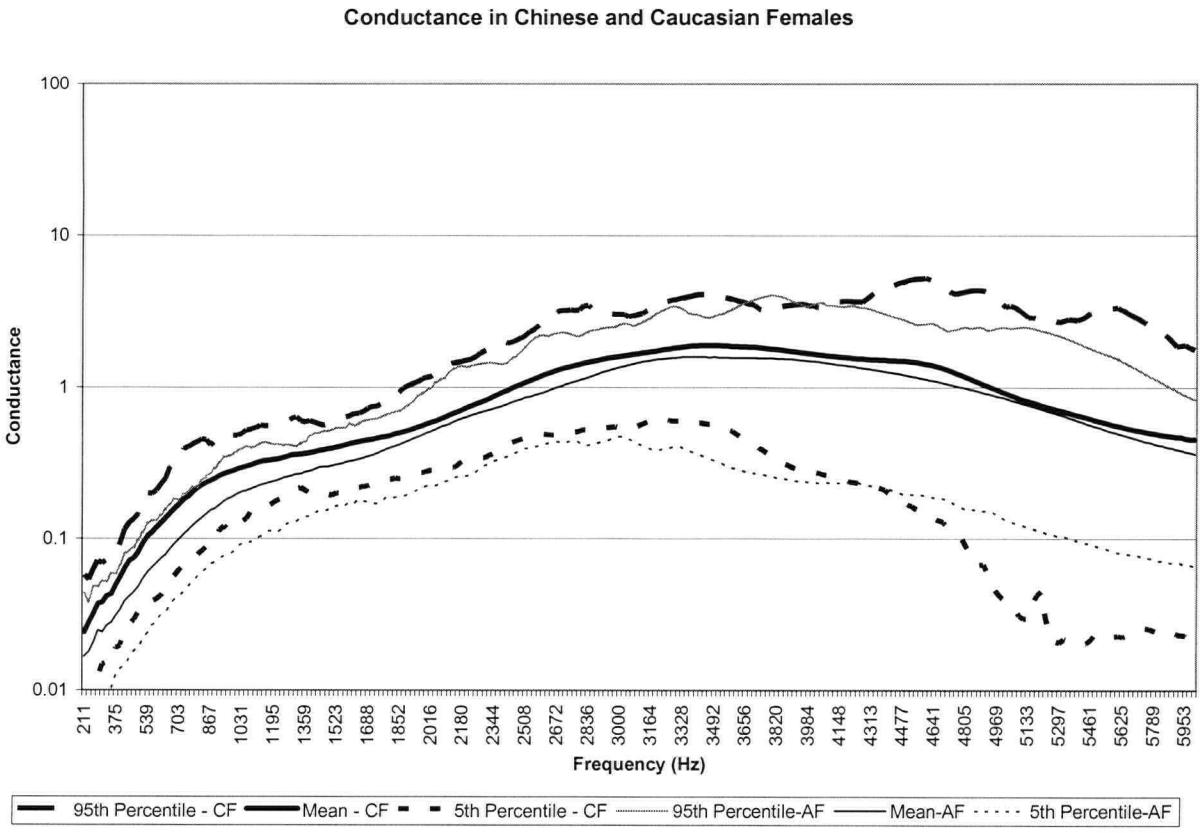

Figure 4.17: Conductance as a function of frequency comparing normative data from Chinese and Caucasian females. AF refers to Chinese females; CF refers to Caucasian females. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.4.4 Discussion of conductance results

Repeated measures ANOVA found no difference between means for Chinese males and females. Racial differences between means were not confirmed by the repeated measures ANOVA. However, 95% CI plots did confirm short segment differences between races for both genders. Visual inspection confirmed a wide spread between means at the lower frequencies between Chinese and Caucasian groups for both genders (Figure 4.16 and 4.17).

Throughout the G data of Caucasian subjects there appears to be an unusual drop of the 5th percentile scores away from mean scores beginning in the mid-frequencies and continuing through the high frequencies. The curves generated with Chinese male and female data showed a slight widening of 90% range in higher frequencies over that of lower frequencies. The approximation of the 95th percentile of values to mean values for Caucasian males remains unexplained (Figure 4.15 and 4.16).

The statistical analysis did not confirm mean race differences within G. Only a few differences were seen in small frequency segments suggesting less mean resistance for the Caucasian middle ear. There is greater evidence for less mean resistance of the male middle ear among Caucasians at least in the range of 2016-2297 Hz. This was not noted for Chinese. However, although statistical differences for G reflected only a trend, observations of the 90% range were very informative. These cutoff curves suggest Chinese males had less resistance than females at all frequencies. Caucasian females had less resistance at higher frequencies than males, but this reversed at low frequencies. Caucasian males had less resistance at low frequencies than Chinese and this was reversed at higher frequencies. The findings were similar for Caucasian females over Chinese in the lower frequencies; this was reversed at higher frequencies.

4.5 Summary of results

Repeated measures ANOVA results and visual inspection of graphic results for determined gender and race differences are summarized in Table 4.1 below. From graphically determined cutoff levels for low frequencies, it can be seen that both males and Caucasians have larger values. One likely reason for this finding is the anatomical variations among these groups. As previously mentioned, Huang, et al. (2000) noted that the size of middle ear structures in

animals is closely associated to body size. This study supports their findings. High frequency findings show much less consistency and deserve further study.

Comparison groups	Variable	Statistical differences in means (p-value)	Graphically Determined Cutoff Level: Low Frequency 95th Percentile	Low Frequency 5th Percentile	High Frequency 95th Percentile	High Frequency 5th Percentile
Within race Chinese: Male vs. Female	PA	NS	M > F	M ~ F	F > M, M > F (>5000 Hz)	F > M
	Y	NS	M > F	M > F	M > F	M > F
	B	.001	M > F	M > F	M > F	M > F
	G	NS	M > F	M > F	M > F	M > F
Within race Caucasian: Male vs. Female	PA	NS	M > F	M > F	F > M	F > M, M > F (>4800 Hz)
	Y	.032	M > F	M > F	F > M	F > M
	B	.001	M > F	M > F	M ~ F	M > F (2500-4000 Hz), F > M (>4000 Hz)
	G	.041	M > F	M ~ F	M > F, F > M (>4300 Hz)	F > M, M > F (>4800 Hz)
Between race male: Chinese vs. Caucasian	PA	.001	C > A	C > A	A > C	A > C
	Y	.000	C > A	C > A	C > A, A > C (>5500 Hz)	A ~ C, A > C (>5100 Hz)
	B	NS	C > A	C > A	C > A	C > A
	G	NS	C > A	C > A	A > C	A > C
Between race female: Chinese vs. Caucasian	PA	.001	C > A	C > A	A > C	A > C
	Y	.000	C > A	C > A	C > A	C > A
	B	.000	C > A	C > A	C > A	C > A
	G	NS	C > A	C > A	C > A	A > C

Table 4.1: Statistical and visual findings for within and between race comparisons for power absorption (PA), admittance (Y), susceptance (B), and conductance (G). Low frequency cutoff = 1500 Hz; High frequency cutoff = 4000 Hz; NS = Not significant; M = Male; F = Female; C = Caucasian; A = Chinese. An alpha level of .05 was used for all statistical tests.

4.6 Discussion of normative data

Both statistical analyses and graphic presentation of data are needed to determine differences within race and gender groups for WBR normative data. The repeated measures ANOVA and 95% CI plots assessed differences for the four variables. The plotted 5th and 95th percentile curves allowed determination of cutoffs as is needed clinically. Within limits, the greater the sample size, the more accurate these percentile curves should become.

The data as graphically displayed demonstrates the need for gender and race specific normative data. Throughout the four variables of the WBR measures there were few occasions where the mean, 5th or 95th percentile curves overlap for gender or race. Most of the curves share separations. The separations that were not statistically significant are the data from Chinese males and females for PA, Y, and G; Caucasian males and females for PA; and Chinese and Caucasian males for B. The mean differences for G between Chinese and Caucasians did not show a significant race effect. Moreover, 95% CI plots did not overlap at a number of frequencies for both males and females, thus, there were segmental level of frequency differences. However, for the rest, statistical differences occurred between males and females and between Chinese and Caucasian subjects. Regardless of the statistical results, where there were differences between the lower and upper margins of the 90% range, cutoff levels would be affected and this could have clinical consequences. Values beyond the 90% range are considered abnormal and serve to distinguish normal from diseased ears. It is a common practice to use the 90% range to define the lowest and highest cutoffs for clinical purposes. However, it is recognized that a few normal subjects could have values below the 5th percentile or above the 95th percentile.

There are at least two possible reasons for the differences in males and females, and Chinese and Caucasian subjects. First, mechano-acoustical properties may account for these

disparities. It was shown, for instance, using PA, that Caucasian middle ears were more efficient in the lower frequencies than Chinese middle ears. This finding may be due to differences in properties of the middle ear between the two races. The second alternative, as previously discussed, are anatomical variations.

As gender and race specific curves have been shown to be necessary, the number of subjects available to create these specific curves is lower than with combined data. Future research comparing race and gender specific normative values to middle ear pathologies encompassing from low to high impedance will determine whether using race and gender specific normative data can improve the overall test performance.

The present data show similarities to previous tympanometric data. For admittance, this data found no difference in means for Chinese females and males. Similarly for SA, Shahnaz and Davies (2004) and Wan and Wong (2002) found no differences in means; however, differences within the 90% range were reported by Shahnaz and Davies (2004), but not by Wan and Wong (2002). The present study also suggests lack of difference of means by gender among Chinese for admittance. Differences by gender within Caucasian groups were noted by Shahnaz and Davies (2004) and are found in this study. With regard to RF, Shahnaz and Davies (2004) found no gender effects within the race groups; however, for F45°, there was a gender effect within the Chinese group. Although a direct parallel cannot be drawn, in this study the gender effect within the Chinese group was present for B and not present for G. For this study there were gender effects within the Caucasian group for Y, B, and G, but not for PA.

From visual inspection of the curves, the pattern of PA is similar to Voss and Allen normative values included in the WBR machine by Mimosa Acoustics. Comparing the curves to the reciprocal ER curve of Feeney and Sanford (2004) has been disappointing, particularly in the lower frequencies where the mean of the present study approaches the 95th percentile of that of

Feeney and Sanford. This may be related to the use of different machines, calibration, unit presentation, or ear canal compensation. Credible cutoff levels cannot be established for general clinical use unless these levels become more similar. There are no normative data curves for comparison with the Y, B, and G curves of this study.

The differences found in this study attributed to gender and race for the WBR measures are likely due, in part, to variations in ear canal and middle ear volume. Keefe, et al. (2003) discussed the effect ear canal volume had on ER measurements and explored curve estimates to account for these differences. Another approach to improve WBR measurements would be establishing actual individual measurements of ear canal volume. A possible method for measuring ear canal size would be to place distilled water in the ear canal to measure its volume. Obviously, there are concerns with regard to this method, including additional time and patient discomfort. Another alternative would be to measure real ear to coupler differences and then compensate for the specific size of the ear canal. This method could theoretically be incorporated into the Mimosa machine and be used to calculate the characteristic impedance automatically for each individual. This would be extremely beneficial in decreasing the amount of error when testing.

4.7 Case histories of patients with otosclerosis

In order to investigate the clinical utility of WBR, seven otosclerotic patients who have been scheduled for surgery were tested. Each case history of an otosclerosisis patient is presented with the accompanying WBR graphic data followed by a general interpretation and discussion. The variable of PA was chosen to compare the otosclerotic subjects with above normative data. Admittance, susceptance, and conductance were chosen as variables as they can be most comparable to tympanometric measures.

4.7.1 Case history of an otosclerotic male: OM1

This 56-year-old Caucasian male patient had a five-year history of hearing loss in his left ear. A family history of unilateral hearing loss was noted on the maternal side. OM1 had no memory of middle ear infections. No history of tinnitus or vestibular symptoms was found; a history of noise exposure was noted. No evidence of eardrum abnormality was observed through otoscopy. A hearing aid was worn on the left ear, but is no longer of benefit to the patient. Audiometry results showed a severe-to-profound mixed hearing loss with a large conductive component in the low frequencies as seen in Figure 4.18. TEOAEs were found to be absent from 1000 to 4000 Hz in the surgical ear. Standard tympanometry results showed a SA of 0.3 mmhos, at the lower limit of the 90% range of normative data; and a TW of 89.3 daPa which was within normal limits. Multi-frequency tympanometry results showed that F45° was at 1000 Hz, while RF was 1250 and 1400 Hz for positive and negative compensations, respectively; these results were at or above the 95th percentile of normative data. Wideband reflectance results were separated into the four variables measured and deviations from the 90% range values were estimated from the graphs. Figure 4.19 shows results from the PA variable in relation to normal hearing Caucasian males. Deviations from the normal cutoff values occurred. Between 398-1219 Hz, PA results were below the 5th percentile; between 1594-1875 Hz and 2320-2859 Hz, PA results were above the 95th percentile. These low frequency results suggest decreased percent of PA with less efficiency and increased stiffness of the middle ear system (Figure 4.19). This result is comparable to that found by Feeney, et al. (2003) in subjects with otosclerosis and supports the diagnosis of otosclerosis. One possible explanation of these results in the lower frequencies could be an increase in the imposed stiffness of the annular ligament. Results from Y are shown in Figure 4.20 and are seen to extend below the normative cutoff values from 211-750 Hz. This suggests that there is more opposition to energy entering the

middle ear in this patient than in normal male subjects at these frequencies. Figure 4.21 depicts OM1's variation from normative values when using the measure of B. The frequencies of 211-586 Hz, 1711-2273 Hz, and 3820-3914 Hz are all below the 5th percentile. These findings of B suggest increased stiffness. Frequencies of between 305-1219 Hz were also below the 5th percentile for the G variable, as seen in Figure 4.22, suggesting increased resistance. Figure 4.22 suggests that G contributes more than B at low frequencies in differentiating otosclerotic ears which is consistent with the results of Shahnaz and Polka (2002). OM1 is scheduled for surgery. At this time his WBR results cannot be compared with surgical findings, but are compatible with his diagnosis of otosclerosis.

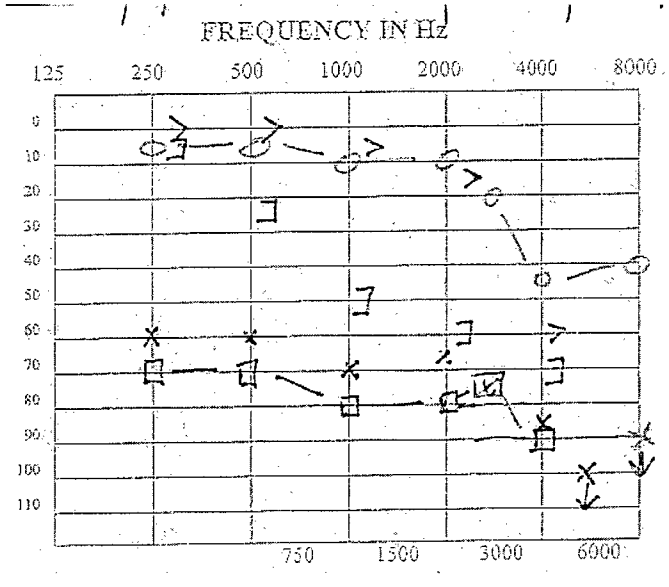

Figure 4.18: Pre-operative audiometric results of otosclerotic male OM1.

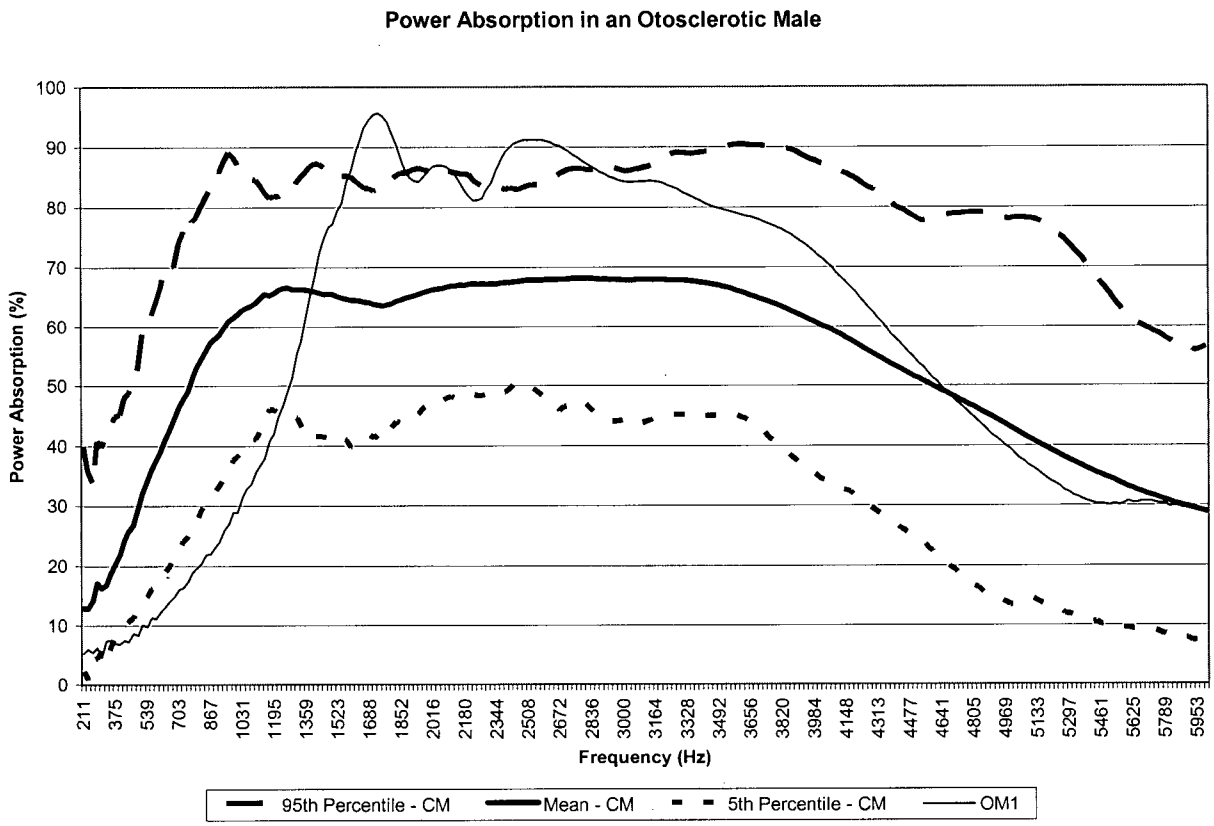

Figure 4.19: Power absorption as a function of frequency in otosclerotic male patient OM1. CM refers to Caucasian male.

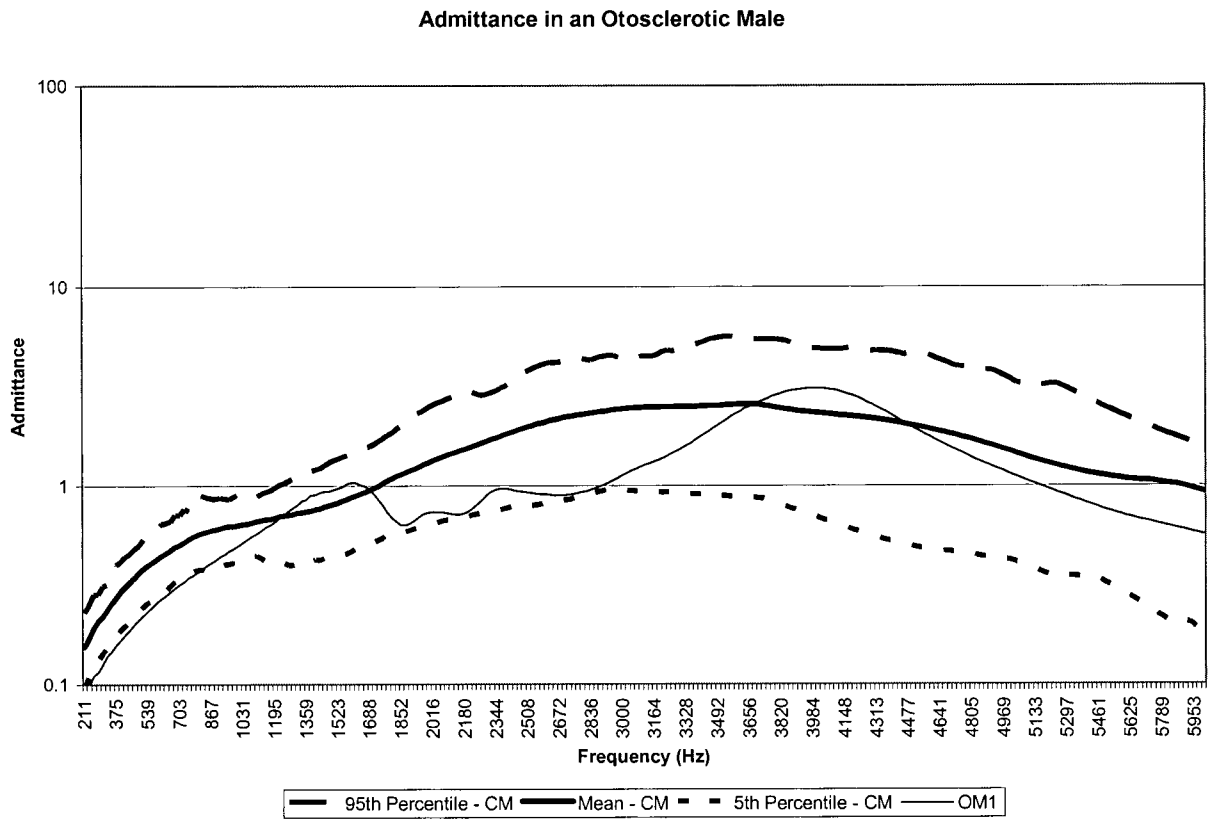

Figure 4.20: Admittance as a function of frequency in otosclerotic male OM1. CM refers to Caucasian male. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

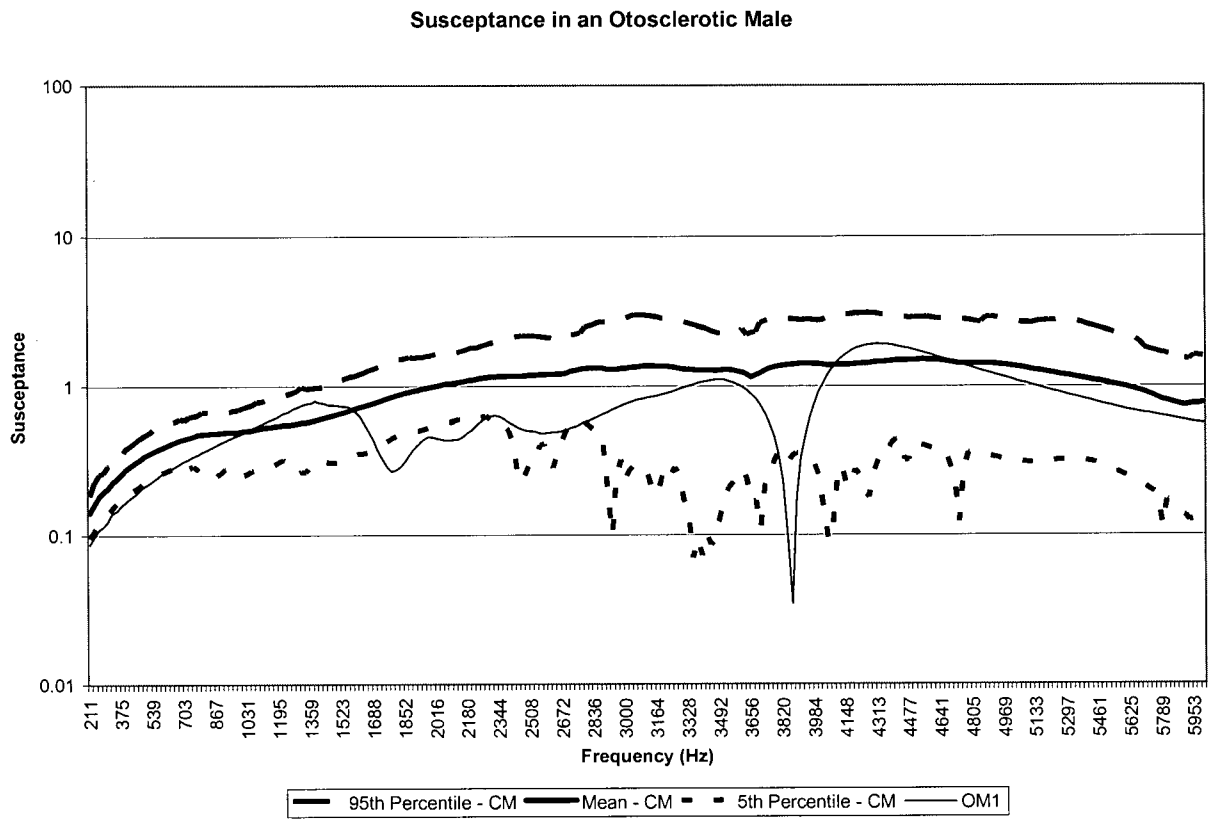

Figure 4.21: Susceptance as a function of frequency in otosclerotic male OM1. CM refers to Caucasian male. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

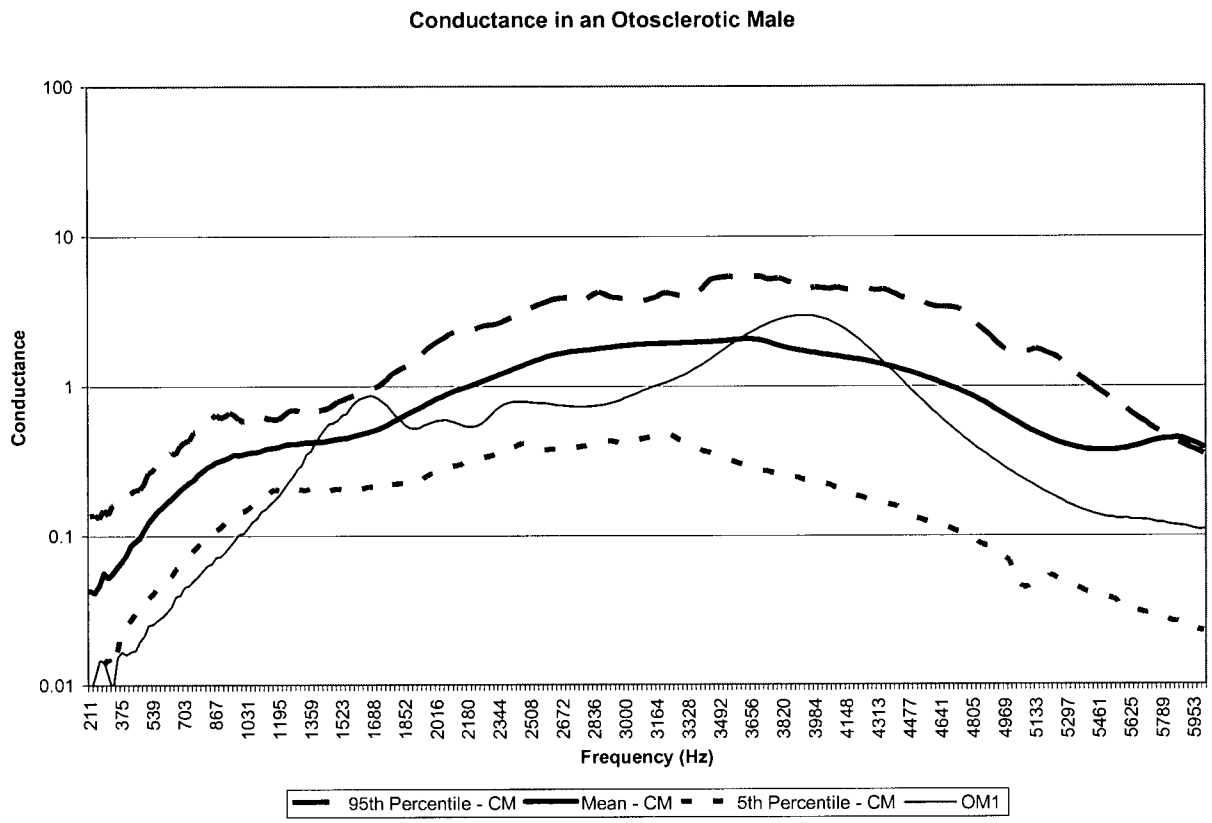

Figure 4.22: Conductance as a function of frequency in otosclerotic male OM1. CM refers to Caucasian male. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.7.2 Case history of an otosclerotic female: OF1

This 42-year-old Caucasian female had a history of left ear hearing loss beginning during her first pregnancy. Progression of this hearing loss had been gradual, progressing to involving a sensorineural component. A severe mixed hearing loss was present in the surgical ear. Carhart's notch was noted at 2000 Hz (Figure 4.23). There was no family history of hearing loss. A positive history of tinnitus was present in her left ear. There was no history of vestibular symptoms or middle ear infections. A hearing aid is worn only on the non-surgical side. Visual inspection of the eardrum through otoscopy revealed no abnormal findings. TEOAEs were found to be absent from 1000 to 4000 Hz in the surgical ear. Standard tympanometry showed a

SA of 0.6 mmhos and a TW of 98.7 daPa, both within normal range. Multi-frequency tympanometry revealed F45° to be 710 Hz, at the upper limits of normative values for females; while RF was 1000 and 1120 Hz for positive and negative compensations, respectively, and were within normal limits. Results for WBR are shown in Figures 4.24, 4.25, 4.26, and 4.27 below. For PA there was a deviation above of the 95th percentile of normal at frequencies between 2906 and 3492 Hz. This suggests an increase in middle ear efficiency in this frequency range. This is not consistent with Feeney, et al.'s (2003) findings in otosclerotic ears. The reason for this difference is unexplained. Perhaps surgical results may allow for a better understanding of the results. For B, a notch, or reversed spike complex, below the 5th percentile occurred for frequencies between 3961 to 4008 Hz. This deviation is a common occurrence throughout all subjects, both normal and otosclerotic. It is considered to represent the transition between a stiffness dominated middle ear system to a mass dominated middle ear system. For Y and G, results remained within the 90% range of normative values.

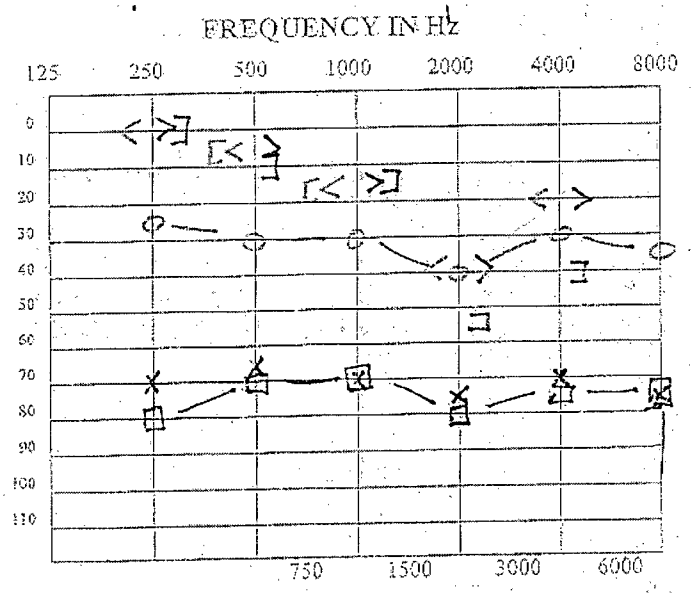

Figure 4.23: Pre-operative audiometric results of otosclerotic female OF1.

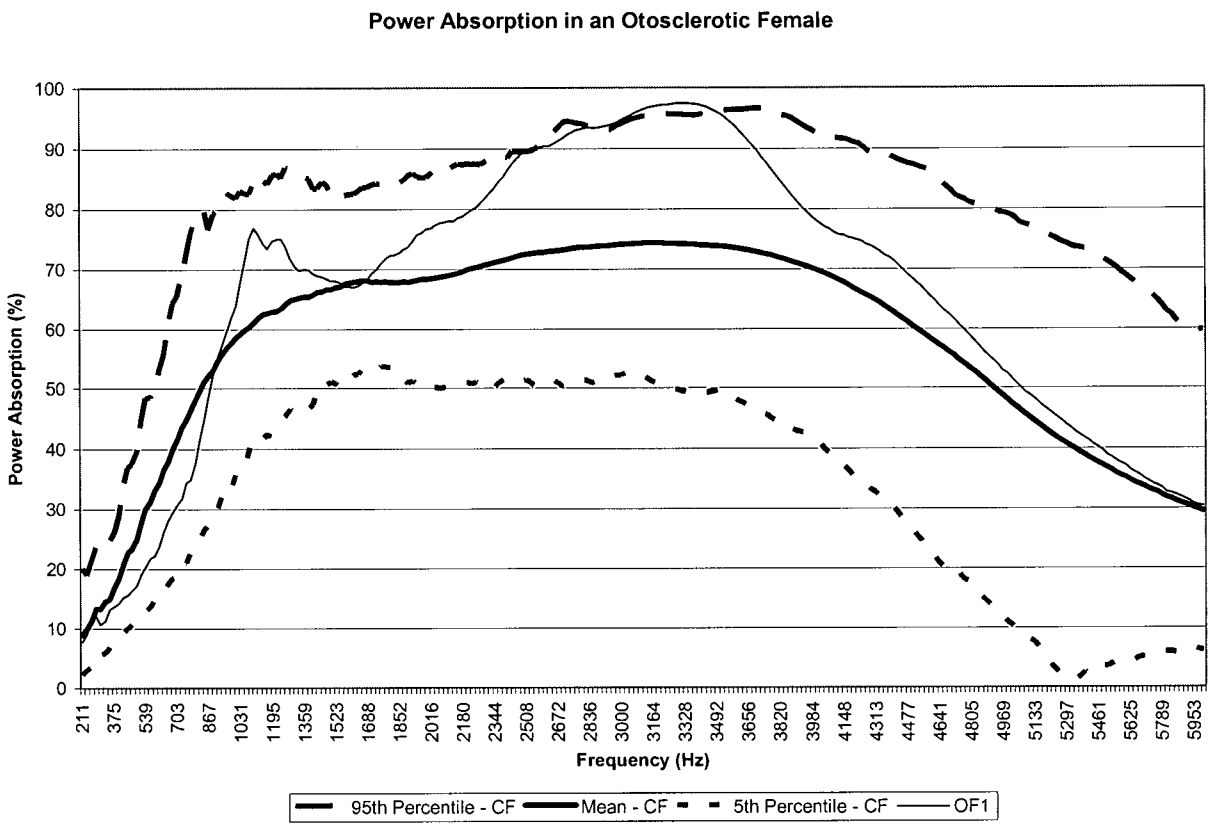

Figure 4.24: Power absorption as a function of frequency for otosclerotic female OF1. CF refers to Caucasian female.

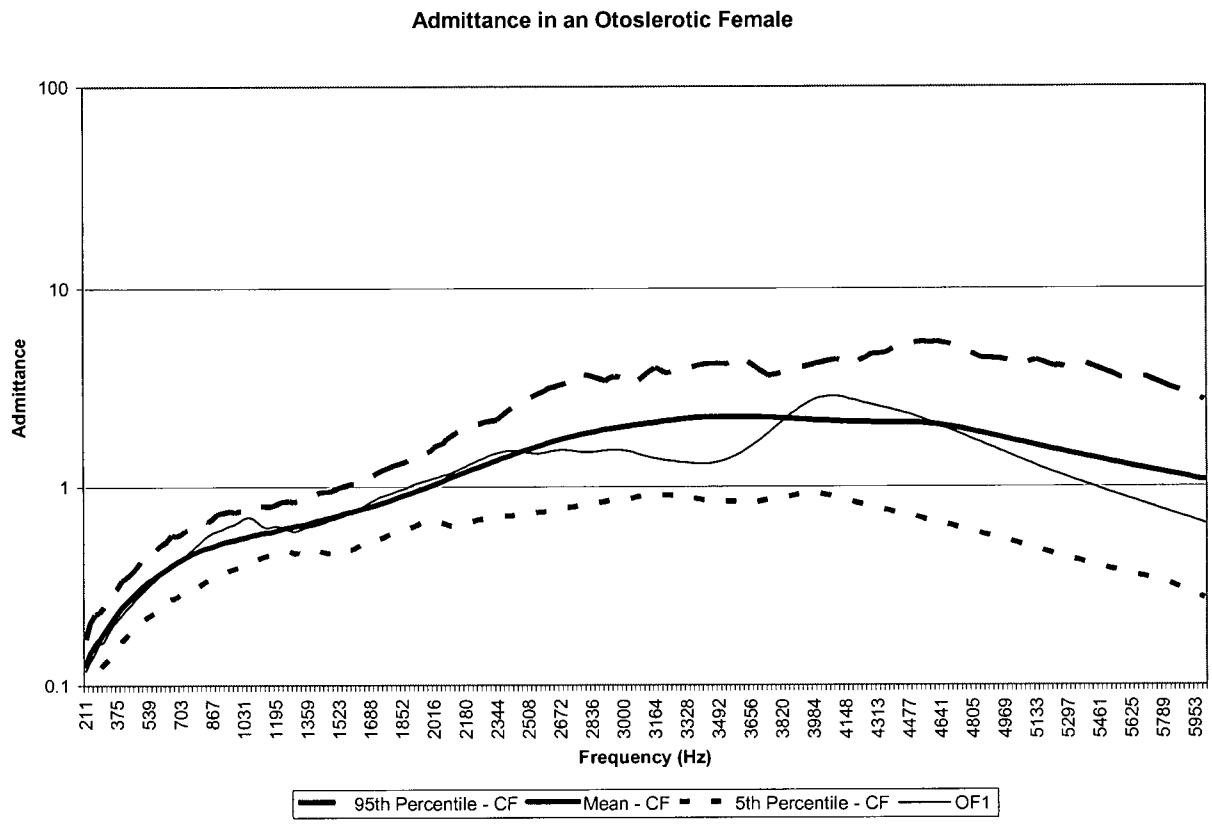

Figure 4.25: Admittance as a function of frequency for otosclerotic female OF1. CF refers to Caucasian female. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

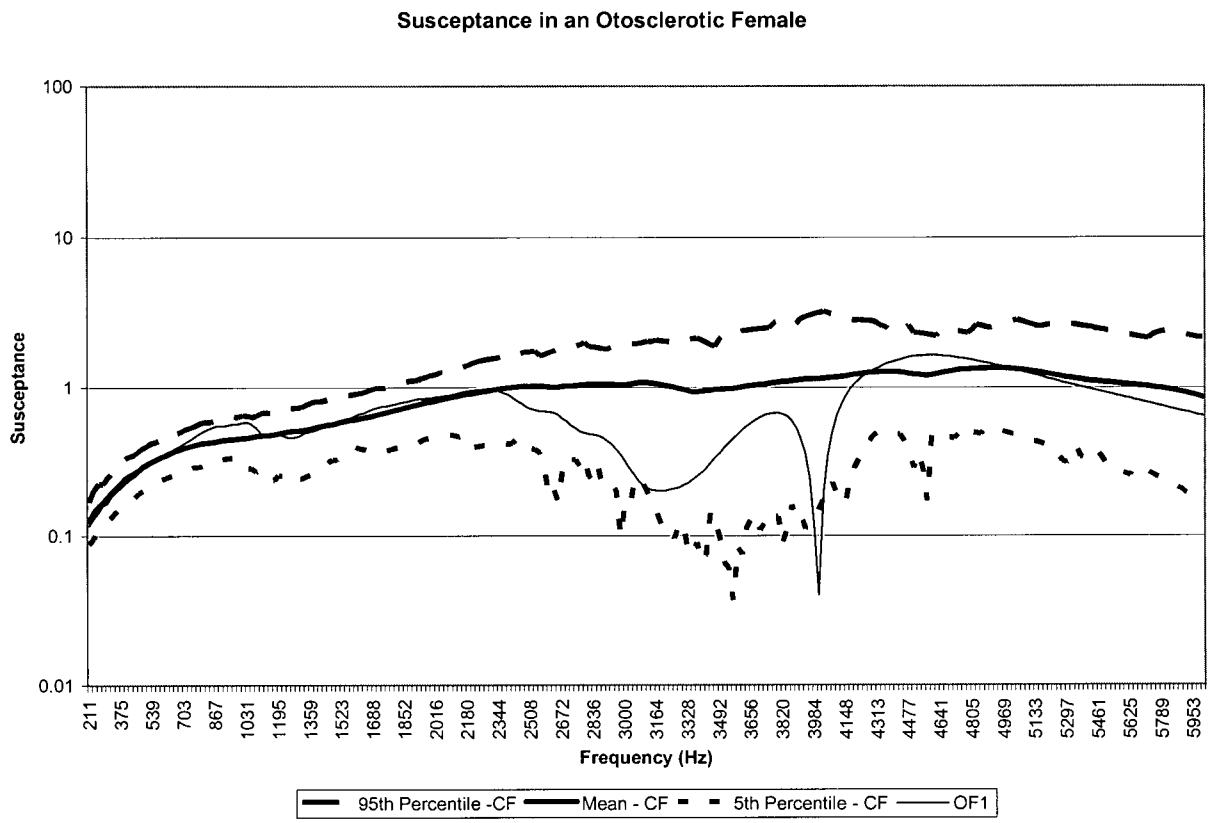

Figure 4.26: Susceptance as a function of frequency for otosclerotic female OF1. CF refers to Caucasian female. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

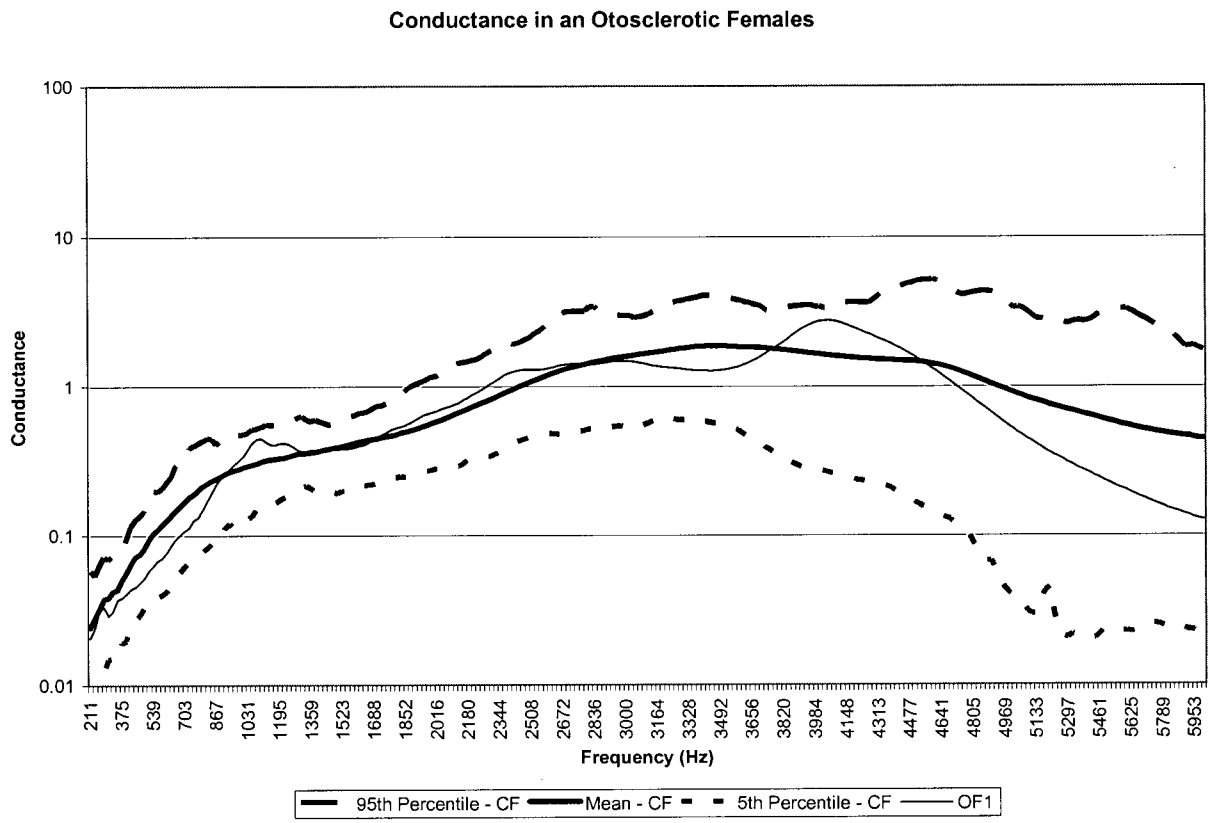

Figure 4.27: Conductance as a function of frequency for otosclerotic female OF1. CF refers to Caucasian female. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.7.3 Case history of an otosclerotic female: OF2

This 35-year-old Caucasian female had a seven-year history of hearing loss in her left ear. There was no family history of hearing loss. No history of tinnitus, vestibular symptoms, or middle ear infections was evident. No hearing aids were worn. Visual inspection, using otoscopy, revealed no abnormal findings. A left moderately severe sloping to profound mixed hearing loss was found as seen in Figure 4.28. TEOAEs were found to be absent from 1000 to 4000 Hz in the surgical ear. Standard tympanometry revealed a SA value of 1.3 mmhos, at the upper limits of normative of normative values, and a TW of 70.5 daPa was within normal limits.

Multi-frequency tympanometry revealed a F45° of 560 Hz and RF positive and negative compensation values of 800 and 900 Hz, respectively; all within normal limits. Wideband reflectance results can be compared with normative values in Figures 4.29, 4.30, 4.31, and 4.32. Power absorption values for OF2 were above the 95th percentile of the normative data for frequencies between 1219-1406 Hz, indicating increased middle ear efficiency in this frequency region. This does not correspond with Feeney, et al.'s (2003) findings. Admittance values for OF2 were all within the normative range of Caucasian females. Susceptance values were below the 5th percentile from 3070-3234 Hz displaying a typical reverse spike complex, while conductance values were above the 95th percentile from 1195-1336 Hz. Of note, for all of the variables OF2 had a slight sigmoidal shape between 1000-1500 Hz. This finding remains unexplained. Within the current limited knowledge of otosclerosis using WBR, these findings remain helpful in the diagnosis, i.e. even though OF2 had results for tympanometry tests within the normal limits, WBR results were abnormal.

A post-operative surgical report was obtained. OF2 had laser stapedotomy. A significant amount of bone was noted at surgery. A modified piston bucket prosthesis with vein graft was used. The diagnosis of left otosclerosis was confirmed. See Appendix II.

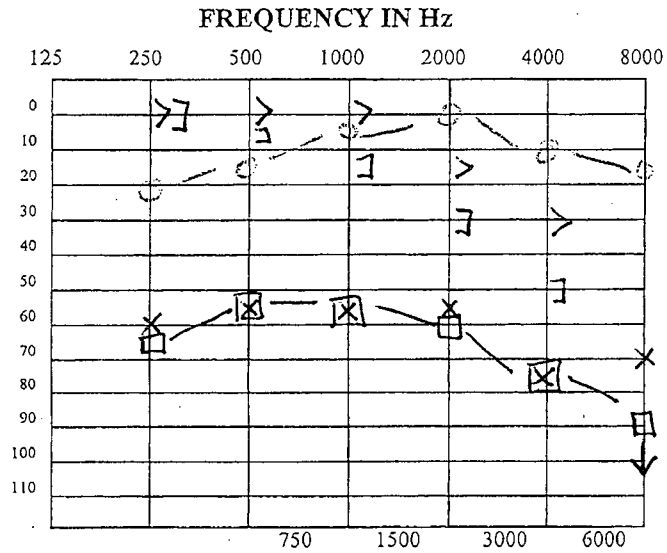

Figure 4.28: Pre-operative audiometric results of otosclerotic female OF2.

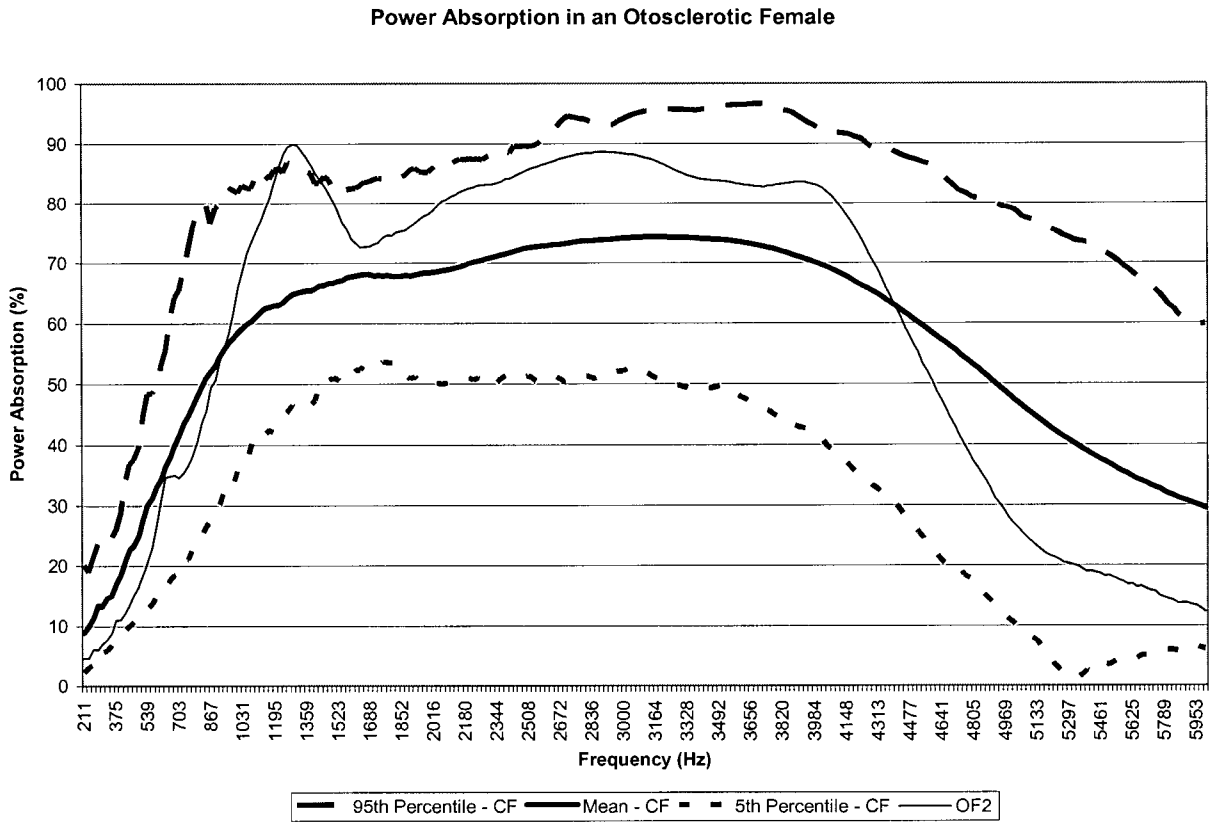

Figure 4.29: Power absorption as a function of frequency for otosclerotic female OF2. CF refers to Caucasian female.

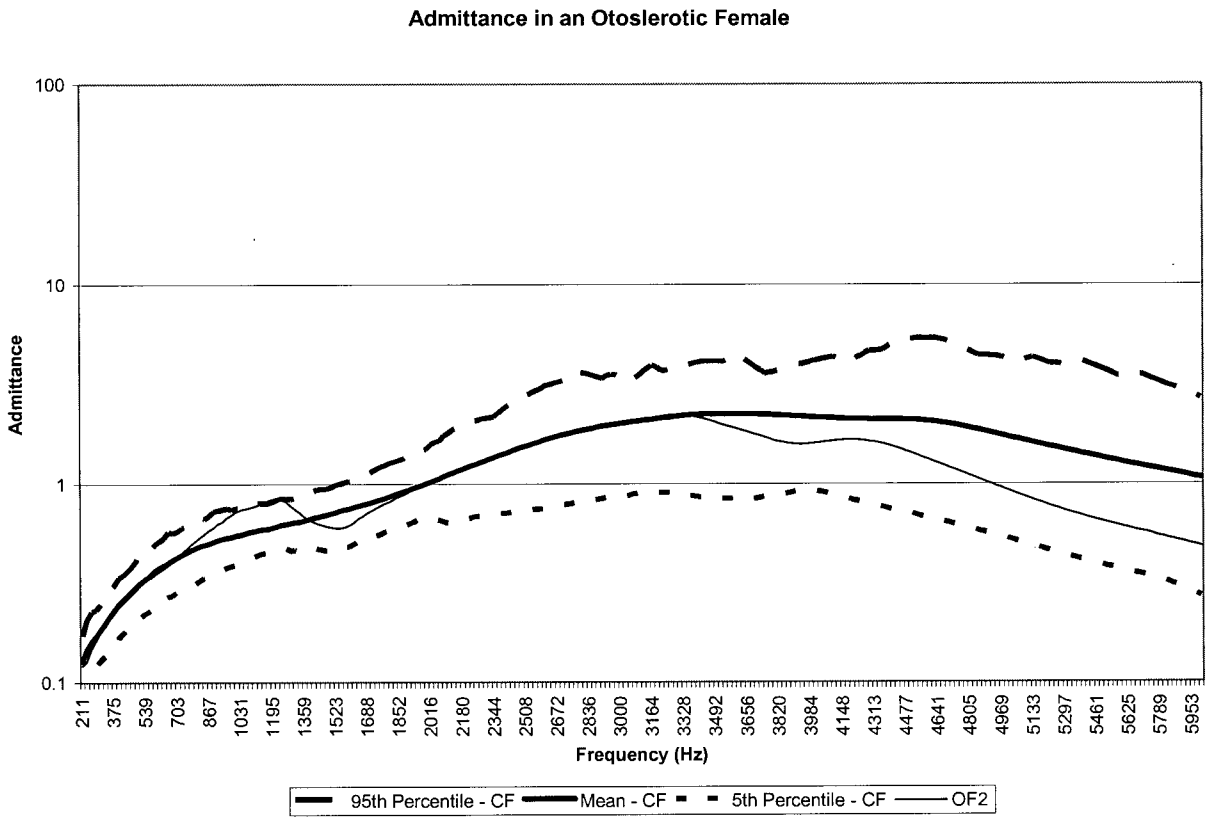

Figure 4.30: Admittance as a function of frequency for otosclerotic female OF2. CF refers to Caucasian female. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

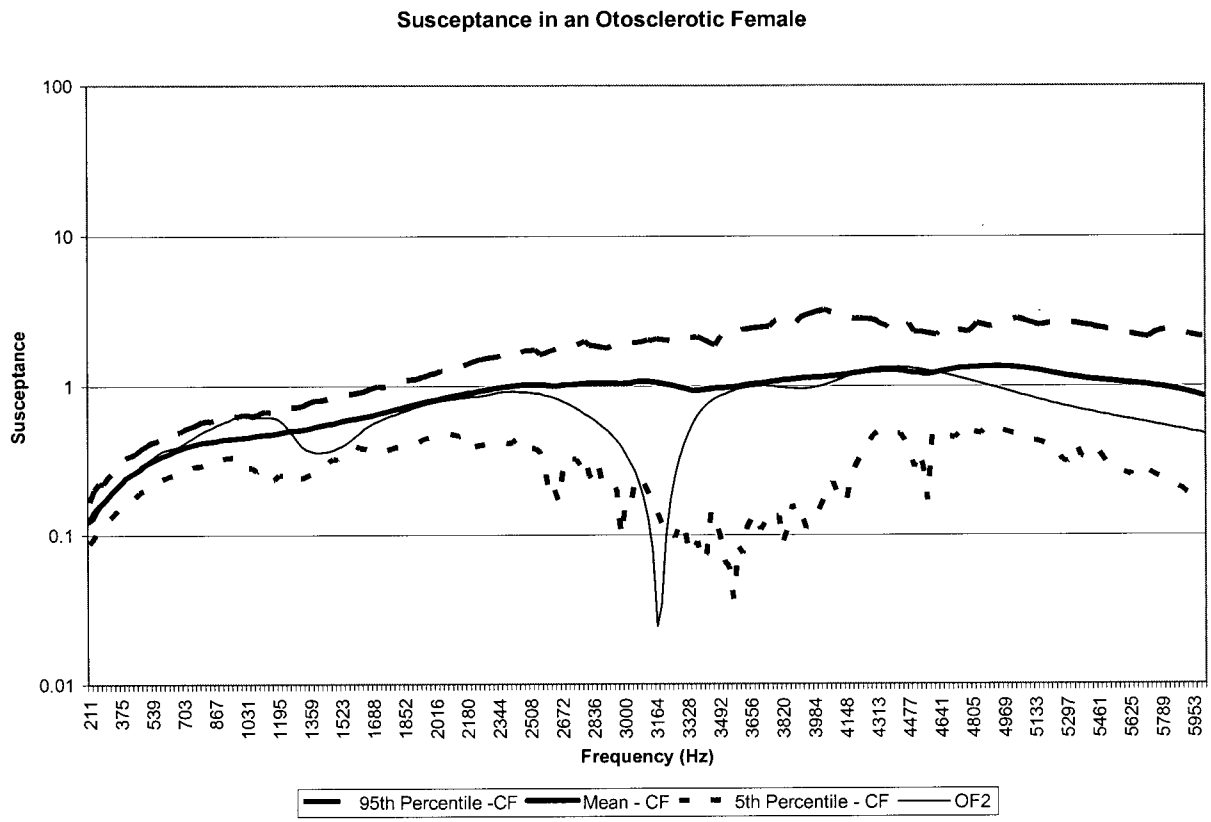

Figure 4.31: Susceptance as a function of frequency for otosclerotic female OF2. CF refers to Caucasian female. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

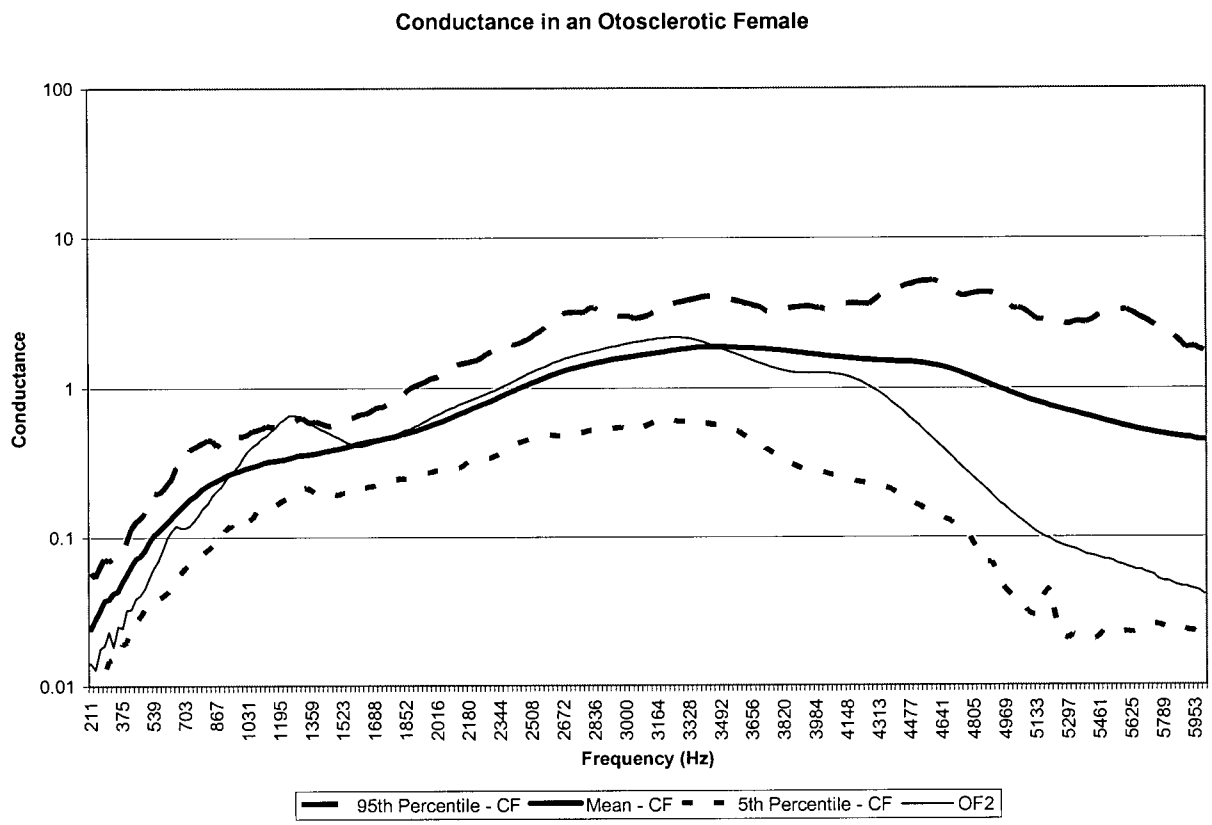

Figure 4.32: Conductance as a function of frequency for otosclerotic female OF2. CF refers to Caucasian female. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.7.4 Case history of an otosclerotic female: OF3

This 50-year-old Caucasian female has had a slowly progressing history of bilateral hearing loss. No family history is present. No history of tinnitus, or vestibular symptoms was present. A history of at least one middle ear infection as a child was recollected. Hearing aids were worn bilaterally. The left ear was chosen for surgery. Visual inspection, using otoscopy, revealed no abnormal findings. Audiological testing showed an upward sloping moderate to mild conductive hearing loss in the left ear (Figure 4.33). Carhart's notch was present at 2000 Hz. TEOAEs were found to be absent from 1000 to 4000 Hz in the surgical ear. Standard

tympanometry revealed a SA value of 1.3 mmhos, at the upper limits of normal range; and a TW of 47 daPa which was below the 5th percentile of normative values. Multi-frequency tympanometry showed F45° to be 500 Hz and RF for positive and negative compensation to be 800 Hz, which were at or just within the lower limits of normal. Results from WBR show a deviation from the 90% range in all four variables. For PA, deviations above the upper cutoff occurred between 516-1078 Hz. These findings do not correspond with those of Feeney, et al. (2003). For Y, deviations occurred above the 95th percentile for frequencies between 281-867 Hz and below the 5th percentile for frequencies from 1101-1289 Hz. A rapid change from less opposition to significantly more opposition within a small frequency range might indicate an abnormality in sound transfer through the system. This might account for the sigmoidal type curve from approximately 500-1200 Hz in all of the variables. For B, deviations occurred between the frequencies of 281-656 Hz where values were above the 95th percentile, and between 844-1195 Hz and 4195-4242 Hz where values fell below the 5th percentile. The pattern for B for frequencies below 1200 Hz parallels the pattern found for Y and suggests a sudden increase in stiffness well below the lower cutoff from normative values. For G, values extended above the 90% range between 492-984 Hz; a pattern that is similar to that found in Y and B. Figures 4.34 through 4.37 show these results. Left otosclerosis was confirmed at surgery. Sclerotic bone growth anteriorly over the footplate was removed with a special drill prior to laser stapedotomy (Appendix II).

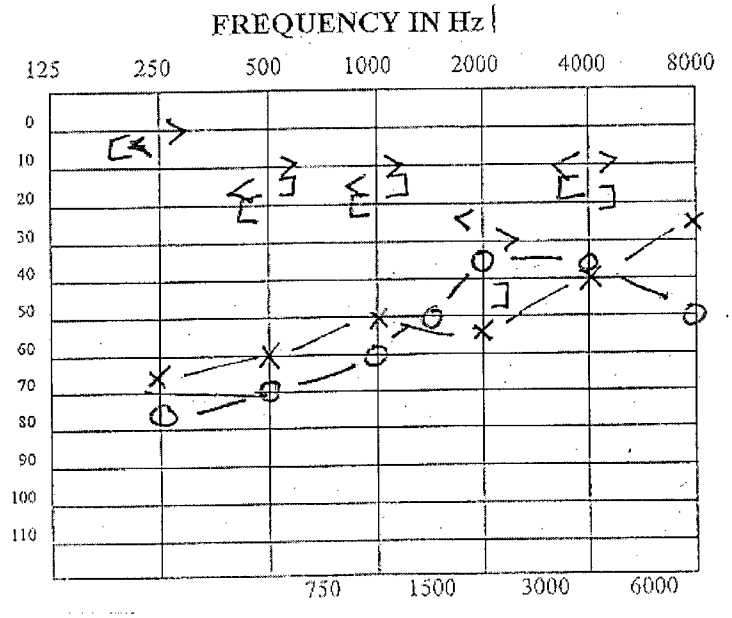

Figure 4.33: Pre-operative audiometric results of otosclerotic female OF3.

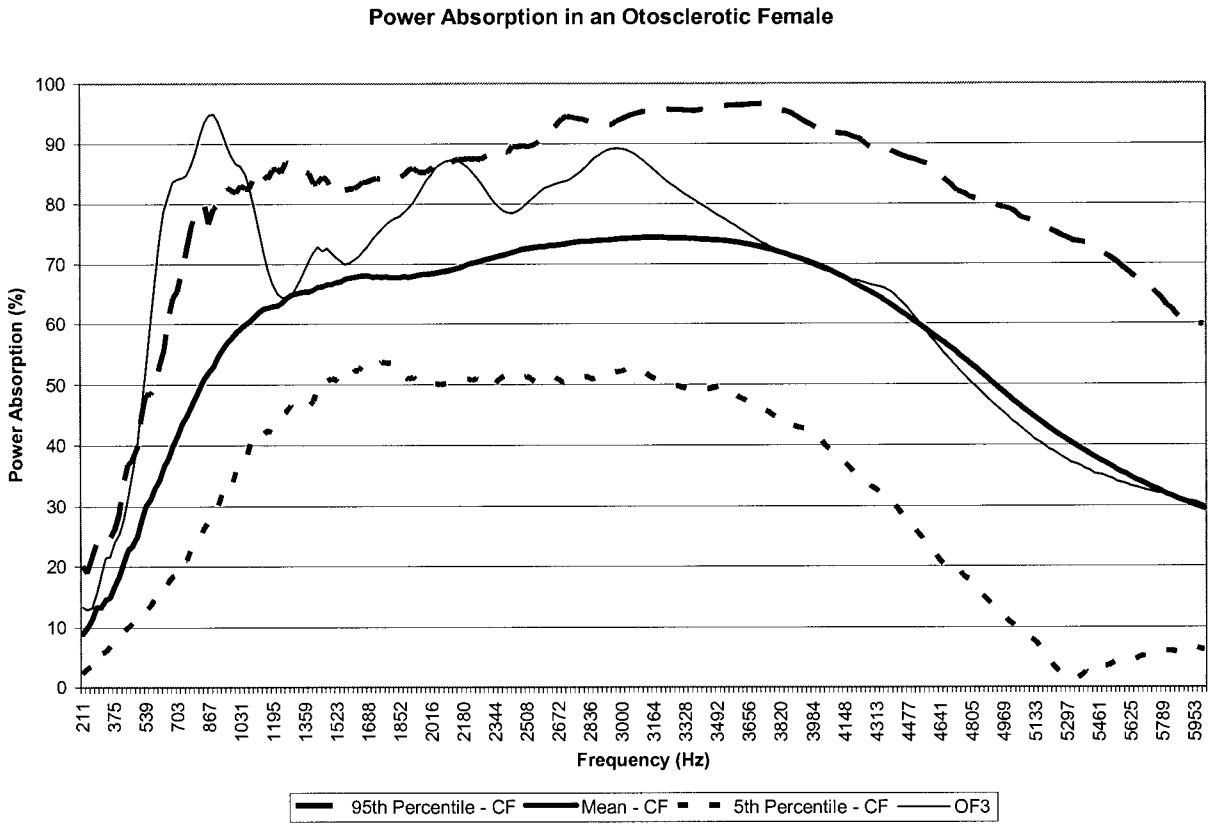

Figure 4.34: Power absorption as a function of frequency for otosclerotic female OF3. CF refers to Caucasian female.

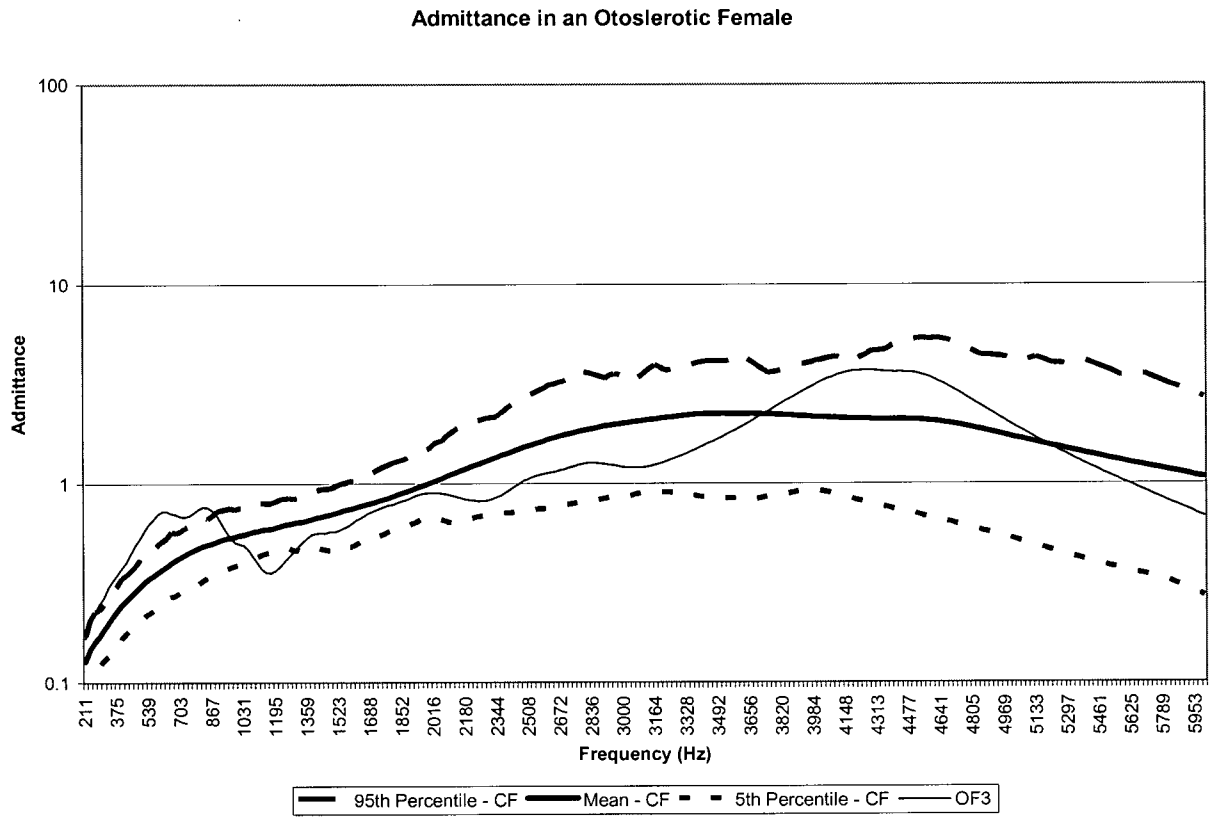

Figure 4.35: Admittance as a function of frequency for otosclerotic female OF3. CF refers to Caucasian female. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

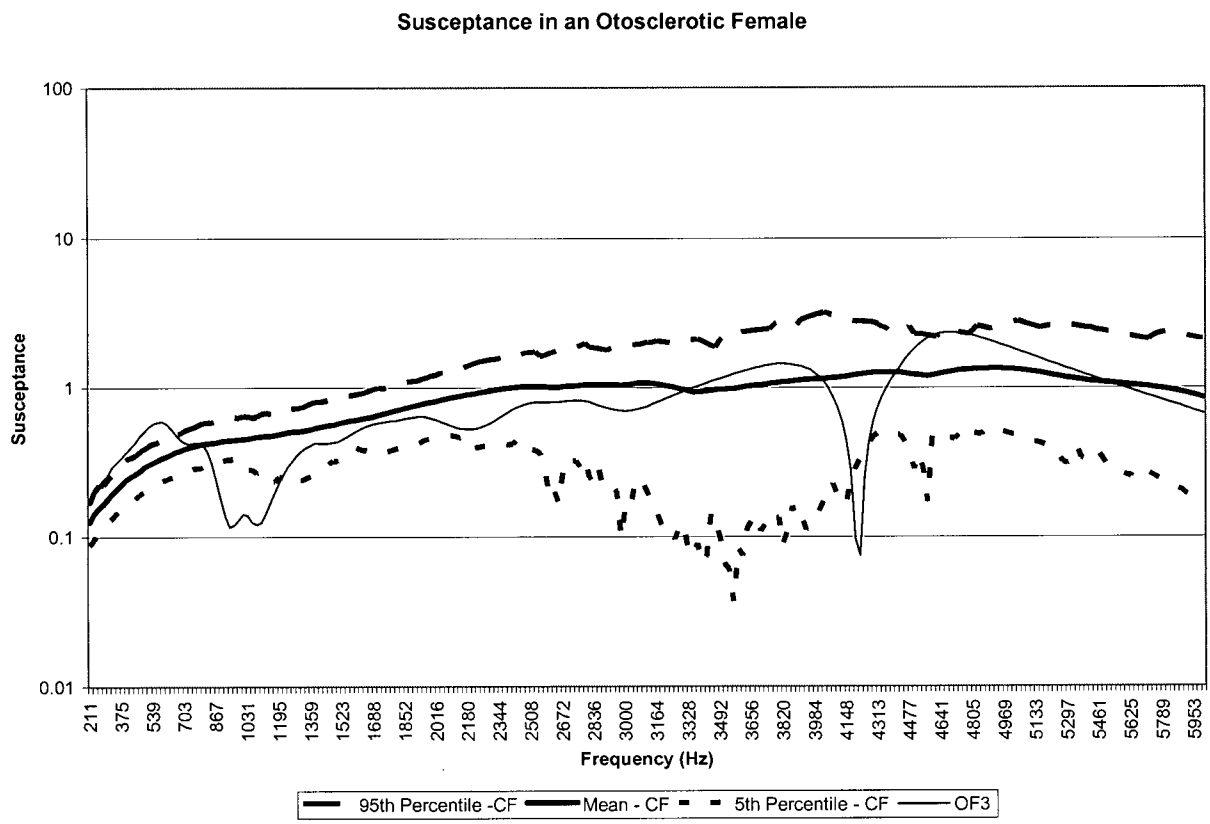

Figure 4.36: Susceptance as a function of frequency for otosclerotic female OF3. CF refers to Caucasian female. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

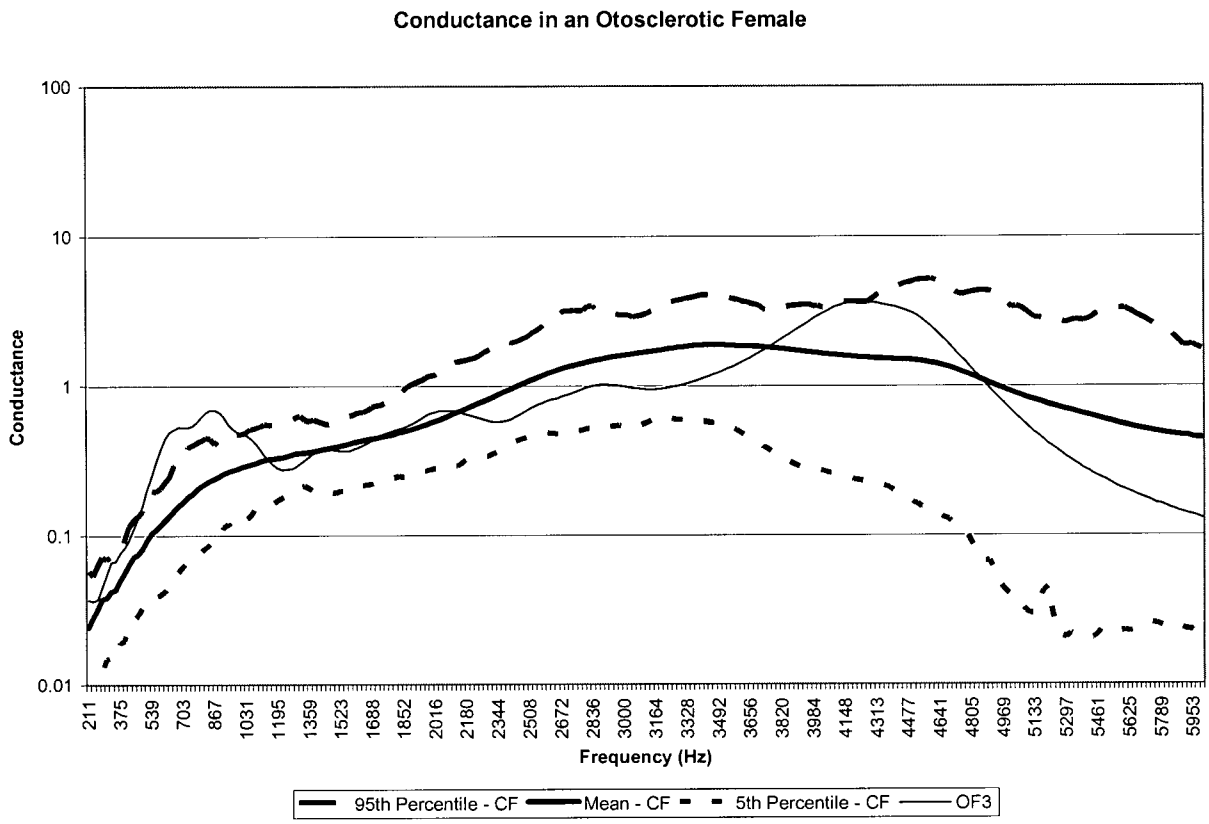

Figure 4.37: Conductance as a function of frequency for otosclerotic female OF3. CF refers to Caucasian female. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.7.5 Case history of an otosclerotic female: OF4

This 33-year-old Caucasian female has a ten-year history of bilateral hearing loss. A positive history of tinnitus was present. No history of vestibular symptoms or middle ear infections was present. As well, there was no family history of hearing loss. Hearing aids were worn bilaterally. The right ear was chosen for surgery. Visual inspection, using otoscopy, revealed no abnormal findings. Audiological testing showed an upward sloping moderate to mild conductive hearing loss in the right ear as seen in Figure 4.38. TEOAEs were found to be absent from 1000 to 4000 Hz in the surgical ear. Standard tympanometry revealed a SA value of

0.4 mmhos and a TW of 103.4 daPa, which were within normal limits. Multi-frequency tympanometry showed F45° to be 1120 Hz and RF at 1400 and 1600 Hz for positive and negative compensation, respectively; all above the 95th percentile of normal values of Shahnaz & Davies (2004). Wideband reflectance results are shown in figures 4.39 through 4.42. Power absorption results for OF4 were below the 90% range for frequencies between 938-1219 Hz and 3891-4195 Hz. These lower frequency findings are similar to OM1 and to the two cases published by Feeney, et al. (2003). They suggest an increased stiffness and less efficiency of the middle ear system, which is typical of otosclerosis. Admittance results extended above the 90% cutoff range for frequencies between 4547-5766 Hz suggesting reduced opposition to energy transfer in this range. For B, frequencies between 4219-4922 Hz and 5039-6000 Hz are above the 90% range and frequencies between 4992-5016 Hz are below the 90% range. These elevations are part of the reverse spike complex. It is interesting to note that both this reverse spike complex and the RF value found through MFT are higher in frequency. This complex is different than similar findings in the normal subjects because: (1) it occurs at higher frequencies and (2) it extends well above the 95th percentile curve. As well, for conductance, frequencies between 914-1125 Hz are below the 5th percentile, while frequencies between 4688-5367 Hz are above the 95th percentile. These findings suggest an increased resistance of the middle ear structure to low frequencies and a decreased resistance in higher frequencies. Results from Y, B, and G suggest a pattern of abnormality occurring in this high frequency range (4500-5700 Hz). It would be worthwhile to carry out further investigation on this finding.

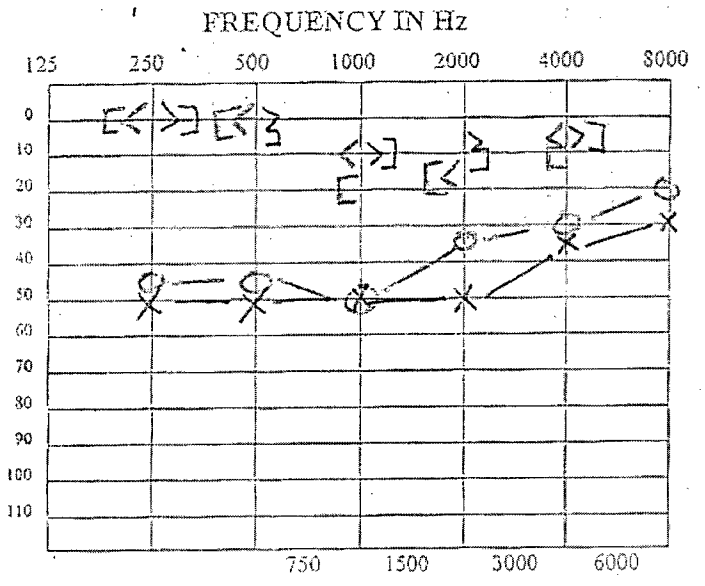

Figure 4.38: Pre-operative audiometric results of otosclerotic female OF4.

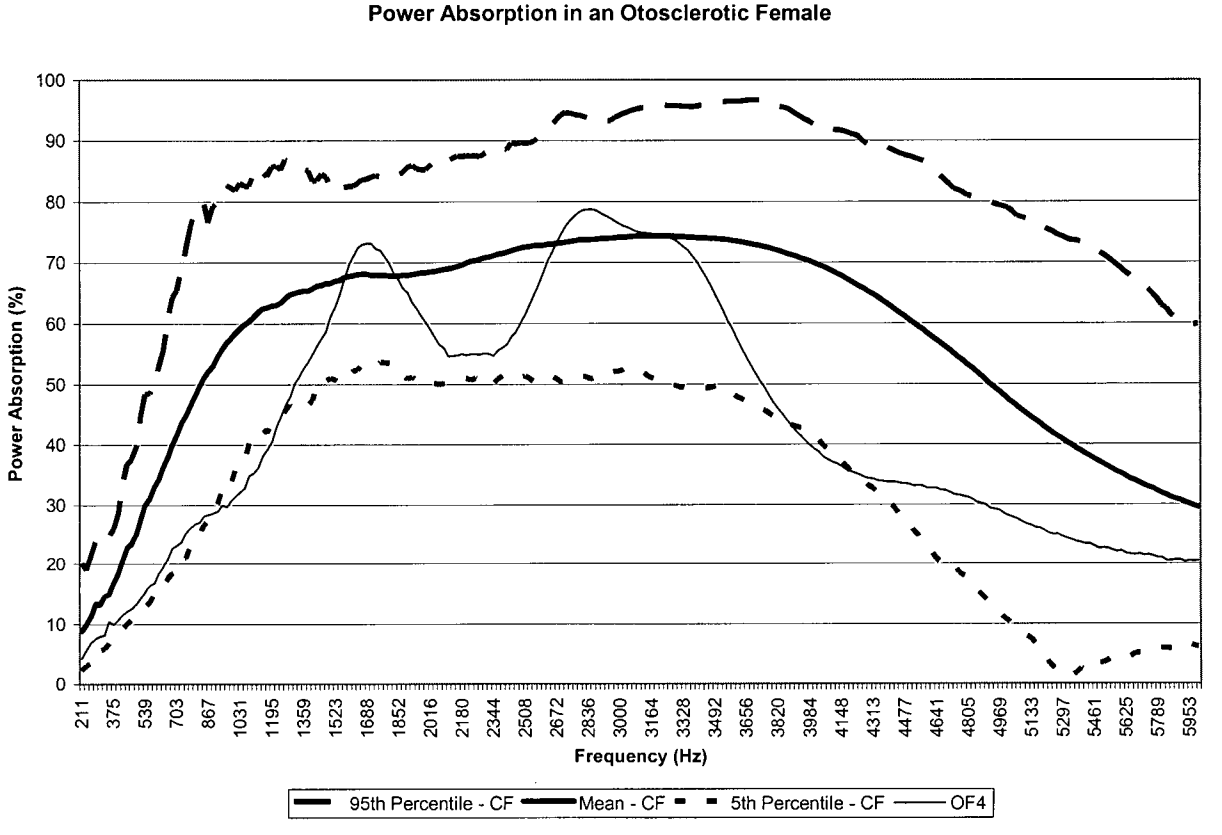

Figure 4.39: Power absorption as a function of frequency in otosclerotic female OF4. CF refers to Caucasian female.

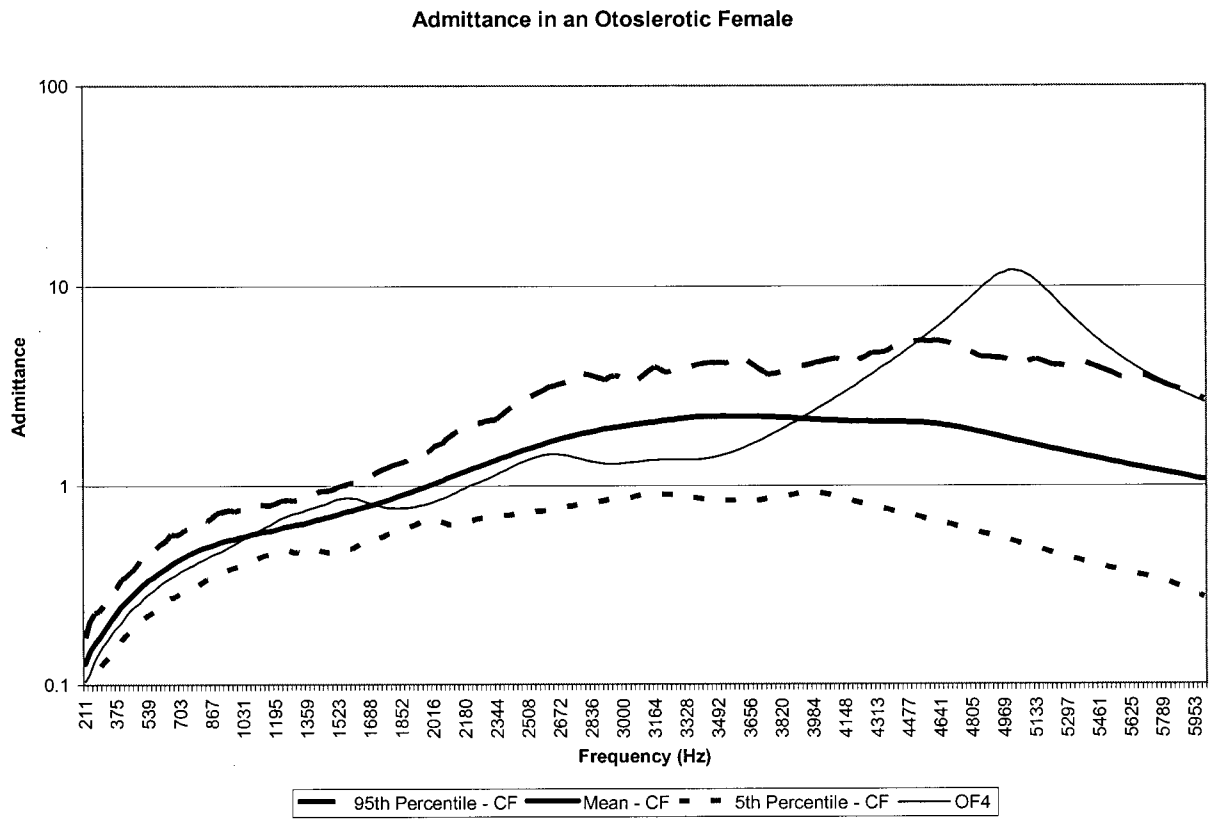

Figure 4.40: Admittance as a function of frequency in otosclerotic female OF4. CF refers to Caucasian female. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

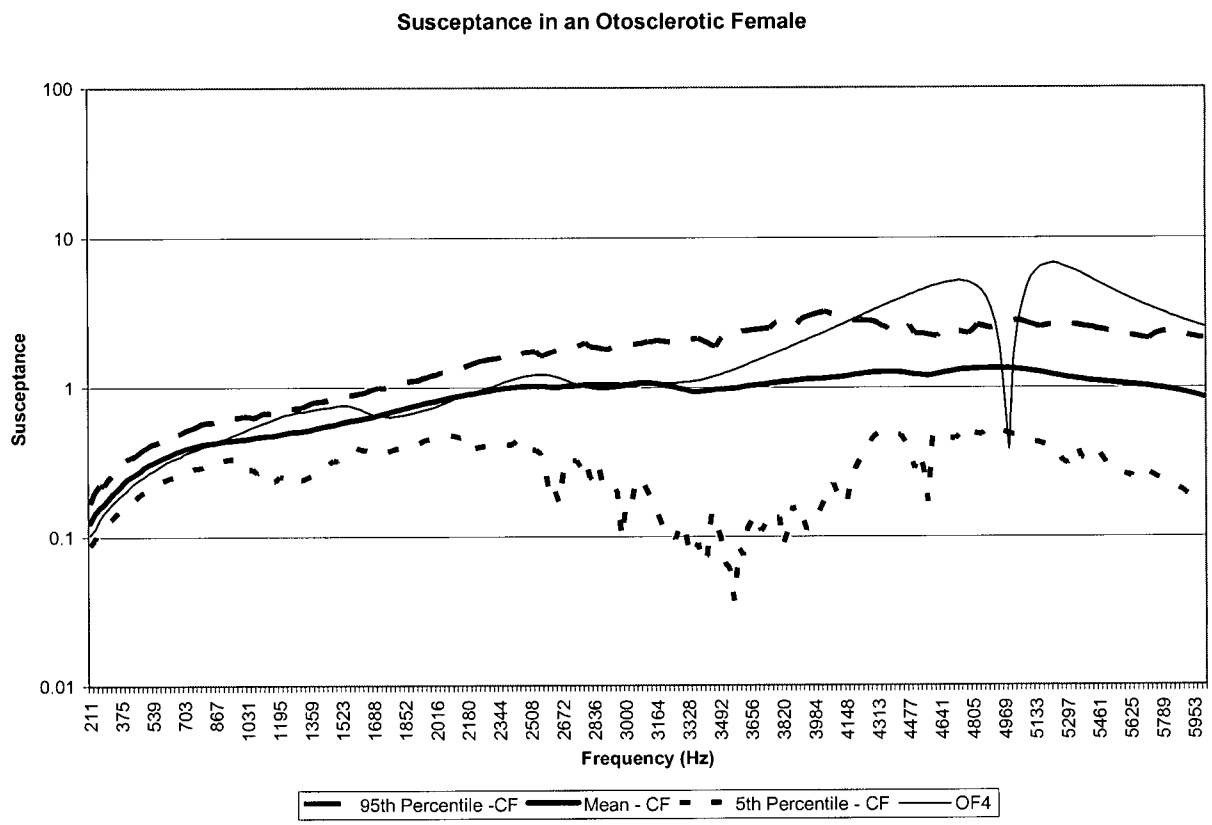

Figure 4.41: Susceptance as a function of frequency in otosclerotic female OF4. CF refers to Caucasian female. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

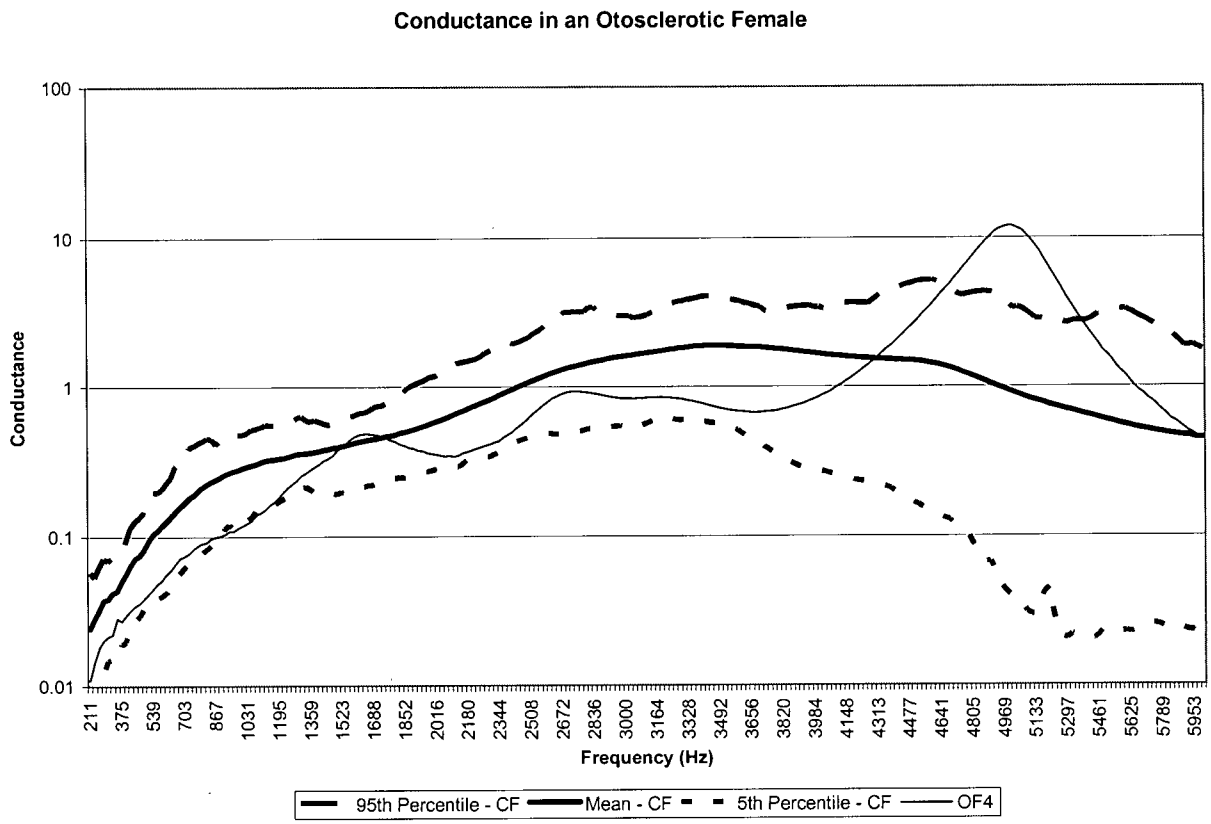

Figure 4.42: Conductance as a function of frequency in otosclerotic female OF4. CF refers to Caucasian female. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.7.6 Case history of an otosclerotic female: OF5

This 24-year-old Caucasian female had a hearing loss in her right ear since childhood. A positive history of tinnitus was present. No history of vestibular symptoms or middle ear infections was present. As well, there was no family history of hearing loss. No hearing aids are worn. Visual inspection, using otoscopy, revealed no abnormal findings. Audiological testing showed a moderate to mild conductive hearing loss in the right ear (Figure 4.43). Carhart's notch was present at 2000 Hz. TEOAEs were found to be absent from 1000 to 4000 Hz in the surgical ear. Standard tympanometry revealed a SA value of 0.3 mmhos was at the lower limits

of normal for normative data, and a TW of 84.6 daPa was within the normal range. Multi-frequency tympanometry showed F45° to be 900 Hz, well above the 90% range; while RF was 1120 and 1250 Hz for positive and negative compensation, respectively, are at or within the upper limits of normal according to Shahnaz and Davies (2004). Results of WBR are shown in Figures 4.44 through 4.47. For PA, frequencies from 328-1148 Hz were below the 90% range. This is the third patient with this finding in this series. Again, a low percent PA in this frequency range suggests poor efficiency of the middle ear system, likely due to increased stiffness imposed by the annular ligament. This explanation is compatible with the diagnosis of otosclerosis. For Y, frequencies between 3188-3492 Hz were above the 90% range, indicating an ease of energy transfer in this region. For B, all frequencies are between the 5th and 95th percentiles; hence, they were within the normal range. For G, OF5's values were outside of the 90% range for two different frequency ranges: below between 398-1102 Hz and above between 3211-3445 Hz. The abnormalities seen for Y, B, and G overlap in the same frequency range (i.e. approximately 3100 Hz) and most likely correspond with a RF of the middle ear. Correlation between this finding and MFT RF values bear further investigation. Figure 4.47 also shows increased resistance in the lower frequencies. OF5 has not yet had surgery.

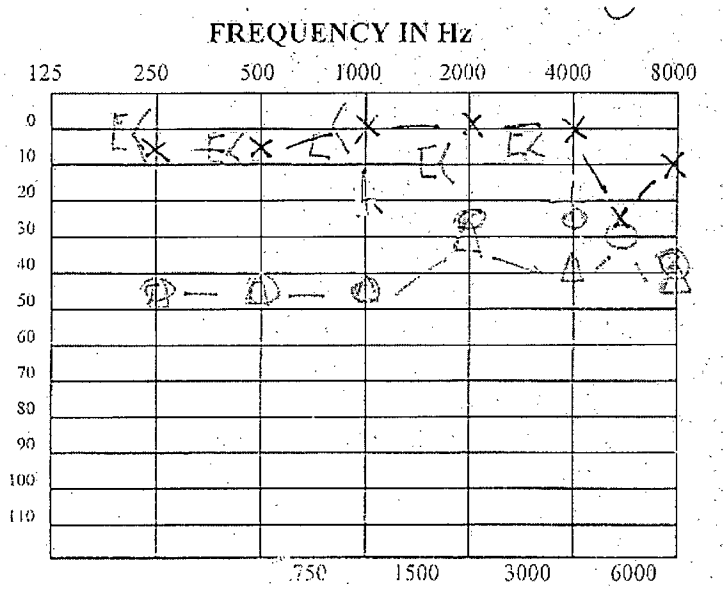

Figure 4.43: Pre-operative audiometric results of otosclerotic female OF5.

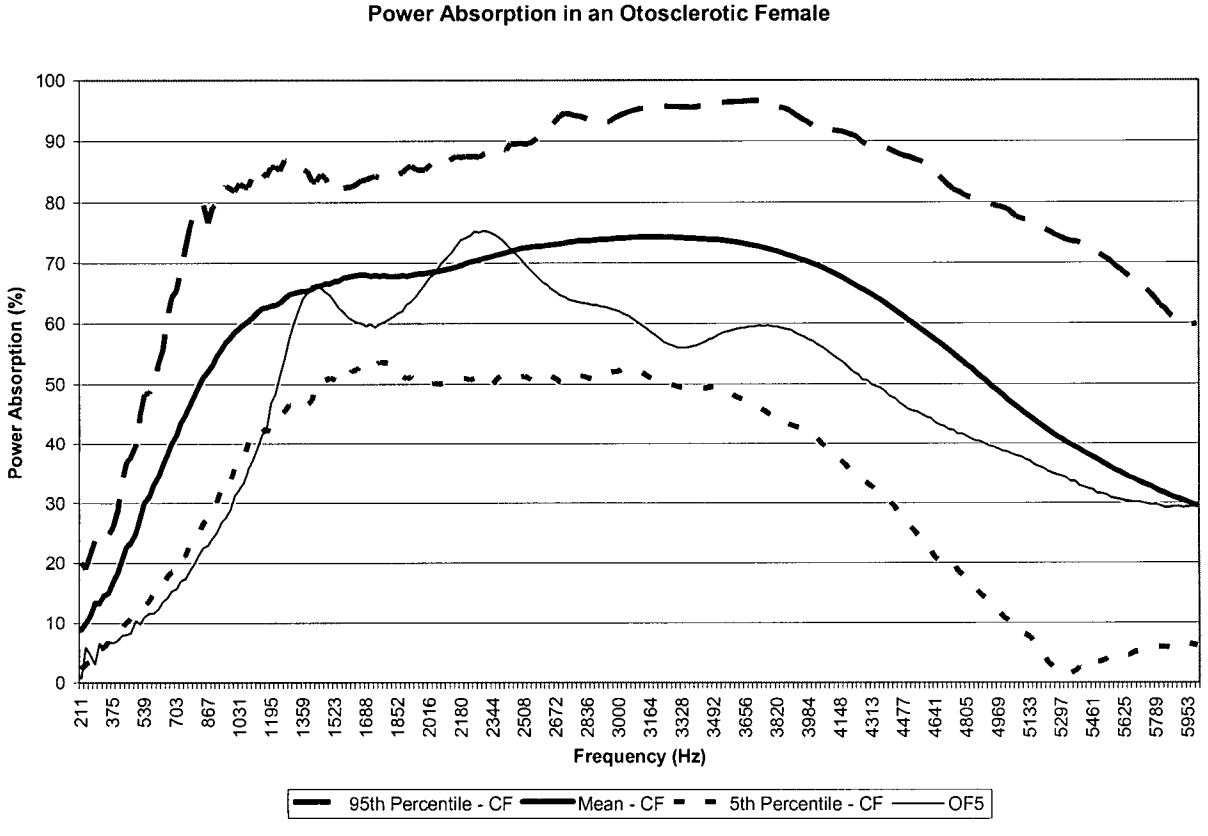

Figure 4.44: Power absorption as a function of frequency in otosclerotic female OF5. CF refers to Caucasian female.

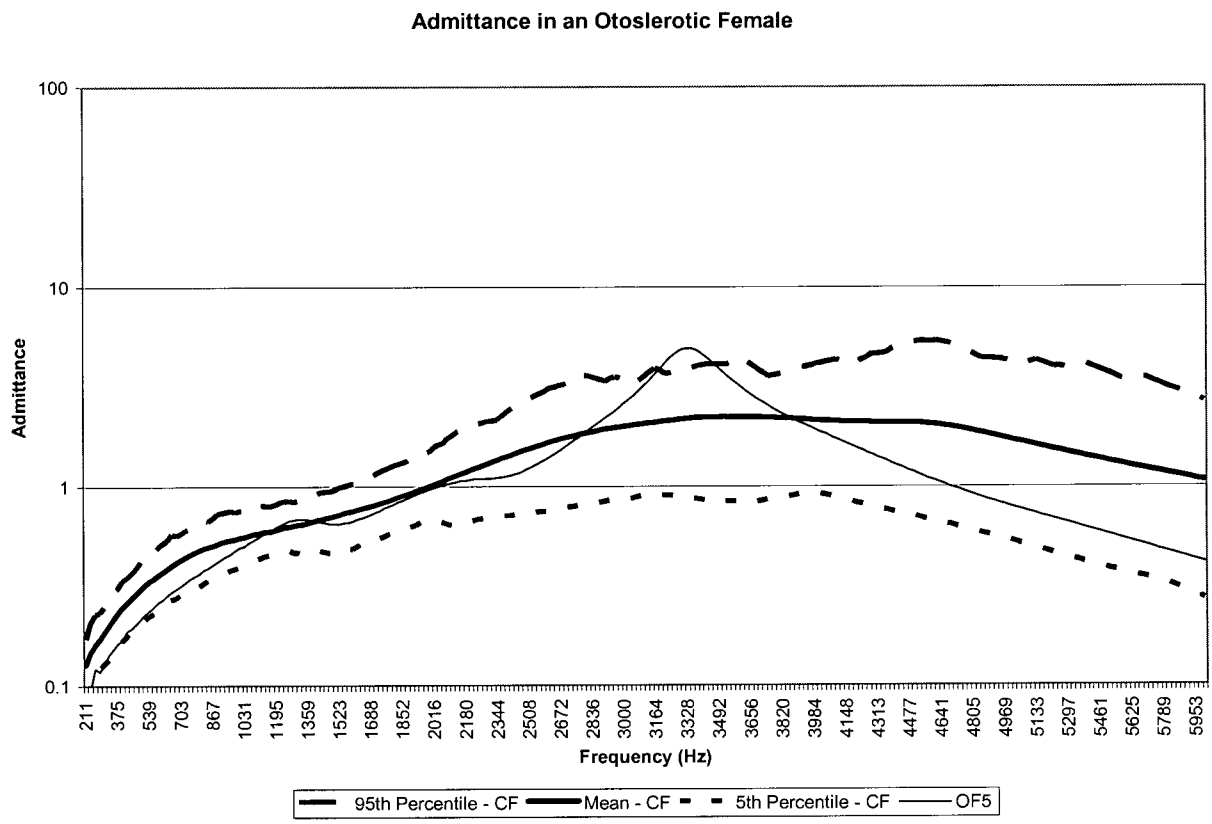

Figure 4.45: Admittance as a function of frequency in otosclerotic female OF5. CF refers to Caucasian female. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

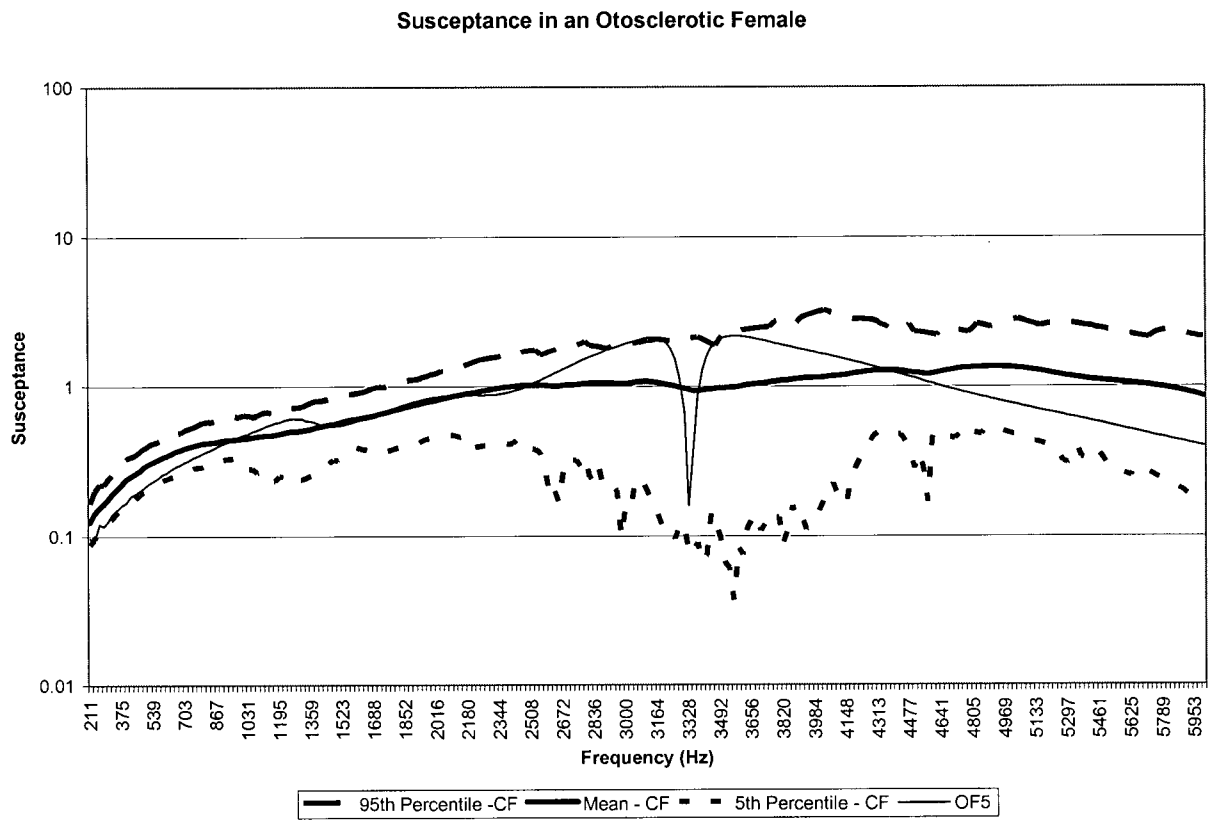

Figure 4.46: Susceptance as a function of frequency in otosclerotic female OF5. CF refers to Caucasian female. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

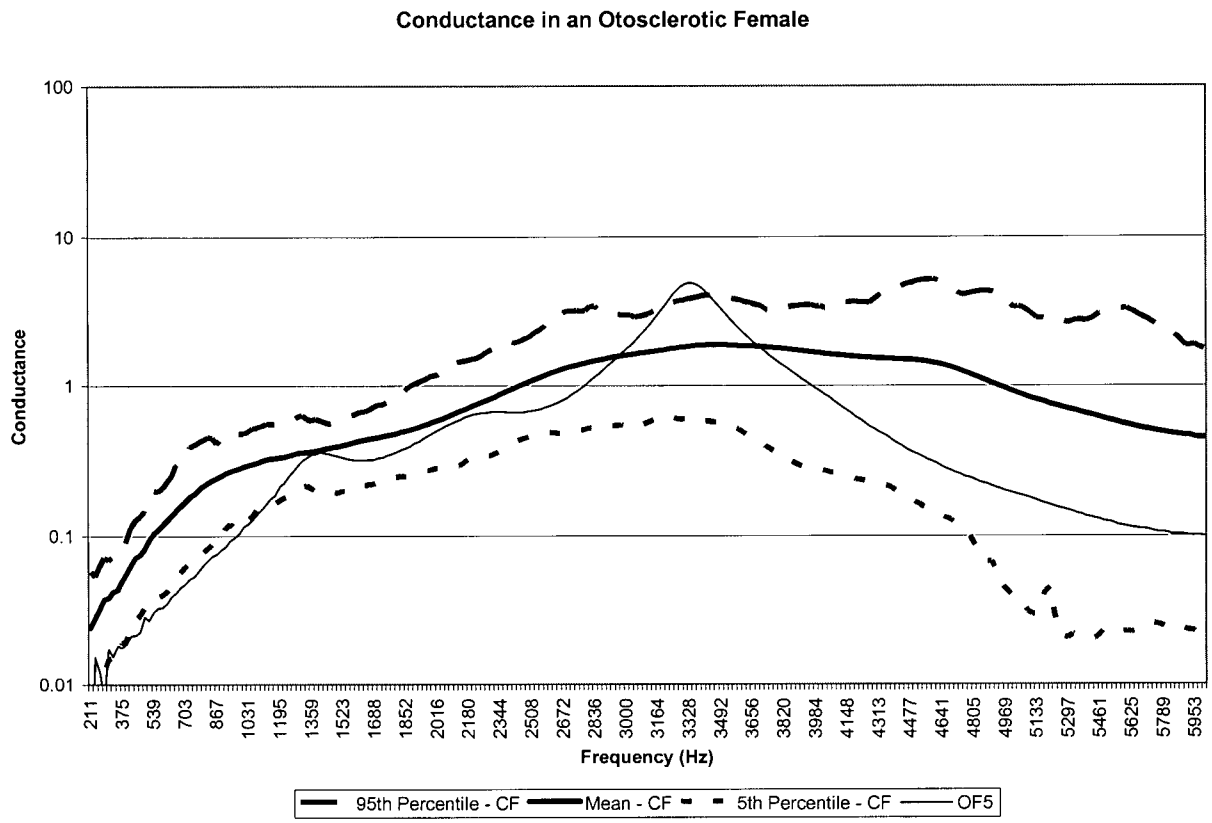

Figure 4.47: Conductance as a function of frequency in otosclerotic female OF5. CF refers to Caucasian female. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.7.7 Case history of an otosclerotic female: OF6

This 50-year-old Caucasian female had a history of hearing loss in her left ear for the last two years. No history of tinnitus, vestibular symptoms, or middle ear infections was present. As well, there was no family history of hearing loss. No hearing aids are worn. Visual inspection, using otoscopy, revealed no abnormal findings. TEOAEs were found to be absent from 1000 to 4000 Hz in the surgical ear. Audiological testing showed a moderate conductive hearing loss in the left ear as seen in Figure 4.48. Standard tympanometry revealed a SA value of 1.2 mmhos and a TW of 70.5 daPa, both of which are within normal limits. Multi-frequency tympanometry

showed F45° to be 630 Hz while RF was 800 and 900 Hz for positive and negative compensation, respectively; all within normal limits (Shahnaz & Davies, 2004). Results of WBR are shown in Figures 4.49 through 4.52. Power absorption for OF6 extends above the 90% range in frequencies 1242-1758 Hz and below the 90% range in frequencies 4898-5203 Hz. This finding of better middle ear efficiency in this frequency range is not consistent with Feeney, et al. (2003), but does correspond with some of the other cases in this study. Perhaps the amount of ankylosed bone present around and on the footplate is related to this finding. Admittance also extends above the 90% range for frequencies between 844-1430 Hz and 2461-2695 Hz indicating an ease of energy transfer in these regions. Susceptance values between 750-1148 Hz were above the 95th percentile, while values between 2648-2695 Hz were below the 5th percentile. For conductance, OF6 had three separate frequency regions where her results extended beyond the 90% range normative values: above between 1031-1617 Hz and 2461-2695 Hz, and below between 5016-5836 Hz. These findings suggest an inconsistency in the transfer of energy through the middle ear as shown by the sigmoidal lines throughout PA, Y, B, and G. Of note, both PA and G show decreased values, indicating a less efficient middle ear system in the higher frequencies due to increased resistance.

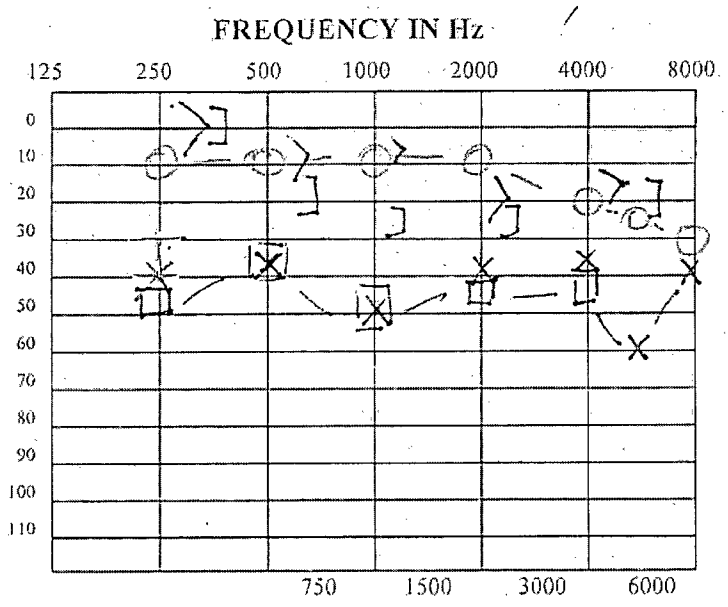

Figure 4.48: Pre-operative audiometric results of otosclerotic female OF6.

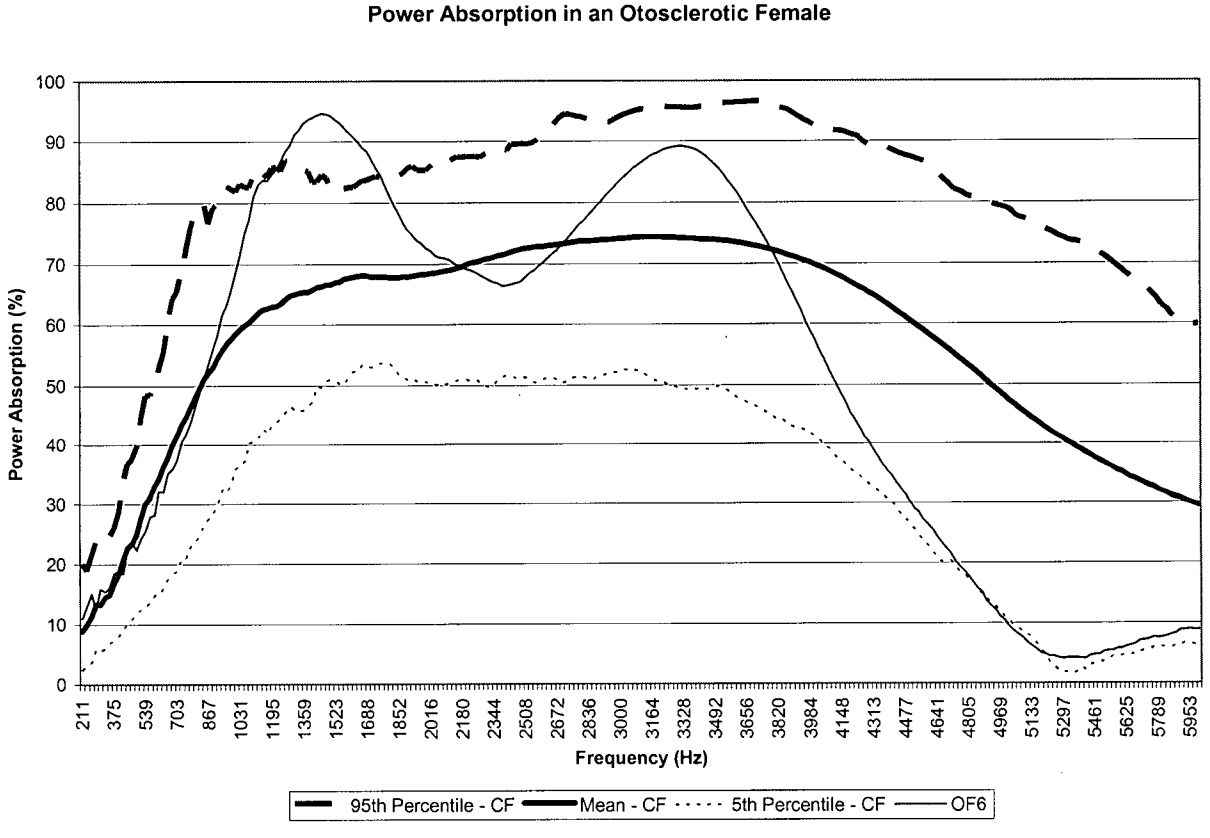

Figure 4.49: Power absorption as a function of frequency in otosclerotic female OF6. CF refers to Caucasian female.

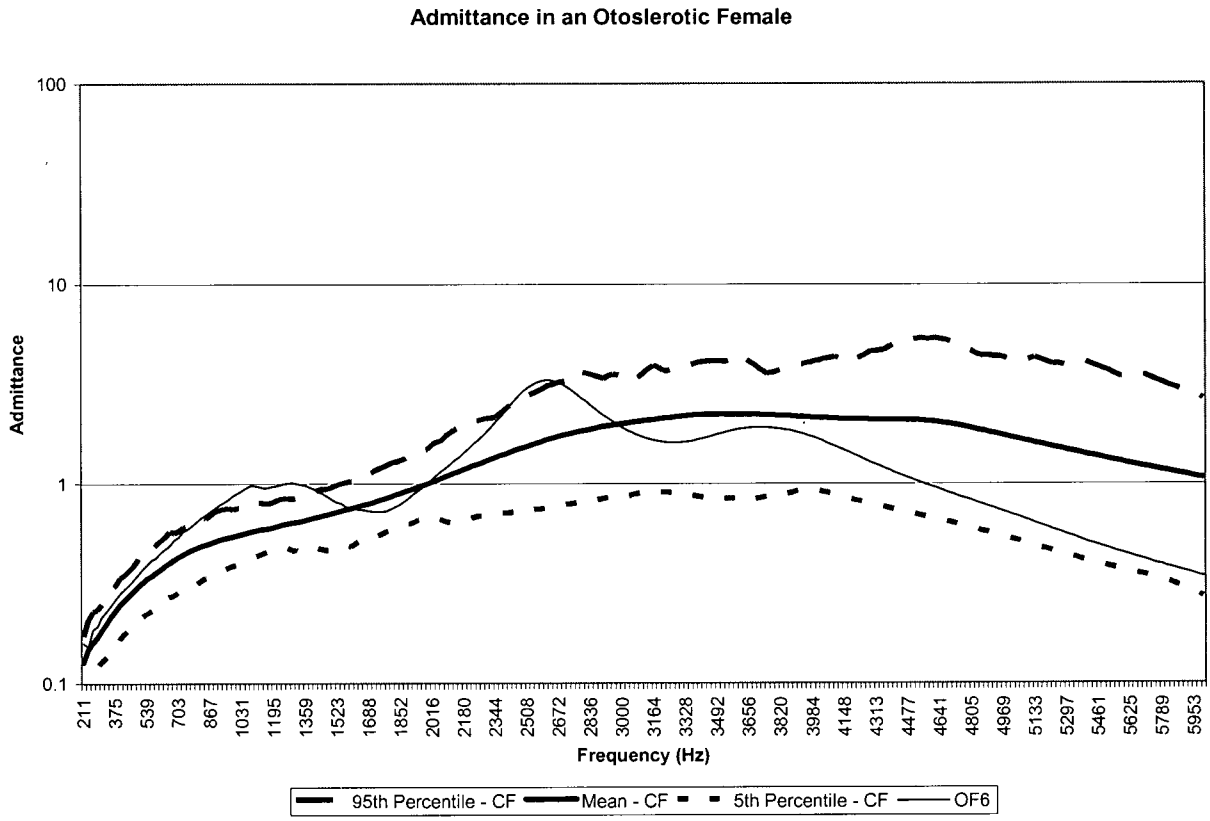

Figure 4.50: Admittance as a function of frequency in otosclerotic female OF6. CF refers to Caucasian female. Admittance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

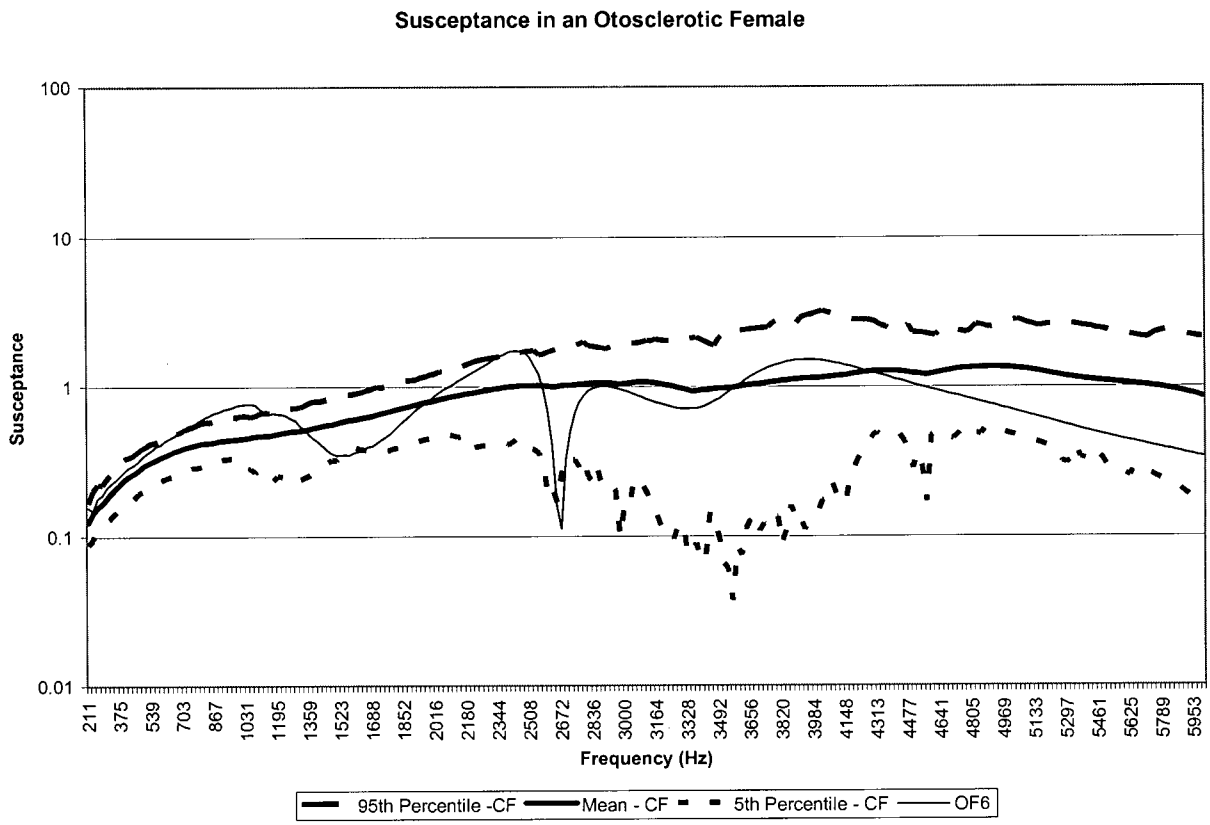

Figure 4.51: Susceptance as a function of frequency in otosclerotic female OF6. CF refers to Caucasian female. Susceptance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

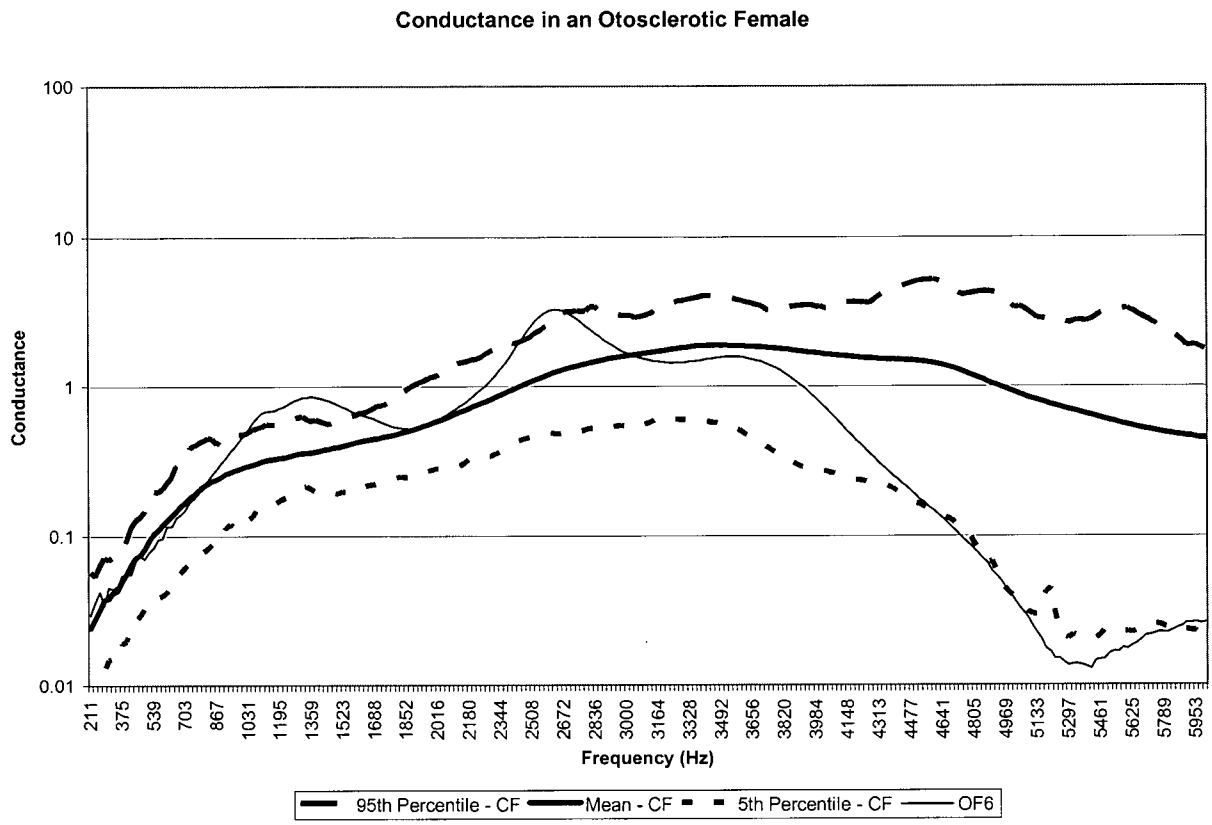

Figure 4.52: Conductance as a function of frequency in otosclerotic female OF6. CF refers to Caucasian female. Conductance values are dimensionless as they are normalized using characteristic impedance of the ear canal.

4.8 Discussion of case studies of otosclerosis

In view of the small sample size of otosclerotic study subjects in this exploratory report, formal statistical analyses are not done. From Feeney, et al.'s (2003) paper there is an expectation that subjects with otosclerosis will have values below the 5th percentile for PA at frequencies below 1000 Hz. From the graphic information, cases OM1, OF4, and OF5 have PA values below the 5th percentile curve of normative values. In view of the common occurrence of lower percent PA values in the low frequencies among subjects, it is likely that otosclerotic patients will have low values in this region with a larger sample size.

It is important to note that all of the otosclerotic patients in this study deviated from the normative values on at least one of the four WBR parameters, even when their MFT results were within normal limits. Although only seven patients were tested, these results provided evidence in favour of the utility of WBR for diagnosis of otosclerosis. Further research should be conducted in this regard to replicate these findings. Of special interest was the reverse spike complex that is present in B. As previously mentioned, this complex is present in individual results in both the normal and otosclerotic groups. It is thought that the reverse spike complex in B shows a transition between the stiffness dominated middle ear system and the mass dominated middle ear system. There is a suggestion from the review of the otosclerotic cases that there is a positive relationship between the RF value and a higher frequency location of the reverse spike complex.

Although data from only seven otosclerotic subjects has been reviewed, the pattern produced using WBR variables is sufficiently different from normal subjects. This suggests that evaluation of qualitative factors should be considered. This approach has worked well in MFT using Vanhuyse patterns.

In summary from this section, information about middle ear dynamic characteristics in otosclerosis from this study can be obtained from the graphic presentation given the small sample size. As experience is gained from more patients with otosclerosis, WBR patterns will develop that can be correlated with surgical findings.

Results may become highly important in the understanding of the clinical utility of WBR in otosclerosis and in understanding middle ear pathologies. The final interpretation of this with regard to diagnosis of otosclerosis or with regard to understanding mechano-acoustical events in the middle ear system awaits clarification of this data.

Chapter V General Discussion

5.1 Summary

Wideband reflectance (WBR) is a new measure for middle ear evaluation that uses a wide range of sound frequencies to establish the ratio of sound energy reflected on its way to the cochlea in relation to the incident energy, or sound that reaches the cochlea. The objectives of this descriptive, cross-sectional, group comparison study were to establish normative data for WBR by gender using Chinese and Caucasian normal hearing adults, and to explore the potential clinical utility of WBR in otosclerosis, a common adult middle ear pathology. The subjects included 66 Asian and 62 Caucasian young adults providing 125 and 115 normal middle ears, respectively; and seven ears from seven Caucasian patients with otosclerosis. The objectives were addressed by measuring four parameters of WBR for each ear tested. These parameters included power absorption (PA), admittance (Y), susceptance (B), and conductance (G).

Three types of analyses were undertaken. First, repeated measures analysis of variance (ANOVA) assessed the frequency as a within subject factor and gender (male or female), race (Chinese or Caucasian), and ear (left or right) as between subject factors. Significance was determined in two ways: (1) by comparison of means of $p < .05$, and (2) by clear separation of the 95% confidence intervals. Second, graphic visual comparisons of mean and 90% range values between race and gender combinations of normal subjects were made for all parameters. Third, data from each individual otosclerotic patient were plotted against appropriate normative curves.

As summarized in Table 4.1, statistical differences in means were found for PA and Y between male Chinese and Caucasian subjects, and female Chinese and Caucasian subjects, with Caucasians having higher values. Similarly, for B, female Caucasians have statistically higher mean values than Chinese. For G, there were no statistical differences. For gender differences

within race, only B showed gender differences among Chinese with males having higher values than females. Among Caucasians, males have higher values for Y, B, and G. These differences in mean values are likely based on anatomical differences with Caucasians having larger middle ear volumes than Chinese, and males having larger middle ear volumes than females. This is consistent with Shahnaz and Davies (2004) finding of larger ear canal volumes in these groups. Differences between all race/gender combinations (i.e. Chinese males and females, Caucasian males and females, Chinese and Caucasian males, and Chinese and Caucasian females) were found by visual exploration of the graphed parameters data. In view of the importance of the cutoff levels in clinical practice and lack of similarity of these levels for all race/gender combinations, it was concluded that for WBR gender and race specific normative data are needed.

For patients with otosclerosis, visual inspection was the analysis method used. When compared to appropriate normative data, all otosclerotic ears had values beyond the 90% range in at least one of the four WBR variables. While there was not one consistent pattern of results for the otosclerotic ears, three main trends were evident: (1) values using the PA variable tended to vary in the frequencies below 1200 Hz, with values lower than the 5th percentile curve indicating less efficient transfer of energy and an increase in stiffness possibly due to growth of spongy tissues around the annular ligament; (2) the reverse spike complex, as visualized using the B variable, seems to advance in frequency in relation to increasing RF as measured by MFT; and (3) conductance measures indicate that there is an increase in resistance in some otosclerotic ears. This latter trend is consistent with Shahnaz and Polka's (2002) finding that conductance plays an important role in otosclerosis.

Wideband reflectance results were found to be abnormal in all seven of the otosclerosis patients tested, including in four cases where both standard and MFT measures were within

normal limits. This suggests the possibility of greater sensitivity of WBR than MFT to the diagnosis of otosclerosis. Further studies should be done to affirm these results.

5.2 Limitations

Given that research in the area of WBR is still in its infancy, preferred graphing variables, as well as their units are, as of yet, still inconsistent. This poses considerable difficulty when organizing collected data to fit with already published normative values.

When establishing normative values, the sample size should be reasonably large to enhance the power of statistical analysis. Although repeated measures ANOVA took these issues into consideration, a larger sample size of normal subjects would still benefit this study, and WBR research in general. It would also have been helpful to have a larger patient group, but given time constraints, this was not possible.

One important variable that was not taken into consideration by this study was age. The normative population in this study was made up of normal, healthy young adults. The subjects with otosclerosis, on the other hand, had a mean age of 41 years. It is unknown whether this age difference would be enough to influence the patient groups' results. There is some evidence that WBR normative distribution is different among various age populations (Feeney, et al., 2003; Keefe, et al., 2000). In the future, this potential confounding variable should be addressed with age-specific normative data.

Other researchers have discussed the effect of ear canal size on results (Voss & Allen, 1994; Keefe, et al., 1993). Controlling for this variable would reduce much of the inter-subject variability seen. Ear canal variation was a limitation to this study. Methods used to reduce the effect of ear canal volume on WBR measurements are recommended as a future research project. Possible methods of measuring ear canal volume include water displacement and using real ear to coupler differences.

5.3 Sources of differences

Within the procedure of this study there were few sources of differences. The protocol was strictly followed for all normal and otosclerotic subjects. The same instrument, the Mimosa Acoustics RMS v4.0.4.4 machine was used for all subjects. It should be noted, however, that the Mimosa Acoustics software was updated part way through this study. Data obtained prior and after this change should be compared for any significant differences.

Instruments could be another source of difference between the results of this study and those of other authors, including Feeney, et al. (2003) and Feeney and Sanford (2004). There has not been a comparison study done using the same test subjects on both the Mimosa Acoustics and the custom-made instrument of Keefe, et al., (1993). Machine variability is a likely source of difference between studies due to possible variations in calibration, units, or methods to calculate variables.

This study has shown differences between racial and gender groups for WBR which is consistent with previous findings reported using both standard and MFT tympanometry (Shahnaz & Davies, 2004; Wan & Wong, 2002). These variations may be due to anatomical differences as discussed previously in section 4.6. Huang, et al. (2000) noted that there were correlations between the volume of the middle ear of animals and their size. This supports the finding of this study of apparent anatomical differences affecting test results. That is, if the middle ear cavity is smaller, there would be increased stiffness in the middle ear system allowing a more efficient transfer of energy at higher frequencies.

Consideration must be given to sources of differences among otosclerotic subjects. As this exploratory study had only one male, male/female differences within race could not be tested. However, it is likely that gender differences would contribute to differences in study

subjects. Similarly, the greater mean age of the otosclerotic patients relative to the normative subjects may contribute to differences in results.

Another source of difference among otosclerotic subjects is the degree, or stage, of otosclerosis. Clinically otosclerosis is a progressive disorder. Even after the diagnosis of clinical otosclerosis is made, progression occurs. A way of determining the degree of stapes fixation, which is a measure of the amount or stage of otosclerosis, is by the degree of conductive hearing loss present. As the new bone growth fixes the stapes further, the conductive hearing loss increases.

Differences may also relate to the amount of stiffness present in different subjects with otosclerosis. Although otosclerosis is a middle ear pathology that is considered to increase stiffness, there have been some exceptions to this in the literature. In some cases otosclerosis could be present with less or no stiffness, possibly related to less bone accumulation. Based on RF tests, Zhao, Wada, Koike, Ohyama, Kawase, and Stephens (2002) found 44.4% of 36 ears with otosclerosis had high stiffness, but 13.9 % had low stiffness and the remaining had normal stiffness status. The occurrence of low or normal stiffness in otosclerotic ears has often been thought to be due to low diagnostic accuracy of the test used. It is possible that low stiffness occurs in otosclerosis particularly in earlier stages. The degree of otosclerosis as well as the test measure used may both be sources of difference. While it is not clear that stiffness as determined by RF relates to WBR testing, nonetheless differences in amount of stiffness among subjects needs to be considered.

5.4 Implications

While WBR is still in early clinical application development, it has so far shown great promise. It has many advantages over conventional middle ear measures in both technical and practical aspects of testing. Wideband reflectance allows testing of a larger range of frequencies,

giving the clinician more information about the middle ear; concern over ear canal compliance is reduced; a pressure seal is not needed; and dependency on the location of the probe tip in the ear canal is not as critical. In addition, WBR testing is extremely time efficient, both in the testing phase, as well as in the analysis of results as it can be readily represented in Y, B, and G, as well as 11 other parameters as needed. Wideband reflectance is objective, non-invasive, and safe. These latter attributes are particularly important in post-operative otosclerosis, where pressure changes, as induced with tympanometric measures, can potentially damage middle ear structures.

One problem that has yet to be resolved is the issue of how the WBR data will be commonly represented (i.e. ER, PA, Y, B, G, etc.). Before the establishment universally clinical normative values, this issue must be resolved. Closely related to this issue is the fact that the most useful measure of WBR has yet to be determined. It may be proven that different pathologies will have preferred measures for diagnosis and/or differential diagnosis. Once these issues have been resolved, it seems likely that WBR will become a promising diagnostic tool.

Wideband reflectance has potential clinical utility in a number of middle ear pathologies beyond otosclerosis. In addition to its usefulness as a diagnostic tool, WBR may become important in the post-operative evaluation of middle ear surgeries due to its safety. Thus, various surgical procedures and different prosthetic devices could be accurately evaluated. The present evaluation methods of surgery for otosclerosis include direct or indirect measures of the hearing level, such as, pure tone average including 4000 Hz and air-bone gap (Goldenberg & Berliner, 1995); word recognition scores (Lippy, et al., 1998); questionnaires of improvement (Aarnisalo, et al., 2003); and quality of life measures (Stewart, et al., 1997). Should a more direct discriminating test be available post-operatively, treatment evaluation would be enhanced. With the ease of administration and safety of WBR testing, this could become an excellent tool for measuring outcomes.

The race and gender specific normative values established in this study are vitally important as the basis for further studies of WBR use in middle ear pathologies. These studies require accurate and reliable cutoff levels. Ultimately, these normative data may provide the basis for clinically useful cutoff levels for WBR in adults. This could be further refined by formulating cutoff levels at specific frequencies for individual middle ear disorders.

The results of this study have wide implications for further understanding of middle ear functioning and middle ear pathologies. Specifically, with regard to otosclerosis, WBR is likely to have greater potential than low frequency tympanometric measurements, as is the case with MFT. Low frequency tympanometry forces the middle ear system to behave as a stiffness dominated system. As frequency increases, as occurs with WBR, middle ear stiffness is reduced and the middle ear system is less stiffness dominated. By charting how much energy is transferring into the middle ear system across a wide range of frequencies, the relative contribution of mass, stiffness, and resistance can be evaluated. In the past, the general consideration in otosclerosis has been that B is the component most affected. Thus, both stiffness and mass have been considered. Shahnaz and Polka (2002) have suggested that G may be more affected than B. That is, in otosclerosis conductance (resistance) may be more affected than stiffness. Thus, findings of increased resistance in the middle ear system may assist in a better understanding of the underlying mechanisms of otosclerosis. More otosclerotic subjects need to be studied before these findings can be clarified.

5.5 Future research

Findings from this study suggest that it is critical to have both gender and race specific normative data. These results should be replicated to assist in generalization and confirmation of the differences found. Measurements of body size, i.e. height, weight, and head circumference, may be useful in determining normative data. In addition, the confounding variable of age

should be addressed. A preliminary study to investigate the effect of age on WBR data should be conducted. This is especially important when comparing to middle ear pathologies, such as otosclerosis, as the diseased group is very likely to have a higher average age. If age is discovered to influence WBR parameters, age specific normative data should be sought. This would allow for better diagnostic capability of the WBR measures.

This study was limited by its exploratory nature. A larger sample size of subjects with otosclerosis would allow for meaningful statistical analysis and reliable results. Such further studies of otosclerosis using WBR measures would be enhanced by several changes in approach. These include: (1) surgical confirmation of the degree and exact location of otosclerosis as the amount of ankylosed growth present at the time of surgery, would be exceedingly helpful in allowing researchers to correlate gradations of otosclerosis with WBR findings. This would allow researchers to narrow in on the precise measurement that would be most clinically and diagnostically beneficial; and (2) testing of subjects both before and after surgery would allow monitoring of treatment effects and changes in the WBR measure.

Variations between this study and others (Feeney & Sanford, 2004) should be explored. One way of doing this would be to test the same subjects using both the Mimosa Acoustics and custom made machines. This would allow for differences between the two machines to be monitored, such as, output stimulus and recording filters, while other confounding variables are minimized.

Once differences in instrumentation and nomenclature have been overcome, further gender and race specific normative data collection would allow for comparisons between different researchers as well as for clinical purposes. Finally, once ample normative data have been gathered, it is essential to complete test performance analysis on the results to calculate both the clinical utility of WBR, as well as its ability to provide a differential diagnosis.

As previously discussed, WBR is a ratio of the sound energy reflected on its way to the cochlea in relation to the sound that reaches the cochlea. Theoretically, then if the impedance of the cochlea were higher in certain pathologies, i.e. Meniere's disease, then this would be observed in the test results. Extending this further, other situations where cochlear fluid pressure changes occur, as with cerebral spinal fluid pressure changes, may affect impedance results. Thus, it might be possible that WBR could be used as a measurement of a change in the pressure, or density of cochlear fluids. Hence, WBR could become a useful diagnostic tool in Meniere's disease, or other similar diseases. This remains to be seen.

Future research using WBR may also be expanded to include other middle ear pathologies. This will increase understanding of the mechano-acoustical properties of the middle ear system and continue to expand knowledge of the relative contribution of mass, stiffness, and resistance to these pathologies. This basic understanding will assist in the development of better diagnosis and treatment of middle ear diseases.

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Appendix I Requested Raw Data from Feeney and Sanford (2004).

	Energy Reflectance (%)		
Frequency (Hz)	Mean	5th Percentile	95th Percentile
250	96.3	92.3	99.1
315	95.1	89.5	98.7
397	92.6	86.2	98.0
500	88.1	77.9	96.8
630	81.8	63.2	93.9
794	75.8	54.2	92.0
1000	68.8	45.1	89.2
1260	63.2	32.3	86.1
1587	60.3	27.1	81.6
2000	58.1	30.0	79.8
2520	48.9	26.2	71.7
3175	35.0	8.3	55.8
4000	23.9	5.3	46.1
5040	32.9	7.2	70.2

Table A1: Mean, 5th, and 95th percentile energy reflectance data from Feeney and Sanford (2004).

Frequency (Hz)	Admittance		
	Mean	5th Percentile	95th Percentile
250	1.45	1.06	2.05
315	1.77	1.26	2.53
397	2.24	1.63	3.24
500	2.82	2.06	4.09
630	3.46	2.58	4.95
794	4.21	3.07	6.46
1000	5.00	3.66	7.93
1260	5.87	4.16	9.32
1587	7.04	4.67	11.64
2000	9.21	5.88	14.76
2520	13.33	7.53	24.09
3175	18.18	8.34	36.72
4000	26.23	6.64	45.76
5040	30.92	3.95	63.87

Table A2: Mean, 5th, and 95th percentile admittance data from Feeney and Sanford (2004).

Frequency (Hz)	Susceptance		
	Mean	5th Percentile	95th Percentile
250	1.44	1.05	2.04
315	1.75	1.26	2.49
397	2.21	1.63	3.17
500	2.75	2.03	4.03
630	3.30	2.48	4.82
794	3.93	2.94	6.22
1000	4.55	3.26	6.85
1260	5.21	3.44	8.01
1587	6.19	3.78	9.60
2000	8.05	4.93	13.32
2520	9.67	-1.89	18.76
3175	11.70	-6.30	21.46
4000	6.51	-18.82	23.15
5040	-5.71	-25.0	33.22

Table A3: Mean, 5th, and 95th percentile susceptance data from Feeney and Sanford (2004).

	Conductance		
Frequency (Hz)	Mean	5th Percentile	95th Percentile
250	0.151	0.029	0.291
315	0.213	0.050	0.393
397	0.343	0.099	0.660
500	0.578	0.213	1.035
630	0.957	0.430	1.729
794	1.390	0.568	2.522
1000	1.963	1.093	4.047
1260	2.543	1.171	4.925
1587	3.113	1.710	6.562
2000	4.001	1.969	7.017
2520	6.678	3.168	17.015
3175	11.279	3.809	27.530
4000	20.837	2.214	44.684
5040	23.140	1.508	51.200

Table A4: Mean, 5th, and 95th percentile conductance data from Feeney and Sanford (2004).

Appendix II Confirmation of Diagnosis

Study subject	Pre-operative diagnosis	Surgical procedure	Amount of bone	Prosthesis type	Window closure	Post-operative diagnosis
OF2	Left otosclerosis	Laser stapedotomy	Significant	Modified piston bucket handle	Vein graft from patient's left hand	Left otosclerosis
OF3	Left otosclerosis	Laser stapedotomy*	N/A	Lippy modified piston bucket handle	Vein graft from patient's left hand	Left otosclerosis

Table A5: Results from operative reports and surgical confirmation of diagnosis. NA = Not available, * Skeeter drill was also used to remove sclerotic growth anteriorly over the footplate.

Appendix III Telephone Questionnaire

Name:

Contact info:

Phone:

Email:

Time that they are available:

How they heard about the study:

To book subjects, the following criteria must be met:

1. Are between the ages of 18-34 years.
2. They have normal hearing (to the best of their knowledge).
3. Have had no middle ear disease/infection.
4. Have had no head trauma.
5. Of Chinese or Caucasian descent:
   a) Have parents and grandparents from mainland China, Taiwan, or Hong Kong, or
   b) Have parents and grandparents of European descent (i.e. non-Hispanic, non-Aboriginal, non-Arab/West Arab, non-Black, and non-East/South/South-East Asian, with white or light skin).

Location of MEL:

Woodward Biomedical Library/IRC building
Room B28
Phone: 822-9474

Appendix IV Email Questionnaire

_____,

Thank you for your interest in our study. The study is, in part, investigating if there are differences between the middle ears of Chinese and Caucasian young adults. The other part is to compare normal hearing subjects to patients with otosclerosis (a type of hearing loss).

To be a participant in the study I need to confirm that:
(1) you are either Caucasian or Chinese (with parents and grandparents from mainland China, Taiwan, or Hong Kong),
(2) you have no history of head trauma or middle ear infections,
(3) you are between the ages of 18-34, and
(4) you have normal hearing to the best of your knowledge.

If you meet these criteria, I can arrange a time for you to participate in the study. Participation involves a hearing test to confirm that you have normal hearing, followed by some middle ear measurement tests. All of the tests are easy to participate in and are not invasive or painful. There is a $10 honorarium for 1 hour of participation. Testing takes place in room B28 of the Woodward IRC building on UBC campus.

Please let me know when you will be available for the study so that I can set up an appointment with you. If you need more information or have any questions, please contact the Middle Ear Lab at (604) 822-9474, or email at mel@audiospeech.ubc.ca.

Thank you,
Middle Ear Lab Researchers

Appendix V Consent Form for Otosclerotic Subjects

THE UNIVERSITY OF BRITISH COLUMBIA
&
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Consent Form

Project Title:

Wide Band Reflectance in Surgically Confirmed Otosclerosis

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Purpose:

You have been invited to participate in this research project because we are studying patients with otosclerosis who have been booked for surgery. We want to improve how we test for otosclerosis (the fixation of the third ear bone in your middle ear) that causes hearing loss.

The usual hearing test that is done before surgery includes a measure of your hearing in a sound room. This test is called pure-tone audiometry. The usual measurement of the eardrum and middle-ear will be done with standard tympanometry. These are both safe and routine tests. You may remember that you may feel some pressure with the tympanometry test as well as a low volume tone.

For this study, we want to learn more about newer tests of middle ear function. These tests are called multi-frequency tympanometry and wide band reflectance. These tests measure a much wider frequency range than the regularly used tests. This provides a more detailed picture of your middle ear. We expect to find two main results:

1. The new tests will show a difference between normal middle ears and ears of patients with otosclerosis.
2. Used together, these tests will diagnose otosclerosis better than the old tests.

Your participation in these extra tests is voluntary. If you do not take part, your care will continue normally. If you choose to volunteer, you may stop the tests at any time. Withdrawal will not change your care.

Study Procedures:

If you do choose to volunteer to participate in this research study, all testing will be conducted by Dr. N. Shahnaz, Ph.D., who is a certified audiologist, or by his co-investigator Karin Bork under his supervision. The tests will be done as part of your pre-operative evaluation in the Rotary Hearing and ENT clinic at St. Paul's Hospital. Should there be any findings from this study that may be useful to your doctor, this information will be communicated to him/her with your permission.

Before the tests start we will look at your eardrum and ear canal. An Ear, Nose & Throat physician will clean your ear canal if necessary.

The tests for this research study are:

1) Transient-evoked otoacoustic emissions,
2) Multi-frequency tympanometry, and
3) Wide band reflectance.

The three tests together take approximately fifteen minutes. This will be in addition to the 20-30 minutes required for the usual tests before surgery.

In each of the three tests, a small earphone will be placed into the entrance of your ear canal using a soft and delicate plastic or sponge tip. It is designed not to cause any allergic reactions. The presence of the earphone may be a bit uncomfortable to some patients, but not painful. The earphone and the attached tip pose no danger to your ear or hearing and has been used widely in the testing of newborns, children, and adults.

The first test, transient-evoked otoacoustic emissions, is commonly used in clinics to detect hearing loss. You will hear a clicking sound through a small earphone placed at the entrance of your ear canal. The level of sound is the same as normal talking. Echoes to the sound come back out of your ear. These echoes are measured by a computer. This test will give us information about your middle and inner ear. It will take 2-3 minutes in each ear.

The second test, multi-frequency tympanometry, presents a pure tone while the air pressure in the ear canal is changed. We will test at the frequencies of speech. It will take about 4 minutes in each ear.

The third test, wide band reflectance, presents chirping sounds. This helps us see how well the middle ear reacts to sounds that span the human speech range. This test will take about 2-3 seconds for each ear.

Advantages

These are tests of middle ear function. They are not treatments. We hope these tests will better help us to check middle ears. We hope to improve the diagnosis and treatment of otosclerosis in the future. There are no direct benefits to you.

Disadvantages

The tympanometry tests give small pressure changes in the ear. All tones that are presented during the testing are safe. Pressure changes are well below any level that could damage your eardrum or middle ear. However, as a safety measure, the tester will carefully examine each ear before beginning. If you choose to end your participation in this study, we will stop the testing at any time. There will be no change in the care you would normally receive.

How your information will be used

Your test results will be compared with test results from adults with no middle ear disease. We will find out if these new tests are better to separate normal and diseased middle ears. Your results will also be compared to the observations of your doctor during the surgery on your ear. This will show if the tests are correct in what they tell us about otosclerosis.

Confidentiality:

Your identity will be coded using a code known only to the researchers. All information that is collected from you will remain confidential. Only group results or coded individual results will be given in any reports about the study. Coded results only will be kept in computer files on a password protected hard drive. No personal information will be kept in these files.

No private or confidential information that discloses your identity will be released or published, unless required by law, without your specific consent. However, research records and medical records identifying you may be inspected in the presence of the investigator or his designate by representatives of Health Canada, and the UBC Research Ethics Board for the purpose of monitoring the research. No records which identify you by name or initials will be allowed to leave the Investigators' offices.

Compensation for Injury:

Signing this consent form in no way limits or restricts your legal rights against the investigators, or anyone else.

Consent:

I, _____, have read the above test protocol and I consent to participate in this study undertaken by Dr. Navid Shahnaz, Dr. Brian David Westerberg, Dr. Sipke Pijl, and Karin Bork at St. Paul's Hospital. The researcher tells me that my participation

in this study is completely voluntary. The researcher also assures me that I may withdraw from this research at any time without consequences.

If I have any question or desire further information with respect to this study, I may contact Dr. Navid Shahnaz at 604-822-5953. If I have any concerns about my treatment or rights as a research subject, I may contact the Director at the Office of Research Services at the University of British Columbia, at 604-822-8598, or Dr. Stephan Shalansky, Chair – UBC/Providence Health Care Research Ethics Board, at (604) 682-2355 local 62325.

I have received a copy of this consent form for my records.

_____ _____

Subject signature Date

_____

Subject name (please print)

_____ _____

Signature of principle/co- investigator Date

_____

Name of principle/co-investigator (please print)

Appendix V Analysis of Variance (ANOVA) Tables for Power Absorption, Admittance, Susceptance, and Conductance Data with regard to Normal Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Significance
RACE	238507.602	1	238507.602	12.439	.001
GENDER	29303.929	1	29303.929	1.528	.218
EAR	15017.481	1	15017.481	0.783	.377
RACE * GENDER	41062.205	1	41062.205	2.141	.145
RACE * EAR	5684.753	1	5684.753	0.296	.587
GENDER * EAR	270.822	1	270.822	0.014	.905
RACE * GENDER * EAR	1269.102	1	1269.102	0.066	.797
Error	4506021.287	235	19174.559		

Table A6: Summary of ANOVA for power absorption data.

Source	Type III Sum of Squares	df	Mean Square	F	Significance
RACE	83.346	1	83.346	12.896	.000
GENDER	30.016	1	30.016	4.644	.032
EAR	0.215	1	0.215	0.033	.856
RACE * GENDER	11.698	1	11.698	1.810	.180
RACE * EAR	20.024	1	20.024	3.098	.080
GENDER * EAR	1.077	1	1.077	0.167	.683
RACE * GENDER * EAR	3.344E-02	1	3.344E-02	0.005	.943
Error	1512.308	234	6.463		

Table A7: Summary of ANOVA for admittance data.

Source	Type III Sum of Squares	df	Mean Square	F	Significance
RACE	113.275	1	113.275	17.270	.000
GENDER	67.912	1	67.912	10.354	.001
EAR	6.929E-02	1	6.929E-02	0.011	.918
RACE * GENDER	4.332	1	4.332	0.660	.417
RACE * EAR	17.912	1	17.912	2.731	.100
GENDER * EAR	0.133	1	0.133	0.020	.887
RACE * GENDER * EAR	1.086E-02	1	1.086E-02	0.002	.968
Error	1541.389	235	6.559		

Table A8: Summary of ANOVA for susceptance data.

Source	Type III Sum of Squares	df	Mean Square	F	Significance
RACE	9.131	1	9.131	2.578	.110
GENDER	14.999	1	14.999	4.234	.041
EAR	4.907	1	4.907	1.385	.240
RACE * GENDER	20.531	1	20.531	5.796	.017
RACE * EAR	11.877	1	11.877	3.353	.068
GENDER * EAR	0.319	1	0.319	0.090	.764
RACE * GENDER * EAR	0.148	1	0.148	0.042	.838
Error	839.487	237	3.542		

Table A9: Summary of ANOVA for conductance data.