Wideband Acoustic Immittance Normative Data: Ethnicity, Gender, Aging, and Instrumentation

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This article describes the effect of ethnicity, gender, aging, and instrumentation on wideband acoustic immittance (WAI). This is an important topic to investigate as the goal of any audiological test is optimize the test's sensitivity and specificity. One way to improve the test's sensitivity and specificity is to reduce the variability of the normative data. The impact of the aforementioned demographic characteristics on WAI norms has been reviewed, and where applicable its potential impact on clinical outcome has been discussed. Overall, differences observed between Caucasian and Chinese ethnic groups in adults population may warrant the use of ethnicity-specific norms especially for detection of otosclerosis; however, these differences in the school-aged children are not large enough to warrant the use of ethnicity-specific norms. It is important to explore whether the observed differences between Caucasian and Chinese ethnic groups is due to body-size indices and whether these differences can be replicated in other East Asian ethnic groups that share similar body-size indices. The differences observed between school-aged children and adults could also potentially impact clinical decision analysis. Therefore, use of age-specific norm is recommended. The differences in WAI between different systems are not clinically significant, and the use of instrument-specific norms does not result in improved test performance at least for the detection of otosclerosis. However, measuring WAI at ambient pressure (static) or at pressure corresponding to the peak (dynamic mode) could potentially impact the normative data and may prove to be clinically useful in cases of negative and positive middle ear pressure.

(Ear and Hearing 2013;34;27S–35S)

FACTORS IMPACTING WAI PATTERNS

The collection of population-based normative data is a necessary step in the process of standardization of wideband acoustic immittance (WAI). The variability of WAI patterns in the normal population across frequencies is partially affected by their demographic characteristics, including ethnicity, gender, and age. Moreover, the characteristics of the instruments used to generate these measures are also equally important. One particularly important question concerns comparability. Can the same set of normative data be used across all instruments? The aim of this review is to examine the differences between WAI patterns among various demographic groups based on ethnicity, gender, and age. It is also within the scope of this review to assess the comparability of the two middle ear analyzer systems that have been used to generate most of the published WAI norms: the Mimosa Acoustics middle ear transduction with acoustic power assessment and Interacoustics WAI tympanometry systems. This review also incorporates some original data that have not been published in peer-reviewed journals (Shaw 2009, Reference Note 1; Kenny 2011, Reference Note 2).

Importance of Studying the Source of Variability in the Normative Data—Clinical Implications

Once norms are established for a particular measurement, using a particular instrument, for a particular population, it is crucial to assess the efficacy with which a test can distinguish between normal and diseased conditions. The goal of any audiological test is to optimize the test's sensitivity and specificity. This can be accomplished in three primary ways: by adjusting the criterion level, by using instrument-specific norms, by using population-specific norms. A test's specificity and sensitivity can be improved by adjusting the criterion value (β), which is the criterion that is used to determine whether an ear is normal or abnormal (Turner et al. 1999). For instance, for measures of WAI, the criterion for the detection of otosclerosis could be power reflectance >0.82 for the frequency of 500 Hz (Shahnaz et al. 2009). Each criterion value is associated with a particular sensitivity and specificity, which changes if the criterion is adjusted. Making the criterion more stringent (e.g., increasing to power reflectance >0.85) will result in greater test specificity and poorer sensitivity, because fewer healthy ears will be incorrectly identified as being disordered (fewer false alarms) but fewer of the disordered ears will be detected (more misses). Meanwhile, making the criterion less stringent (e.g., decreasing power reflectance to >0.75) would result in poorer test specificity and greater test sensitivity, because more healthy ears will be incorrectly identified as being disordered (more false alarms) and more of the disordered ears will be identified as being disordered (more hits). The criterion can be adjusted to improve specificity or sensitivity depending on the population that is used and depending on the cost required to have patients be seen by a medical specialist (Turner et al. 1999).

Another way in which a test's sensitivity and specificity may be altered is by using instrument-specific norms. If the use of instrument-specific norms does not result in improved sensitivity and specificity, then instrument-specific norms are not warranted because the test's predictive value is not improved. One study analyzed whether tympanometric norms using a specific instrument would result in improvements in the detection of otosclerosis. Shahnaz and Bork (2008) analyzed whether the Virtual 310 System and the GSI Tympstar Middle Ear Analyzer System (Grason-Stadler, Eden Prairie, Minnesota) would generate comparable tympanograms and whether the two instruments were comparable in the detection of otosclerosis. Standard tympanometric measures of peak compensated static admittance (Ytm), tympanometric peak pressure (TPP), tympanometric width (TW), and equivalent ear-canal volume (Vea) were made. It was found that some differences existed between

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the two systems on measures of Vea. Differences also existed between the two systems for the multifrequency tympanometric measures of resonant frequency and the phase angle of 45°. These differences, however, were not as significant as the differences that exist between normal and otosclerotic ears (Shahnaz & Bork 2008). Thus, the use of instrument-specific norms did not result in improved specificity and sensitivity for the detection of otosclerosis.

It is also possible that a test's sensitivity and specificity will be improved as a result of applying population-specific norms. For example, Shahnaz and Davies (2006) analyzed whether ethnicity-specific norms are warranted, by gathering ethnicity-specific norms (Caucasian versus Chinese) for conventional 226 Hz tympanometric measures of Ytm, TW, and Vea. Next, they compared these norms with data obtained from 36 individuals with otosclerosis, most of whom were Caucasian (32 of 36; Shahnaz & Davies 2006). It was found that the use of ethnicity-specific norms resulted in improvements in test sensitivity and specificity. In a subsequent study, Shahnaz et al. (2009) examined whether the parameter of reflectance at 500 Hz, frequency corresponding to admittance phase angle of 45° (F45°), or Ytm was the best predictor of otosclerosis. In that study, ethnicity-specific norms were compared with data of 28 individuals with otosclerosis, most of whom were Caucasian. It was found that reflectance at 500 Hz had the best performance in detecting otosclerosis, followed by F45°. Ytm had the poorest overall test performance (Shahnaz et al. 2009). Beers et al. (2010) reported that despite differences observed between normal Caucasian and Chinese school-aged children, application of ethnicity-specific data did not improve the test performance of power reflectance in distinguishing middle ear effusion from that of normal control group.

Effect of Ethnicity on WAI

The use of norms in evidence-based practice is a critical concept that has been used for decades. By knowing the range of results that one would expect in people with normal hearing or normal middle ears, it is possible to more accurately assess whether somebody has a hearing loss or a middle ear problem. Clinicians generally use the same normative data for the entire adult population despite the fact that there is evidence to suggest that hearing thresholds (Henselman et al. 1995; Ishii & Talbott 1998; Dreisbach et al. 2007), tympanometric parameters (Robinson et al. 1988; Chan & McPherson 2001; Wan & Wong 2002; Shahnaz & Davies 2006; Wong et al. 2008), and WAI patterns vary in different ethnic groups (Shahnaz & Bork 2006; Shaw 2009, Reference Note 1; Kenny 2011, Reference Note 2). It has also been shown that otoacoustic emissions are different in different ethnic groups (Caucasianhead et al. 1993; Chan & McPherson 2001; Dreisbach et al. 2008; Shahnaz 2008).

A number of studies have investigated differences in hearing sensitivity related to ethnicity (Asian, Caucasian, and African American) and gender. These investigations indicate that threshold differences exist between certain ethnic groups in both the conventional frequency range of 0.25 to 8 kHz (Caucasianhead et al. 1993; Cooper 1994; Ishii & Talbot 1998; Shahnaz 2008) and the extended high-frequency range of > 8 kHz (Dreisbach et al. 2007). Studies involving noise exposure have likewise reported that some races are more susceptible to noise-induced hearing loss than others (Jerger et al. 1986; Henselman et al. 1995). In an earlier study, Bunch and Raiford (1931) had examined hospital patients and reported that African American males had lower hearing thresholds than Caucasian males at frequencies above 2000 Hz (Ishii & Talbot 1998). Dreisbach et al. (2007) extended this work and reported that that African Americans had better hearing thresholds at 14 and 16 kHz than Caucasians or Asians. As reviewed earlier in this article, a range of findings from hearing sensitivity research point to racial and gender differences that invite further investigations. To date candidate explanations have focused either on characteristics of the outer and middle ear, or on cochlear function. A number of findings (e.g., Shahnaz 2008) support the conclusion that characteristics of the outer and middle ear do affect hearing measurement.

It has been reported that Asians have lower Ytm, smaller ear-canal volume, and wider TW than Caucasians (Caucasianhead et al. 1993; Chan & McPherson 2001; Wan & Wong 2002; Shahnaz & Davies 2006). Furthermore, studies using multifrequency tympanometry reported higher middle ear resonant frequencies for Asians compared with that of Caucasians. The multifrequency tympanometry measure of Ytm has also been shown to be higher in Caucasian subjects as opposed to Chinese subjects, up to 1200 Hz (Shahnaz & Davies 2006). Caucasianhead et al. (1993) also reported lower middle ear muscle reflex thresholds for African Americans in comparison with Asians and Caucasians. Variations in middle ear function across different ethnicities may also shed light on differences in disease prevalence between these groups, particularly differences in the prevalence of otitis media with effusion. It has been shown that the prevalence of different middle ear pathologies varies across different ethnicities. The low prevalence of otitis media (OM) reported in studies involving populations of African extraction (e.g., Nigerian population in the study by Ogisi 1988, Jamaican in the study by Jadusingh et al. 1998) and Chinese (e.g., Hong Kong population in the study by Tong et al. 2000) ethnic groups could be attributed to differences of mechano-acoustical properties of the middle ear or anatomical variations in Eustachian tube. Williamson et al. (1994) reported a point prevalence for OM with effusion of 17% for Caucasian children at the age of 5 years in Southwest Hampshire, Britain. In comparison, the point prevalence for a comparable group of Chinese children in Hong Kong was only 2.2% (Tong et al. 2000).

Shahnaz and Bork (2006) established normative adult WAI values for reflectance in 126 subjects (237 ears) between the ages of 18 and 32 years (62 subjects in the Caucasian group and 64 subjects in the Chinese group) using Mimosa Acoustics (RMS-system v. 4.0.4.4) WAI equipment. Shahnaz and Bork reported that Chinese young adults have significantly higher reflectance at the low frequencies in comparison with Caucasian young adults. Meanwhile, Caucasians have significantly higher reflectance at the high frequencies compared with their Chinese counterparts. Replication of differences between these groups would support the idea that different norms should be used for Caucasian and Chinese individuals when assessing middle ear function. Most researchers agree that systematic replication and cross-validation of research findings is a necessary step for knowledge advancement in a discipline and essential for establishing external validity. Campbell and Stanely (1963) stated that "...the experiments we do today, if successful, will need replication and cross-validation at other times under other conditions before they can become an established part of

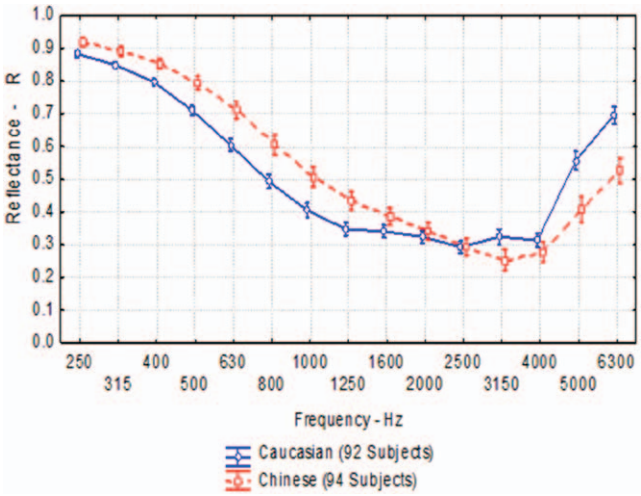

Fig. 1. Reflectance. at each of the 15 frequencies for Caucasian and Chinese young adults. Data from Mimosa middle ear analyzer systems are pooled together.

science, before they can be theoretically interpreted with confidence" (p.3). To that end, Shaw (2009, Reference Note 1) measured WAI for reflectance and absorbance using the Mimosa Acoustics and Reflwin Interacoustics middle ear analyzer systems in 60 normal-hearing participants (113 ears), with an equal number of Chinese and Caucasian males and females. Using a mixed model analysis of variance the patterns of the reflectance obtained using a Mimosa Acoustics system were compared between Shahnaz and Bork (2006) and Shaw (2009, Reference Note 1) studies in Caucasian and Chinese participants. There were no statistical differences between the patterns of reflectance between the two studies in either ethnicity.

Similar to Shahnaz and Bork (2006), Shaw (2009, Reference Note 1) also found that Chinese young adults have significantly higher reflectance for frequencies of 1250 Hz and below in comparison with Caucasian young adults using Mimosa Acoustics system. Meanwhile, Caucasians have significantly more reflectance at at frequencies of 4000 to 6000 Hz compared with their Chinese counterparts. Shaw (2009, Reference Note 1) also tested the same group of participants using Reflwin Interacoustics (Eclipse-system v.1, Interacoustics AS, Assens, Denmark) in static (nonpressurized) and dynamic (pressurized) mode and found similar findings between the two ethnic groups. As there were no statistical differences between the studies by Shahnaz and Bork (2006) and Shaw (2009, Reference Note 1) using the Mimosa Acoustics system, the data were pooled together and a mixed model analysis of variance was conducted. The results replicated the findings of Shahnaz and Bork (2006), as shown in Figure 1. This analysis represents 186 subjects (92 subjects in the Caucasian group and 94 subjects in the Chinese group).

Table 1 shows the descriptive statistics, including the mean and 90% range for Mimosa Acoustics (combined data from Shahnaz & Bork 2006; and Shaw 2009, Reference Note 1) at 15 frequencies (250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, and 6000 Hz) for both ethnic groups (Caucasian and Chinese) for the parameter of reflectance at static pressure. Kenny (2011, Reference Note 2) tested a total of 50 young adults (30 women, 20 men) using REFLWIN Interacoustics (Build v. 2.60500) WAI machine, a PC-based system capable of performing both static (at ambient pressure) and dynamic (with introduced pressure changes) measures of reflectance. These groups were equally distributed between two ethnic groups (Caucasian and Chinese), resulting in four subject groups: 15 Chinese females, 10 Chinese males, 15 Caucasian females, and 10 Caucasian males. The descriptive statistics, including the mean and 90% range for the Interacoustics system, are also shown in Table 1 for comparative purposes. Kenny found that Caucasian subjects demonstrated significantly higher absorbance in dynamic mode from 800 to 1250 Hz compared

TABLE 1. Descriptive statistics, including the mean and 90th percentile range at each of the 15 frequencies for measurements made at ambient pressure

	Caucasian						Chinese					
	Mean		5th Percentile		95th Percentile		Mean		5th Percentile		95th Percentile	
Frequency (Hz)	M	I	M	I	M	I	M	I	M	I	M	I
250	0.88	0.90	0.77	0.80	0.97	0.97	0.92	0.92	0.84	0.86	0.97	0.97
315	0.85	0.89	0.72	0.80	0.94	0.98	0.90	0.92	0.81	0.83	0.96	0.98
400	0.80	0.84	0.62	0.76	0.92	0.94	0.87	0.87	0.76	0.76	0.94	0.95
500	0.71	0.77	0.48	0.66	0.88	0.91	0.81	0.81	0.66	0.65	0.92	0.91
630	0.61	0.63	0.33	0.45	0.81	0.79	0.73	0.67	0.55	0.45	0.87	0.81
800	0.49	0.56	0.21	0.36	0.72	0.79	0.63	0.60	0.42	0.37	0.81	0.74
1000	0.41	0.45	0.16	0.23	0.62	0.70	0.53	0.51	0.29	0.31	0.72	0.68
1250	0.35	0.37	0.17	0.20	0.55	0.58	0.45	0.44	0.22	0.29	0.66	0.60
1600	0.34	0.42	0.17	0.24	0.56	0.63	0.41	0.47	0.15	0.29	0.60	0.68
2000	0.32	0.41	0.13	0.19	0.51	0.59	0.34	0.41	0.11	0.24	0.54	0.63
2500	0.29	0.40	0.09	0.19	0.49	0.59	0.28	0.37	0.07	0.08	0.47	0.65
3150	0.32	0.29	0.07	0.02	0.60	0.50	0.24	0.26	0.05	0.03	0.49	0.57
4000	0.31	0.25	0.08	0.02	0.59	0.47	0.24	0.22	0.04	0.02	0.51	0.52
5000	0.56	0.44	0.22	0.17	0.87	0.70	0.37	0.37	0.09	0.13	0.73	0.69
6000	0.70	0.61	0.38	0.36	0.96	0.73	0.51	0.54	0.19	0.35	0.79	0.76

The Mimosa System (M) representing combined data from works by Shahnaz and Bork (2006) and Shaw 2009, Reference Note 1) (n = 186) and the Interacoustic System (I) from the study by Kenny 2011, Reference Note 2) (n = 50) were used.

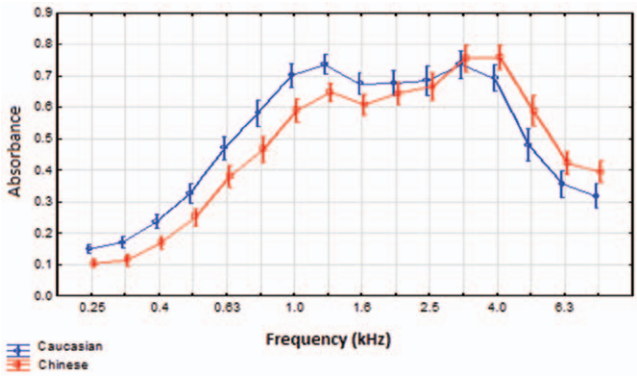

Fig. 2. Dynamic absorbance measured at tympanometric peak pressure across frequency in 25 Caucasian (50 ears) and 25 Chinese (50 ears) normal-hearing adults. The error bars denote the 95% confidence intervals at each frequency (Kenny 2011, Reference Note 2).

with their Chinese counterparts. At higher frequencies, Chinese subjects demonstrated significantly higher absorbance in the dynamic mode from 5000 to 8000 Hz compared with Caucasian subjects. Figure 2 illustrates the absorbance between the two ethnicities across 1/3 octave frequencies between 250 and 8000 Hz.

Beers et al. (2010) established normative WAI data in 78 (144 ears) normal school-aged children with an average age of 6.15 years (ranged in age from 5 years 1 month to 6 years 11 month). There were 63 ears in the Caucasian group and 60 ears in the Chinese group. Twenty-one ears had mixed origin. As illustrated in Figure 3, the mean power reflectance value is closer to 1 (high reflectance) for both the Caucasian and Chinese groups at low- and high-frequency values. Over the mid-frequency range (between approximately 1000 and 5000 Hz), where middle ear sound transmission is most efficient, the mean power reflectance values fall closer to 0%. The mean power reflectance reaches a different minimum value for each racial group. The Caucasian mean power reflectance is lowest at approximately 3492 Hz, where the lowest mean power reflectance value for the Chinese group occurs at approximately 2367 Hz. The shape of the power reflectance curve is different between the two subject groups.

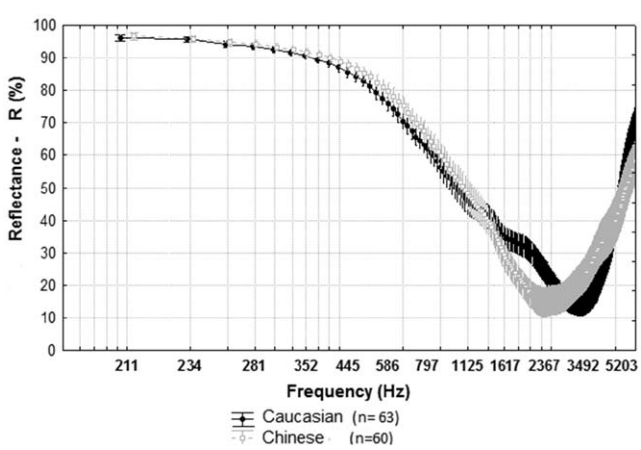

Fig. 3. Mean reflectance as a function of frequency for Caucasian and Chinese pediatric control groups. Vertical bars denote the 95% confidence intervals.

Previous explanations with regard to the variation in hearing sensitivity and middle ear mechano-acoustical properties among different ethnicities have been attributed to the differences in melanin level in the cochlea (Garber et al. 1982); genetics (Yanz et al. 1985); anatomical and body-size differences (Robinson et al. 1988; Chan & McPherson 2001; Shahnaz & Davies 2006). It has been shown that the average height and weight is larger in the Caucasian than the Chinese group in both males and females (Bell et al. 2002). The results of several research studies have shown that body size in animal models correlates to the size of the ear canal, middle ear volume, area of tympanic membrane, and footplate (Werner et al. 1998; Huang et al. 2000; Werner et al. 2005). These studies have shown that increasing body size in animal models is accompanied by an increase in the compliance of the middle ear air space. Differences in middle ear mechano-acoustical properties observed between the Caucasian and Chinese adults have been suggested to relate to differences in body size among these groups (Wan & Wong 2002; Shahnaz & Bork 2006; Shahnaz & Davies 2006).

Effect of Gender on WAI

Numbers of studies have investigated the effect of gender on hearing sensitivity. While some studies have shown hearing sensitivity differences, with females showing a better sensitivity than males (Stelmachowicz et al. 1989; Löppönen et al. 1991; Hallmo et al. 1994), other studies have shown no gender differences (Osterhammel & Osterhammel 1979; Frank 1990; Betke 1991; Dunckley & Dreisbach 2004). Several investigators have shown that transient evoked otoacoustic emission responses are larger and Spontaneous Otoacoustic Emission (SOAE) responses are more common in female subjects compared with male subjects (Strickland et al. 1985; Bilger et al. 1990; Martin et al. 1990; Robinette 1992; Stover & Norton 1993; Prieve & Falter 1995; Aidan et al. 1997; Khalfa et al. 1997; Tavartkiladze et al. 1999; Chan & McPherson 2001).

The effect of gender on normative tympanometric data obtained at conventional 226 Hz probe-tone frequency has not been conclusive. While Wiley et al. (1998), Wiley et al. (1999), and Roup et al. (1998) have shown statistically higher peak Ytm, narrower TW, and equivalent larger ear-canal volume for adult males than females. Shahnaz and Davies (2006) also found higher peak Ytm and Vea for adult males than females. However, the lower cutoff of the 90% range was not different between the two genders; therefore, it may not have any impact in detecting pathologies such as OM and otosclerosis but may have an impact in detecting pathologies such as ossicular discontinuity as the higher cutoff of the 90% range was different between the two genders. In contrast, Holte (1996), Margolis and Goycoolea (1993), Margolis and Heller (1987), and Wan and Wong (2002) did not find any gender differences. The effect of gender on resonant frequency obtained using multifrequency tympanometry is also not conclusive. While Margolis et al. (1997) reported a higher value for resonant frequency for adult males than females, Wiley et al. (1999) found lower resonant frequency values for adult males than females. Shahnaz and Davies (2006) did not find any statistical difference between adult males and females for resonant frequency in either Caucasian or Chinese group. The effect of gender on normative tympanometric data obtained at conventional 226 Hz probe-tone frequency has also not been conclusive in children. While Li et al. (2006) did not find any

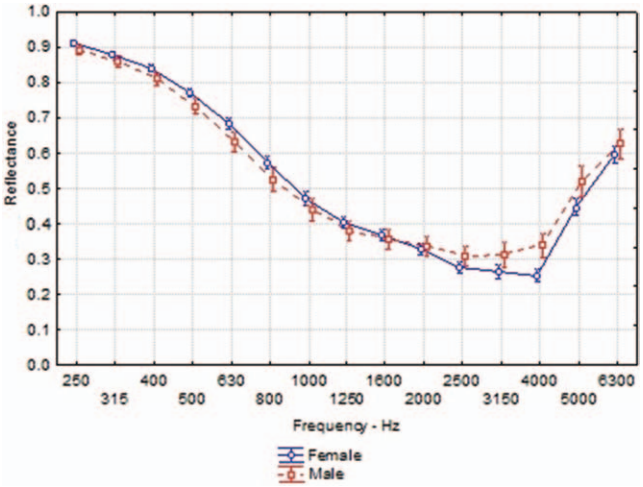

Fig. 4. Reflectance at each of the 15 frequencies for female and male young adults. Data from Mimosa Middle Ear Analyzer Systems are pooled together from studies by Shahnaz and Bork (2006) and Shaw (2009, Reference Note 1).

gender differences in the school-aged children, Driscoll et al. (2008) noted a significant gender effect in children (6 to 13 years of age), with females having smaller equivalent ear canal volume than males.

The effect of gender on WAI and its related parameters has also been investigated. Margolis et al. (1999) reported statistically higher resistance for males below 1000 Hz and lower resistance between 2000 and 4000 Hz than females. They also reported that reactance values were more positive below 1500 Hz in males than in females. The effect of gender on WAI was not significant in adults (Shahnaz & Bork 2006) and children (Hunter et al. 2008; Beers et al. 2010) at ambient pressure. The pooled data from the studies by Shahnaz and Bork (2006) and Shaw (2009, Reference Note 1) obtained at ambient pressure using Mimosa Acoustics system revealed that the interaction between frequency and gender was significant, indicating that reflectance varies different between the two genders across frequency. As shown in Figure 4, females have lower reflectance than males at 4000 Hz and 5000 Hz.

Kenny (2011, Reference Note 2) reported that the interaction between gender, frequency, and ethnicity was significant for absorbance obtained at ambient pressure, indicating that the variation of absorbance across frequency varied differently between genders in Caucasian and Chinese groups (Fig. 5). As seen in Figure 5 Chinese females differed significantly from Chinese males at 4000 and 5000 Hz, with Chinese females showing higher absorbance than the Chinese male subjects in these frequency bands; however, Caucasian females were not significantly different from Caucasian males across frequencies. Kenny (2011, Reference Note 2) also reported that the interaction between frequency and gender was also significant for dynamic (pressurized) absorbance obtained at the peak pressure, with female subjects having higher absorbance than male subjects at 5000 Hz.

Effect of Aging on WAI

In an earlier article in this supplement (Kei et al., this issue, pp. 17S–26S), have covered the developmental impact of the conductive system on WAI during the first year of life. The pediatric data (Beers et al. 2010) from children with normal middle ear function were compared with the normative adult data gathered by Shahnaz and Bork (2006) to determine whether the WAI patterns differ among these two populations, and whether it is in fact important to establish separate norms for younger-age groups. They reported that in both Caucasian and Chinese young adults power reflectance values were significantly higher between 2500 to 5000 Hz than Caucasian and Chinese school-aged children. However, in the Caucasian group, school-aged children had significantly higher power reflectance values than Caucasian adults at low frequencies (315 to 1250 Hz). These differences may be attributable to the discrepancy in body size between adults and children. If adults are larger in size, they will have larger middle ear volume, hence their middle ear systems will have a lower resonant frequency and be better able to transfer low-frequency sounds. This is consistent with the observed differences in power reflectance values at low frequencies between children and adults. On the contrary, as children have a smaller body size and, consequently, smaller middle ear volume, they will have a higher middle ear resonant frequency and a better system for the acoustical transmission of high-frequency sounds. The resonant frequency of the middle ear system has been estimated to be 1003 Hz in children aged 6 to 15 years (Hanks & Rose 1993). Within an adult population the middle ear resonant frequency has been estimated at 894 Hz for

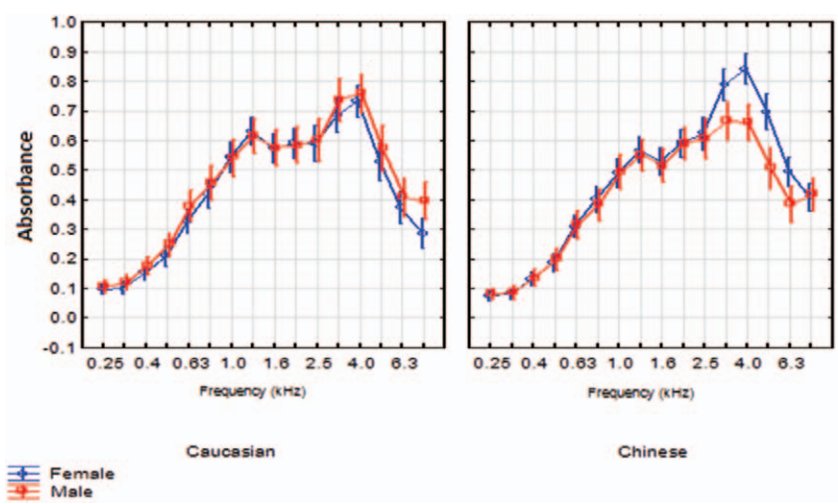

Fig. 5. Frequency, gender, ethnicity interaction: static absorbance displayed across frequency. Ethnic groups are displayed in separate panes. Error bars denote the 95% confidence intervals (Kenny 2011, Reference Note 2).

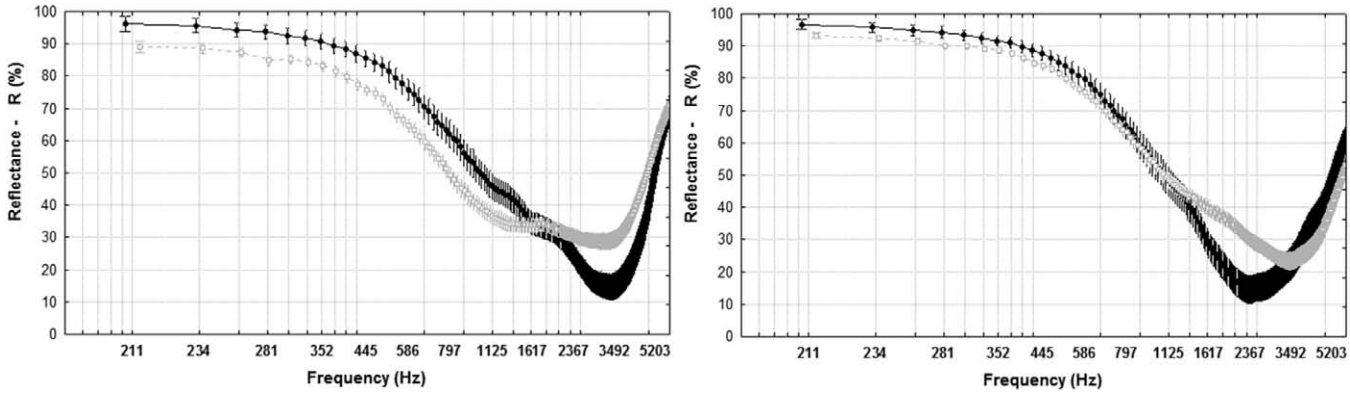

Fig. 6. Mean reflectance as a function of frequency for pediatric and adult groups, in Caucasian and Chinese groups. Vertical bars denote the 95% confidence intervals (Beers et al. 2010).

individuals aged 20 to 43 years (Shahnaz & Polka 1997) or 817 Hz among individuals ranging between 20 and 40 years (Shanks et al. 1993). Figure 6 shows mean and 95% confidence interval of power reflectance values (in %) in school-aged children and adults in both Caucasian and Chinese ethnicities (modified from the study by Beers et al. 2010).

It is not known whether sound-transmission properties of the middle ear in humans are affected by aging process in adulthood. It has been shown that the tympanic membrane and the middle ear structures in humans undergo structural changes at older ages (Ruah et al. 1991). These changes could potentially affect forward and backward transmission of otoacoustic emission signal through the middle ear as well as WAI patterns. Power reflectance was measured in young and elderly adults (Feeney & Sanford 2004). The elderly group had a lower reflectance than the young group at frequencies below the reflectance minimum (the frequency at which reflectance is closer to 0) and higher reflectance at frequencies above the reflectance minimum.

Effect of Instrumentation on WAI

As the application of WAI becomes more common in both pediatric and adult settings, clinicians require information about the characteristics of the instruments used to generate these measures. One particularly important question concerns comparability. Can the same set of normative data be used across all instruments? Currently, there are two available systems to measure WAI. First is the Mimosa Acoustics HearID System (Fig. 7), which comprises an audio-processing unit that connects to laptop via USB connection, calibration cavity, ER-10C probe unit, and foam tips (for adults and children) and rubber tips (for infants). This system relies on determining the sound pressure of the sound source (Ps) and the acoustic impedance at the source (Zs). Ps and Zs are the quantities that are measured during the calibration procedure, which makes use of a sound-pressure technique (Voss & Allen 1994; Keefe & Levi 1996; Withnell et al. 2009). This system is only capable of measuring WAI at ambient pressure. The details of calibration procedure have been explained in Rosowski et al. this issue, pp. 9S–16S, and by Withnell et al. (2009) and Voss and Allen (1994).

The second system, wideband acoustic immittance tympanometry (WAIT), has been developed by Interacoustics in collaboration with Douglas Keefe, Ph.D., at Boys Town National Research Hospital. This is a research instrumentation for measuring WAI. This system is capable of measuring absorbance and reflectance at ambient pressure (static) and at multiple pressure points similar to tympanometry (dynamic). The WAIT is also capable of measuring WB acoustic reflex (see Schairer, this issue, pp. 43S–47S). It consists of an AT235 probe tip and a probe interface cable that is connected to an AT235h audiometer, which is capable of changing the pressure within the ear canal for making measurements of WAI. The AT235h audiometer is also connected to a personal computer (Fig. 8). WAIT measurements first require a calibration phase in which the waveform responses will be obtained in two plastic tubes that are 295 and 8.4 cm in length (adult's tube). The tube diameter is approximately 0.794 cm (Keefe & Simmons 2003), which

Fig. 7. Mimosa Acoustics HearID System comprises an USB base audio-processing unit, ER-10C probe, and four cavities of different sizes calibration set, and a selection of foam and rubber ear tips.

Fig. 8. Wideband Acoustic Immittance Tympanometry System by Interacoustics.

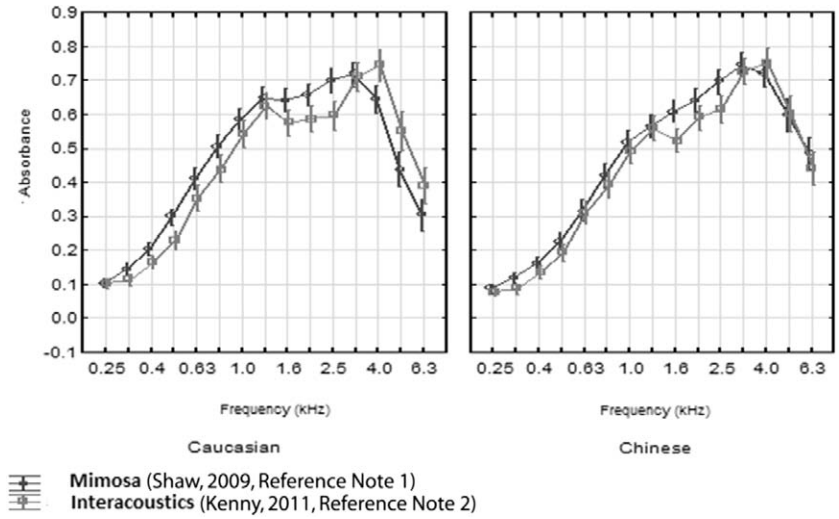

Fig. 9. Comparison of static absorbance measurements across frequency from the study by Kenny (2011, Reference Note 2) with those taken by Shaw's (2009, Reference Note 1) study using the Mimosa Acoustics device. Error bars denote the 95% confidence intervals. Ethnic groups are displayed in separate panels.

is larger than the estimation of ear-canal diameter of 0.74 cm, which is made for the Mimosa acoustics system. The waveform characteristics obtained within these two tubes are compared to determine the Fourier transform of the incident sound-pressure wave, and the SPL spectra within the tubes are also compared to determine the reflectance of the probe (Liu et al. 2008). The calibration procedure for this system relies on the analysis of the wave characteristics within two calibration tubes. For further information on calibration procedure refer to Keefe and Simmons (2003) and Liu et al. (2008).

Kenny (2011, Reference Note 2) compared the absorbance obtained from WAIT system at ambient pressure (static mode) with the absorbance obtained from Mimosa Acoustics HearID system also obtained at ambient pressure by Shaw (2009, Reference Note 2) in a group of Caucasian and Chinese young adults. He reported that the interaction between instrument, ethnicity, and frequency was significant. The results indicated that Caucasian subjects measured using the Interacoustics device differed significantly from those measured using the Mimosa device at 5000 Hz (Kenny 2011, Reference Note 2). Figure 9 shows that Caucasian subjects measured using the Interacoustics device produced higher estimates of absorbance at this frequency. Chinese subjects measured using each device did not differ significantly at any frequency. Differences between the current Interacoustics system and the Mimosa Acoustics system could be attributed to differences in the calibration of the devices, the estimation of ear-canal area, and differences in the type of probe tip used to seal the ear canal (Kenny 2011, Reference Note 2). However, the observed differences between the systems are much smaller than differences observed between different middle ear pathologies and normal middle ear system in other published literature (Feeney et al. 2003; Shahnaz & Bork 2006; Shahnaz et al. 2009). For example, the differences observed between normal and otosclerotic ears at low frequencies (Shahnaz et al. 2009) are significantly larger than differences observed between the two systems at corresponding frequencies; therefore, applying system-based norm would have not made any difference in test sensitivity or specificity.

Kenny (2011, Reference Note 2) also compared absorbance obtained at ambient pressure (static mode) with absorbance obtained at pressure corresponding to the peak (similar to the TPP), which is also called dynamic mode. The interaction between ethnicity, frequency, and mode of measurement (static versus dynamic) was significant. Figure 10 demonstrates that Caucasian subjects produced significantly lower estimates of absorbance using the static measurement mode from 250 to

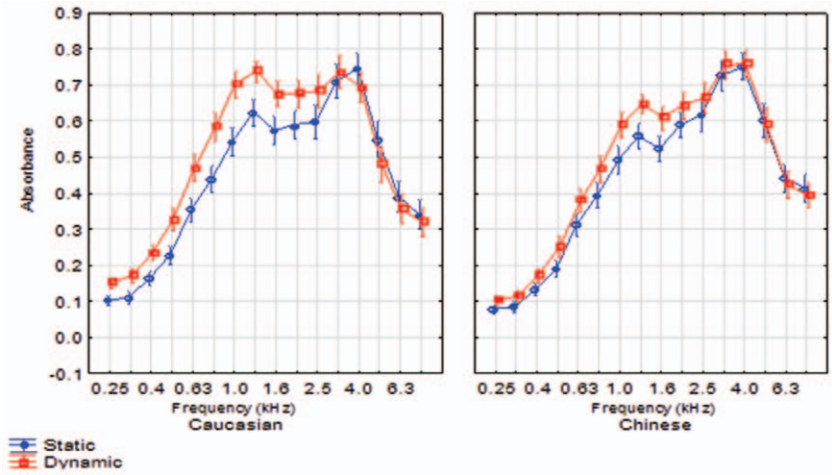

Fig. 10. Estimates of baseline absorbance taken using the static and dynamic modes of measurement in Chinese and Caucasian subjects (Kenny 2011, Reference Note 2). Error bars denote the 95% confidence intervals.

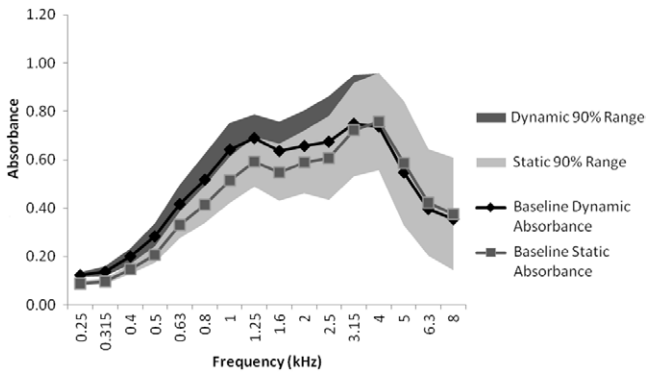

Fig. 11. Baseline static and dynamic absorbance across frequency. The lighter shaded region represents the 90% range of the static measurement while the darker shaded area represents the 90% range of the dynamic measurement (Kenny 2011, Reference Note 2).

2500 Hz as well as higher estimates of absorbance using the static measurement mode from 4000 to 5000 Hz. Chinese subjects also showed lower estimates of absorbance using the static mode of measurement at low frequencies, but for a reduced range of frequencies from 500 to 2500 Hz. They did not produce a difference in estimates at higher frequencies (Kenny 2011, Reference Note 2). Kenny (2011, Reference Note 2) also reported a noticeable difference between the 90% ranges of the baseline static and dynamic absorbance measurements (Fig. 11). Figure 11 demonstrates that the 90% range of the dynamic measurement is significantly higher than that of the static measurements in the low- to mid-frequency region. The 90% range for the static measurements is significantly different than the dynamic measurements. This suggests that the normative region for each measure differs. As a result, the implication is that in clinical practice it would be appropriate to use separate sets of normative data for each measurement (Kenny 2011, Reference Note 2).

These observations are consistent with the measurements reported by Liu et al. (2008), who also demonstrated lower estimates of absorbance at low frequencies and higher estimates at high frequencies when measuring at ambient pressure. They postulated that this difference could arise due to a residual positive pressure present in the external ear canal in the ambient measurement state. This pressure would arise due to the compression of air, which occurs when the probe tip is inserted into the ear. They note that this impact would not affect clinical use of the measurements as these effects would be shared by both healthy and pathological ears. The difference in these effects between Chinese and Caucasian subjects could be related to differences in the resting pressure of the middle ear between ethnic groups. Chinese individuals have been demonstrated to show higher (more positive) TPP compared with their Caucasian counterparts (Shahnaz & Davies 2006). A more positive middle ear pressure would result in closer agreement between the pressures in the outer and middle ears when the positive pressure in the external canal is introduced due to insertion of the probe tip (Kenny 2011, Reference Note 2). As such, the ambient pressure measurement would be closer to TPP and should result in fewer differences compared with the dynamic measurement, which occurs at TPP, consistent with the current observations (Kenny 2011, Reference Note 2).

CONCLUSION

This article reviewed the source variability in normative data for WAI. Understanding the source of variability in the normative data could potentially improve the overall test performance of WAI measures in distinguishing different middle ear pathologies. It will also help clinicians to better understand the mechano-acoustical properties of the middle ear. The observed differences between different ethnic groups could be potentially due to differences in body size. Further research is needed to investigate the effects of body size on WAI with other ethnic groups that are significantly different in body-size indices. Overall differences observed between different ethnic groups in adult populations may warrant the use of ethnicity-specific norms specially for detection of otosclerosis; however, these differences in the school-aged children are not large enough to warrant the use of ethnicity-specific norms. The differences observed between school-aged children and adults could also potentially impact clinical decision analysis. Therefore, use of age-specific norm is recommended. The differences in WAI between different systems are not clinically significant and the use of instrument-specific norms does not result in improved test performance, at least for the detection of otosclerosis. However, measuring WAI at ambient pressure (static) or at pressure corresponding to the peak (dynamic mode) could potentially impact the normative data and may prove to be clinically useful in cases of negative and positive middle ear pressure.

ACKNOWLEDGMENTS

The views presented in this article do not represent the views of the Department of Veterans Affairs or of the U.S. Government.

The authors declare no conflict of interest.

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Received February 4, 2013; accepted May 15, 2013.

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