Effect of Age and Direction of Pressure Sweep on Wideband Absorbance

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June- 2026

CERTIFICATE

This is to certify that this dissertation entitled **'Effect of Age and Direction of Pressure Sweep on Wideband Absorbance'** is a bonafide work submitted as part of fulfilment of the degree of Master of Science **(Audiology)** of the student with Registration Number P01II24S023015. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled **'Effect of Age and Direction of Pressure Sweep on Wideband Absorbance'** is the result of my own study under the guidance of Dr. Animesh Barman, Professor of Audiology, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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June, 2026	P01II24S023015

॥ श्रीकृष्णार्पणमस्तु ॥

(Srikrishnaarpanamastu – May this work be offered to Lord Krishna)

योगस्थः कुरु कर्माणि सङ्गं त्यक्त्वा धनञ्जय ।

सिद्ध्यसिद्ध्योः समो भूत्वा समत्वं योग उच्यते ॥

(Bhagavad Gita 2.48)

Transliteration:

Yogasthaḥ kuru karmāṇi saṅgaṁ tyaktvā dhanañjaya;

Siddhy-asiddhyoḥ samo bhūtvā samatvaṁ yoga ucyate.

Meaning:

"Perform your duties with steadfast devotion, abandoning attachment to success or failure. Such equanimity is called Yoga."

With profound devotion and gratitude, I humbly dedicate this dissertation to Lord Krishna, whose divine grace have been my constant source of strength and inspiration. His words in the Bhagavad Gita taught me to remain sincere in my efforts, persevere through challenges, and place faith in the journey rather than the outcome. Whatever I have achieved through this work is offered at His lotus feet with humbleness and reverence.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
ANSI	American National Standards Institute
AP	Ambient Pressure
dB HL	Decibel Hearing Level
daPa	Decapascal
EAC	External Auditory Canal
ICC	Intraclass Correlation Coefficient
IRB	Institutional Review Board
LDL	Loudness Discomfort Level
M	Mean
MFT	Multifrequency Tympanometry
PCA	Principal Component Analysis
SD	Standard Deviation
TPP	Tympanometric Peak Pressure
WAI	Wideband Acoustic Immittance
WBA	Wideband Absorbance

ABSTRACT

Aim: This study investigated the effect of ear-canal pressure sweep direction (ascending vs. descending) on wideband absorbance (WBA) in individuals with clinically normal hearing and middle ear across children, adolescents, and young adults. The study aimed to: (i) compare WBA at tympanometric peak pressure (TPP) and ambient pressure (AP) under each sweep condition across children, adolescents, and young adults; (ii) examine the influence of sweep direction on WBA at both pressure conditions across children, adolescents, and young adults; and (iii) determine whether the effect of sweep direction on WBA differs across children, adolescents, and young adults at both TPP and AP, reflecting developmental differences in middle-ear function.

Methods: Forty-five individuals (age range: 5–30 years) with normal hearing and normal middle ear function were divided into three equal groups: children, adolescents, and young adults (n = 15 each). WBA was measured using the GSI TympStar Pro™ under ascending (−400 to +200 daPa) and descending (+200 to −400 daPa) pressure sweep directions at both tympanometric peak pressure (TPP) and ambient pressure (AP), at a constant pump speed of 200 daPa/s. Principal component analysis was done to group frequency-specific absorbance data into four regions, and Mixed ANOVA was used to examin the effects of age group, pressure condition, and sweep direction.

Results: A frequency-specific absorbance pattern was observed across all groups, with lower absorbance at low frequencies, highest at mid frequencies, and reduced at high frequencies. Absorbance was significantly higher at TPP than AP in low and mid frequency regions ($p < .001$), while the reverse was observed at high frequencies ($p = .041$). Descending sweeps produced significantly higher absorbance values than ascending sweeps across all frequency regions ($p < .001$). Significant pressure condition × sweep direction interactions were found across all regions ($p < .001$). Notably, three-way interactions among pressure condition, sweep direction, and age group were observed in the region of around 2000 to 4000 Hz ($p = .015$; $p = .045$), with a significant age effect around 4000 Hz ($p = .024$).

Conclusion: WBA measurements are significantly influenced by both pressure condition and pressure sweep direction. Age-related differences, predominantly in mid-frequency regions, suggest a maturational contribution to WBA patterns. These findings emphasize the clinical importance of standardizing pressure conditions, sweep direction, and age-specific consideration when interpreting WBA measurements.

Keywords: Wideband Absorbance, Pressure Sweep Direction, Tympanometric Peak Pressure, Middle-Ear Function, Developmental Age Groups, Normal Hearing.

CHAPTER 1
INTRODUCTION

The auditory system relies on the efficient transmission of sound from the external environment to the inner ear. This process begins when sound waves enter the external auditory canal and reaches to the tympanic membrane, causing it to vibrate. These vibrations are transmitted through the ossicular chain of the middle ear to the cochlea, where mechanical energy is converted into neural impulses that are interpreted as sound by the brain (Martin and Clark, 2003). The middle ear plays a crucial role in hearing by functioning as an impedance-matching system between the air-filled external ear and the fluid-filled cochlea. Without this mechanism, a large portion of incoming acoustic energy would be reflected at the air-fluid interface, resulting in inefficient sound transmission. Through the combined action of the tympanic membrane and ossicular chain, the middle ear enhances the transfer of acoustic energy to the cochlea and ensures optimal auditory sensitivity (Hunter et al., 2013). The efficiency of sound transmission through the middle ear is influenced by the anatomical and physiological characteristics of the auditory system. Any alteration in the tympanic membrane, ossicular chain, middle-ear cavity, or external auditory canal can affect the movement of acoustic energy and modify middle-ear transfer characteristics (Norrix et al., 2013). Such variations may occur because of developmental changes, aging, gender-related differences, ethnicity, or the presence of middle-ear pathology (Beers et al., 2010; Mazlan et al., 2015; Shahnaz and Davies, 2006).

Age-related changes are particularly important because the auditory system undergoes continuous maturation throughout childhood and gradual structural alterations with advancing age. During early life, the external auditory canal is smaller and more compliant, while the middle ear is characterized by a relatively small cavity volume, immature ossicular orientation, and greater mass dominance. As growth progresses, enlargement of the ear canal and middle-ear cavity, maturation of the tympanic membrane, and improved ossicular alignment contribute to more efficient sound transmission and adult-like middle-ear function (Keefe et al., 1993; Saunders and Kaltenbach, 1983; Sanford and Feeney, 2008). Developmental changes continue throughout childhood and adolescence, resulting in gradual improvements in middle-ear mechanics and acoustic transfer efficiency. On the other hand, advance aging is associated with structural and mechanical alterations such as reduced elasticity of middle-ear tissues, degenerative changes in ossicular joints, and increased stiffness of the middle-ear system, all of which may influence sound transmission characteristics (Feeney & Sanford, 2004; Hall, 1979).

Tympanometry to assess middle ear function

Assessment of middle-ear function is an essential component of audiological evaluation because abnormalities in the middle ear can significantly affect sound transmission to the cochlea. Immittance audiometry is a non-invasive and objective procedure used to evaluate the acoustic transfer characteristics of the middle ear by measuring the relationship between sound energy entering the ear canal and the energy transmitted through or reflected from the middle-ear system (Keefe et al., 1993; Margolis et al., 1999). The two fundamental concepts underlying immittance measurements are acoustic impedance and acoustic admittance. Acoustic impedance refers to the opposition of flow of sound energy by the auditory system, whereas acoustic admittance is the flow of sound energy, that is transmitted through the system. Because admittance is the reciprocal of impedance, it provides an indication of the mobility and efficiency of the middle-ear mechanism in transmitting sound (Margolis and Hunter, 2000).

Among the various immittance procedures, tympanometry is the most commonly used clinical tool for assessing middle-ear status. The tympanogram provides information regarding middle-ear pressure, tympanic membrane mobility, ear canal volume, and overall middle-ear function (Margolis et al., 2000). In routine clinical practice, tympanometric assessment is most commonly performed using a 226 Hz probe tone. Conventional 226 Hz tympanometry has proven useful in identifying middle-ear disorders such as middle-ear effusion, Eustachian tube dysfunction, tympanic membrane abnormalities, and ossicular pathology (Feldman, 1977; Gaihede, 2000; Renvall and Holmquist, 1976). The tympanometry procedure is simple, rapid, and widely accepted as a standard clinical measure of middle-ear function.

Despite its clinical utility, conventional tympanometry has several limitations. The middle ear is a frequency-dependent system, and assessment using a single low-frequency probe tone may not provide its complex mechanical behaviour. Thus, subtle abnormalities affecting middle-ear structures may undetected when evaluation is completely restricted to a 226 Hz probe tone (Hunter et al., 2013; Shahnaz & Polka, 1997). In some cases, individuals with middle-ear pathology may exhibit tympanograms that appear clinically normal despite the presence of abnormalities affecting sound transmission (Feeney et al., 2003; Hunter & Margolis, 1992). The limitations of conventional tympanometry become particularly evident when assessing populations with age-related differences in middle-ear anatomy and mechanics. Developmental changes during childhood and structural alterations associated with aging can influence tympanometric findings and complicate interpretation when adult normative criteria are applied universally (Feeney and Sanford, 2004; Keefe and Levi, 1996; Sanford and Feeney, 2008). Furthermore, several studies have demonstrated that procedural factors such as pressure sweep direction and sweep rate may influence tympanometric peak pressure, static admittance, and tympanogram morphology because of the hysteresis and viscoelastic properties of the middle-ear system (Decraemer et al., 1984; Shanks and Wilson, 1986; Therkildsen and Gaihede, 2005). These limitations highlight the need for more comprehensive evaluation of middle-ear function across a wider frequency range. This could be achieved by of multifrequency tympanometry, wideband acoustic immittance, which offer greater insight into the frequency-specific characteristics of middle-ear sound transmission.

Since the mechanical properties of the middle ear vary across frequencies, to address this, multifrequency tympanometry (MFT) was introduced, allowing assessment of middle-ear responses across multiple probe frequencies and providing additional information regarding resonance frequency and middle-ear mechanics (Margolis and Goycoolea, 1993; Margolis et al., 1985; Shahnaz and Polka, 1997). Although MFT offered greater insight into middle-ear function than conventional tympanometry, its clinical application remained limited. Measurements obtained at higher probe frequencies are susceptible to standing-wave effects within the ear canal, making the results sensitive to probe placement and ear canal dimensions. In addition, tympanograms recorded at higher frequencies often exhibit multiple peaks and troughs, making interpretation more complex and reducing clinical practicality (Feeney et al., 2014; Fowler and Shanks, 2002; Margolis et al., 1999; Sanford et al., 2009).

Wideband Acoustic Immittance (WAI)

To overcome the limitations of tympanometry, wideband acoustic immittance can be opted for as a more advanced approach for assessing middle-ear function. Unlike conventional and multifrequency tympanometry, WAI uses a broadband click stimulus and evaluates sound transmission across a wide frequency range, typically from 226 Hz to ~8000 Hz. This enables assessment of middle-ear transfer characteristics across multiple frequencies within a short testing period (Hunter et al., 2013; Liu et al., 2008).

When sound enters the ear canal, a portion of the acoustic energy is transmitted through the middle ear while the remaining energy is reflected back into the ear canal. WAI quantifies this interaction through measures such as reflectance and absorbance. Reflectance represents the proportion of sound energy reflected from the middle ear, whereas absorbance represents the proportion of energy absorbed and transmitted through the middle-ear system. Therefore, absorbance provides a direct estimate of the efficiency of middle-ear sound transmission across frequencies (Keefe and Levi, 1996). Wideband absorbance (WBA) values range from 0 to 1, where a value of 1 indicates complete absorption of sound energy and a value of 0 indicates complete reflection of sound energy (Stinson, 1990). In individuals with normal middle-ear function, absorbance is generally low at very low frequencies, reaches its highest values within the mid-frequency region where sound transmission is most efficient, and gradually decreases at higher frequencies (Liu et al., 2008).

Compared to conventional immittance measures, WAI offers several clinical advantages. It provides frequency-specific information regarding middle-ear transfer function, is less influenced by probe placement, and can be measured either at ambient pressure or across tympanometric pressure sweeps (Keefe and Levi, 1996; Voss et al., 2001). Furthermore, WAI has demonstrated greater sensitivity in identifying middle-ear abnormalities which may not be detected using conventional tympanometry, including middle-ear effusion, Eustachian tube dysfunction, ossicular abnormalities, and other conductive pathologies (Hunter et al., 2013; Margolis et al., 1999).

Because of its broad frequency coverage, reduced susceptibility to measurement artifacts, and improved diagnostic sensitivity, WAI has emerged as a valuable tool for middle-ear assessment in both clinical and research settings. However, several factors, including age-related developmental changes and procedural variables such as pressure sweep direction, may influence wideband absorbance measurements. Understanding these influences is essential for accurate interpretation of WAI findings.

Factors influencing WAI

Wideband absorbance (WBA) is influenced by the anatomical and physiological characteristics of the auditory system. Since the outer and middle ear undergo continuous developmental and age-related changes throughout life, absorbance patterns also vary across age groups. These variations reflect differences in ear canal dimensions, middle-ear cavity volume, tympanic membrane characteristics, ossicular mechanics, and resonance properties, all of which influence the efficiency of sound transmission through the middle ear (Beers et al., 2010; Mazlan et al., 2015). As developmental progresses, maturation of the outer and middle ear improves sound transmission efficiency and gradually alters absorbance characteristics toward adult-like patterns (Keefe and Levi, 1996; Sanford & Feeney, 2008; Saunders and Kaltenbach, 1983). Children generally exhibit lower absorbance at low frequencies and higher absorbance at mid- and high frequencies compared to adults, reflecting differences in middle-ear anatomy and resonance characteristics (Hunter et al., 2008; Keefe et al., 1993). These age-related differences gradually reduce with maturation, and absorbance patterns become increasingly similar to those of adults during late childhood and adolescence (Mishra et al., 2017; Voss and Allen, 1994).

In addition to biological factors such as age and maturation, procedural variables may also influence middle-ear measurements. Pressure sweep direction refers to whether ear-canal pressure is varied from positive to negative values (descending sweep) or from negative to positive values (ascending sweep). Although both approaches assess middle-ear function across a range of pressure conditions, previous studies have demonstrated that the direction of pressure change can affect immittance measurements (Decraemer et al., 1984; Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005). Descending pressure sweeps generally produce broader tympanograms with fewer notches, whereas ascending sweeps may result in greater notching and shifts in tympanometric peak pressure (Decraemer et al., 1984; Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005). These findings indicate that measured middle-ear characteristics may be influenced by procedural factors in addition to the underlying mechanical properties of the auditory system. The influence of pressure sweep direction has also been explored in wideband tympanometry. Tympanometric peak pressure obtained using wideband absorbance measurements may vary as a function of sweep direction and sweep rate, suggesting that wideband measures are similarly affected by the mechanical behaviour of the middle-ear system during pressure changes (Liu et al., 2008). Furthermore, absorbance measured at tympanometric peak pressure is generally higher than absorbance measured at ambient pressure, particularly at low and mid frequencies, indicating more efficient sound transmission when pressure across the tympanic membrane is equalized (Feeney et al., 2017; Karuppannan & Barman, 2020; Liu et al., 2008). Therefore, further investigation is needed to examine the combined influence of age and pressure sweep direction on wideband absorbance measurements.

1.1 Need for the Study

Wideband acoustic immittance (WAI), particularly wideband absorbance (WBA), has emerged as an advanced method for evaluating middle-ear function because it provides frequency-specific information regarding the transmission of acoustic energy across a broad frequency range. Compared to conventional tympanometry, WBA offers a more comprehensive assessment of middle-ear mechanics and has demonstrated greater sensitivity in identifying subtle middle-ear abnormalities that may not be detected using single-frequency immittance meas0ures (Aithal et al., 2019; Hunter et al., 2013).

Various studies have consistently shown that WBA is influenced by age-related anatomical and physiological changes in the auditory system. Developmental maturation of the external and middle ear affects sound transmission characteristics, resulting in age-dependent variations in absorbance patterns across frequencies (Beers et al., 2010; Downing et al., 2022; Hunter et al., 2008; Mishra et al., 2017; Voss & Allen, 1994). These emphasize the importance of considering age when interpreting WBA measurements and highlight the need for age-specific normative data.

Another factor known to influence middle-ear measurements is the direction of ear-canal pressure sweep. Various studies showed ascending and descending pressure sweeps can affect tympanometric peak pressure, static admittance, and tympanogram morphology because of the hysteresis and viscoelastic properties of the middle-ear system (Decraemer et al., 1984; Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005). More recent investigations have suggested that pressure-related factors may also influence wideband absorbance measurements, particularly under tympanometric peak pressure conditions (Feeney et al., 2017; Karuppannan & Barman, 2020; Liu et al., 2008).

Although the independent effects of age and pressure sweep direction have been reported in the literature, their combined influence on wideband absorbance remains poorly understood. Existing studies have largely focused either on developmental changes in WBA or on the influence of pressure conditions in adult populations. Consequently, there is limited information regarding whether the effect of pressure sweep direction varies across different age groups and whether developmental differences in middle-ear mechanics influence absorbance measurements obtained under different sweep conditions.

Therefore, the present study was undertaken to investigate the effect of age and direction of pressure sweep on wideband absorbance in individuals with normal hearing and normal middle-ear function across childhood, adolescence, and young adulthood. The findings of this study are expected to contribute to a better understanding of developmental variations in middle-ear sound transmission and facilitate the selection of optimal measurement protocols for clinical and research applications of wideband absorbance.

1.2 Aim of the study

The aim of this study is to investigate the effect of ear-canal pressure sweep direction (ascending vs. descending) on wideband absorbance in individuals with clinically normal hearing across different age groups (childhood to adulthood).

1.3 Objectives

I. To compare wideband absorbance values across frequencies at tympanometric peak pressure (TPP) and ambient pressure in individuals from different age groups, under each pressure sweep condition.

II. To examine the influence of pressure sweep direction (ascending vs. descending) on wideband absorbance across frequencies at tympanometric peak pressure (TPP) and AP in different age groups.

III. To determine whether the effect of sweep direction on wideband absorbance differs across age groups, at both pressure conditions (TPP and AP), reflecting developmental or age-related differences in middle-ear function.

CHAPTER 2

REVIEW OF LITERATURE

The effective transmission of the sounds to the inner ear depends on mechano-acoustical properties of the middle ear. Any structural or physiological changes in the middle ear can affect the sound transduction to the inner ear (Norrix et al., 2013). This change may be due to a variety of factors, such as the presence of middle ear pathology or anatomical differences observed by gender, ethnicity, and maturation, which can attenuate frequency-specific sound transmission (Beers et al., 2010; Mazlan et al., 2015; Shahnaz & Davies, 2006).

The change in sound transmission through the middle ear can easily be assessed by using tympanometry, it is a rapid and non-invasive diagnostic technique, which uses a single or multiple frequencies tones and measures transmission of sound energy across the pressure (Keefe et al.,1993; Margolis et al., 1999; Shahnaz & Polka, 2002; Voss & Allen, 1994). However, the introduction of WBA tympanometry in recent years has the potential to assess the middle ear function at a wide range of frequencies and can also be measured even without any change in pressure (Keefe et al., 1993; Liu et al., 2008). Wideband tympanometry implements a more comprehensive analysis of tympanic cavity dynamics than the traditionally used 226-Hz single frequency tympanometry as it provides particulars about the acoustic energy reaching the cochlea and sensory receptors across a wide range of sound frequencies up to or above 8000 Hz. However, there are several factors that can influence the sound transmission through the middle ear, including mechanical properties of middle ear, structural changes in one or more parts of the middle ears, procedural variations and pathological conditions of middle ear structures. Thus, the information gathered from the literature has been arranged under the following headings:

- Age-related changes in auditory system structures and functions:
- Effect of maturation and age on immittance measurement
- Effect or pressure sweep direction (ascending and descending) in immittance measurement
- Effect of middle ear disorders in immittance measurement:
- Other general factors and their effect on immittance measurement:
- Reliability of immittance measurement
- Effect of maturation and age on wideband tympanometry measurement
- Effect of pressurization in wideband tympanometry measurement

2.1. Age-related changes in the external and middle ear structures and functions:

Age-related anatomical and physiological changes of the outer and middle ear take place throughout life, with the most changes occurring during early childhood and older adulthood (Mazlan et al., 2015). These differences are mainly maturation and structural development of the tympanic membrane, external auditory canal (EAC), and middle ear system (Ruah et al., 1991). In newborns and young infants, the EAC is shorter, narrower, more compliant, and mainly cartilaginous due to incomplete ossification (Holte et al., 1991; McLellan and Webb, 1957); Lee, 2012; Kanka et al., 2020). Compliance of the canal walls is highest immediately after birth and reduces rapidly within the first few months of life, as the canal walls stiffen and ossify (Holte et al., 1991). Throughout infancy and early childhood, the EAC increases quickly in length, diameter, and rigidity, and the tympanic membrane gradually becomes an adult-like orientation (Keefe et al., 1993). Other anatomical factors, including vernix caseosa and unclear tympanic membrane landmarks, can further complicate otoscopic and immittance assessments in infants (McLellan & Webb, 1957). Development of the EAC continues throughout childhood, and by early adolescence the canal is nearly adult-like, although some age-related differences in canal curvature and cross-sectional area may still continue (Balouch et al., 2023; Voss et al., 2025). Significant inter-subject variation in EAC dimensions has also been reported, emphasizing the importance of individualized acoustic assessment (Stinson, 1990). Research has shown that EAC volume increases non-linearly with age because of growth in both the cartilaginous and bony portions of the canal (Noh & Lee, 2012). Whereas, auricular growth reaches near-adult size around puberty and very minimal changes takes place during adulthood (Heathcote, 1995). Functionally, the outer ear plays an important role in sound transmission and resonance. Thus, acoustic characteristics are strongly influenced by EAC dimensions and compliance, both of which change with age. In neonates, the smaller and more compliant canal shifts resonance toward higher frequencies and reduces amplification, resulting in poorer sensitivity to high-frequency sounds (Rubel, 1984; Saunders et al.). As the ear matures, resonance characteristics gradually resemble those of adults, leading to improvements in spectral sensitivity and sound localization.

During adulthood, the anatomy of the outer ear remains relatively stable, with only minor changes in canal size and shape (Staab, 2023). However, ageing is associated with several physiological changes, including thinning of the epithelial lining, reduced glandular activity, changes in cerumen composition, increased hair growth, and reduced cartilaginous support. These factors may contribute to cerumen impaction and ear canal collapse in older adults (Zalewski, 2015; Staab, 2023). Additionally, mastoid volume increases until approximately 30 years of age before gradually declining (Lee et al., 2005).

In neonates and young infants, the middle ear is predominantly mass-dominated because of residual mesenchymal tissue, small middle ear cavity volume, compliant ear canal walls, and immature ossicular orientation (Keith, 1973; Keefe and Levi, 1996; Saunders et al., 1983). These characteristics reduce the efficiency of acoustic energy transfer and alter immittance measurements, particularly at low frequencies, resulting in lower reflectance and poorer sound transmission through the middle ear (Keefe et al., 1993; Keefe and Levi, 1996). Additional developmental factors, including a more horizontal tympanic membrane, incomplete fusion of the tympanic ring, and persistence of mesenchymal tissue or amniotic fluid, contribute to high compliance and variable tympanic membrane mobility during infancy (Ruah et al., 1991; Saunders et al., 1983; Weatherby & Bennett, 1980). During childhood, progressive enlargement and pneumatization of the middle ear cavity, ossicular remodeling and alignment, maturation of the Eustachian tube, and increasing stiffness of the external and middle ear structures improve middle ear mechanical efficiency and sound transmission (Paparella et al., 1994; Sadler-Kimes et al., 1989). These developmental changes facilitate the transition from a mass-dominated to a stiffness-controlled middle ear system, resulting in more stable impedance characteristics and better transmission of acoustic energy across frequencies. Histological maturation of the tympanic membrane, including collagen compaction, reduced vascularity, and elastin redistribution, further contributes to improved acoustic transmission and middle ear stability through adolescence and early adulthood (Ruah et al., 1991).

Middle ear mobility is reported to be maximal during early and middle adulthood, after which age-related degenerative changes gradually increase stiffness and reduce viscoelasticity of the middle ear system ((Hall, 1979). Degeneration of ossicular joints, calcification, cartilage thinning, bone remodeling, and reduced compliance alter impedance characteristics and reduce the efficiency of sound transmission in older adults (Gaihede, 2000; Lannigan et al., 1995). These changes increase middle ear impedance and decrease compliance, thereby reducing the efficiency of acoustic energy transmission, especially at higher frequencies (Hall, 1979; Wedel & Opitz, 1978).

Overall, age-related anatomical and physiological changes across the outer and middle ear significantly influence the mechanical and acoustical properties of the auditory system. These alterations affect impedance, compliance and acoustic energy transfer, thereby influencing audiological measurements and perception abilities across the age group. Understanding these developmental and degenerative changes is essential for accurate interpretation of audiological evaluation.

2.2. Effect of maturation and age on immittance measurement

Age-related anatomical and physiological changes in the middle ear have a considerable influence on its mass and stiffness characteristics, which affects acoustic immittance and sound transmission across the age (Mazlan et al., 2015). In neonates and young infants, the middle ear is predominantly mass-dominated (Keith, 1973). These characteristics reduce the efficiency of acoustic energy transfer and produce atypical acoustic responses, including enhanced low-frequency transmission, reduced reflectance at lower frequencies, and increased reflectance at higher frequencies. As a result, infants commonly demonstrate atypical tympanometric patterns such as flat or multi-peaked tympanograms when assessed using a 226 Hz probe tone, limiting the diagnostic reliability of conventional low-frequency tympanometry for evaluating infant middle ear status (Keefe & Levi, 1996).

During the early postnatal period, rapid maturation of middle ear structures causes noticeable changes in immittance characteristics, with improved middle ear mechanical efficiency and sound transmission as the system gradually transforms from a mass-dominated mechanism to a more stiffness-controlled system (Holte et al., 1991; Meyer et al., 1997; Sanford & Feeney, 2008). These maturational changes are accompanied by progressive increases in resonance frequency, typically shifting from values below 550 Hz in neonates to approximately 800–1200 Hz within the first few months of life (Holte et al., 1991; Sanford & Feeney, 2008). Tympanometric patterns also become more stable with maturation, changing from irregular or multiple-peaked responses in newborns to single-peaked, adult-like tympanograms by approximately 4–6 months of age (Bennett, 1975; Meyer et al., 1997).

Admittance values generally increase with age, while absorbance and reflectance characteristics gradually approach adult-like patterns as middle ear resonance properties mature (Sanford & Feeney, 2008; Shahnaz et al., 2014). Static immittance measures also demonstrate age-related alterations, with compliance values increasing during early adulthood, remaining relatively stable through middle age, and gradually decreasing after approximately 60 years because of stiffening and degenerative changes within the middle ear system (Hall, 1979).

Overall, middle ear immittance characteristics undergo rapid maturation during infancy, continue to develop throughout childhood, remain relatively stable during early and middle adulthood, and gradually decline in older age. Parameters such as admittance, compliance, resonance frequency, absorbance, and reflectance characteristics are therefore strongly influenced by both age and frequency. Understanding these ageing-related changes is essential for accurate interpretation of clinical immittance findings across different age groups.

2.3. Effect or pressure sweep direction (ascending and descending) in immittance measurement

Pressure sweep direction has been shown influence on tympanometric and immittance measurements, including tympanometric peak pressure, peak admittance, tympanometric morphology, and sealing characteristics during recording. In tympanometry measurement, tympanogram can be obtained by varying pressure in the ear canal. Pressure variation can be either an ascending sweep (-/+), in which ear-canal pressure changes from negative to positive values, or a descending sweep (+/-), in which pressure changes from positive to negative values. Variations between these sweep directions are mainly due to hysteresis and the viscoelastic behavior of the tympanic membrane, ossicular system, which changes the mechanical response of the middle ear during pressure transitions (Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005). These biomechanical properties influence middle ear impedance, admittance, and acoustic energy transfer, thereby affecting the accuracy and repeatability of immittance measurements.

Several studies have demonstrated systematic differences in tympanometric measures between ascending and descending pressure sweeps. Tympanometric peak pressure is generally more positive during ascending sweeps and more negative during descending sweeps, with reported differences of approximately 10–12 daPa in normal adults (Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005), this occurs likely due to hysteresis within the middle ear system, where the viscoelastic properties of the tympanic membrane and ossicular chain produce different mechanical responses during positive-to-negative and negative-to-positive pressure transitions. However, increasing sweep rates may further influence the directional differences, particularly at higher probe-tone frequencies (Shanks & Wilson, 1986). This may occur because the middle ear system may not respond instantly to rapid pressure transitions at faster sweep rates, resulting in mechanical lag, greater viscoelastic damping, and delayed pressure equilibration within the middle ear system (Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005). Variations in peak static admittance, conductance, susceptance, reactance, and phase angle have also been reported across opposite sweep directions, indicating that middle ear mechanical behavior changes dynamically during pressure alteration (Decraemer et al., 1984; Shanks & Wilson, 1986). These variations may occur because pressure changes alter the relative contribution of stiffness-controlled and mass-controlled components of the middle ear system, thereby affecting resonance behavior and acoustic energy transmission through the middle ear (Decraemer et al., 1984).

The influence of pressure sweep direction appears to be frequency dependent and is more prominent near middle ear resonance. Ascending sweeps have been associated with reduced phase angles, greater tympanometric notching, and lower peak susceptance at higher probe-tone frequencies, whereas descending sweeps typically produce broader tympanometric patterns with less notching (Shanks & Wilson, 1986). Similarly, differences in the extrema of admittance components, including susceptance, conductance, admittance, and reactance, have been observed across 220 Hz and 660 Hz probe tones when opposite pressure sweep directions were used (Decraemer et al., 1984)).These variations are likely related to changes in resonance characteristics and phase relationships of the middle ear system during pressure transitions, particularly at higher probe-tone frequencies where the middle ear becomes less stiffness dominated and more sensitive to dynamic mechanical alterations (Decraemer et al., 1984; Shanks & Wilson, 1986). These findings suggest that pressure sweep direction alters the balance between stiffness- and mass-related contributions to middle ear mechanics, thereby influencing resonance characteristics and altered frequency specific sound transmission.

Overall, previous investigations indicate that pressure sweep direction significantly affects tympanometric peak pressure, admittance characteristics, tympanometric morphology, and recording stability through hysteresis, viscoelasticity, and phase-related mechanical changes within the middle ear system (Decraemer et al., 1984; Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005). These effects become more evident at higher probe-tone frequencies and faster pressure sweep rates. Therefore, pressure sweep direction should be taken under consideration during interpretation of immittance findings.

2.4. Other general Factors and their effect on immittance measurement

General factors influencing immittance measurements include biological, physiological, and procedural variables that can alter middle ear mechanics and acoustic energy transmission. Factors such as gender, body posture, head movement, and probe-tip placement may affect immittance measurement and findings.

Gender is considered as an important biological factor that influence acoustic immittance measurements. Several studies have reliably shown that males usually reveal higher peak compensated static acoustic admittance and larger equivalent ear canal volumes than females, possibly because of anatomical differences in ear canal and middle ear sizes which has an influence on acoustic impedance and sound transmission (Roup et al., 1998; Wahab and Rashid, 2009). In wideband immittance assessments, females tend to have greater absorbance at higher frequencies, whereas males tented to have greater absorbance at lower frequencies (Kavruk and Öztürk, 2024). These findings suggest that gender-related differences in middle ear mechano-acoustical properties.

Body posture and head position also have also significant influence on immittance findings. Changes in body position alters middle ear and inner ear pressure dynamics.

Changes from upright to supine or head-dependent positions can modify tympanometric peak pressure, width, and resonance characteristics because of alterations in cerebrospinal fluid pressure, venous congestion, and labyrinthine hydrostatic pressure (Daniel et al., 1985). Similarly, prolonged maintenance of altered head positions has demonstrated to have influence on tympanometric pressure gradient, possibly because of gravitational and vascular effects on middle ear structures and transient changes in middle ear air volume (Chatterjee et al., 2017). These findings indicate that patient posture and movement should be carefully controlled during immittance evaluation.

Procedural factors, particularly probe-tip insertion depth and residual ear canal volume, can substantially influence immittance recordings. Variations in probe insertion depth alter the residual ear canal volume and influence acoustic admittance values. Increased residual ear canal volume reduces impedance and increases admittance because of pressure-volume relationships described by Boyle's law, whereas deeper probe insertion may reduce admittance values (Sahu & Mahallik, 2021). Such variations can influence tympanometric peak amplitude and immittance characteristics without reflecting true middle ear pathology. Therefore, consistent and appropriate probe placement is essential for obtaining reliable and clinically accurate immittance measurements.

2.5. Effect of middle ear disorders in immittance measurement:

Conventional 226 Hz tympanometry is been widely used in the identification of middle ear disorders. However, several studies have reported limitations in order to differentiating between normal and pathological middle ear conditions. Negative tympanometric peak pressure, reduced compliance, and flat type B tympanograms were commonly associated with Eustachian tube dysfunction, secretory otitis media, and middle ear effusion (Feldman, 1977; Renvall & Holmquist, 1976). Increasing middle ear fluid levels were reported to gradually transform the tympanogram into a flat configuration, while reduced functional middle ear volume produced highly negative tympanometric peak pressure values (Gaihede, 2000). Type As and Type C tympanograms were often reported in both normal and pathological ears, and normal tympanometric findings were observed even in ears with confirmed middle ear effusion, particularly in infants with cleft palate (Harris et al., 2005; Wimmer et al., 2010). Pathological conditions such as tympanic membrane retraction, ossicular abnormalities, cholesteatoma, granulation tissue, and adhesive changes were also reported to alter middle ear transmission characteristics and affect immittance findings at 226Hz (Jaisinghani et al., 1999).

Studies using higher probe tone frequencies such as 660 Hz and 678 Hz reported greater sensitivity in identifying middle ear pathology when compared to conventional low-frequency tympanometry. Shurin et al., 1977, demonstrated that acoustic susceptance measurements obtained at 660 Hz differentiated normal ears from ears with middle ear effusion more effectively than low-frequency measurements. Similar findings were also reported by Harris et al., 2005 and Wimmer et al., 2010, who observed that 678 Hz tympanometry identified middle ear abnormalities and residual pathology more accurately than 226 Hz tympanometry. In infants with cleft palate, 678 Hz tympanometry showed strong agreement with intraoperative findings of middle ear effusion, whereas 226 Hz tympanometry frequently yielded apparently normal findings despite confirmed pathology (Wimmer et al., 2010). These findings suggested that higher-frequency probe tones were more sensitive to pathological alterations affecting the tympano-ossicular mechanism and middle ear transmission properties.

The usefulness of 1000 Hz and multifrequency tympanometry in identifying middle ear pathology has also been reported in several studies, particularly in infants and young children. Zhiqi et al., 2010. demonstrated significantly higher concordance between 1000 Hz tympanometry and computerized tomography findings of middle ear effusion when compared to 226 Hz tympanometry. Costa et al., 2013, reported that greater sensitivity and specificity of high-frequency probe tones, especially 1000 Hz, for identifying middle ear dysfunction in infants. Multifrequency tympanometry was also reported to be useful in differentiating middle ear disorders. Abou-Elhamd et al., 2006, observed evidently reduced resonant frequency values in otitis media with effusion and elevated resonant frequency values in adhesive otitis media, reflecting alterations in stiffness and mass characteristics of the middle ear system.

2.6. Reliability of immittance measurement:

Immittance measurements demonstrate generally high reliability, though variability depends on measurement type, probe frequency, and subject factors. Chermak & Luchini, 1978, found all test-retest correlations statistically significant ($p < 0.05$) for tympanometric measures in children across intervals from 1 minute to 1 week. Feldman et al., 1971, reported “extremely high” test-retest reliability for both mechanical and electroacoustic impedance bridges in normal-hearing subjects. However, Wiley and Block (1979) documented important variability patterns: intra-event standard deviations were less than 50 acoustic ohms at 220 Hz and less than 25 ohms at 660 Hz, with session-to-session variability varying greatly across subjects (30-40% of mean values). Karzon, (1991) found static acoustic admittance showed statistically significant changes between sequential measures in pediatric patients, though tympanometric width and peak pressure remained stable. Overall, immittance measurements are sufficiently reliable for clinical use, with reliability strongest at higher probe frequencies and for compliance measures.

2.7. Effect of maturation and age on wideband tympanometry measurement:

Studies have explored the effect of maturation and age on wideband tympanometry and reported developmental as well as age-related changes in wideband absorbance, energy reflectance, resonance frequency, and middle ear transmission characteristics across different age groups. These changes are due to anatomical and physiological maturation of the outer and middle ear system.

Sanford and Feeney,2008; studied how maturation affects tympanometric wideband acoustic transfer functions in infants aged 4, 12, and 24 weeks, and compared them with young adults. They measured wideband energy reflectance and admittance magnitude at different static ear-canal pressures. The study found significant age-related changes. At low frequencies (0.25–0.75 kHz), mean energy reflectance and admittance changed up to 30% with changes in static ear-canal pressure between 4 and 24 weeks of age. Between 0.75 and 2 kHz, developmental effects were relatively stable. At higher frequencies (2–6 kHz), negative ear-canal pressure increased sound reflection and admittance in younger infants, whereas positive pressure caused a reduction in these responses. These pressure-related effects became smaller as age increased. The authors suggested that these maturational changes were due to anatomical development of the outer and middle ear during the first few months of life. They explained that the infant middle ear is more mass-dominated in early infancy because of residual mesenchyme, differences in ossicular density, and variations in the orientation of the tympanic membrane and ossicles. Mishra et al. (2017) investigated the maturation of middle ear transmission in children between 5 and 12 years of age using wideband acoustic immittance measures. Absorbance and grouped measurements were obtained from adults and children grouped into 5–6 years, 7–9 years, and 10–12 years age categories. The authors reported significant age effects for absorbance at several frequencies between 211

Hz and 6000 Hz. Older children between 10 and 12 years demonstrated absorbance patterns similar to adults. The study reported that absorbance maturation continued through childhood, particularly for higher frequencies, suggesting a prolonged maturation period for middle ear transmission characteristics. The authors further stated that wideband absorbance patterns in infants and young children differ from adults because of developmental changes in the middle ear system. Higher absorbance values at low frequencies in infants were attributed to the flaccid ear canal wall and mass-dominated middle ear characteristics. The study also reported that the absorbance pattern gradually changed from a relatively flat configuration in newborns to a peaked adult-like configuration by approximately 6 months of age. Downing et al. (2022) investigated the effects of age, gender, ear laterality, and ethnicity on wideband tympanometry findings in school-aged children between 4 and 13 years of age. However, no significant main effects of gender, ear laterality, or ethnicity were observed. Özgür et al. (2016) studied normative wideband tympanometry data across different age groups. The study reported that resonance frequency was significantly lower in infants aged 0–1 month compared to other age groups. Absorbance at 250 Hz was significantly higher in infants younger than 2 years compared to older age groups. Feeney and Sanford (2004) investigated age effects in the human middle ear using wideband acoustical measures in young adults and older adults above 60 years of age. The authors reported no significant differences in conventional 226 Hz tympanometric measures between younger and older adults. However, significant age-related differences were observed in wideband energy reflectance and impedance measures. Older adults demonstrated decreased reflectance between 800 and 2000 Hz and increased reflectance near 4000 Hz compared to younger adults. The authors suggested that these findings reflected a decrease in middle ear stiffness with aging. Anatomical studies cited by the authors also demonstrated age-related changes in the tympanic membrane and ossicular joints including reduced elasticity, arthritic changes, and ossicular joint degeneration in elderly individuals. Kavruk and Öztürk (2024) examined the effects of age and gender on middle ear characteristics using wideband tympanometry in young, middle-aged, and older adults. Energy absorbance at tympanometric peak pressure and ambient pressure was analyzed across frequencies from 226 to 8000 Hz. The study reported significantly higher absorbance values between 500 and 794 Hz and significantly lower absorbance values between 1587 and 3175 Hz in older adults compared to younger adults. Resonance frequency was significantly lower in older adults. The authors suggested that age-related changes in wideband absorbance may occur because of alterations in middle ear stiffness and sound transmission characteristics with aging. Shivaprakash et al. (2026) investigated the effect of aging on middle ear absorbance characteristics across frequencies using wideband tympanometry. The study compared wideband absorbance in older adults between 50 and 70 years of age and young adults between 20 and 30 years of age under ambient and peak pressure conditions. Older adults demonstrated significantly higher absorbance at low frequencies between 250 and 600 Hz and lower absorbance at high frequencies between 2000 and 8000 Hz compared to younger adults. Pressure-related absorbance differences were more pronounced in younger adults at low and mid frequencies. The authors attributed these age-related changes to ossicular joint loosening, tissue degeneration, and alterations in middle ear mechanical properties associated with aging. The study further reported that wideband tympanometry was more sensitive than conventional tympanometry in identifying subtle age-related changes in middle ear function. Zhao et al. (2025) conducted a systematic review investigating the age effect on wideband absorbance in individuals with normal middle ear function. The review analyzed normative wideband acoustic immittance data from 30 studies including participants from neonates to 80 years of age. The authors reported that the highest energy absorbance values were observed in infants younger than 6 months, whereas lower average absorbance values were seen in the 6- and 12-month age groups. Absorbance values gradually increased after 12 months of age and peaked between 10 and 13 years before declining after adolescence. Significant frequency-specific age-related differences were observed between 0.25 and 8 kHz, particularly around 1 and 4 kHz. The authors suggested that the observed age-related changes in wideband absorbance are mainly due to developmental and anatomical changes in the auditory system, including maturation of the outer and middle ear structures, ossification and remodeling of the middle ear, changes in ear canal dimensions and tympanic membrane properties during infancy, as well as age-related increases in middle ear stiffness, ossicular degeneration, and structural tissue changes in older adults.

Thus, previous studies have shown that maturation and aging significantly influence wideband tympanometry findings across frequencies. Thus indicate the importance of considering age-related changes while interpreting wideband tympanometry findings in both clinical and research settings.

2.8. Effect of pressurization in wideband tympanometry measurement:

Several studies have confirmed that pressure sweep direction and sweep rate influence wideband tympanometry measurements. Thus, includes wideband absorbance, tympanometric peak pressure (TPP), equivalent admittance, and test–retest reliability; because of hysteresis, viscoelastic behaviour, and phase-related changes in middle ear mechanics during pressure variation (Feeney et al., 2017; Liu et al., 2008). Wideband tympanometry evaluates middle ear sound transmission across a broad frequency range under varying ear-canal pressures, and alterations in sweep direction may modify the mechanical response of the middle ear system, thereby affecting acoustic energy transfer and impedance characteristics. Liu et al. (2008) reported that ascending and descending pressure sweeps causes systematic shifts in TPP across different sweep rates, although absorbance measured at TPP remained relatively stable. The authors further observed that absorbance below 2 kHz was generally higher at TPP than at ambient pressure. Similarly, Feeney et al. (2017) confirmed that absorbance measured at TPP showed a broad band-pass pattern with lower test-retest variability than ambient-pressure measurements, particularly between approximately 0.7 and 3 kHz. Peak-to-tail absorbance differences were greatest within the mid-frequency range, indicating increased sensitivity of TPP-based measurements to pressure-related changes in middle ear mechanics. Admittance at the tympanic membrane was also lower at ambient pressure than at TPP below approximately 1.2 kHz, reflecting altered compliance and sound transmission under non-optimal pressure conditions. Although differences between upswept and downswept conditions were relatively small in normal adult ears, both studies emphasized that measurements obtained at TPP provide more reliable and clinically sensitive assessment of middle ear transfer characteristics than ambient-pressure recordings, particularly at low- and mid-frequency regions where middle ear impedance effects are more prominent (Feeney et al., 2017; Liu et al., 2008).

In summary, previous studies have shown both age and pressurization have effect on wideband tympanometry findings across frequencies. Developmental and age-related changes in the outer and middle ear affect absorbance, reflectance, resonance frequency, and middle ear sound transmission from infancy to older adulthood (Sanford & Feeney, 2008; Mishra et al., 2017; Zhao et al., 2025). Similarly, pressure sweep direction and pressure conditions can influence absorbance, tympanometric peak pressure (TPP), admittance, and reliability because of hysteresis and viscoelastic changes in middle ear mechanics during pressure variation (Liu et al., 2008; Feeney et al., 2017). However, most of the studies have either studied age effect or pressure weep effect independently. None of them have studied the interaction effect of age and sweep direction on wide band absorbance. Hence, this study was taken up to see the effect of age and sweep direction on wideband absorbance.

CHAPTER 3

METHODS

3.1. Study Design

The objective of this study was to compare wideband absorbance values across frequencies obtained at tympanometric peak pressure (TPP) and ambient pressure (AP) among individuals belonging to different age groups under ascending and descending pressure sweep directions. The study also aimed to examine the influence of pressure sweep direction (ascending vs. descending) on wideband absorbance across frequencies at both TPP and AP, and to determine whether the effect of sweep direction differs across age groups. To achieve these objectives, the collected data were compared across different age groups based on wideband absorbance values, constituting a between-subjects design. In addition, wideband absorbance values obtained under ascending and descending pressure sweep directions were compared within the same group of participants, constituting a within-subject design. Hence, this study adopted a mixed-design repeated-measures study because it includes both within-subject and between-subject comparisons.

3.2. Participants

A total of 45 individuals between 5 and 30 years of age were included in the study. The participants were divided into three groups (childhood, adolescence and young adulthood) with each group consisting of 15 individuals. A structured case history was taken to rule out any history of ear pain, ear discharge, history of medically and surgically treated ear diseases and symptoms associated with outer and middle ear disorders. The All India Institute of Speech and Hearing, Institute Review Board (IRB) gave ethical approval for Biobehavioral research on 06/01/2026 with Reference number

SH/IRB/M.4/AUD, dated on 18/2025-26. All the testing procedures in the present study were performed using a non-invasive approach. The test procedures were clearly explained to the participants before the testing, and written informed consent was taken from all the individuals for their cooperation in the study.

3.3. Participant Inclusion Criteria

All three groups of participants had to fulfil the following criteria to be considered for the study:

I. Hearing thresholds of ≤15 dB HL for air-conduction testing at octave frequencies from 250 Hz to 8000 Hz, and bone-conduction thresholds from 250 Hz to 4000 Hz with an air–bone gap of ≤10 dB HL (ANSI, 2009).

II. Loudness Discomfort Level (LDL) for speech more than 100 dB HL.

III. Absence of symptoms related to otological disorders.

IV. Absence of obvious neurological symptoms.

V. All those who had type 'A' tympanogram with presence of acoustic reflexes in 1000 Hz and 2000 Hz frequencies on ipsilateral and contralateral stimulations were included in the study.

3.4. Test Environment

All test procedures were conducted in a soundproof room. The ambient noise levels in all test rooms conformed to the standards set by the American National Standards Institute (ANSI S3.1-1991). A double-room suite was utilized for pure tone and speech audiometry, while tympanometric evaluations were conducted in a single-room setup. All rooms were adequately illuminated and air-conditioned.

3.5. Instrumentation

A GSI 61 Clinical audiometer with Radioear B-71 bone vibrator and DD45 Earphone was used to obtain bone-conduction, air-conduction threshold, and loudness discomfort level respectively. Tympanometric measures, including the wideband tympanometry, were accomplished using an GSI TympStar Pro™ middle-ear analyser. The instrument used in the study consisted of receivers to present stimuli and a microphone for capturing the pressure of sound in the ear canal. To vary the ear canal pressure, a probe inbuild pump was used. To create an air-tight seal in the ear canal, appropriate size tips made of silicon material were used.

3.5.1 Calibration of the instrument

Throughout the data collection phase, the audiological instruments, including the GSI AudioStar Pro™ dual-channel clinical audiometer and the GSI TympStar Pro™, underwent calibration once in every three months in adherence to the ANSI S3.6-2004 (R2010) and ANSI S3.39-1987 (R2012) standards, as prescribed by ANSI (2010, 2012). The GSI TympStar Pro™ advanced research analyzer required daily calibration, which was performed by positioning the probe assembly into a calibration unit with a standardized volume of 2 cc. During calibration, source reflectance and incident pressure were evaluated to ensure accurate wideband absorbance (WBA) measurements. Calibration competence was confirmed when reflectance values remained below 15% up to 2 kHz and below 30% above 2 kHz, in accordance with manufacturer recommendations and previously reported procedures (Liu et al., 2008).

3.6 Test Procedure

To check for the eligibility criteria of the participants, they all underwent a preliminary case history taking and audiological evaluation before the experimental phase.

3.6.1. Preliminary evaluations

Structured Case History: A detailed case history was carried out to obtain information about each participant's hearing health and, their medical symptoms. This included common ear-related issues such as ear pain, a feeling of fullness, discharge, previous infections, itching in the ear canal, and tinnitus. Medical records were also reviewed and documented, with particular attention given to any confirmed diagnosis of tympanic membrane perforation by an otologist. Additionally, the chart review screened for neurological symptoms, including headaches, facial pain, numbness or weakness, tinnitus, dizziness or vertigo, difficulty in swallowing, voice changes, double vision, and cognitive impairments.

Otoscopic Examination: All participants underwent an otoscopic examination to evaluate the condition of the external ear canal and the tympanic membrane. The goal of this assessment was to identify issues such as earwax blockage (cerumen impaction), dry perforations, discharge, the presence of foreign objects in the ear canal, tympanic membrane perforation, retracted or bulged tympanic membrane.

Pure Tone Audiometry: Each participant completed both pure tone and speech audiometry tests. Thresholds were estimated using a modified version of the Hughson and Westlake method (Carhart & Jerger, 1959) to determine air conduction thresholds at 0.25, 0.5, 1, 2, 4, and 8 kHz, and bone conduction thresholds at 0.25, 0.5, 1, 2, and 4 kHz.

Speech Audiometry: The Loudness Discomfort Level (LDL) of speech for each ear was individually assessed, and the LDL was greater than 100 dB HL.

Immittance Audiometry: Tympanometry was carried out using 226Hz probe tone as well as the measurement of acoustic reflex thresholds (ipsilateral and contralateral) at 1 and 2kHz was done to know the status of the middle ear. Principal tympanometric parameters including ear canal volume, static admittance, tympanometric peak pressure and gradient were recorded.

Based upon the result obtained from the preliminary examinations, the participants were selected for the main experimental procedure, those who has fulfilled the criteria mentioned in **3.3**.

3.6.2. Experimental Test Procedure

It was ensured that, before assessing Wideband Tympanometry using the GSI TympStar Pro, the instrument was powered on and allowed to stabilize for a few minutes. The probe tip and tubing were checked for wax, moisture, or blockage. The system automatically checked the probe microphone, speaker response, pressure pump, and leak status. Before beginning the experimental procedure, calibration of the GSI TympStar Pro™ was performed daily. The participants were explained the entire test procedure and were instructed to remain relaxed and avoid movement during the assessment. They were briefed about the testing process, which involved the insertion of a probe tip into the ear canal to obtain an airtight seal, followed by pressure changes and the presentation of click stimuli. For younger participants, the parents and teachers were also informed about the test procedure and the approximate duration required for testing. Additionally, all participants were instructed to refrain from swallowing, coughing, or speaking while the test was in progress.

A suitably sized probe tip was securely placed in the participant's ear canal, and a wideband click stimulus at 100 dBpeSPL was presented at a rate of 21.5/sec (GSI, 2022). The air pressure in the ear canal was automatically swept from +200 daPa to –400 daPa in the descending direction and from –400 daPa to +200 daPa in the ascending direction at a constant medium pump speed of 200 daPa/sec. Wideband Absorbance (WBA) values, expressed as percentages, were obtained using the GSI TympStar Pro. The instrument automatically recorded and displayed WBA measurements on its inbuilt monitor across 1/24th octave bands under two pressure conditions: ambient pressure (0 daPa) and tympanometric peak pressure (TPP).

The direction of pressure sweep was manually changed after completing testing in one pressure sweep direction. Absorbance values at each one-third octave frequency (16 frequencies in total), peak pressure, static compliance, and overall absorbance percentage were noted manually in a data entry record sheet for both ascending and descending pressure sweep directions and later entered into a computer for analysis. To ensure measurement accuracy and reduce the influence of artifacts, wideband absorbance (WBA) recordings were obtained at least three times for each pressure sweep direction. The recording that showed the smoothest absorbance curve and the highest absorbance values was selected for analysis. A minimum break of one minute was provided between changes in the direction of pressure sweep.

3.6.3. Reliability Measures

Reliability testing was carried out for wideband absorbance (WBA) measurements. To investigate test–retest reliability, five participants (approximately 10% of the total sample) were selected randomly. The measurements were repeated 15 days after the initial assessment. Prior to the WBA measurement, single frequency tympanogram and reflexes were checked at 1 KHZ and 2 KHz. Only after ascertaining the A type tympanogram with presence of reflexes, WBA was measured. Data obtained from both the initial and repeated measurements of the selected participants were used for further analysis. Intraclass Correlation Coefficient (ICC) analysis was performed to evaluate the reliability of the WBA measures.

3.7. Statistical Analysis

Absorbance values at each one-third octave frequency (16 frequencies in total) were obtained from each participant for both ascending and descending pressure sweep directions under both pressure conditions, tympanometric peak pressure and ambient pressure.

Initial results of Shapiro–Wilk test revealed that most of the variables were not normally distributed. Therefore, the measured values were transformed into logarithmic scale. Following the transformation, data across condition was averaged and Principal Component Analysis (PCA) was performed on the absorbance data. After the PCA, results revealed that most of the variables were found to be normally distributed, except for four variables out of the sixteen variables analysed. These included low-frequency absorbance values under the descending sweep direction at ambient pressure condition, first mid-frequency absorbance values under the descending sweep direction at peak pressure condition, and high-frequency absorbance values under both ascending and descending sweep directions at peak pressure condition.

Since Analysis of Variance (ANOVA) is generally robust to minor deviations from normality, parametric statistical methods were employed for further inferential statistical analysis. Accordingly, a Mixed ANOVA was conducted to examine the effects of pressure condition, pressure sweep direction, and age group on wideband absorbance values. The analysis was performed separately for all four extracted components.

CHAPTER 4

RESULTS

The present study investigated the effect of pressure sweep direction (ascending and descending) and pressurization condition (tympanometric peak pressure [TPP] and ambient pressure) on wideband absorbance (WBA) measures across children, adolescents, and young adults with normal hearing sensitivity. To address the objectives of the study, the obtained data were analyzed quantitatively using descriptive and inferential statistical methods.

Descriptive statistics were computed on actual wideband absorbance values obtained from the participants to determine the mean and standard deviation of wideband absorbance (WBA) values across all 1/3-octave frequencies obtained under tympanometric peak pressure (TPP) and ambient pressure conditions for both ascending and descending pressure sweep directions. Table 4.1–4.3 presents the mean (M) and standard deviation (SD) for the children, adolescents, and young adult groups under the different pressure conditions and sweep directions. Graphical representations of the mean absorbance values across frequencies for the different age groups under ascending and descending pressure sweep directions at both TPP and ambient pressure conditions are presented in Figures 4.1–4.4.

Table 4.1:

Mean and Standard Deviation of Wideband Absorbance Values Across 1/3-Octave Frequencies 258Hz to 8010 Hz Under Ascending and Descending Pressure Sweep Directions at Tympanometric Peak Pressure and Ambient Pressure Conditions for Children

Age Group	Frequency (Hz)	Ascending-Peak	Ascending-Ambient	Descending-Peak	Descending-Ambient

		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Children	258	6.50	3.59	0.30	0.47	2.81	3.29	1.44	1.02
	301	10.19	4.25	0.60	0.75	5.32	3.96	3.51	1.74
	409	18.85	6.94	1.90	1.69	11.69	5.24	8.59	2.79
	517	29.57	11.51	3.66	2.86	20.06	6.65	15.41	4.56
	603	37.87	10.97	5.53	3.95	29.77	8.53	23.01	7.06
	818	56.79	11.86	10.10	7.27	53.80	13.59	42.57	14.17
	1012	70.64	7.69	13.33	10.33	66.75	15.06	54.43	17.17
	1249	75.06	7.67	17.78	10.17	68.49	11.32	58.00	13.48
	1507	69.73	5.73	24.34	11.85	65.02	9.91	60.31	11.81
	2024	72.07	10.78	42.71	19.30	65.98	9.36	68.22	8.09
	2519	81.89	6.95	60.46	15.93	75.23	11.43	76.47	12.04
	3036	81.23	9.75	64.47	13.79	82.98	10.06	83.10	10.36
	4048	75.97	9.82	71.12	10.98	82.54	6.99	82.93	7.61
	5039	64.49	10.99	65.40	12.00	73.04	6.13	73.13	7.33
	6072	42.72	8.60	50.98	12.37	49.25	6.28	50.36	7.52
	8010	22.87	8.99	28.57	13.59	29.17	10.27	31.01	10.79

As the above table (table. 4.1) shows, across most frequency absorbance measured at peak pressure was higher than at ambient pressure. Additionally, descending sweeps generally produced slightly higher absorbance values than ascending sweeps across several mid- and high-frequency regions, particularly under ambient pressure conditions.

Table 4.2:

Mean and Standard Deviation of Wideband Absorbance Values Across 1/3-Octave Frequencies 258 Hz to 8010 Hz Under Ascending and Descending Pressure Sweep Directions at Tympanometric Peak Pressure and Ambient Pressure Conditions for Adolescents

Age Group	**Frequency (Hz)**	**Ascending-Peak**		**Ascending-Ambient**		**Descending-Peak**		**Descending-Ambient**	
		M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Adolesces	258	8.23	6.84	0.99	1.19	4.86	4.25	3.77	2.12
	301	11.85	8.37	2.44	1.97	8.08	5.53	6.48	2.91
	409	22.38	13.63	6.17	4.27	14.99	7.97	14.07	5.28
	517	33.41	17.63	9.81	5.92	23.05	9.92	21.71	7.92
	603	40.83	17.41	14.75	7.70	31.42	11.41	29.12	9.87
	818	55.78	16.08	20.73	11.10	47.62	12.44	43.07	13.35
	1012	67.06	13.49	23.81	17.34	58.28	12.15	54.35	15.71
	1249	73.44	11.18	26.24	23.68	68.23	11.46	64.43	16.77
	1507	67.72	11.49	27.89	24.70	71.69	9.45	69.21	15.92
	2024	64.46	16.93	40.20	23.06	66.39	17.30	65.63	17.61
	2519	70.05	13.72	50.12	15.13	73.48	15.64	73.30	15.69
	3036	62.71	15.39	53.43	13.61	74.79	12.22	73.48	12.44

	4048	66.06	17.08	63.27	15.69	70.08	10.80	68.46	11.19
	5039	56.00	15.70	60.80	15.22	61.99	11.12	63.12	11.75
	6072	37.47	10.34	44.83	13.10	38.24	9.33	41.98	9.53
	8010	24.88	19.51	29.76	19.95	31.72	21.78	30.56	20.90

As the above table (table. 4.2) shows, across most frequency absorbance measured at peak pressure was higher than at ambient pressure. Additionally, descending pressure sweeps showed slightly higher absorbance values than ascending sweeps across several mid- and high-frequency regions, particularly under ambient pressure conditions.

Table 4.3:

Mean and Standard Deviation of Wideband Absorbance Values Across 1/3-Octave Frequencies 258Hz to 8010 Hz Under Ascending and Descending Pressure Sweep Directions at Tympanometric Peak Pressure and Ambient Pressure Conditions for Young Adults

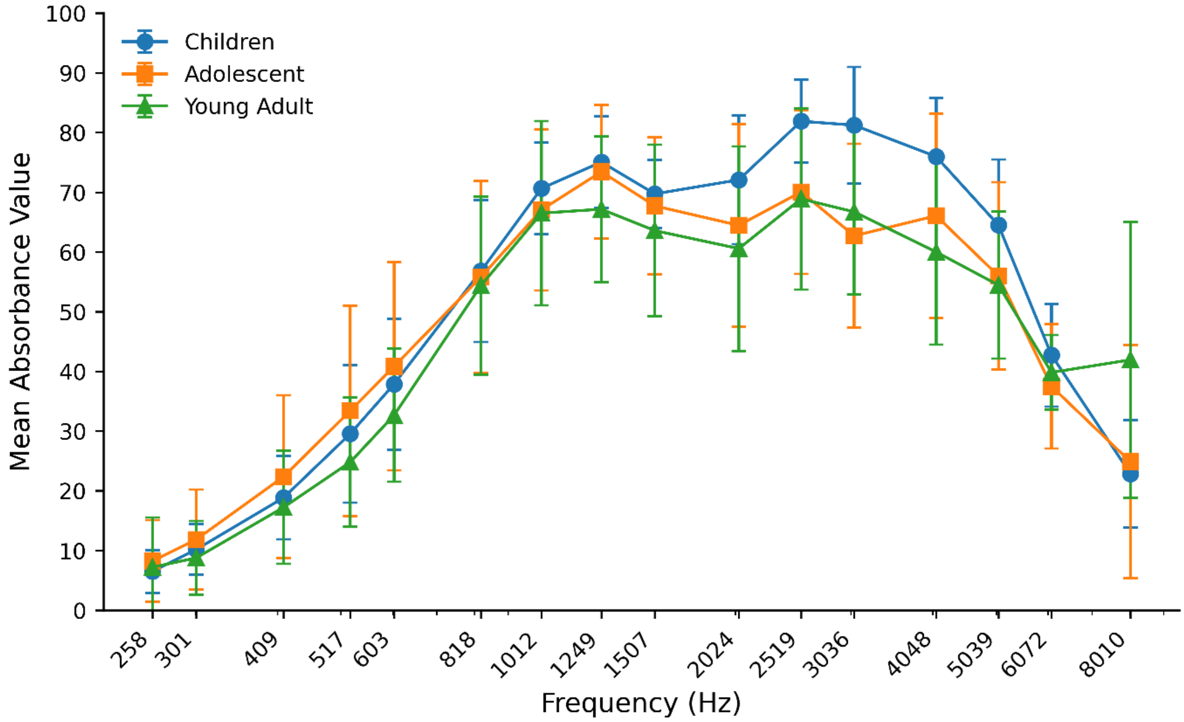
Age Group	**Frequency (Hz)**	**Ascending-Peak**		**Ascending-Ambient**		**Descending-Peak**		**Descending-Ambient**	
		M	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Young Adults	258	7.21	8.31	1.15	2.54	4.90	6.37	4.23	6.55
	301	8.77	6.19	2.22	3.40	8.09	6.99	6.58	6.89
	409	17.24	9.44	5.90	8.18	17.37	14.47	14.75	13.36
	517	24.82	10.82	8.99	10.98	25.92	15.47	21.69	12.47
	603	32.67	11.12	11.21	13.25	34.40	17.34	29.09	11.86
	818	54.36	14.90	13.90	17.37	58.18	19.26	51.41	16.79

1012	66.50	15.41	14.79	23.52	66.96	13.75	63.54	15.57
1249	67.15	12.20	14.54	20.66	66.85	11.65	65.70	14.63
1507	63.58	14.38	17.29	17.88	62.93	13.14	61.17	13.61
2024	60.56	17.13	34.05	26.13	62.62	15.15	61.54	15.90
2519	68.88	15.16	50.43	20.04	69.82	14.94	70.03	15.14
3036	66.72	13.80	51.34	14.70	65.77	13.31	68.53	13.63
4048	60.00	15.50	63.03	15.07	61.30	14.52	62.32	13.79
5039	54.44	12.28	60.62	11.76	56.09	13.17	56.14	13.28
6072	39.83	6.26	47.70	9.28	40.13	7.52	40.76	8.79
8010	41.94	23.06	47.10	19.46	39.88	19.41	39.76	18.93

As the table (table 4.3) sows, absorbance values measured at peak pressure were generally higher than those obtained at ambient pressure. Additionally, descending pressure sweeps showed higher absorbance values compared to ascending sweeps across several mid- and high-frequency regions, particularly under ambient pressure conditions.

Figure 4.1:

Frequency-Specific Mean Absorbance Values along with ± 1 SD, *for Children, Adolescents, and Young Adults During Ascending Direction obtained at Tympanometry Peak Pressure Condition*

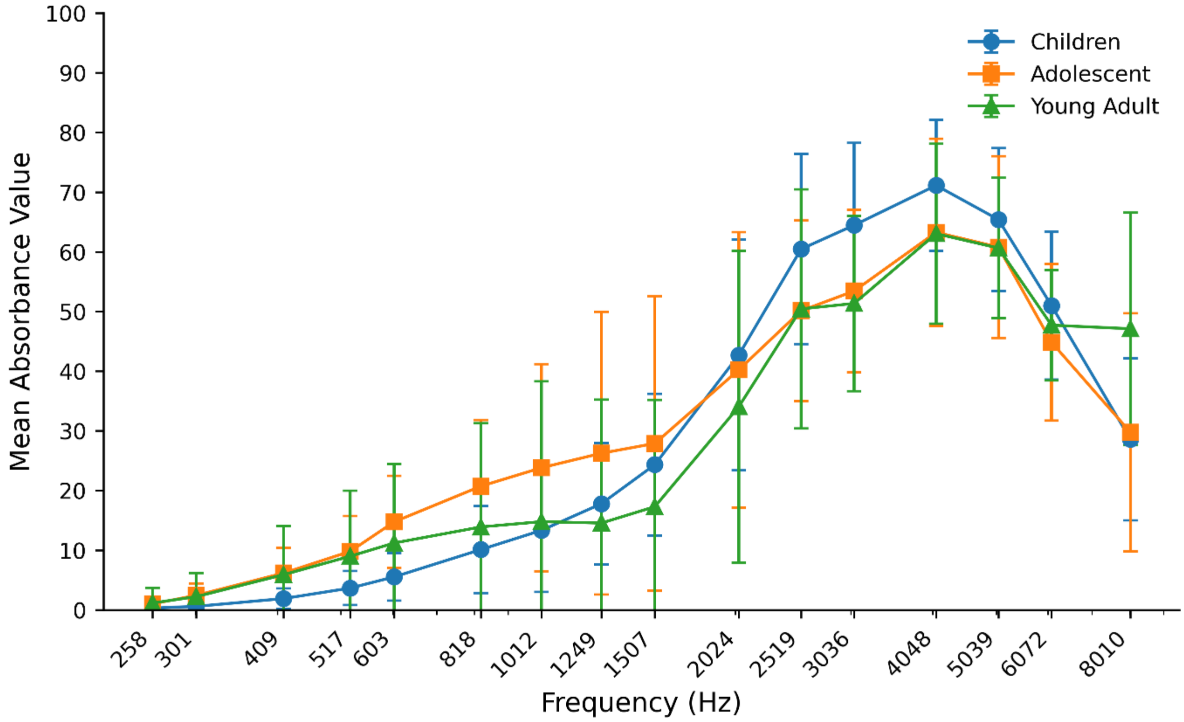


Note. Error bars represent ±1 SD.

It is evident in the above figure (fig. 4.1) that, in all age group absorbance values were lowest at low frequencies, gradually increased and reached peak at mid frequencies, again declined at higher frequencies. Children showed comparatively higher absorbance values than adolescents and young adults in some mid- and high-frequency regions.

Figure 4.2:

Frequency-Specific Mean Absorbance Values along with ± 1 SD, *for Children, Adolescents, and Young Adults During Ascending Direction obtained at Ambient Pressure Condition*

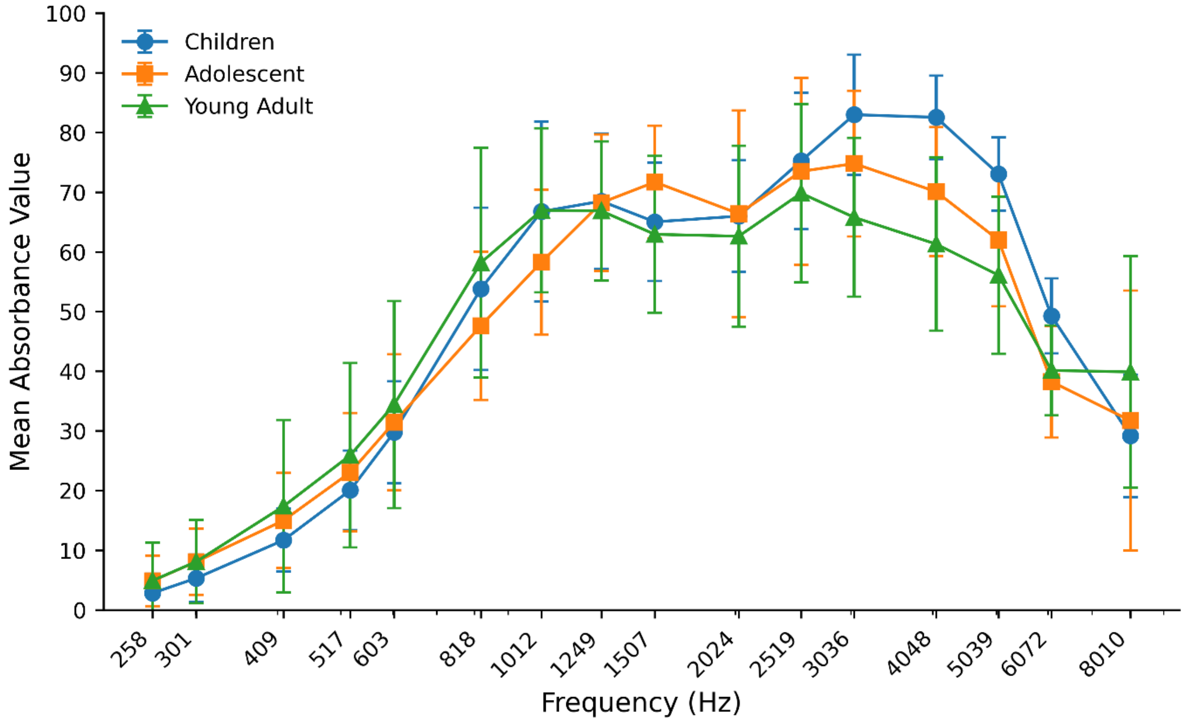


Note. Error bars represent ±1 SD.

It is evident in the figure (fig. 4.2) that, in all age group absorbance values were lowest at low frequencies, gradually increased and reached peak at mid frequencies, again declined at higher frequencies. Children showed comparatively higher absorbance values in several mid- and high-frequency regions compared to other two groups. Young adults showed slightly lower absorbance values at some mid-frequencies.

Figure 4.3:

Frequency-Specific Mean Absorbance Values along with ± 1 SD*, for Children, Adolescents, and Young Adults During Descending Direction obtained at Tympanometry Peak Pressure Condition*

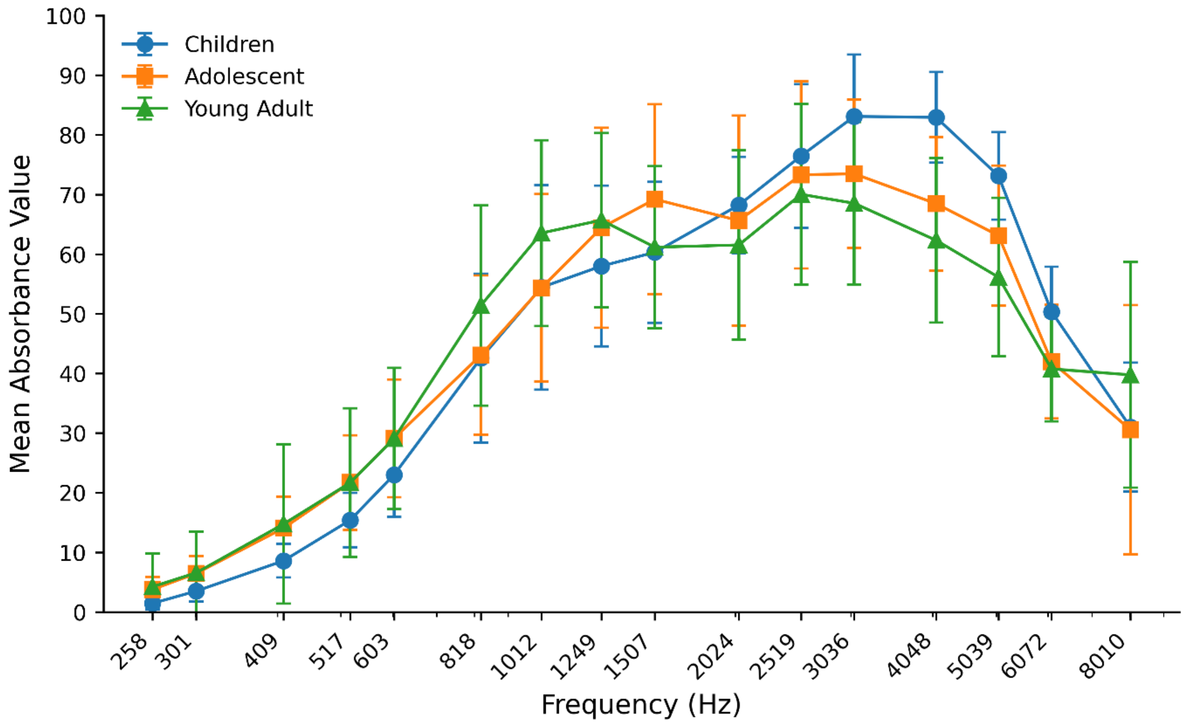


Note. Error bars represent ±1 SD.

It is evident in the figure (fig. 4.3) that, in all age group absorbance values were lowest at low frequencies, gradually increased and reached peak at mid frequencies, again declined at higher frequencies. Children showed comparatively higher absorbance values across several mid- and high-frequency regions compared to other age groups. Young adults generally exhibited lower absorbance values at higher frequencies.

Figure 4.4:

Frequency-Specific Mean Absorbance Values along with ± 1 SD, *for Children, Adolescents, and Young Adults During Descending Direction obtained at Ambient Pressure Condition*



Note. Error bars represent ±1 SD.

It is evident in the figure (fig. 4.4) that, in all age group absorbance values were lowest at low frequencies, gradually increased and reached peak at mid frequencies, again declined at higher frequencies. Children showed comparatively higher absorbance values in few mid- and high-frequency regions compared to other age groups.

To reduce the risk of Type I errors associated with multiple comparisons across the 16 frequency variables, Principal Component Analysis (PCA) was performed to reduce the dimensionality of the data. After the principal component analysis (PCA), the one-third octave frequencies were grouped into four components based on the statistical loading patterns (Table 4.4) (Liu et al. 2008; Liang et al. 2021). Collectively, these four components accounted for approximately 85% of the total variance among all variables (Figure 4.5).

The components obtained from PCA are,

I. The first component represented the mean absorbance values of low frequencies ranging from 258 Hz to 603 Hz.

II. The second component represented the mean absorbance values of the first mid-frequency range from 818 Hz to 1249 Hz.

III. The third component represented the mean absorbance values of the second mid-frequency range from 1507 Hz to 3036 Hz.

IV. The fourth component represented the mean absorbance values of the high-frequency range from 4048 Hz to 8010 Hz.

Table 4.4:

Pattern/Structure Matrix Showing Factor Loadings of Wideband Absorbance Variables Across Components

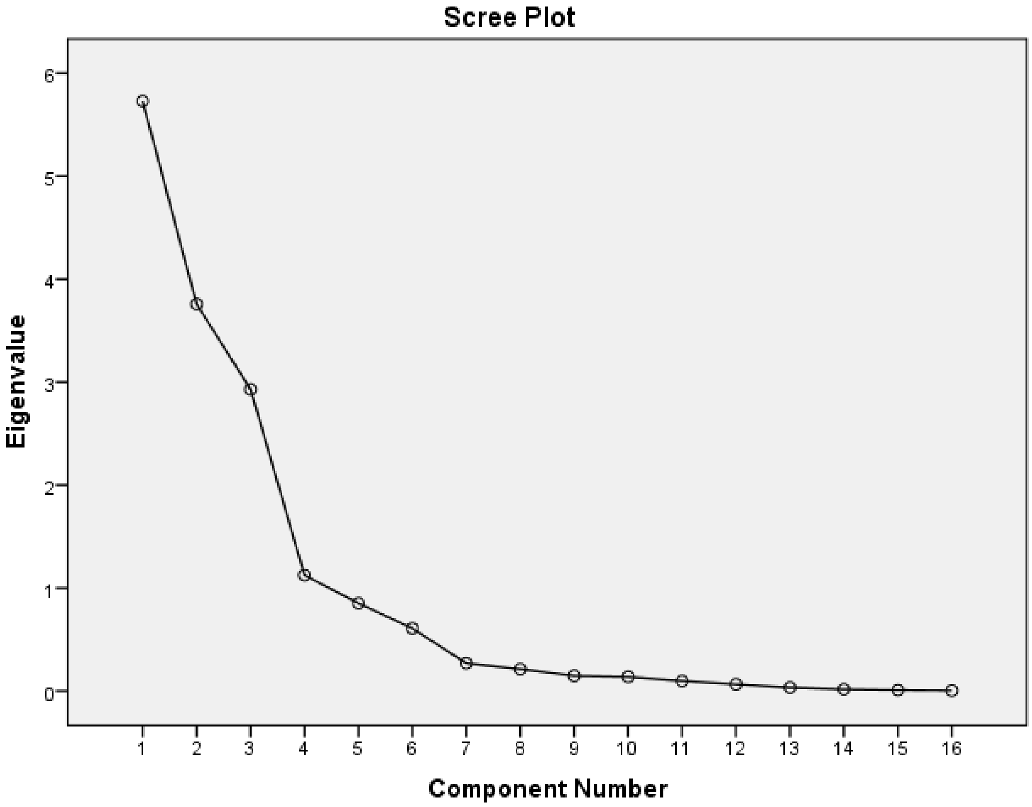
Variable	Component 1	Component 2	Component 3	Component 4
F409	.978	—	—	-.288
F301	.972	—	—	-.188
F517	.965	—	—	-.370
F603	.955	—	—	-.417
F258	.950	—	—	-.118
F2024	—	-.921	-.333	-.348
F2519	—	-.910	—	-.388
F1507	—	-.703	-.360	-.540
F8010	.134	.515	.509	.349
F6072	—	.374	.912	.114

F5039	—	.301	.858	—
F4048	—	-.121	.822	-.231
F3036	—	-.491	.720	-.114
F1012	.362	-.195	.115	-.910
F1249	—	-.548	—	-.860
F818	.680	—	—	-.715

As represented in table 4.4, principal component analysis (PCA) with Oblimin rotation and Kaiser normalization identified four components representing distinct groupings of frequency-specific absorbance variables across low-, mid-, and high-frequency regions. Some variables demonstrated overlap across multiple components, indicating partial relationships between the extracted factors. Overall, the findings suggest that the absorbance measures are grouped into different underlying patterns.

Figure 4.5:

Scree Plot Showing Eigenvalues Across Extracted Components



The scree plot (fig. 4.5) illustrates the distribution of eigenvalues across the extracted principal components obtained from Principal Component Analysis (PCA). A clear inflection ("elbow") is observed after the fourth component, indicating that the first four components account for the majority of the variance in the dataset. Components beyond the fourth show substantially smaller eigenvalues and contribute minimally to the explained variance. This pattern supports the retention of four principal components according to the scree test criterion.

Farther, descriptive and internecinal statistics were computed on each component obtained from the principal component analysis (PCA) **(**Table 4.4**)**; in order to analyse frequency specific variations of variables.

Low frequencies

Descriptive statistics were carried out for first component of PCA (low frequencies) to examine the wideband absorbance values obtained across the different pressure conditions and pressure sweep directions in children, adolescents, and young adults. The findings showed higher absorbance values under the tympanometric peak pressure (TPP) condition than under the ambient pressure (AP) condition. Also, comparison across sweep directions showed that absorbance values obtained during the descending pressure sweep direction were relatively higher than those obtained during the ascending pressure sweep direction.

Highest absorbance values were observed under the ascending direction and tympanometric peak pressure condition across (AP) all age groups. Under this condition, adolescents showed the highest mean absorbance value, followed by children and young adults. The overall mean absorbance value for this condition was relatively highest, indicating that absorbance values is relatively highest in this condition.

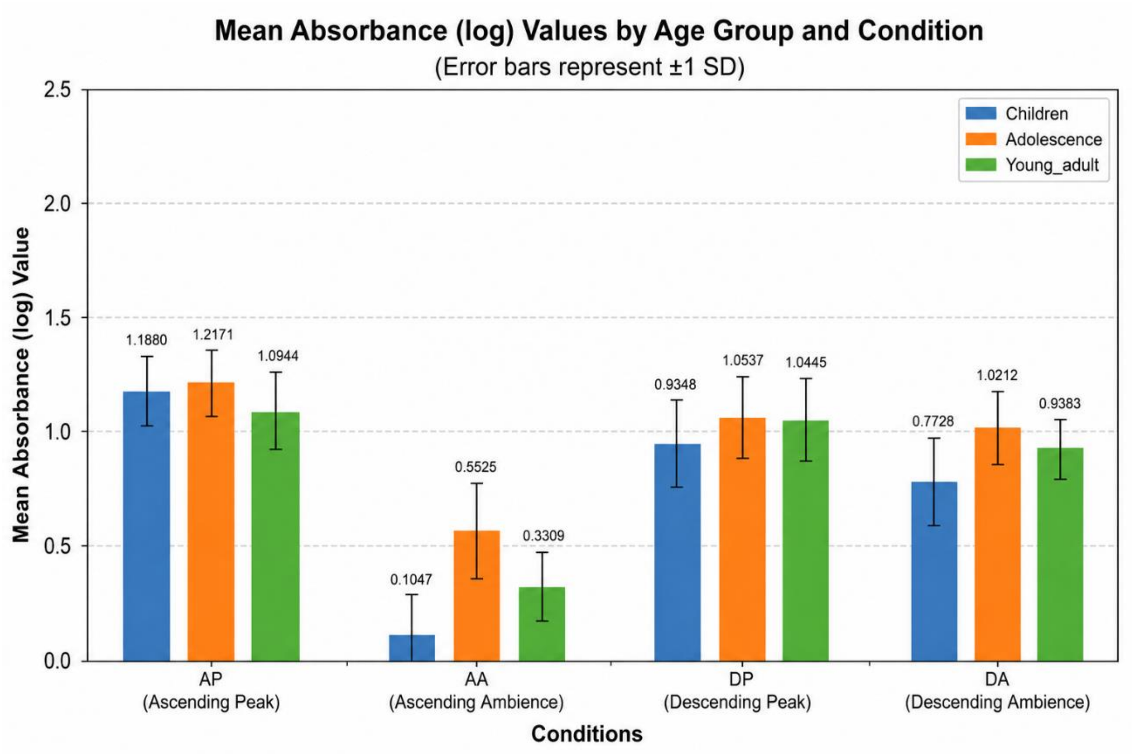
Under the ascending ambient pressure (AA) condition, adolescents showed the highest mean absorbance value, followed by young adults, while children demonstrated the lowest absorbance value. The overall mean absorbance value for this condition was lower most, indicating a marked reduction in absorbance values under ambient pressure conditions during the ascending pressure sweep direction.

Under the descending peak pressure (DP) condition, adolescents demonstrated the highest mean absorbance value, followed closely by young adults, whereas children showed comparatively lower absorbance values.

Under the descending direction and ambient pressure (DA) condition. Adolescents demonstrated the highest mean absorbance value, followed by young adults and children. The overall mean absorbance value obtained under this condition was comparatively higher than ascending ambient pressure condition across all age groups. The details can be seen in figure 4.6.

Figure 4.6.

Mean Absorbance (Log) Values at Low Frequency Across Ascending and Descending Sweep Directions Under Peak and Ambient Pressure Conditions for Children, Adolescents, and Young Adults



A Mixed ANOVA was done with the pressure condition (tympanometric peak pressure [TPP] and ambient pressure [AP]), and pressure sweep direction (ascending and descending) as within subject factors, and age group as the between subject factor.

The analysis revealed a significant main effect of pressure condition, $F(1, 42) = 43.95$, $p < .001$, $\eta p^2 = .511$, indicating significant differences in absorbance values between TPP and AP conditions across participants. Overall, absorbance values obtained under the tympanometry peak pressure (TPP) found to be higher than those obtained under ambient pressure (AP) conditions.

Further, the interaction effect between pressure condition and age group was not statistically significant, $F(2, 42) = 1.29$, $p = .286$, $\eta p^2 = .058$, indicating that the influence of pressure condition on absorbance values did not differ significantly across the age groups.

The analysis also demonstrated a significant main effect of pressure sweep direction, $F(1, 42) = 224.13$, $p < .001$, $\eta p^2 = .842$, indicating significant differences in absorbance values between ascending and descending pressure sweep directions. Overall, absorbance values obtained during the descending pressure sweep direction were higher than those obtained during the ascending pressure sweep direction.

Additionally, a significant interaction effect between pressure sweep direction and age group was observed, $F(2, 42) = 6.68$, $p = .003$, $\eta p^2 = .241$, suggesting that the effect of sweep direction on absorbance varied significantly across the age groups. To further investigate the interaction between sweep direction and age group, paired-samples t-tests were performed separately within each age group by comparing absorbance values between ascending and descending pressure sweep directions under both ambient pressure (AP) and tympanometry peak pressure (TPP) conditions. The details of the t-tests results are given in table 4.5. Table 4.5 shows that sweep direction had a significant effect on absorbance values at the peak pressure condition in children and adolescents, with large effect sizes (Cohen's d = 0.98–1.12). However, no significant difference between sweep directions was observed in young adults, with a small effect size (Cohen's d = 0.31). In contrast, under the ambient pressure condition, sweep direction showed a significant effect on absorbance values across all age groups, with large effect sizes (Cohen's d = 1.24–1.73).

Table 4.5:

Paired-Samples t-Test Comparison of Ascending and Descending Sweep Directions at Peak and Ambient Pressure Conditions Across Age Groups at Low Frequency

Comparison	Age Group	Mean Difference	95% CI	t	p	d
Peak_ Ascending Vs. Descending	Children	0.253	0.110 – 0.397	3.789	.002	0.98
	Adolescents	0.163	0.083 – 0.244	4.352	.001	1.12
	Young Adults	0.050	-0.039 – 0.139	1.201	.250	0.31
Ambient_ Ascending Vs. Descending	Children	-0.668	-0.882 – -0.454	-6.698	< .001	1.73
	Adolescents	-0.469	-0.619 – -0.318	-6.674	< .001	1.72
	Young Adults	-0.607	-0.878 – -0.336	-4.804	< .001	1.24

Note. Cohen’s d is reported for pairwise comparisons across age groups.

Further, a significant interaction effect between pressure condition and sweep direction was observed, $F(1, 42) = 122.83$, $p < .001$, $\eta p^2 = .745$, indicating that the effect of pressure condition on absorbance values varied significantly depending on the direction of pressure sweep.

Though, the three-way interaction among pressure condition, sweep direction, and age group was not statistically significant, $F(2, 42) = 1.94$, $p = .157$, $\eta p^2 = .084$, indicating that the combined influence of pressure condition and sweep direction on absorbance values did not differ significantly across age groups.

The main effect of age group was also not statistically significant, $F(2, 42) = 2.96$, $p = .063$, $\eta p^2 = .124$, indicating that overall absorbance values did not differ significantly across children, adolescents, and young adults when averaged across pressure conditions and sweep directions.

First midfrequency:

Descriptive statistics were carried out for the second component of PCA (first midfrequency) to examine the wideband absorbance values obtained across the different pressure conditions and pressure sweep directions in children, adolescents, and young adults.

The findings showed higher absorbance values under the tympanometric peak pressure (TPP) condition than under the ambient pressure (AP) condition. Also, comparison across sweep directions showed that absorbance values obtained during the descending pressure sweep direction were relatively higher than those obtained during the ascending pressure sweep direction.

Highest absorbance values were observed under the ascending direction and tympanometric peak pressure condition (AP) across all age groups. Under this condition, children showed the highest mean absorbance value, followed by adolescents and young adults. The overall mean absorbance value for this condition was comparatively highest indicating that absorbance values were relatively highest in this condition.

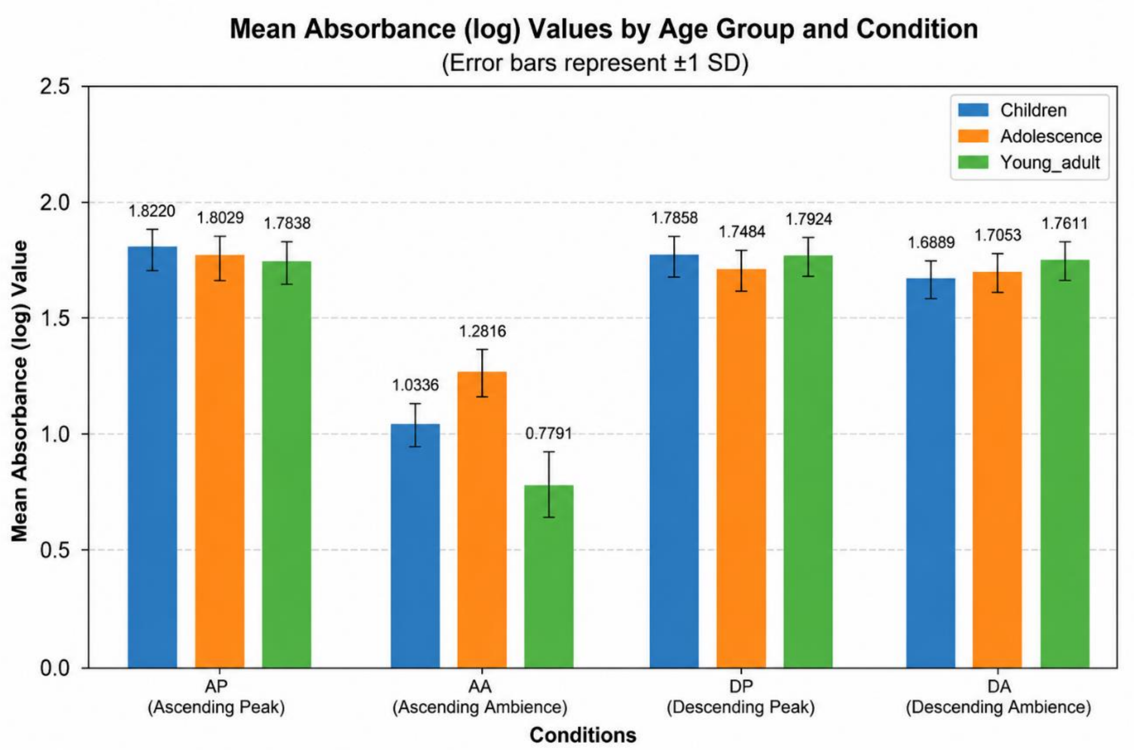
Under the ascending ambient pressure (AA) condition, adolescents showed the highest mean absorbance value, followed by children, while young adults demonstrated the lowest absorbance value. The overall mean absorbance value for this condition was comparatively lower indicating a reduction in absorbance values under ambient pressure conditions during the ascending pressure sweep direction.

Under the descending peak pressure (DP) condition, children and young adults and adolescence demonstrated the closely and high mean absorbance. The overall mean absorbance value for this condition was relatively high.

Under the descending direction and ambient pressure (DA) condition, young adults demonstrated the highest mean absorbance value, followed by adolescents and children. The overall mean absorbance value obtained under this condition was comparatively higher than the ascending ambient pressure (AA) condition across all age groups. The details can be seen in figure 4.7.

Figure 4.7.

Mean Absorbance (Log) Values at First Mid-frequency Across Ascending and Descending Sweep Directions Under Peak and Ambient Pressure Conditions for Children, Adolescents, and Young Adults



A Mixed ANOVA was done with the pressure condition (tympanometric peak pressure [TPP] and ambient pressure [AP]), and pressure sweep direction (ascending and descending) as within subject factors, and age group as the between subject factor.

The analysis revealed a significant main effect of pressure condition, $F(1, 42) = 103.87$, $p < .001$, $\eta p^2 = .712$, indicating significant differences in absorbance values between TPP and AP conditions across participants. Overall, absorbance values obtained at TPP were significantly higher than those obtained at AP conditions.

Further, a significant interaction effect between pressure condition and age group was observed, $F(2, 42) = 7.78$, $p = .001$, $\eta p^2 = .270$, suggesting that the influence of pressure condition on absorbance varied significantly across the age groups. To further explore the significant interaction effect between pressure condition and age group, paired-samples t-tests were performed separately within each age group by comparing absorbance values obtained at tympanometry peak pressure (TPP) and ambient pressure (AP) for both ascending and descending pressure sweep directions. The details of the t-tests results are given in table 4.6. Table 4.6 shows that absorbance values obtained at TPP were significantly higher than those obtained at ambient pressure for the ascending sweep direction across all age groups, with very large effect sizes (Cohen's d = 1.63–2.61). On the other hand, the descending sweep direction do not show a significant difference between the two pressure conditions in adolescents and young adults' group, exhibiting small effect sizes (Cohen's d = 0.35 and 0.46, respectively). However, in children, absorbance values at TPP were significantly higher than ambient pressure during the descending sweep direction, with a large effect size (Cohen's d = 1.01).

Table 4.6:

Paired-Samples t-Test Comparison of Peak and Ambient Pressure Conditions at Ascending and Descending Sweep Direction Across Age Groups at First Mid-frequencies

Comparison	Age Group	Mean Difference	95% CI	t	p	d
Ascending_	Children	0.788	0.621 – 0.956	10.120	< .001	2.61

Peak	Adolescents	0.521	0.374 – 0.668	7.614	< .001	1.97
Vs.	Young Adults	1.005	0.663 – 1.347	6.303	< .001	1.63
Ambient						
Descending_	Children	0.097	0.044 – 0.150	3.904	.002	1.01
Peak	Adolescents	0.043	−0.025 – 0.112	1.349	.199	0.35
Vs.	Young Adults	0.031	−0.006 – 0.069	1.796	.094	0.46
Ambient						

Note. Cohen's d is reported for pairwise comparisons across age groups.

The analysis also demonstrated a significant main effect of pressure sweep direction, $F(1, 42) = 168.25$, $p < .001$, $\eta p^2 = .800$, indicating significant differences in absorbance values between ascending and descending pressure sweep directions. Overall, absorbance values obtained during the descending sweep direction were higher than those obtained during the ascending sweep direction.

Additionally, a significant interaction effect between pressure sweep direction and age group was observed, $F(2, 42) = 4.74$, $p = .014$, $\eta p^2 = .184$, suggesting that the effect of sweep direction on absorbance differed significantly across the age groups. To further investigate the interaction between sweep direction and age group, paired-samples t-tests were performed separately within each age group by comparing absorbance values between ascending and descending pressure sweep directions under both ambient pressure (AP) and tympanometric peak pressure (TPP) conditions. The details of the t-tests results are given in table 4.7. Table 4.7 shows that sweep direction had a significant effect on absorbance values at the peak pressure condition only in adolescents, with a large effect size (Cohen's d = 0.97). In contrast, no significant difference between ascending and descending sweep directions was observed at peak pressure in children and young adults, with small effect sizes (Cohen's d = 0.46 and 0.16, respectively). However, under the ambient pressure condition, sweep direction showed a significant effect on absorbance values across all age groups, with very large effect sizes (Cohen's d = 1.57–1.86), with higher absorbance values for the descending sweep direction than for the ascending sweep direction.

Table 4.7:

Paired-Samples t-Test Comparison of Ascending and Descending Sweep Directions at Peak and Ambient Pressure Conditions Across Age Groups at First Mid-frequency

Comparison	Age Group	Mean Difference	95% CI	t	p	d
Peak_ Ascending Vs. Descending	Children	0.036	-0.008 – 0.080	1.761	.100	0.455
	Adolescents	0.054	0.023 – 0.086	3.756	.002	0.970
	Young Adults	-0.009	-0.038 – 0.021	-0.632	.537	-0.163
Ambient_ Ascending Vs. Descending	Children	-0.655	-0.850 – -0.460	-7.203	< .001	-1.860
	Adolescents	-0.424	-0.552 – -0.296	-7.101	< .001	-1.834
	Young Adults	-0.982	-1.327 – -0.637	-6.098	< .001	-1.574

Note. Cohen's d are reported for pairwise comparisons across age groups.

Further, a significant interaction effect between pressure condition and sweep direction was observed, $F(1, 42) = 116.33$, $p < .001$, $\eta p^2 = .735$, indicating that the effect of pressure condition on absorbance varied depending on the pressure sweep direction. This finding suggests that the influence of tympanometric pressure conditions on absorbance measurements was not uniform across ascending and descending sweep directions.

Also, the three-way interaction among pressure condition, sweep direction, and age group was also statistically significant, $F(2, 42) = 4.69$, $p = .015$, $\eta p^2 = .182$, suggesting that the combined influence of pressure condition and sweep direction on absorbance values differed significantly across the age groups.

The main effect of age group was not statistically significant, $F(2, 42) = 2.21$, $p = .122$, $\eta p^2 = .095$, indicating that the overall absorbance values did not differ significantly across the age groups when averaged across pressure conditions and sweep directions.

Second midfrequency:

Descriptive statistics were carried out for the third component of PCA (second midfrequency) to examine the wideband absorbance values obtained across the different pressure conditions and pressure sweep directions in children, adolescents, and young adults.

The findings showed higher absorbance values under the tympanometric peak pressure (TPP) condition than under the ambient pressure (AP) condition. Also, comparison across sweep directions showed that absorbance values obtained during the descending pressure sweep direction were relatively higher than those obtained during the ascending pressure sweep direction.

Under the ascending direction and tympanometric peak pressure (AP) condition, children showed the highest mean absorbance value, followed by adolescents and young adults. The overall mean absorbance value for this condition was relatively high.

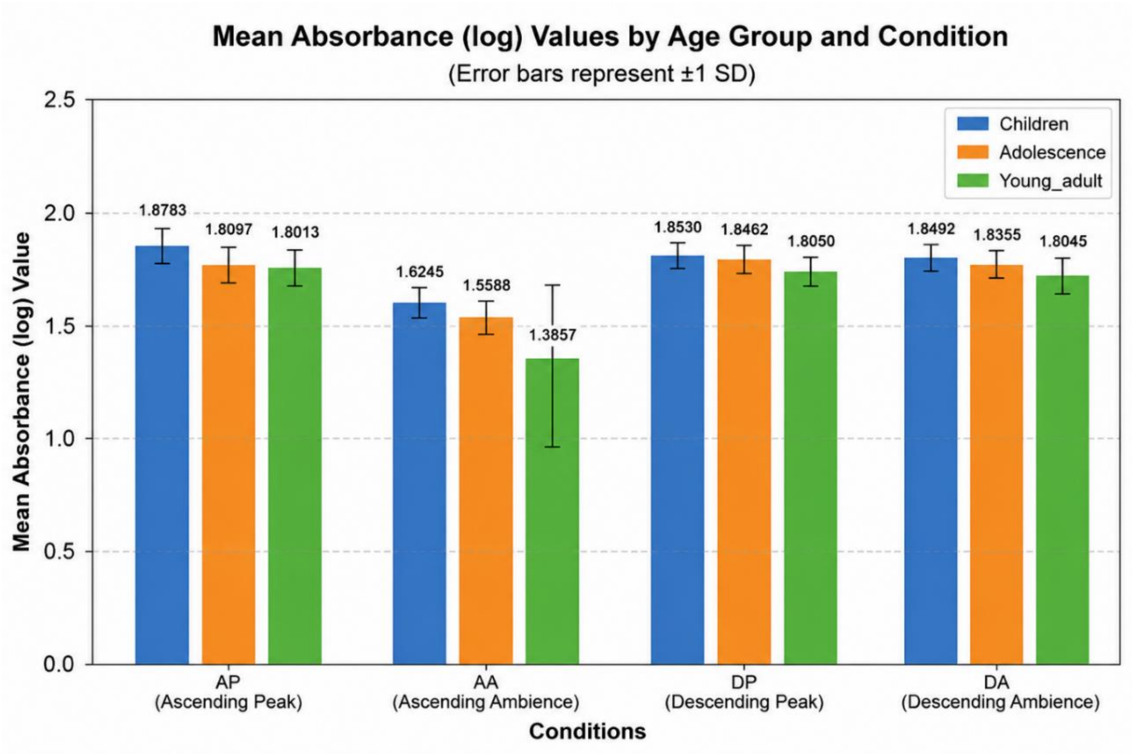
Under the ascending ambient pressure (AA) condition, children showed the highest mean absorbance value, followed by adolescents, while young adults demonstrated the lowest absorbance value. The overall mean absorbance value for this condition was comparatively lowest.

Under the descending peak pressure (DP) condition, children and adolescents demonstrated the highest and closely mean absorbance value, followed by young adults.

Under the descending direction and ambient pressure (DA) condition, children demonstrated the highest mean absorbance value, followed closely by adolescents and young adults. The overall mean absorbance value obtained under this condition was comparatively higher than the ascending ambient pressure (AA) condition across all age groups. The details can be seen in figure 4.8.

Figure 4.8.

Mean Absorbance (Log) Values at Second Mid-frequency Across Ascending and Descending Sweep Directions Under Peak and Ambient Pressure Conditions for Children, Adolescents, and Young Adults



A Mixed ANOVA was done with the pressure condition (tympanometric peak pressure [TPP] and ambient pressure [AP]), and pressure sweep direction (ascending and descending) as within subject factors, and age group as the between subject factor.

The analysis revealed a significant main effect of pressure condition, $F(1, 42) = 89.60$, $p < .001$, $\eta p^2 = .681$, indicating significant differences in absorbance values between TPP and AP conditions across participants. Overall, absorbance values obtained at TPP conditions were found to be significantly higher than those obtained at ambient pressure conditions.

Further, a significant interaction effect between pressure condition and age group was observed, $F(2, 42) = 3.83$, $p = .030$, $\eta p^2 = .154$, suggesting that the influence of pressure condition on absorbance varied significantly across the age groups. To further explore the significant interaction effect between pressure condition and age group, paired-samples t-tests were conducted separately within each age group by comparing absorbance values obtained at tympanometric peak pressure (TPP) and ambient pressure

(AP) for both ascending and descending pressure sweep directions. The details of the t-tests results are given in table 4.8. Table 4.8 shows that absorbance values obtained at tympanometric peak pressure were significantly higher than those obtained at ambient pressure for the ascending sweep direction across all age groups, with very large effect sizes in children and adolescents and a large effect size in young adults (Cohen's d = 1.32–2.20). In contrast, for the descending sweep direction there are not significant difference between peak and ambient pressure conditions in any age group, exhibiting negligible to small effect sizes (Cohen's d = 0.03–0.29).

Table 4.8:

Paired-Samples t-Test Comparison of Peak and Ambient Pressure Conditions at Ascending and Descending Sweep Direction Across Age Groups at Second Mid-frequency

Comparison	Age Group	Mean Difference	95% CI	t	p	d
Ascending_ Peak Vs. Ambient	Children	0.254	0.190–0.318	8.527	< .001	2.20
	Adolescents	0.251	0.174–0.327	7.024	< .001	1.81
	Young Adults	0.416	0.241–0.590	5.103	< .001	1.32
Descending_ Peak Vs.	Children	0.004	−0.003–0.011	1.131	.277	0.29
	Adolescents	0.011	−0.015–0.036	0.904	.381	0.23

Ambient	Young Adults	0.001	−0.009–0.010	0.111	.913	0.03

Note. Cohen's d are reported for pairwise comparisons across age groups.

The analysis also demonstrated a significant main effect of pressure sweep direction, $F(1, 42) = 94.20$, $p < .001$, $\eta p^2 = .692$, indicating significant differences in absorbance values between ascending and descending pressure sweep directions. Overall, absorbance values obtained during the descending sweep direction were higher than those obtained during the ascending sweep direction. However, the interaction effect between pressure sweep direction and age group was not statistically significant, $F(2, 42) = 2.64$, $p = .083$, $\eta p^2 = .112$, suggesting that the effect of sweep direction on absorbance did not significantly differ across the age groups.

Further, a significant interaction effect between pressure condition and sweep direction was observed, $F(1, 42) = 94.75$, $p < .001$, $\eta p^2 = .693$, indicating that the effect of pressure condition on absorbance varied depending on the sweep direction. This finding suggests that the influence of tympanometry pressure conditions on absorbance measurements was not uniform across ascending and descending sweep directions.

Additionally, the three-way interaction among pressure condition, sweep direction, and age group was statistically significant, $F(2, 42) = 3.35$, $p = .045$, $\eta p^2 = .138$, suggesting that the combined influence of pressure condition and sweep direction on absorbance values differed significantly across the age groups.

The main effect of age group was statistically significant, $F(2, 42) = 4.07$, $p = .024$, $\eta p^2 = .162$, indicating that the overall absorbance values differed significantly across the age groups when averaged across pressure conditions and sweep directions.

High frequency:

Descriptive statistics were carried out for the fourth component of PCA (high frequency) to examine the wideband absorbance values obtained across the different pressure conditions and pressure sweep directions in children, adolescents, and young adults.

The findings showed slightly higher absorbance values under the ambient pressure (AP) condition than under the tympanometric peak pressure (TPP) condition. Also, comparison across sweep directions showed that absorbance values obtained during the descending pressure sweep direction were relatively higher than those obtained during the ascending pressure sweep direction.

Under the ascending tympanometric peak pressure (AP) condition, young adults showed the highest mean absorbance value, followed closely by children, while adolescents demonstrated the lowest absorbance value. The overall mean absorbance value for this condition was comparatively lower, indicating a slight reduction in absorbance values under this condition.

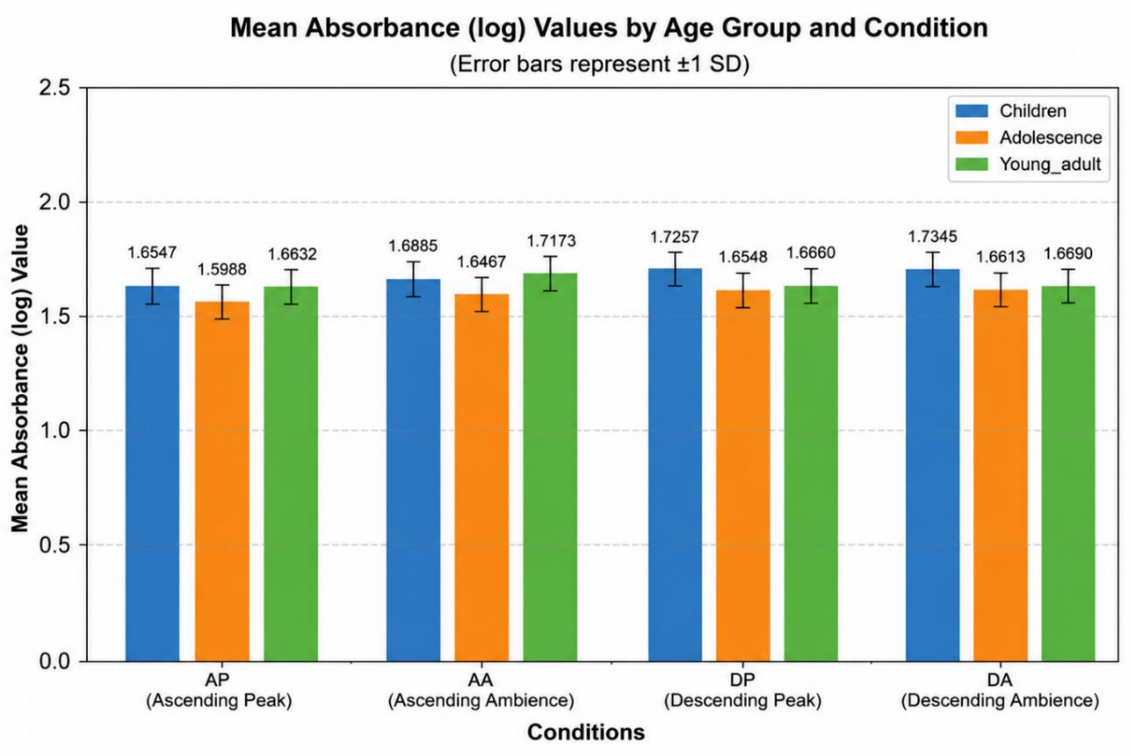
Under the ascending direction and ambient pressure condition (AA), young adults showed the highest mean absorbance value, followed by children and adolescents.

Under the descending peak pressure (DP) condition, children demonstrated the highest mean absorbance value, followed by young adults and adolescents.

Under the descending direction and ambient pressure (DA) condition, children demonstrated the highest mean absorbance value, followed by young adults and adolescents. The details can be seen in figure 4.9.

Figure 4.9.

Mean Absorbance (Log) Values at High Frequency Across Ascending and Descending Sweep Directions Under Peak and Ambient Pressure Conditions for Children, Adolescents, and Young Adults at High Frequency



A Mixed ANOVA was done with the pressure condition (tympanometry peak pressure [TPP] and ambient pressure [AP]), and pressure sweep direction (ascending and descending) as within subject factors, and age group as the between subject factor.

The analysis revealed a significant main effect of pressure condition, $F(1, 42) = 4.43$, $p = .041$, $\eta p^2 = .095$, indicating significant differences in absorbance values between TPP and AP conditions across participants. Overall, absorbance values obtained at ambient pressure conditions (AP) were slightly higher than those obtained at tympanometry peak pressure conditions (TPP).

Further, a significant interaction effect between pressure condition and age group was observed, $F(2, 42) = 4.61$, $p = .015$, $\eta p^2 = .180$, suggesting that the influence of pressure condition on absorbance varied significantly across the age groups. To further explore the significant interaction effect between pressure condition and age group, paired-samples t-tests were conducted separately within each age group by comparing absorbance values obtained at tympanometry peak pressure (TPP) and ambient pressure

(AP) for both ascending and descending pressure sweep directions. The details of the t-tests results are given in table 4.9. Table 4.9 shows that absorbance values obtained at ambient pressure were significantly higher than absorbance obtained at peak pressure condition for the ascending sweep direction for all the age groups, with large effect sizes (Cohen's d = 1.01–1.17). In contrast, the descending sweep direction do not show significant difference between peak and ambient pressure conditions in adolescents and young adults, with small effect sizes (Cohen's d = 0.29–0.41). However, a significant difference was observed in children for the descending sweep direction, with a medium effect size (Cohen's d = 0.62).

Table 4.9:

Paired-Samples t-Test Comparison of Peak and Ambient Pressure Conditions at Ascending and Descending Sweep Direction Across Age Groups at High Frequency

Comparison	Age Group	Mean Difference	95% CI	t	p	d
Ascending_ Peak Vs. Ambient	Children	-0.034	-0.052, – -0.015	-3.893	.002	-1.01
	Adolescents	-0.048	-0.071 – -0.025	-4.430	.001	-1.14
	Young Adults	-0.054	-0.080 – -0.028	-4.519	< .001	-1.17
Descending_ Peak Vs. Ambient	Children	-0.009	-0.017 – -0.001	-2.393	.031	-0.62
	Adolescents	-0.007	-0.015 – 0.002	-1.579	.137	-0.41
	Young Adults	-0.003	-0.009 – 0.003	-1.117	.283	-0.29

Note. Cohen’s d is reported for pairwise comparisons across age groups.

There was a highly significant main effect of Direction, $F(1, 42) = 60.200$, $p < .001$, partial $\eta^2 = .589$. This indicates a strong difference between ascending and descending directions irrespective of pressure condition or age group. The absorbance values obtained in the descending direction were higher than those obtained in the ascending direction.

The interaction between Direction and Age group was not statistically significant, $F(2, 42) = 0.449$, $p = .641$, partial $\eta^2 = .021$. This indicates that the effect of direction remained relatively consistent across the different age groups.

A statistically significant interaction effect was found between Pressure and Direction, $F(1, 42) = 39.182$, $p < .001$, partial $\eta^2 = .483$. This demonstrates that the influence of pressure condition depended on the direction of measurement.

The three-way interaction among Pressure, Direction, and Age group was not statistically significant, $F(2, 42) = 1.487$, $p = .238$, partial $\eta^2 = .066$. This suggests that the combined effect of pressure and direction did not significantly differ across age groups.

The Tests of Between-Subjects Effects revealed that there was no statistically significant main effect of age group, $F(2, 42) = 1.617$, $p = .211$, partial $\eta^2 = .071$. This indicates that the absorbance values did not differ significantly among children, adolescents, and young adults when averaged across all pressure and direction conditions.

Overall, the study revealed, a significant main effect of pressure condition ($p < .001$), with significantly higher absorbance values at tympanometric peak pressure than the ambient pressure across most frequency ranges. At high frequencies absorbance values at ambient pressure were significantly higher than at tympanometric peak pressure ($p = .041$). A significant main effect of pressure sweep direction was observed ($p < .001$), descending sweeps produced significantly higher absorbance values than ascending sweeps. A significant interaction between pressure condition and sweep direction was found across all frequency ranges ($p < .001$), indicating that pressure effects on absorbance varied depending on sweep direction. The three-way interaction among pressure condition, sweep direction, and age group was significant at the first mid-frequency range ($p = .015$) and second mid-frequency range ($p = .045$), whereas at low and high frequencies, this interaction was not significant. At low frequencies, sweep direction effects differed by age. At peak pressure, children and adolescents showed significant differences between sweep directions ($p = .002$ and .001, respectively). At ambient pressure, all age groups showed significant differences ($p < .001$). At first mid-frequencies, only adolescents showed significant differences between sweep directions at peak pressure ($p = .002$). At ambient pressure, all age groups showed significant differences ($p < .001$). At second mid-frequencies, a significant main effect of age group was observed ($p = .024$). At high frequencies, the main effect of age group was not significant ($p = .211$), but pressure condition effects (peak vs. ambient) varied by age at descending sweep direction, with only children showing significant differences ($p = .031$), while all age groups showed significant differences at ascending sweep direction ($p = .002$ to $p < .001$).

CHAPTER 5

DISCUSSION

The present study was carried out to investigate the effect of pressure condition [tympanometric peak pressure (TPP) and ambient pressure (AP)] and pressure sweep direction (ascending and descending sweep) on wideband absorbance (WBA) measures in children, adolescents, and young adults with clinically normal hearing sensitivity. Principal component analysis (PCA) was performed to classify the measured frequencies into four major frequency regions representing low, first mid, second mid, and high-frequency components. Statistical analyses were carried out using Mixed ANOVA, followed by t-test as and when it required to determine the significance effect of parameters and difference between any two conditions. The results of the present study are discussed under the following categories:

- Overall frequency-specific pattern of wideband absorbance
- Effect of pressure condition [tympanometric peak pressure (TPP) and ambient pressure (AP)] on wideband absorbance across different age groups.
- Effect of pressure sweep direction (ascending and descending sweep) on wideband absorbance across different age groups.
- Interaction effect of age group, pressure condition, and pressure sweep direction on wideband absorbance.

5.1. Overall Frequency-Specific Pattern of Wideband Absorbance

The present study showed a frequency-specific pattern of wideband absorbance in all age groups and conditions. Absorbance values were comparatively lower at low frequencies, increased gradually at the mid-frequency regions where the highest absorbance values were observed, and then declined at higher frequencies. This overall absorbance configuration was consistently observed across children, adolescents, and young adults under both ambient pressure (AP) and tympanometric peak pressure (TPP) conditions, as well as across ascending and descending pressure sweep directions.

The overall absorbance pattern observed in the present study is constant with previous wideband tympanometry literature findings, reported a broad band-pass absorbance configuration in individuals with normal middle-ear function. Feeney et al. (2017) reported that mean absorbance values at both ambient pressure and TPP has a broad band-pass pattern, with lower absorbance values at low frequencies and increased absorbance within the mid-frequency regions. Similarly, Karuppannan and Barman (2020) reported that wideband absorbance values were comparatively greater at mid-frequency regions both at peak pressure conditions and ambient pressure conditions. Downing et al. (2022) also specified frequency-dependent absorbance variations in school-aged children, where absorbance generally increased from low frequencies toward the mid frequencies and subsequently reduced at higher frequencies. These observations collectively support the characteristic absorbance configuration obtained in the present study.

The frequency-specific absorbance pattern observed in the present investigation can be explained based on the biomechanical properties of the outer- and middle-ear systems. At lower frequencies, sound transmission through the middle ear is predominantly stiffness controlled. Under these conditions, the tympanic membrane, ossicular chain, and middle-ear cavity oppose the transmission of low-frequency acoustic energy, this causes reduced absorbance values. Özgür et al. (2016) reported that energy reflectance in adults is approximately 100% at low frequencies, indicating reduced energy transfer through the middle-ear system within this frequency range. Similarly, Feeney and

Sanford (2004) reported that wideband acoustic measurements are sensitive to middle-ear stiffness characteristics.

As frequency increased toward the mid-frequency regions, absorbance values also increased among all the age groups and recording conditions. This increase indicates the better sound transmission through the middle ear system. Feeney et al. (2017) reported that wideband absorbance is highest at frequencies where the middle ear most effectively absorbs and transmits sound energy. Mishra et al. (2017) similarly reported that absorbance in children and adults gradually increased from low frequencies toward the mid frequencies. The high absorbance values observed in the first and second mid-frequency components in the present study possible indication of the frequency regions where the middle ear transmits sound most efficiently.

At higher frequencies, absorbance values decreased across all age groups and recording conditions in the present study, suggesting reduced efficiency of sound transmission within the high-frequency region. This may be related to the increasing influence of ossicular mass, resonance interactions, and complex ear canal acoustics at higher frequencies. Similarly, Feeney et al. (2017) reported a broad band-pass absorbance pattern in normal-hearing adults, with absorbance gradually decreasing toward higher frequencies..

5.2. Effect of pressure condition [tympanometric peak pressure (TPP) and ambient pressure (AP)] on wideband absorbance across different age groups

Low-Frequency Region

The present study finding showed significantly greater wideband absorbance (WBA) values at tympanometric peak pressure (TPP) compared to ambient pressure (AP) within the low-frequency region across children, adolescents, and young adults. This effect was significantly observed at the ascending sweep direction, whereas under the descending sweep direction the pressure-related differences were less consistent. These findings indicate that low-frequency sound transmission is highly sensitive to middle-ear pressure compensation.

The greater absorbance observed at TPP within the low-frequency region may be explained by the stiffness-dominated nature of low-frequency middle-ear transmission. Residual pressure mismatch across the tympanic membrane under ambient conditions increases middle-ear stiffness and restricts tympanic membrane mobility, whereas pressure equalization at TPP improves compliance and facilitates more efficient acoustic energy transfer (Karuppannan & Barman, 2020; Liu et al., 2008). Feeney et al. (2017) similarly demonstrated that absorbance differences between TPP and AP conditions were particularly evident within low- and lower mid-frequency regions, suggesting greater sensitivity of these frequencies to pressure-related stiffness alterations. Hougaard et al. (2020) further emphasized that WBA measured at TPP provides more stable and physiologically representative absorbance patterns because pressure-compensated recordings reduce variability associated with middle-ear pressure mismatch.

These findings indicate that low-frequency WBA is strongly influenced by stiffness-related mechanical properties of the middle-ear system and emphasize the clinical importance of evaluating low-frequency absorbance under pressure-compensated conditions.

Mid-Frequency Region

Within the first and second mid-frequency regions, the present study showed significant higher absorbance values at TPP compared to AP across all age groups. This pressure-related effect was most evident during the ascending sweep direction, whereas the differences between TPP and AP were reduced or absent during the descending sweep direction. The mid-frequency region consistently demonstrated the overall higher absorbance values under both pressure conditions, indicating that this frequency range represents the region of optimal resonance-mediated sound transmission within the middle-ear system.

The increased absorbance observed at TPP within the mid-frequency region may be associated with improved resonance efficiency following pressure equalization. Mid-frequency sound transmission is strongly influenced by resonance interactions among the tympanic membrane, ossicular chain, middle-ear cavity, and external auditory canal. Under ambient pressure conditions, residual pressure differences may alter resonance tuning and reduce the efficiency of acoustic energy transfer, whereas pressure compensation stabilizes resonance-mediated transmission and consequently enhances absorbance (Feeney et al., 2017; Karuppannan & Barman, 2020). Aithal et al. (2015) similarly reported that WBA is particularly sensitive between 1 and 4 kHz for evaluating middle-ear status, supporting the present finding that pressure-related absorbance differences were most evident within low- and mid-frequency regions.

The findings therefore suggest that mid-frequency absorbance reflects resonance-mediated middle-ear sound transmission and that pressure compensation at TPP optimizes resonance efficiency across age groups.

High-Frequency Region

At high frequencies, the present study demonstrated a reversal of the pressure effect observed within the low- and mid-frequency regions. Absorbance values obtained under ambient pressure conditions were generally greater than those obtained at tympanometric peak pressure (TPP), particularly during the ascending sweep direction, although the magnitude of these pressure-related differences was considerably smaller than those observed at low and mid frequencies.

The reversal of pressure effect at high frequencies may be explained by the complex transition from stiffness-dominated transmission to mass- and resonance-dominated transmission mechanisms (Sanford and Feeney, 2008). High-frequency sound transmission is influenced more strongly by ossicular mass characteristics, damping properties, ear canal acoustics, and resonance interactions than by compliance-related stiffness changes. Consequently, pressure equalization at TPP applies comparatively smaller effects on high-frequency sound transmission than on low- and mid-frequency transmission (Feeney et al., 2017; Karuppannan & Barman, 2020).

Slightly greater absorbance under ambient pressure conditions at certain high frequencies may additionally reflect subtle alterations in tympanic membrane tension and external auditory canal resonance behavior under ambient conditions. Minor tension variations across the tympanic membrane may occasionally facilitate resonance-related high-frequency acoustic transmission, resulting in marginally greater absorbance at AP than at TPP. Sanford and Feeney (2008) similarly reported substantial developmental variability in high-frequency acoustic transfer functions because of complex resonance-related and mass-related mechanical interactions within the auditory system.

5.3. Effect of pressure sweep direction (ascending and descending sweep) on wideband absorbance across different age groups at each pressure condition

The findings of the present study revealed that the effect of sweep direction was frequency dependent and varied across pressure conditions and age groups. In general, the influence of sweep direction was most evident at lower frequencies and gradually decreased as frequency increased.

Low-Frequency Region

The present study demonstrated that pressure sweep direction significantly influenced absorbance values in the low-frequency region. Under ambient pressure conditions, absorbance values obtained during the descending sweep were significantly higher than those obtained during the ascending sweep. Under tympanometric peak pressure (TPP) conditions, the influence of sweep direction was comparatively smaller, with absorbance values generally being higher during the ascending sweep than during the descending sweep. These findings suggest that the effect of sweep direction on low-frequency absorbance varies according to the pressure condition under which measurements are obtained.

The greater absorbance observed during descending sweep direction under ambient pressure conditions may be because of viscoelastic properties of the middle-ear system. Low-frequency sound transmission is primarily influenced by stiffness-related mechanisms associated with the tympanic membrane, ossicular chain, and middle-ear ligaments. When pressure within the ear canal is altered, these structures do not respond instantaneously but instead exhibit a delayed mechanical response. As a result, the acoustic characteristics measured during a descending sweep may differ from those obtained during an ascending sweep even when identical pressure values are reached. This phenomenon is commonly described as hysteresis, in which the mechanical state of the middle-ear system depends partly on its previous pressure condition (Shanks and Wilson, 1986; Therkildsen and Gaihede, 2005).

Shanks and Wilson (1986) demonstrated that several tympanometric characteristics, including peak static admittance, tympanometric shape, and tympanometric peak pressure, vary according to the direction of pressure change. They suggested that these directional differences arise from the dynamic mechanical behaviour of the middle-ear system. Similarly, Decraemer et al. (1984) reported that tympanometric peak pressure estimates were influenced by sweep direction, indicating that the middle ear does not respond identically during ascending and descending pressure changes. Instead, the middle-ear system exhibits a delayed and non-linear mechanical response to changing pressure conditions. These findings support the view that the directional differences observed in the present study are likely related to the inherent biomechanical properties of the middle ear, particularly its viscoelastic and hysteretic behaviour, rather than to measurement variability alone.

The findings indicate that sweep direction has a noticeable influence on low-frequency absorbance measurements under both ambient pressure and tympanometric peak pressure (TPP) conditions. However, the magnitude of the directional effect was smaller under TPP than under ambient pressure conditions. This observation is consistent with Liu et al. (2008), who reported that absorbance measured at TPP remained relatively stable across different sweep directions, suggesting that pressure compensation reduces the influence of directional and pressure-history effects on middle-ear sound transmission.

Mid-Frequency Region

In the mid-frequency region, the influence of pressure sweep direction was considerably smaller than that observed at low frequencies. In the mid-frequency region, absorbance values obtained during the descending sweep were generally higher than those obtained during the ascending sweep, particularly under ambient pressure conditions. Within the first mid-frequency region, these directional differences were significant across children, adolescents, and young adults under ambient pressure conditions, whereas under tympanometric peak pressure (TPP) conditions a significant sweep-direction effect was observed only in adolescents. In the second mid-frequency region, descending sweeps also tended to be higher absorbance values than ascending sweeps; however, the influence of sweep direction did not differ significantly across age groups.

The reduced influence of sweep direction in this frequency region may be explained by the acoustic characteristics of the middle-ear system. The mid-frequency region corresponds to the range where the middle ear functions most efficiently and demonstrates the highest absorbance values, reflecting optimal sound transmission through the auditory system (Feeney et al., 2017; Mishra et al., 2017). Consequently, minor changes in tympanic membrane position or ossicular mobility resulting from pressure history are likely to have a smaller impact on acoustic energy transmission than those observed at lower frequencies.

The slight tendency for descending sweeps to produce higher absorbance values under ambient pressure conditions may still reflect the effects of hysteresis within the middle-ear system. Therkildsen and Gaihede (2005) reported that differences between ascending and descending pressure sweeps arise from intrinsic hysteresis and phase-delay phenomena associated with the viscoelastic nature of middle-ear structures. Because the middle-ear system does not respond immediately to changes in pressure, measurements obtained during different sweep directions may produce slightly different results even under otherwise identical conditions.

The limited age-related differences observed in this frequency region further suggest that developmental changes have only a modest influence on mid-frequency sound transmission. Although maturation of middle-ear structures continues throughout childhood and adolescence, the middle ear appears to transmit sound efficiently within this frequency range regardless of age, thereby reducing the impact of both developmental and procedural factors.

High-Frequency Region

Although there was influence of pressure sweep direction on absorbance in high frequency, the magnitude of this effect was considerably smaller than lower and mid frequencies. The overall main effect of sweep direction was statistically significant, indicating that descending sweeps produced significantly higher absorbance values than ascending sweeps within the high-frequency region. Also, the absence of a significant interaction between sweep direction and age group suggests that this directional effect was relatively consistent across children, adolescents, and young adults.

The reduced influence of sweep direction at high frequencies may be due to increase of mass and resonance related mechanical characteristics of the middle-ear system, it becomes more prominent as frequency increases. At higher frequencies, sound transmission is influenced more strongly by the inertial properties of the tympanic membrane and ossicular chain and less by stiffness related mechanisms (Sanford & Feeney, 2008). Thus, the effects of direction of pressure change may have a comparatively smaller influence on acoustic energy transmission than at lower frequencies, which may explain the reduced magnitude of sweep-direction effects within the high-frequency region. This interpretation is consistent with Liu et al. (2008), who reported that pressure-related effects became progressively smaller as frequency increased.

Therefore, the findings indicate that high-frequency absorbance measurements are comparatively resistant to sweep-direction influences and may be less susceptible to procedural variability than measurements obtained at lower frequencies.

In summary, the findings indicate that sweep-direction effects are largely associated with stiffness-related transmission mechanisms that dominate at lower frequencies and become progressively less influential as frequency increases. While sweep direction should be considered when interpreting WBA measurements, particularly in the low-frequency region, its influence likely to be reduced when measurements are obtained under pressure-compensated conditions.

5.4. Effect of Sweep Direction on Wideband Absorbance Differs Across Age Groups at Both Pressure Conditions

The present study examined whether the effect of pressure sweep direction on wideband absorbance varied across children, adolescents, and young adults under ambient pressure (AP) and tympanometric peak pressure (TPP) conditions. The findings revealed that sweep-direction effects were influenced by both age and pressure condition, with directional differences generally being more pronounced under AP than under TPP conditions. Across frequency regions, at TPP condition appeared to reduce the magnitude of sweep-direction effects and minimize age-related variability in absorbance measurements. These findings suggest that developmental changes in middle-ear structure and mechanics may influence the viscoelastic and hysteretic behaviour of the middle-ear system during pressure transitions. Under ambient pressure conditions, where residual pressure differences across the tympanic membrane remain present, these biomechanical characteristics may contribute more strongly to sweep-direction effects. In contrast, in pressure equalization condition at TPP appears to reduce stiffness-related restrictions and reduce the influence of viscoelastic mechanisms. It resulting in more stable absorbance measurements across age groups in TPP. The influence of these factors was most evident in the low-frequency region, became less pronounced within the mid-frequency region, and was comparatively minimal at high frequencies.

Low-Frequency Region

The present study showed that the effect of sweep direction on wideband absorbance in the low-frequency region differed across age groups under both ambient pressure and tympanometric peak pressure (TPP) conditions. Under ambient pressure conditions, descending sweeps produced significantly higher absorbance values than ascending sweeps across all age groups. The magnitude of this difference was greatest in children, followed by adolescents and young adults, and all differences were statistically significant. In contrast, under TPP conditions, ascending sweeps produced significantly higher absorbance values than descending sweeps in children and adolescents, whereas no significant difference between sweep directions was observed in young adults. These findings indicate that the influence of sweep direction on low-frequency absorbance varies across age groups and that the effect of direction changes according to the pressure condition under which measurements are obtained. Furthermore, sweep-direction effects were more pronounced under ambient pressure conditions than under TPP conditions, suggesting that pressure compensation reduces directional variability in low-frequency absorbance measurements.

The influence of pressure condition on sweep-direction effects has been discussed in detail in Section 5.3. Briefly, sweep-direction effects were more noticeable under ambient pressure conditions than tympanometric peak pressure (TPP) conditions across all age groups. Thus, sweep-direction effects become less pronounced under TPP conditions than under ambient pressure conditions.

The variation in sweep-direction effects across age groups may reflect developmental differences in the biomechanical and viscoelastic properties of the middle-ear system. Throughout childhood and adolescence, the external and middle ear continue to undergo structural and functional maturation, including increases in middle-ear cavity volume, changes in tympanic membrane orientation, and refinement of ossicular mechanics (Sanford & Feeney, 2008). These developmental changes alter the mechanical characteristics of the middle ear and may influence the extent to which the system exhibits viscoelastic and hysteretic behaviour during pressure transitions. Mishra et al. (2017) reported that wideband absorbance patterns gradually become more adult-like with increasing age, suggesting continued maturation of middle-ear transmission mechanisms throughout childhood. Similarly, Downing et al., 2022, observed significant age-related changes in wideband tympanometry measures among school-aged children and justify these findings as progressive maturation of middle-ear acoustic transmission. Therefore, the developing middle-ear system in children may be more susceptible to directional pressure effects than the adult ear, resulting in larger sweep-direction differences. Consistent with this interpretation, children showed the largest sweep-direction effects in the present study, whereas young adults generally exhibited smaller directional differences, suggesting that maturation of middle-ear biomechanics may reduce susceptibility to sweep-direction influences.

Mid-Frequency Region

The present study demonstrated that the effect of sweep direction on wideband absorbance within the mid-frequency region differed across age groups under both ambient pressure and tympanometric peak pressure (TPP) conditions. Similar to the low-frequency region, descending sweeps produced significantly higher absorbance values than ascending sweeps under ambient pressure conditions across children, adolescents, and young adults in both the first and second mid-frequency regions. However, unlike the low-frequency region, the influence of sweep direction was noticeably reduced under TPP conditions. Within the first mid-frequency region, a significant sweep-direction effect was observed only in adolescents, whereas children and young adults did not demonstrate significant differences between ascending and descending sweeps. Furthermore, a significant interaction between sweep direction and age group was observed within the first mid-frequency region, whereas no significant interaction was found within the second mid-frequency region. These findings indicate that sweep-direction effects remained evident under ambient pressure conditions but became substantially reduced following pressure compensation at TPP, suggesting that pressure condition exerts a greater influence on directional variability than age alone.

Additionally, in the second mid-frequency region, children demonstrated higher absorbance values than adolescents and young adults in all measurement conditions. The differences among age groups were more noticeable during ascending sweeps under ambient pressure conditions and became less evident during descending sweeps and under TPP conditions. Zhao et al. (2025), in a systematic review of wideband absorbance across the lifespan, reported significant age-related variations in absorbance across frequencies and observed that absorbance generally increased from childhood, reaching a highest around 10–13 years of age before declining after adolescence. The authors further reported significant frequency specific differences, particularly at 1- 4 kHz, highlighting the influence of age on absorbance characteristics across the frequency spectrum. Similarly, André et al. (2012) reported significant developmental changes in middle-ear resonance during early life and demonstrated that resonance frequency increases as the middle ear system matures. Collectively, these studies suggest that age-related changes in absorbance may be influenced by ongoing maturation of the tympanic membrane, middle-ear structures, and external auditory canal, together with reductions in middle ear mass, increases in ear canal size, and progressive alteration of middle ear sound transmission and resonance characteristics (André et al., 2012; Zhao et al., 2025). Although the study focused on infants rather than older children, the findings provide partial support for the present results by highlighting the influence of developmental changes in middle ear function on sound transmission. Thus, the higher absorbance observed in children in the present study may be associated with developmental changes in middle ear resonance and sound transmission characteristics.

Reasons for more shift in AP compare to TPP is already discussed in detailed under 5.3. However, this effect seems to be similar across age group. This suggests that age related changes in the middle ear structure from childhood to adulthood his insignificant with refrence to effect of pressure sweep on WBA.

The variation in sweep-direction effects across age groups may be related to developmental changes in the biomechanical and viscoelastic properties of the middle-ear system. Previous studies have shown that the external and middle ear continue to mature throughout childhood, resulting in age-related changes in middle-ear transmission characteristics and wideband absorbance patterns (Mishra et al., 2017; Downing et al., 2022). Developmental changes in middle-ear structures, including the tympanic membrane, ossicular chain, and middle-ear space, may alter the mechanical behaviour of the system and consequently influence its viscoelastic response during pressure sweeps. Because sweep-direction differences are thought to arise from hysteresis and phase-delay phenomena associated with the viscoelastic properties of middle-ear tissues (Shanks and

Wilson, 1986; Therkildsen and Gaihede, 2005), age-related maturation of these structures may contribute to variations in the magnitude of directional effects on WBA. However, unlike the low-frequency region, sweep-direction effects in the mid-frequency region were relatively small and showed no consistent developmental trend. This may be because the mid-frequency region corresponds to the frequency range where sound transmission is most efficient and the influences of stiffness- and mass-related mechanisms are more balanced, reducing the impact of minor age-related differences in middle-ear viscoelastic behaviour on absorbance measurements. Consequently, although developmental changes may contribute to some age-related variation in sweep-direction effects, their influence appears less pronounced in the mid-frequency region than in the low-frequency region.

Overall, the results indicate that sweep-direction effects in the mid-frequency region are primarily evident under ambient pressure conditions and become negligible when measurements are obtained under TPP conditions, highlighting the stabilizing influence of pressure compensation on middle-ear sound transmission.

High-Frequency Region

The present study demonstrated that pressure sweep direction significantly influenced wideband absorbance within the high-frequency region. Overall, absorbance values obtained during descending sweeps were significantly higher than those obtained during ascending sweeps across children, adolescents, and young adults. Unlike the low- and first mid-frequency regions, the effect of sweep direction did not differ significantly across age groups, indicating that the influence of direction on high-frequency absorbance remained relatively stable throughout development.

The influence of pressure condition on sweep-direction effects has been discussed in detail in Section 5.3.

At high frequency, sound transmission is influenced less by stiffness-related mechanisms and more by the mass and resonance related characteristics of the middle-ear system (Sanford & Feeney, 2008). Since sweep-direction effects are thought to be largely associated with viscoelastic influences on middle-ear stiffness, age-related variations in these properties are likely to have a smaller impact at high frequencies. Consequently, developmental differences in middle-ear biomechanics may exert only a limited influence on sweep-direction effects, which may explain why similar directional patterns were observed across children, adolescents, and young adults in the present study.

Collectively, these findings suggest that the interaction between sweep direction and age group is strongest at low frequencies, decreases within the mid-frequency region, and becomes minimal at high frequencies, reflecting the frequency-dependent influence of middle-ear biomechanics and maturation on wideband absorbance.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. Summary

The present study investigated the influence of pressure conditions (tympanometric peak pressure [TPP] and ambient pressure [AP]) and pressure sweep directions (ascending and descending) on wideband absorbance (WBA) measures among children, adolescent, and young adult age groups with normal hearing sensitivity. Wideband absorbance has an important role in clinical measure of middle-ear function because it provides frequency-specific information about acoustic energy transmission across a broad frequency range. Although various studies have confirmed the effects of pressurization and developmental maturation on WBA, limited information was available about the combined influence of age and pressure sweep direction on absorbance measurements.

A total of 45 participants with normal hearing sensitivity have taken and divided into three age groups: children, adolescents, and young adults. Wideband absorbance measurements were obtained using the GSI TympStar Pro™ tympanometer under ascending and descending pressure sweep directions at both tympanometric peak pressure and ambient pressure conditions. Principal component analysis (PCA) was performed to reduce the frequency-specific data and reduce false positive rate, into four major components representing low-frequency (258–603 Hz), first mid-frequency (818–1249 Hz), second mid-frequency (1507–3036 Hz), and high-frequency (4048–8010 Hz) regions. Mixed ANOVA statical test were employed to evaluate the effects of age group, pressure condition, and pressure sweep direction.

The results revealed a consistent frequency-specific absorbance pattern for all age groups and test conditions. Absorbance values were lowest at low frequencies, increased progressively toward the mid-frequency regions with a maximum absorbance, and then decreased at high frequencies. This pattern is consistent with the known biomechanical characteristics of the middle-ear system and previous reports in the literature (Feeney et al., 2017; Liu et al., 2008).

The study further revealed that pressure condition significantly influenced WBA measurements. In the low, first and second mid frequency regions, absorbance values at tympanometric peak pressure were significantly higher than obtained at ambient pressure. But, in the high frequency region, absorbance values were slightly higher under ambient pressure conditions than TPP. These findings suggest that pressure compensation improves sound transmission mainly at stiffness and resonance dominated frequency regions.

Pressure sweep direction also has a significant influence on absorbance measurements. Descending pressure sweeps generally produced higher absorbance values than ascending sweeps, particularly under ambient pressure conditions. The magnitude of this effect varied across frequency regions and age groups, demonstrating that the influence of middle ear hysteresis and viscoelastic properties on WBA recordings.

Although the overall main effect of age group was not significant in most the frequency regions, influence of maturational changes was observed in specific frequency ranges. Children generally showed comparatively higher absorbance values across several mid and high frequency regions than adolescents and young adults. Significant interactions between age group and pressure-related variables were observed in the first and second mid-frequency regions, suggesting that maturation related changes in middle ear mechanics may influence the effect of pressure compensation and sweep direction on sound transmission.

Overall, the findings indicate that wideband absorbance is influenced by frequency, pressure condition, and pressure sweep direction, and that maturational factors effects in a frequency-specific manner.

6.2. Conclusion

The present study confirmed that wideband absorbance (WBA) follows a frequency specific pattern across children, adolescents, and young adults, with lower absorbance at low frequencies, maximum absorbance at mid-frequency region, and reduced absorbance at high frequency region. This pattern reflects the bio-mechanical properties of the middle-ear system and its frequency specific sound transmission characteristics. The pressure condition (TPP and ambient pressure) also had a significant influence-absorbance values were generally higher TPP than at ambient pressure at low and mid frequency regions, indicating improved sound transmission due to pressure compensation. On the other hand, high frequency absorbance showed only minimal pressure related differences, with higher values observed under ambient pressure conditions. Pressure sweep direction also had a significant effect on WBA, with descending sweeps generally producing higher absorbance values than ascending sweep direction, particularly under ambient pressure conditions. Finally, the magnitude of these effects varied across frequency regions and age groups, suggesting that developmental changes in middle-ear mechanics influence absorbance measurements. Overall, the findings indicate that wideband absorbance is influenced by frequency, pressure condition, pressure sweep direction, and age-related developmental changes of middle ear. Therefore, these factors should be carefully considered when interpreting WBA findings.

6.3. Implications of the Study

I. The findings support the use of tympanometric peak pressure (TPP) measurements in clinical WBA assessment, particularly in low and mid frequency regions where pressure compensation significantly improves absorbance values.

II. Clinical consideration of the pressure sweep direction is needed as it affects WBA outcomes, especially under ambient pressure conditions.

III. Age-related differences observed in the mid frequency regions indicate that interpretation of WBA results should consider developmental maturation also rather than relying solely on adult normative data.

IV. The PCA-derived frequency regions, it may facilitate more clinically meaningful interpretation of WBA findings by reducing dependence on individual frequency specific analysis.

V. The study provides support that procedural variables such as pressure condition and sweep direction can influence WBA outcomes and should be consider in future investigations.

VI. The study supports further investigation of hysteresis related mechanisms underlying sweep direction effects in wideband tympanometry.

6.4. Strength of the study

I. The study investigated the combined effect of age, pressure condition, and pressure sweep direction on wideband absorbance.

II. Both ascending and descending pressure sweep directions were assessed in wideband absorbance measurements.

III. Wideband absorbance measurements were obtained under both ambient pressure and TPP conditions, that gave a detailed evaluation of pressure-related influences on absorbance.

IV. Inclusion of three separate age groups provided age related understandings into wideband absorbance characteristics.

V. Participants were carefully screened through comprehensive audiological and immittance assessments, ensuring that only individuals with normal hearing sensitivity and normal middle ear function were included.

VI. The study evaluated absorbance across a broad frequency range and employed principal component analysis (PCA) to identify meaningful frequency regions, enabling a clearer interpretation of frequency-specific absorbance patterns.

VII. Strong statistical methods, including principal component analysis and Mixed ANOVA, were used to analysis of both within subject and between subject effects.

6.5. Limitations and Future Directions

While the present study provides valuable insights into the effects of pressure condition and pressure sweep direction on wideband absorbance across different age groups, certain limitations should be considered. The study included a comparatively small sample size, which may limit the generalization of the findings in broader population. In addition, only participants with normal hearing sensitivity and normal middle-ear function were included. Thus, the findings may not be directly applicable to individuals with middle-ear pathologies or pathological population. Also, the study focused on children, adolescents, and young adults, and did not include clinically important age groups such as infants and older adults, whose middle ear characteristics differ considerably due to developmental and age-related anatomical and physiological changes. In addition, the cross-sectional design of the study limits the to monitor changes in wideband absorbance within individuals over time.

In future research should include larger number of samples to establish comprehensive normative data for wideband absorbance measures across the lifespan. Studies involving infants and older adults would further improve the understanding of developmental and age-related variations in middle ear sound transmission. In addition, studying wideband absorbance under different pressure conditions and sweep directions in individuals with middle ear disorders would help to determine the clinical applicability of the present findings.

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