Comparison of Standard and Multi-Frequency Tympanometric Measures obtained with the Virtual 310 System and the Grason-Stadler Tympstar

Une comparaison entre des mesures tympanométriques standard et celles à fréquences multiples obtenues par les systèmes Virtual 310 et Grason-Stadler Tympstar

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Abstract

The goal of this study was to compare the performance of two middle ear analyzer systems on a range of tympanometric parameters, including both the standard 226 Hz and multi-frequency tympanometric measures. 53 normal hearing adults (26 females and 27 males) were tested with two commercially available middle-ear analyzer systems, Virtual 310 middle-ear analyzer and Grason-Stadler (GSI) Tympstar (version 2). Statistically, only the equivalent ear canal volume (EECV), the frequency corresponding to phase angle of 45 degree (F45°), and the static admittance (SA) obtained at 1 kHz were different between the two systems. The clinical significance of the norms obtained using each system was also examined in 20 cases of surgically confirmed otosclerotic ears that were either tested by the GSI or the Virtual systems. Applying the system-specific norm to a group of surgically confirmed otosclerotic ears resulted in comparable overall hit rates for the two systems for the SA, the resonance frequency (RF) and the F45°. The difference between normal and otosclerotic ears on these tympanometric variables was larger than the cut off (90% range) difference of these variables in the normal group between the two systems. The clinical significance of the differences found will have to be examined in other middle ear pathologies such as ossicular discontinuity and otitis media.

Abrégé

La présente étude visait à comparer la performance de deux analyseurs de l'oreille moyenne selon une série de paramètres tympanométriques, y compris les mesures standard à 226 Hz et les mesures à fréquences multiples. Deux analyseurs de l'oreille moyenne offerts sur le marché - Virtual 310 et Grason-Stadler (GSI) Tympstar (version 2) - ont été testés auprès de 53 adultes ayant une acuité auditive normale (26 femmes et 27 hommes). Ces deux systèmes différaient statistiquement seulement pour le volume du conduit auditif équivalent, la fréquence correspondant à un angle de phase de (F45°) et l'admittance statique obtenue à 1 kHz. L'importance clinique des normes obtenues par chaque analyseur a été examinée auprès de 20 cas d'otosclérose confirmée par chirurgie. En utilisant la norme particulière de chaque système pour un groupe de personnes atteintes d'otosclérose confirmée par chirurgie, des taux de bon diagnostic comparables ont été obtenus pour les deux systèmes en ce qui a trait à l'admittance statique, à la fréquence de résonance et à l'angle de phase de 45°. La différence des variables tympanométriques entre une oreille normale et une atteinte d'otosclérose dépassait la différence limite (fourchette de 90 %) de ces variables pour le groupe normal entre les deux systèmes. Il faudra examiner l'importance clinique des différences relevées par rapport à d'autres pathologies de l'oreille moyenne, comme la dislocation de la chaîne ossiculaire et l'otite moyenne.

Keywords: tympanometry, multi-frequency tympanometry, otosclerosis, middle ear, Tympstar, Virtual, resonance frequency, static admittance, tympanometric width, tympanometric peak pressure, equivalent ear canal volume, frequency corresponding to phase angle of 45 degree

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Introduction

Tympanometry is a safe and quick method for assessing middle-ear function. A considerable number of studies attest to the value of multi-frequency tympanometry (MFT), especially in clinical decisions concerning infants with middle-ear problems (Balkany, Berman, & Simmons, 1978; Calandruccio, Fitzgerald, & Prieve, 2006; Holte, Margolis, & Cavanaugh, 1991; Hunter & Margolis, 1992; Kei et al., 2003; Marchant, Shurin, Turczyk, Wasikowski, Tutihasi, & Kinney, 1984; Margolis et al., 2003; Shahnaz, Miranda, & Polka, 2008) and adults with ossicular chain abnormalities (Browning, Swan, & Gatehouse, 1985; Colletti, 1975, 1976; Lilly, 1984; Shahnaz & Polka, 1997). As the application of MFT becomes more common in both paediatric 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?

Chicchis and Nozza (1996) have addressed this issue for standard low-frequency tympanometric parameters. They compared three tympanometric parameters of static admittance (SA), tympanometric peak pressure (TPP), and tympanometric width (TW) obtained with seven commercially available immittance systems. The authors argued that in most instances the differences were small enough that the same normative data could be applied across all systems. However, they did not determine the significance of these differences in confirmed middle-ear pathologies. Moreover, similar comparisons have not been made for MFT parameters.

Currently, there are only two commercially available MFT systems that could measure different MFT parameters, such as resonance frequencies (RF): the Grason Stadler Instruments-GSI (Viasis) Tympstar Version 2 and the Virtual 310 with the optional extended high frequency (EHF) middle ear analyzer. These two devices are the only true MF middle-ear analyzer systems as other middle-ear analyzer systems only give access to three probe tone frequencies and are not capable of measuring RF or the frequency corresponding to a phase angle of 45° (F45°), both of which have proven useful in detecting middle-ear pathologies (Shahnaz & Polka, 1997). During the past 15 years, numerous studies have reported normative data for various MFT parameters in adults (Hanks & Mortensen, 1997 [GSI]; Holte, 1996 [Virtual]; Margolis & Goycoolea, 1993 [Virtual]; Shahnaz & Polka, 1997 [Virtual]; Shahnaz & Davies, 2006 [Virtual]; Shanks, Wilson & Cambron, 1993 [Virtual]; Valvik et al., 1994 [GSI]; Wiley et al., 1999 [Virtual]). The norms reported in these studies differ somewhat due in part to the use of different measurement protocols. It has been shown that several procedural issues can affect the responses of multi-frequency tympanometric parameters. Pump speed, recording method (sweep frequency vs. sweep pressure), and compensation procedure (Margolis & Heller, 1987; Margolis & Goycoolea, 1993; Margolis & Smith, 1977; Shahnaz & Polka, 1997) are among the variables that can affect MFT results. More recently, Shahnaz and Davies (2006) attributed some of these differences to the ethnic distribution of the participants in different studies. The authors demonstrated that MFT responses in Caucasian individuals were significantly different from Chinese individuals. Therefore, it is imperative to control for these confounding variables while comparing the normative data between the two systems.

The purpose of this study was to assess the comparability of the two middle ear analyzer systems that have been used to generate most of the published MFT norms: the GSI-Tympstar (formerly GSI-33) and the Virtual 310 middle-ear analyzers. To reach this goal, two different sets of comparisons were conducted. First, we compared the values for a range of tympanometry parameters measured on the same participants by the two different middle ear analyzer systems. Secondly, we evaluated the clinical comparability of the two systems with data obtained from 20 patients with surgically confirmed otosclerosis. Half of the patients were tested using the GSI-Tympstar and half using the Virtual 310, and the identification rates were compared between the two systems..

Methods

An institutional clinical research ethics board approved the study protocol. All participants provided their informed consent.

Participants

Fifty-three normal hearing adults (26 females and 27 males) with an average age of 23 years (range: 18-34 years) participated in this study. As Shahnaz and Davies (2006) have shown that the middle-ear characteristics are different among Caucasian and Chinese individuals, the participants were divided into two groups of Caucasian (26 participants: 14 males and 12 females) and Chinese (27 participants: 13 males and 14 females). The ethnicity of each participant was defined based on criteria set by Statistics Canada for different ethnic groups (2002). To be included in this study, the participants had to (1) achieve pure tone audiometric thresholds better than 25 dB HL at octave frequencies between 250-8000 Hz and an air-bone gap of $\leq$ 10 dB between 250-4000 Hz, (2) report no history of head trauma or middle-ear disease, (3) present no gross eardrum abnormalities or excessive cerumen as evidenced by otoscopic examination and (4) pass a transient evoked otoacoustic emission (TEOAE) screening. The TEOAE was performed to further verify the normal condition of the cochlea and the middle ear. A pass consisted of a greater than 6 dB emission to noise ratio in three frequency bands (2000, 3000 and 4000 Hz). The otosclerotic group consisted of 20 patients with surgically confirmed otosclerosis. Ten of these patients were tested with the GSI Tympstar system and ten of them were tested with the Virtual 310 system. The patient group included 17 females and 3 males ranging in age from 22 to 56 years (mean age = 42 years old). In the patient group, 16 were Caucasian, three were Chinese, and one was East Indian.

Instrumentation

Before the data collection, both systems were calibrated using standard cavities according to the operation manual provided by the manufacturers. Both systems were also calibrated in accordance with American National Standards Institute specifications (ANSI, 1989).

Procedure

Standard 226 Hz tympanometric parameters and multi-frequency tympanometric parameters were measured twice for each participant with normal hearing, once with the GSI system and once with the Virtual system. The order of test, and of systems, was assigned randomly.

Standard Tympanometry: The standard 226 Hz tympanometric parameters, static admittance (SA), tympanometric width (TW), equivalent ear canal volume (EECV), and tympanometric peak pressure (TPP) were calculated automatically from admittance tympanograms by both machines in the same individuals using similar pressure direction (positive to negative) and compensation procedure (positive tail). The pump speed was 200 daPa/sec for the Tympstar and 125 daPa/sec for the Virtual system. The pressure was swept from +200 to -400 daPa in the Tympstar and from +250 to -300 daPa in the Virtual system.

Multi-frequency tympanometric parameters: One potentially useful parameter that can be derived from the MFT is an estimate of the middle-ear resonance frequency (RF). The RF corresponds to the frequency at which mass and stiffness contribute equally to the middle ear admittance (Btm = 0). Another potentially useful parameter is admittance phase angle of 45° (F45°; Shanks & Shelton, 1991; Shahnaz & Polka, 1997). The F45° corresponds to the frequency at which the compensated conductance (G) becomes equal to the compensated admittance B (Gtm = Btm). An additional useful parameter that can be obtained from MF tympanometry is the static admittance (SA) at higher probe tone frequencies. It has been shown that an SA obtained at higher probe tone frequencies is superior to a standard 226 Hz probe tone frequency in detecting otosclerotic ears (Shahnaz & Polka, 2002).

The SA was calculated from the compensated rectangular components, Btm and Gtm, using sweep pressure methods at 226, 678 (630 Hz with the Virtual system) and 1000 probe tone frequencies. A similar recording method was used in the Virtual system to calculate the SA at corresponding frequencies. It was necessary to compute these parameters differently in order to improve the mathematical accuracy of the measures. This was particularly important for the higher probe tone frequencies because the phase angles of these parameters are very different at high frequencies. Vector quantities (variables with magnitude and phase) such as admittance cannot be added or subtracted unless the phase angles of the admittance parameters are identical (Margolis & Shanks, 1991). The static admittance is usually computed by subtracting the peak from the positive or negative tail of admittance tympanogram. At 226 Hz probe tone frequency, the middle ear system is stiffness-dominated and addition or subtraction of the admittance values results in little error. However, as probe tone frequency increases, the error for the same addition or subtraction operations can become substantial. Therefore, only admittance vectors that are represented in a rectangular format (susceptance and conductance) can be added or subtracted (Shanks, Wilson, & Cambron, 1993).

This study used the numerical format calculation method by Shahnaz and Polka (2002) to derive RF and F45°. This method is similar to the method that is used with the GSI Tympstar (Version 2) and the GSI-33 (Version

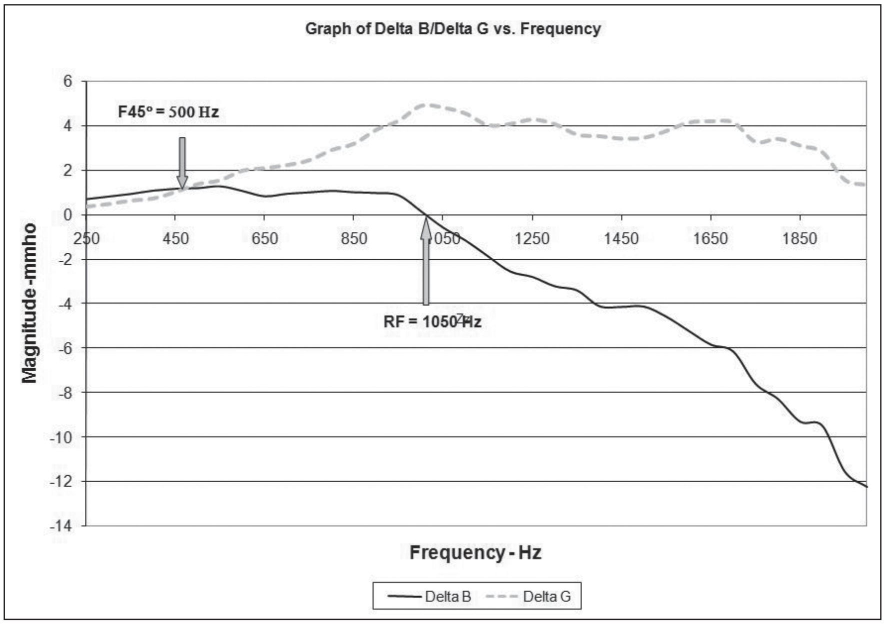

Figure 1. GSI-Tympstar recordings of B and G (in mmho) at +200 daPa and at peak pressure while the probe tone frequency was swept from 220 to 2000 Hz in 50 Hz intervals (sweep frequency recording). The difference between B/G at +200 daPa and peak pressure (referred to as B/G) was computed at each probe tone frequency. This ΔB/G is essentially a compensated B and G measure. The ΔB and ΔG were then plotted as a function of frequency (in Hz). The frequency at which ΔB is closest to ΔG corresponds to an admittance phase angle of 45°. The frequency at which ΔB is closest to 0 dB corresponds to the resonance frequency of the middle ear system.

2) to calculate RF and F45°. The procedure developed by Funasaka, S., Funai, H., and Kumakawa, K. (1984) has been incorporated into the design of the GSI middle ear analyzer. However, with GSI-33 or Tympstar Version 2, the user can choose to measure the admittance or its rectangular components (B and G) and admittance phase angle at extreme ear canal pressure (positive or negative, depending on the user preferences) and at the peak pressure (which is automatically derived by running a 226 Hz "Y" tympanogram or when the user manually defines the peak pressure) while the probe tone frequency is swept from 250 - 2000 Hz in 50 Hz steps (sweep frequency method). These component values (ΔY, ΔB, or ΔG) and phase angle values ($\Delta \Theta$) are compensated for canal volume by computing the difference between their value at extreme pressure (positive or negative, depending on the user choice) and their value at peak pressure. The compensated values are plotted as a function of the probe tone frequency (250-2000 Hz) to determine the resonance frequency. The zero-crossing of the ΔB plot represents the resonance frequency, and the point at which ΔB and ΔG cross each other represents F45° (see Figure 1).

The measures analyzed in this study for the Virtual system were derived from numerical values that were stored in a text format when each tympanogram was run (for details of the methods used and the equations, see Shahnaz and Polka, 2002). In this format, the data are saved as uncompensated polar values (admittance - Y magnitude and corresponding phase angle - Θ values) as a function of air pressure. The rectangular components, susceptance (B) and conductance (G) were derived from these polar values at different probe tone frequencies using the appropriate equations (Margolis and Hunter, 2000, p. 387). Each rectangular component, B and G, was corrected for ear canal admittance at +250 daPa, which is very close to the pressure point (+200 daPa) used with the GSI Tympstar to calculate the B and G values. The pressure corresponding to the peak of the tympanogram was determined from the 226 Hz admittance tympanogram (which is similar to the procedure used with the GSI Tympstar). The same peak pressure was used for all probe tone frequencies to compute the compensated B (as in B in the GSI) and G (as in ΔG in the GSI). Finally, the lowest frequency at which the compensated susceptance (or ΔB) component shifted from a positive (stiffness-dominated system) to a negative (mass-dominated system) value was determined. This frequency is essentially the same as zero susceptance (or ΔB crossing zero in Figure 1) and therefore, is the RF. The F45° was determined as the lowest probe tone frequency at which the compensated B and G became equal. Some of the procedural differences between the Virtual and the GSI systems are as follows: GSI measures the B and G only at two pressure points while the Virtual measures B and G across multiple pressure points. The interval between the multiple probe tone frequencies in the GSI system is set to 50 Hz while the Virtual is using 1/6 octave intervals.

Statistical Analysis

A mixed-model analysis of variance (ANOVA) was used to analyse the data. A 2 x 2 x 2 design was used to determine how the standard 226 Hz tympanometry parameter was influenced by the between-subject factors of ethnicity (Caucasian vs. Chinese) and gender (Male vs. Female), and the middle-ear analyzer system (GSI vs. Virtual), that served as a within subject factor. Subsequently, a 2 (Ethnicity) x 2 (Gender) x 2 (System) x 3 (probe tone frequencies of 226, 678 or 630 and 1000 Hz) design was used to determine how the MFT parameters were influenced. While a group analysis was a necessary step for the evaluation of potential differences between the two systems, it is not an adequate approach for clinical decision analysis. We often use a 90% range (5th or 95th percentiles depending on the type of disease) as a criterion for differential diagnosis. Therefore, looking at the distribution of this range between the two systems was also important.

Results

Standard 226-Tympanometry

Descriptive statistics, mean, standard deviation (SD), and a 90% range (5th to 95th percentile), for SA, TPP, EECV, and TW are shown in Table 1 for both GSI and Virtual systems.

Static Admittance (SA): The main effects of Ethnicity [F (1, 93) = 15.49, $p < 0.05$] and Gender [F (1, 93) = 18.72, $p < 0.05$] proved to be statistically significant. Inspection of the means (Table 1) indicated that the value for SA was higher in Caucasians and in males than in Chinese and females. The effect of System was not significant [F (1, 93) = 1.6, $p > 0.05$] indicating that SA value was not significantly different between the GSI and Virtual systems. This is consistent with the descriptive statistics shown for SA in Table 1. The 90% range between the two systems is quite comparable.

Tympanometric width (TW): The main effects of Ethnicity [F (1, 93) = 9.1, $p < 0.05$] and Gender [F (1, 93) = 6.5, $p < 0.05$] proved to be statistically significant. Inspection of the means (Table 1) indicated that the value for TW was wider in Chinese and females than Caucasian and males. The effect of System was not significant [F (1, 93) = 2.2, $p > 0.05$]; however, the interaction between Ethnicity and System was significant [F (1, 93) = 2.2, $p > 0.05$] indicating that TW value varies between the two systems in the Caucasian and Chinese groups. This is clearly shown in Figure 2. While the Virtual system provides a wider TW value in the Caucasian group than the GSI system, it provides a narrower value in the Chinese group than the GSI system. This is also evident in the 90% range of the TW as shown in Table 1.

Tympanometric Peak Pressure (TPP): The data for the variable TPP were explored using a mixed-model ANOVA. The main effects of Ethnicity [F (1, 93) = 3.76, $p > 0.05$] and Gender [F (1, 93) = 0.74, $p > 0.05$] were not significant. The effect of System was not significant [F (1, 93) = 0.02,

Table 1
Descriptive statistics for static admittance (SA), tympanometric width (TW), tympanometric peak pressure (TPP), and equivalent ear canal volume (EECV) at 226 Hz obtained using both GSI and Virtual systems. Some other published normative studies are also included for comparison. C= Caucasian; A= Chinese; M = male; F = female.

			SA mmho		TW daPa		TPP daPa		EECV mmho	
			C	A	C	A	C	A	C	A
GSI	M	Mean	0.80	0.67	79	107	0.63	-5.0	1.06	1.32
		SD	0.28	0.29	18	72	5.58	13.80	0.25	0.25
		90% Range	0.30-1.30	0.30-1.20	55-110	40-290	-10.0-5.0	-35-5.0	0.7-1.6	1.0-1.7
	F	Mean	0.66	0.37	92	128	0.65	-4.04	1.28	1.06
		SD	0.24	0.20	27	70	9.21	7.5	0.22	0.25
		90% Range	0.30-1.20	0.20-0.70	60-135	70-225	-25.0-5.0	-15-5.0	1.0-1.7	0.7-1.6
	Overall	Mean	0.73	0.51	85	118	0.64	-4.5	1.37	1.18
		SD	0.27	0.29	24	61	7.49	10.9	0.32	0.28
		90% Range	0.30-1.20	0.20-1.10	60-115	50-265	-10.0-5.0	-20-5.0	1.0-1.9	0.7-1.6
Virtual	M	Mean	0.80	0.66	97	99	-1.46	-5.33	0.90	1.18
		SD	0.26	0.42	20	29	8.12	15.40	0.28	0.29
		90% Range	0.40-1.20	0.20-1.30	66-132	47-127	-4.0-14.0	-37-14	0.5-1.5	1.0-1.6
	F	Mean	0.63	0.35	107	126	-0.91	-0.65	1.07	0.90
		SD	0.23	0.19	35	80	8.59	10.2	0.25	0.28
		90% Range	0.30-1.10	0.10-0.70	66-165	80-183	-9.0-14.0	-18-14	0.5-1.5	0.5-1.5
	Overall	Mean	0.72	0.50	102	113	-1.19	-2.9	1.21	1.04
		SD	0.26	0.36	28	33	8.26	13	0.35	0.31
		90% Range	0.30-1.20	0.10-1.10	66-146	66-165	-9.0-14.0	-18-14	0.7-1.9	0.6-1.6
Wan & Wong (2002)	M (*n*=50)	Mean	0.58		88.3		4.80		1.22	
		SD	0.29		34.1		20.73		0.25	
		90% Range	0.30-1.10		45.0-174.5		-24.50–29.7		0.81–1.70	
Chinese	F (*n*=50)	Mean	0.52		94.2		3.10		1.13	
		SD	0.28		29.2		15.81		0.31	
		90% Range	0.20-1.30		45.3-144.8		-19.75–24.7		0.70–1.60	
GSI	Overall (*n*=100)	Mean	0.55		91.2		3.95		1.17	
		SD	0.28		31.8		18.41		0.28	
		90% Range	0.20-1.10		45.0-159.3		-19.75–25.0		0.80–1.60	
Roup et al. (1998)	M (*n*=51)	Mean	0.87		59.8		-26.18		1.40	
		SD	0.46		17.3		31.66		0.32	
		90% Range	0.30-1.80		35.0-87.0		-110.00–9.0		1.00–2.10	
Caucasian	F (n=51)	Mean	0.58		73.9		-27.75		1.18	
		SD	0.27		17.2		23.50		0.22	
		90% Range	0.30-1.12		45.0-107.0		-80.0–$^{-}$3.0		0.80–1.60	
GSI	Overall (*n*=102)	Mean	0.72		66.9		-29.96		1.29	
		SD	0.40		18.6		27.76		0.29	
		90% Range	0.30-1.19		32.8-95.0		-103.50-4.2		0.90–1.80	

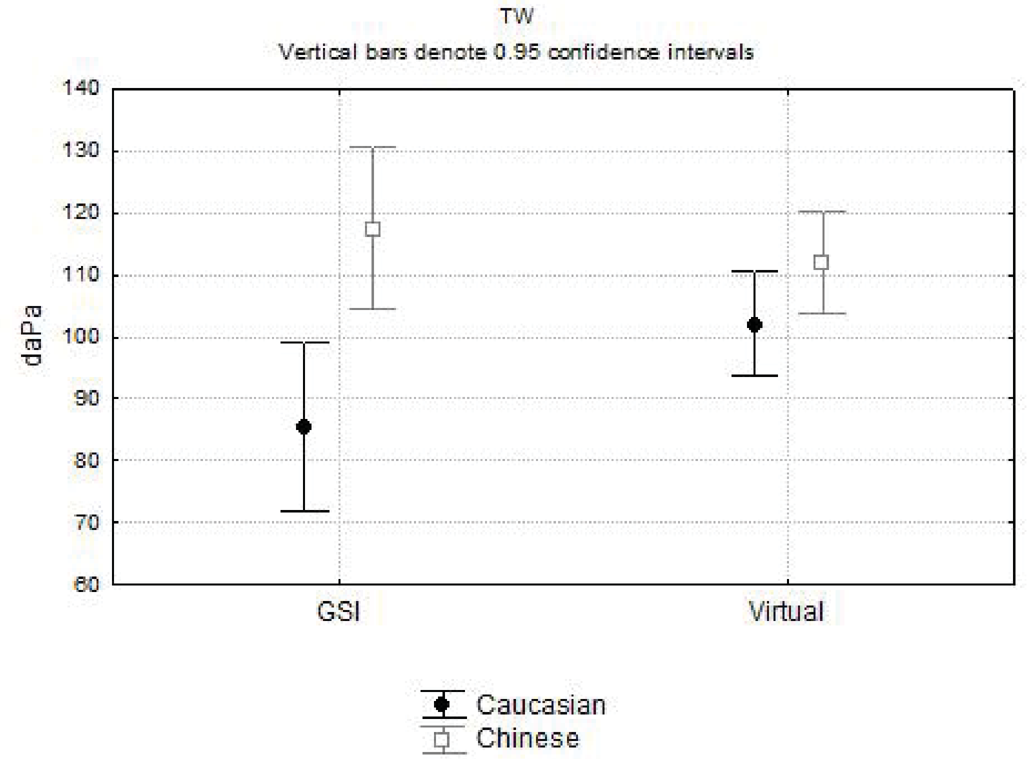

Figure 2. Mean and 0.95 confidence intervals (vertical bars) for tympanometric width (TW in daPa) between the GSI and the Virtual system in the Caucasian and the Chinese group.

Table 2

Descriptive statistics for static admittance (Ytm) measured by sweep pressure (SP) recording with positive (+) compensation at three different probe tone frequencies of 226, 678, and 1000 Hz obtained using both GSI and Virtual systems. C= Caucasian; A= Chinese; M = male; F = female

Y_{tm}			226 Hz		678 Hz		1 kHz	
			C	A	C	A	C	A
GSI	M	Mean	0.94	0.72	2.50	2.18	4.31	3.01
		SD	0.45	0.32	1.29	1.18	1.55	1.60
		90% Range	0.39-1.54	0.29-1.18	1.11-4.54	0.86-4.26	1.61-6.37	1.10-6.33
	F	Mean	0.74	0.40	2.03	1.22	3.86	1.92
		SD	0.25	0.19	0.85	0.64	1.70	1.19
		90% Range	0.37-1.29	0.17-0.78	0.83-3.48	0.49-2.55	1.31-7.26	0.53-4.07
	Overall	Mean	0.84	0.56	2.26	1.69	4.08	2.45
		SD	0.37	0.30	1.10	1.05	1.63	1.49
		90% Range	0.38-1.52	0.19-1.09	0.85-4.51	0.55-3.60	1.50-7.08	0.54-3.22
Virtual	M	Mean	0.82	0.69	2.02	1.90	2.46	2.14
		SD	0.28	0.44	1.86	1.10	2.07	1.04
		90% Range	0.44-1.31	0.23-1.33	0.05-4.37	0.62-3.33	-2.00-4.41	0.61-3.57
	F	Mean	0.69	0.34	2.25	1.13	2.69	1.76
		SD	0.25	0.18	1.03	0.79	1.09	1.09
		90% Range	0.33-1.15	0.15-0.66	0.56-3.90	0.33-2.40	0.75-4.68	0.65-3.23
	Overall	Mean	0.75	0.51	2.13	1.51	2.58	1.94
		SD	0.27	0.37	1.48	1.02	1.63	1.07
		90% Range	0.35-1.25	0.15-1.19	0.56-4.37	0.48-3.30	0.73-4.68	0.61-3.57

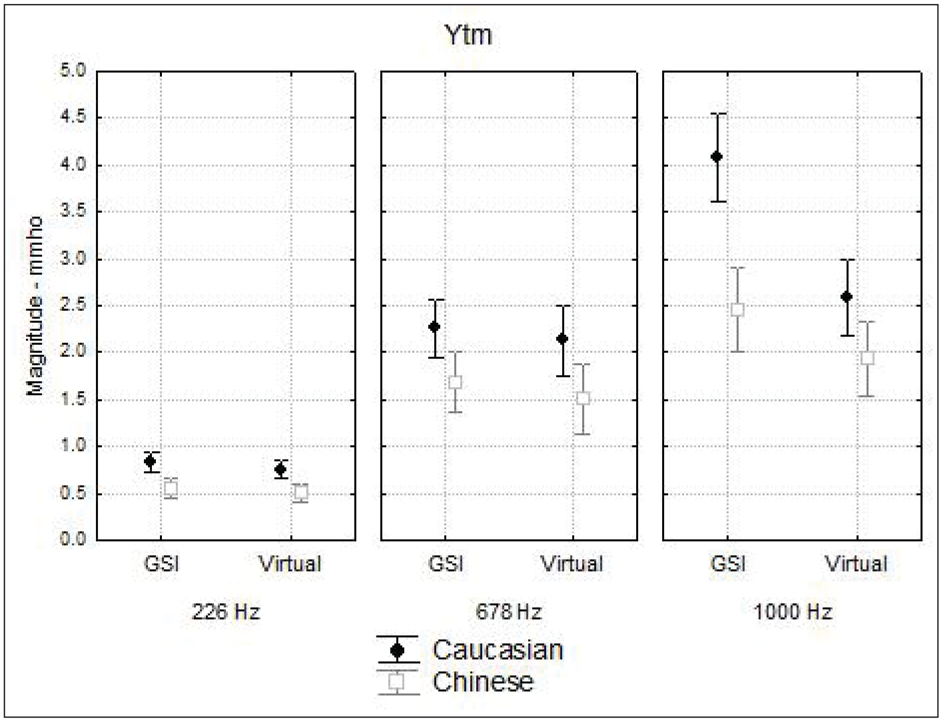

Figure 3. Mean static admittance (Ytm) and 0.95 confidence intervals (vertical bars) obtained using the GSI and the Virtual systems across three probe tone frequencies of 226, 678 (630 in the Virtual system) and 1000 Hz in Caucasian and Chinese young adults.

$p > 0.05$], indicating that the TPP value was not significantly different between the GSI and Virtual systems.

Equivalent Ear Canal Volume (EECV): The main effects of Ethnicity [F (1, 93) = 8.75, $p < 0.05$] and Gender [F (1, 93) = 18.67, $p < 0.05$] proved to be statistically significant. An inspection of the means (Table 1) indicated that the value for the EECV was higher in Caucasian and males than Chinese and females. The effect of System was significant [F (1, 93) = 90.18, $p < 0.05$] indicating that EECV value was significantly higher in the GSI system than the Virtual system. This is consistent with the descriptive statistics shown for EECV in Table 1.

Multi-frequency Tympanometry (MFT)

Static admittance (Ytm) at multiple-probe tone frequencies: Descriptive statistics for the Ytm obtained at multiple probe tone frequencies are shown in Table 2. To investigate the potential differences between the two systems, a mixed-model ANOVA was conducted with System (GSI vs. Virtual-2 levels) and probe tone frequency (226, 678, and 1000 Hz-3 levels) as the within-subject factors and Ethnicity and Gender as between-subject factors (2 x 2 x 2 x 3design). The main effect of Ethnicity [F (1, 88) = 17.42, $p < 0.05$] and Gender [F (1, 88) = 6.05, $p < 0.05$] proved to be statistically significant. Inspection of the means (Table 2) indicated that the value for SA was significantly higher in Caucasian and males than Chinese and females. The within subject factor of the system (GSI vs. Virtual) was significant [F (1, 88) = 23.93; $p < 0.05$], indicating that the Ytm collapsed across the three probe tone frequencies is significantly higher in the GSI system than the Virtual system. The interaction between probe tone frequency, ethnicity, and the system was also significant [F (2, 176) = 7.89; $p < 0.05$] indicating that the Ytm varies differently between the two systems across different probe tone frequencies and the two ethnic groups. A post-hoc Tukey test revealed that the two systems were only different at the 1000 Hz probe tone frequency; however, Ytm was consistently lower in the Chinese group than in the Caucasian group in both systems across all three probe tone frequencies. This is shown in Figure 3 which compares the Ytm between the two systems across the three probe tone frequencies in both the Caucasian and Chinese groups. While at the 226-Hz probe tone frequency, the 5th percentile is similar between the two systems at 678-Hz and 1 kHz, both the 5th and the 95th percentiles are quite different between the two systems (Table 2).

Resonance frequency (RF): The descriptive statistics for the RF obtained from the GSI and the Virtual system are shown in Table 3. The main effects of Ethnicity, Gender and System were not significant ($p > 0.05$). The interaction between Ethnicity, System and Gender was significant [F (1, 93) = 5.45; $p < 0.05$] indicating that the RF scores varied between the two systems in Caucasian and Chinese males and females. As can be seen in Figure 4 in the GSI system, Chinese female had a significantly higher RF than the Caucasian females; however, the Caucasian males had a significantly higher RF than the Chinese males. With the Virtual system, the RF was not significantly different between the two ethnic groups. However, the Chinese group had an overall higher RF frequency than the Caucasian group (see Table 3).

Frequency corresponding to a 45° phase angle (F45°): In both systems, the F45° was determined by plotting compensated B and G as a function of the probe tone frequency (see Figure 1). The descriptive statistics for the F45° obtained using the GSI and the Virtual system are shown in Table 3. The effect of System proved to be statistically significant [F (1, 93) = 70.96; $p < 0.05$]. An inspection of the means (Table 3) indicated that the value for the F45° was higher for the Virtual system than the GSI system. The interaction between the System and Ethnicity was also significant [F (1, 93) = 4.86; $p < 0.05$], indicating that the F45° value between the ethnic groups

Table 3

Descriptive statistics for resonance frequency (RF),and frequency corresponding to admittance phase angle of 45 degree (F45°) measured by sweep frequency (SF) recording with positive (+) compensation obtained using both GSI and Virtual systems. C= Caucasian; A= Chinese; M = male; F = female.

			F45°		RF	
			C	A	C	A
GSI	M	Mean	494	406	944	827
		SD	137	123	228	201
		90% Range	350-700	250-600	600-1300	550-1150
	F	Mean	448	460	898	1013
		SD	117	98	174	225
		90% Range	250-600	250-600	700-1050	650-1450
	Overall	Mean	471	435	921	924
		SD	128	113	202	232
		90% Range	300-700 1.20	250-600	600-1300	600-1250
Virtual	M	Mean	537	517	911	927
		SD	134	91	175	258
		90% Range	400-800	400-630	630-1120	630-1250
	F	Mean	545	489	907	947
		SD	95	114	108	114
		90% Range	400-710	400-710	710-1120	710-1120
	Overall	Mean	541	555	909	937
		SD	115	109	144	195
		90% Range	400-710	400-710	710-1120	630-1250
Hanks & Mortenson (1997)	GSI-33 (age = 18-25 yr)	Mean			908	
		SD			188	
		90% Range			650-1300	

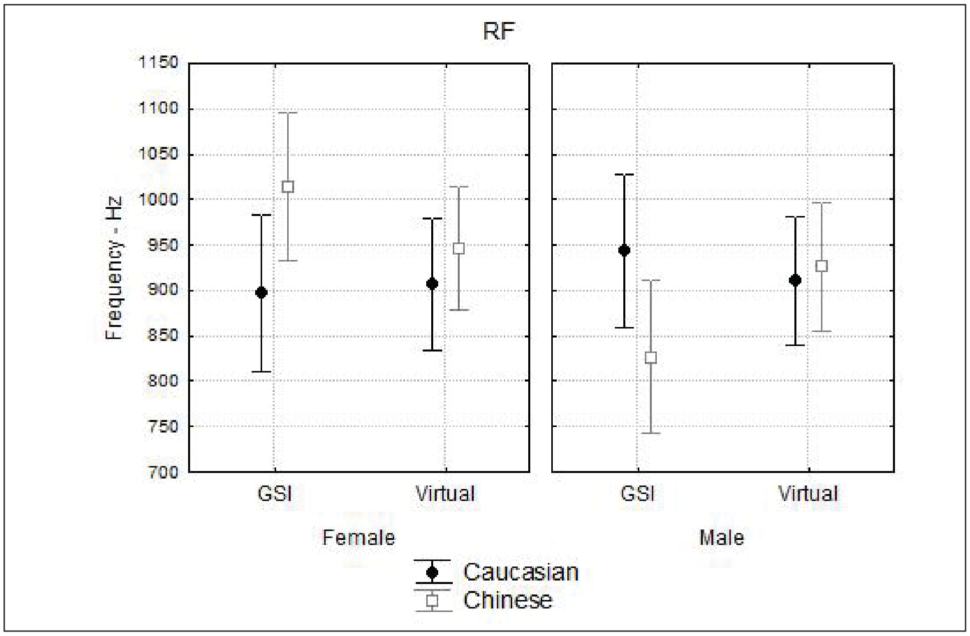

Figure 4. Mean resonance frequency (RF) and 0.95 confidence intervals (vertical bars) obtained using the GSI and the Virtual systems between males and females in Caucasian and Chinese young adults.

Table 4
Outcome of the normative data obtained using the GSI and the Virtual system in 20 cases of surgically confirmed otosclerotic ears

System	Gender	Ethnicity	Ytm 226 Hz mmho	Ytm GSI Norm	Ytm Virtual Norm	TW daPa	TW GSI Norm	TW Virtual Norm	F45° Hz	F45° GSI Norm	F45° Virtual Norm	RF Hz	RF GSI Norm	RF Virtual Norm
GSI	FM	C	0.5	-	-	90	-	-	DNT	DNT	DNT	1400	+	+
GSI	FM	C	0.4	-	-	120	-	-	DNT	DNT	DNT	1250	+	+
GSI	FM	C	0.8	-	-	185	-	-	DNT	DNT	DNT	950	-	-
GSI	FM	C	0.3	-	-	105	-	-	DNT	DNT	DNT	1500	+	+
GSI	FM	C	0.4	-	-	85	-	-	DNT	DNT	DNT	1250	+	+
GSI	M	C	0.5	-	-	105	-	-	DNT	DNT	DNT	1200	-	+
GSI	FM	C	0.3	-	-	110	-	-	DNT	DNT	DNT	1200	+	+
GSI	M	EI	1.0	-	-	60	-	+	DNT	DNT	DNT	1050	-	-
GSI	M	A	0.7	-	-	185	-	-	DNT	DNT	DNT	2000	+	+
GSI	FM	C	0.2	+	+	150	-	-	DNT	DNT	DNT	1250	+	+
Virtual	FM	C	0.09	+	+	94	-	-	1000	+	+	1800	+	+
Virtual	FM	C	0.52	-	-	61	-	+	800	+	+	1120	+	-
Virtual	FM	C	0.48	-	-	99	-	-	1120	+	+	1800	+	+
Virtual	FM	C	0.54	-	-	38	+	+	800		+	1400	+	+
Virtual	FM	C	1.43	-	-	85	-	-	560	-	-	710	-	-
Virtual	FM	A	0.2	+	+	132	-	-	1120	+	+	1400	-	+
Virtual	FM	A	0.47	-	-	75	-	-	1000	+	+	1600	+	+
Virtual	FM	C	0.8	-	-	66	-	-	630	+	-	900	-	-
Virtual	FM	C	0.14	+	+	136	-	-	1250	+	+	1800	+	+
Virtual	FM	C	0.52	-	-	38	+	+	560	-	-	800	-	-
Total+ HR				4 20%	4 20%		2 20%	4 40%		7 70%	7 70%		13 65%	14 70%

Note. Ten of these cases were tested by the GSI system and 10 of them were tested by the Virtual system. The corresponding tympanometric value for each individual otosclerotic ear is provided and is compared to gender and the ethnic specific norm (for the East Indian-EI male subject the Caucasian male norm was used). An appropriate cut-off value was selected from Tables 1 and 2 (5th percentile for the SA and the TW and 95th percentile for the RF and the F45°). This was done to explore how many otosclerotic ears were correctly indentified (hit rate –HR is identified by the + sign) by the normative data obtained using the GSI and the Virtual systems. The negative (-) sign denotes misses (false negative) in the otosclerotic ears. (Ytm: static admittance; TW= tympanometric width; F45°: frequency corresponding to admittance phase angle of 45 degree; RF: resonant frequency; C= Caucasian; A= Chinese; EI= East Indian; M = male; F = female. DNT= did not test; HR: hit rate; DNT: did not test.

varies between the two systems. The F45° obtained with the GSI system was higher in the Caucasian group than the Chinese group; however, the F45° value obtained using the Virtual system was slightly higher in the Chinese group than the Caucasian group. Both the 5th and the 95th percentiles (Table 3) also differed between the two systems.

Implications of Applying System Specific Norms in Detection of Otosclerosis

In order to explore whether using a system specific norm could potentially impact detection of the middle-ear pathology, a group of 20 patients with surgically confirmed otosclerotic ears were included in this study. Of these, 10 participants were tested with the GSI system and the remaining 10 participants were tested with the Virtual system. The appropriate gender and ethnic specific norms obtained using each system (Table 1, 2, and Table 3) were used for each of the variables that have been shown useful for detection of otosclerotic ears (Shahnaz & Polks, 1997). The patterns of test performance were examined in individual otosclerotic ears (Table 4) for the Ytm and the TW obtained at standard 226-Hz probe tone frequency and for the RF and the F45° obtained using MFT. For theYtm, the 5th percentile is commonly used for the detection of high impedance pathologies such as otosclerosis (Shahnaz & Polka, 1997). The 95th percentile of the RF and the F45° was used for the detection of otosclerotic ears as these parameters have been shown to be higher in otosclerosis (Shahnaz & Polka, 1997). For the TW, the 5th percentile cut-off score was selected as previous work indicated that the TW could potentially be narrower in some otosclerotic ears (Shahnaz & Polka, 1997). The cut-off scores for each variable were used to assign each individual to normal or pathological group. This assigned diagnosis was then compared to the real group status for each measure.

In Table 4, the positive sign (+) indicates a correct diagnosis (true positive) in the otosclerotic group. The negative sign (-) indicates incorrect identification as a normal ear (false negative) in the otosclerotic group. As can be seen in Table 4, the norms obtained by the two systems perform equally well in identifying otosclerotic ears. Very few cases that were missed by the norm obtained for one system were identified correctly by the other system. The overall identification rate was very similar regardless of the system used. The only exception was for the TW norm obtained using the Virtual system which resulted in a noticeably higher identification rate than the TW norm obtained using the GSI system.

Discussion

Standard 226-Hz Tympanometry

Static admittance (SA): The normative data generated by each system were comparable between the two systems (see Table 1). This was consistent with findings from Chicchis and Nozza (1996) that showed comparable means and 90% ranges between the GSI-33 (similar to Tympstar used in this study) and the Virtual 310 systems. The Chinese group had a significantly lower mean SA compared to the Caucasian group. Males had a significantly lower mean SA compared to females, regardless of the system (GSI or Virtual) used. This finding was consistent with Shahnaz and Davies (2006). The norms obtained by the GSI system in the Chinese and the Caucasian groups were similar to the norms obtained in the Chinese group studied by Wan and Wong (2002) and in the Caucasian group studied by Roup, Wiley, Safady, and Stoppenbach (1998; see Table 1).

Tympanometric Width (TW): While this measure was not statistically different between the two systems, the 95th percentile in the Chinese group (Table 1) was so different between the two systems that it could potentially change diagnostic outcomes. The 95th percentile can be used for the detection of middle-ear effusion (Nozza, Bluestone, Kardatzke, & Bachman, 1994). Therefore, when testing Chinese individuals with suspected middle-ear effusion, it is advisable to compare the outcome of this measure to the norm obtained with the corresponding system. While Chicchis and Nozza (1996) also did not find statistically different TW values between the two systems, their mean and 90% range was comparable between the two systems. The mean value for TW was significantly higher in the Chinese group than in the Caucasian group and higher in females than males regardless of the system used. However, the effect was more pronounced for the GSI system (see Table 1). This is consistent with findings by Shahnaz and Davies (2006) and Wan and Wong (2002). The 90% ranges obtained using the GSI system in the Chinese group and the Caucasian group were different from the 90% ranges obtained in the Chinese group in the Wan and Wong (2002) study and in the Caucasian group in Roup et al. (1998) study. Similar systems, pressure directions, pump speeds, and compensation procedures were used in all these studies. The sources of these differences could potentially be attributed to the larger sample size used in the Wan and Wong (2002) and Roup et al. (1999) studies.

Tympanometric peak pressure (TPP): The TPP value was not significantly different between the two ethnicitys, genders, and between the GSI and the Virtual system. However, both the 5th and the 95th percentiles (Table 1) were different between the two systems. These differences are not in a magnitude that would potentially skew the differential diagnosis of middle-ear pathology. In contrast, Chicchis and Nozza (1996) found numerically more positive TPP values for the GSI-33 system compared with the Virtual system. While not statistically different, the current study also shows more positive TPP values for the GSI system than for the Virtual system. This measure is the least useful measure in standard tympanometry for differential diagnosis of middle ear pathologies (Margolis & Heller, 1987).

Equivalent ear canal volume (EECV): The EECV obtained using the Virtual system was significantly lower than for the GSI system. This is most likely due to the fact that it was measured at a higher positive pressure (+250 daPa) than the pressure preset in the GSI system (+200 daPa). It has been shown that lower canal volume estimates may be observed as the ear canal pressure used to correct the volume is increased (Van Camp, Margolis, Wilson, Creten, & Shanks, 1986). The 5th percentile (Table 1) was also different between the two systems. The 5th percentile can be used to detect the blockage of the probe by cerumen or ear canal wall. The 95th percentile was comparable between the two systems. The 95th percentile can be used for detection of tympanic membrane perforation, patency of pressure equalization (PE) tubes, and to predict the recovery/recurrence from middle ear disease and the outcome of reconstructive surgeries of the middle ear (Fowler & Shanks, 2002). This measure was not evaluated by Chicchis and Nozza (1996).

The mean EECV value in the Chinese group was significantly lower than in the Caucasian group and the mean EECV value for the females was significantly lower than for the males in the Chinese group, which was consistent with Shahnaz and Davies' (2006) and Wan and Wong's (2002) findings. However, the mean EECV in males was lower than in females in the Caucasian group regardless of the system used. This is contrary to what has been found in the literature, potentially due to a smaller sample size used in this study.

Multi-frequency Tympanometry (MFT)

To our knowledge, the comparability of the multi-frequency tympanometric norms between the GSI-

Tympstar and Virtual 310 systems has not been investigated. These two systems are the only two commercially available MFT systems that can measure different MFT parameters, such as resonance frequencies (RF).

Static admittance (Ytm) at multiple probe tone frequencies: Ytm was consistently lower with the Virtual system than with the GSI system at all three probe tone frequencies; however, it was only significantly different at 1 kHz. These differences became larger as probe tone frequency increased (Figure 3). It should be noted that higher compensated static admittance should have been observed by the Virtual system as the ear canal pressure used to correct the ear canal volume was higher. A potential source for the observed difference is the faster pump speed used by the GSI system (200 daPa/sec) as opposed to that of the Virtual system (125 daPa/sec). Faster pump speed results in a higher Ytm value (Van Camp et al., 1986). While at a standard 226-Hz probe tone frequency, the overall 5th percentile (used for detection of high impedance pathologies such as otosclerosis) is similar between the two systems. However, at 678-Hz and 1 kHz, both the 5th and the 95th percentiles are quite different between the two machines (Table 2). The 95th percentile is being used for detection of low impedance pathologies such as ossicular discontinuity. Therefore, when measuring the Ytm, clinicians should compare their results to norms that were obtained using the same measurement protocol (i.e., pump speed), irrespective of the type of system used. The Ytm was consistently lower in the Chinese group than in the Caucasian group for both systems across all three probe tone frequencies (Figure 3). This finding was consistent with findings from Shahnaz and Davies (2006).

Resonance frequency (RF): The RF of the middle ear system may be shifted higher or lower by various pathologies in comparison to healthy ears. The RF was higher in Chinese females than Caucasian females with both the GSI and Virtual systems (Table 3), which was consistent with Shahnaz and Davies' (2006). However, the RF was lower in Chinese males than Caucasian males with the GSI System but slightly higher in Chinese males than Caucasian males with the Virtual system (Figure 4). The differences between the GSI system and the Virtual system were more pronounced in both males and females in the Chinese group. The mean RF in females was higher in the GSI system than in the Virtual system. However, the mean RF in males was higher in the Virtual system than the GSI system. This was also reflected in the 90% range between the two systems in Chinese males and females (Table 3). The overall 90% range between the two systems was comparable in the Chinese group but it was different in the Caucasian group (Table 3). The 5th percentile can be used for detection of low impedance pathologies such as ossicular discontinuity (Valvik et al., 1994) and the 95th percentile can be used for detection of high-impedance pathologies such as otosclerosis (Shahnaz & Polka, 1997). The overall mean and 90% range of the GSI system in the Caucasian group were comparable to the mean and 90% range of Hanks and Mortenson (1997) who used a similar system.

Frequency corresponding to a 45° phase angle (F45°): Similarly to the RF, this parameter may also be shifted higher or lower by various middle ear pathologies. Preliminary findings suggest that the F45° may be a better index than the RF with respect to distinguishing healthy ears from otosclerotic ears (Shanks, Wilson, & Palmer, 1987; Shahnaz & Polka, 1997). Overall, the F45° was significantly higher in the Virtual system than in the GSI system. While only the 5th percentiles was different between the two systems (Table 3) in the Caucasian group, both 5th and 95th percentile were different between the two systems in the Chinese group. The mean and 90% range of F45° were comparable between the two ethnic groups (Table 3) regardless of the system used. This finding was inconsistent with Shahnaz and Davies (2006), potentially due to the smaller sample size of the current study.

Clinical Implications

While there were some differences in the measured responses for several tympanometric variables between the two systems, the overall identification rate was quite comparable between the two systems for the Ytm, the RF and the F45°. It seems that the difference between normal and otosclerotic ears on these tympanometric variables is larger than the difference between the two systems' norms. However, the clinical significance of these differences needs to be examined in other middle ear pathologies such as ossicular discontinuity and otitis media.

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