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Distribution of ThetaY$_{226}$ in a Clinical Population

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Richard Bishop*
Gerald T. Church†

Abstract

ThetaY (θ_Y) is the phase angle between the admittance vector and the conductance component in an acoustical system. It is determined by the relative contributions of the system's conductance and susceptance. The magnitude of the admittance vector has received almost exclusive attention in clinical admittance measurements. The phase angle, providing information on the relative contribution of energy-dissipating and energy-storing components, has been largely overlooked. One hundred and ninety-five clinical records obtained over a five-year period were used to investigate the distribution of θ_Y and its relationship to other tympanometric variables. The results show that θ_Y has a reasonably symmetrical distribution and is not strongly related to other tympanometric variables. The data suggest that θ_Y may account for a different subset of the total variance than more commonly measured variables. θ_Y appears to meet the criteria of independence and distribution, justifying further study to evaluate its clinical utility.

Key Words: Clinical, multicomponent, multifrequency, theta, tympanometry

Abbreviations: $\Delta\theta$ = change in θ observed with a 226 Hz probe tone and θ observed at the resonant frequency; *ECV* = equivalent canal volume; *Gradient* = "peakedness" of the tympanogram; PP_{pn} = peak pressure; *TW* = tympanic width; *Resf* = middle ear resonant frequency; *Width* = pressure difference between the outermost extrema of the "response at resonance"

Sumario

ThetaY (θ_Y) es el ángulo de fase entre el vector de admitancia y el componente de conductancia en un sistema acústico. Está determinado por las contribuciones relativas de la conductancia y la susceptancia del sistema. La magnitud del vector de admitancia ha recibido una atención casi exclusiva en las mediciones clínicas de admitancia. El ángulo de fase, que proporciona información sobre la contribución relativa de los componentes de disipación de energía y de almacenamiento de energía, ha sido despreciado. Se utilizaron ciento noventa y cinco registros clínicos obtenidos durante un período de cinco años para investigar la distribución del (θ_Y) y su relación con otras variables timpanométricas. Los resultados muestran que el (θ_Y) tiene una distribución razonablemente simétrica y no está fuertemente relacionada con otras variables timpanométricas. Los datos sugieren que el (θ_Y) puede ser responsable de un subgrupo diferente de la variancia total, más que otras variables más comúnmente medidas. El (θ_Y) parece llenar los criterios de independencia y distribución, justificando estudios ulteriores para evaluar su utilidad clínica.

Palabras Clave: Clínico, multi-componente, multi-frecuencia, theta, timpanometría

Abreviaturas: $\Delta\theta$ = el cambio observado en θ con un tono de prueba de 226 Hz y el θ observado a la frecuencia de resonancia; *ECV* = volumen equivalente del canal; Gradient = morfología en pico del timpanograma; PP_{pn} = presión pico; *TW* = ancho timpánico; *Resf* = frecuencia de resonancia del oído medio; *Width* = diferencia de presión entre el extremo más exterior de la "respuesta en el punto de resonancia"

*Bay Audiology Thorndon, Thorndon, Wellington, New Zealand; †Department of Communication Disorders, Central Michigan University

Richard Bishop, Au.D., Bay Audiology Thorndon, PO Box 12614, Thorndon, Wellington, New Zealand; Phone: +64 4 499 4345; Fax: +64 4 499 4346; E-mail: richard.bishop@bayaudiology.co.nz, kayric@orcon.net.nz

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The middle ear is a deceptively simple mechanism that acts as an impedance-matching transformer to improve the flow of acoustic energy from the air into the fluid-filled inner ear. As such it acts as a transducer, changing acoustical energy into mechanical energy (Margolis and Hunter, 2000). However, it is difficult to develop a fine understanding of the function of this mechanism due to the complex interactions of frequency and intensity that constitute acoustical energy.

The middle ear has been modelled as an acoustical system, and most of our understanding of middle ear function, over and above the energy loss depicted as the air-bone gap on pure-tone audiometry, has developed from examining the model's response to constant amplitude acoustical stimuli at various probe-tone frequencies. This systems analysis approach (Van Camp et al, 1986) allows complex functions to be understood in simpler terms and makes it possible to distinguish abnormal from normal characteristics. The weakness of such an approach is that it may result in an overly simplistic rationalization of a complex system, limiting its utility.

Acoustical systems are structures that respond to acoustical energy and consist of three elements: mass, stiffness, and friction. Acoustical energy consists of time-varying fluctuations of pressure. This fluctuating pressure exerts a fluctuating force on an acoustical system, perturbing it about its resting position, with each of the component elements reacting differently to this fluctuating force.

The response of an acoustical system to an applied force is the sum of the response of each of the three elements. These elements respond differently to the applied force, and the resultant sum is complex. Because susceptance (B) and impedance (Z) are dependent on the frequency of the applied force and conductance (G) and resistance (R) are not, the two components are conceptually orthogonal to each other. The resultant response is the vector sum of the frequency-dependent and frequency-independent components. The angle of the resultant vector to the frequency-independent component is the *phase angle*, known as Θ. The quantities Y and Θ_Y, (represented as $Y\angle\Theta$) characterize the admittance of the system at that frequency. The relative contributions of susceptance and conductance, for instance, to the overall susceptance at a given frequency remain unresolved except by examination of Θ.

These concepts are illustrated in Figure 1. Conductance is represented on the horizontal axis; it can only have positive values. Susceptance is represented on the vertical axis. Susceptance due to mass is represented as a negative value, while susceptance due to compliance is represented as a positive value. The actual magnitude of susceptance is the algebraic sum of these two components. The resultant admittance vector is shown; it has a Pythagorean relationship to conductance and overall susceptance.

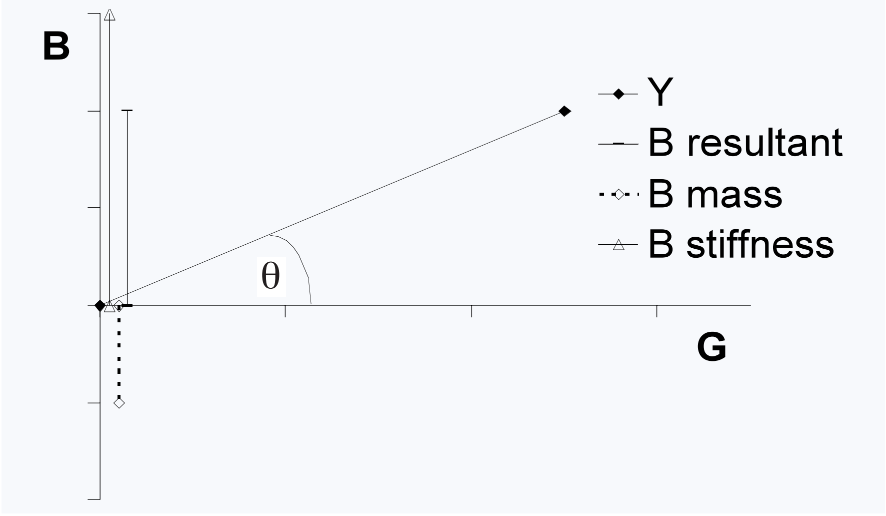

Figure 1. Graphical representation of the relationship of Y to B and G in a simple acoustic system. Y is the vector sum of the orthogonal components G and B'. B' is the algebraic sum of *B stiffness* and *B mass*, which are 180˚ out of phase (*B stiffness* is always positive, *B mass* is always negative. The sign of B' is determined by the relative magnitude of *B stiffness* and *B mass*; in a simple system this is related to the stimulating frequency). Θ is the angle subtended by the Y vector and the G component.

Theta$_{admittance}$ (Θ_Y) is the angle subtended by the admittance vector and the conductance component.

The information presented in Figure 1 could equally be represented in terms of impedance, in which case the resultant vector would be the mirror image of the admittance vector, subtending an equal but opposite phase angle, Θ_Z, with the horizontal resistance axis.

Despite the structural arrangement of the ear canal and the middle ear mechanism being apparently in series—that is, one first encounters the ear canal and then the middle ear—acoustically, at low frequencies, the two systems act in parallel. The same acoustical force acts on each component essentially simultaneously because the wavelengths are long compared to the physical length of the ear canal. This assumption holds true for frequencies below about 1 kHz (Van Camp et al, 1986).

Figure 2 illustrates the relationship of parallel acoustical systems. In the ear, system 1 represents the ear canal, and system 2, the middle ear mechanism, both contributing independently and in parallel to the observed measurement. The mechanisms within the middle ear (ear drum, ossicles, air space, ligaments, and mucosa) act as a serial system; the large area of the ear drum that is not attached to the malleus acts as a shunt (Van Camp et al, 1986). Tympanometry measures contributions from all components of the systems; the parallel component of the external ear canal air volume can be subtracted relatively easily from the overall measure at low probe frequencies, but the contribution from individual middle ear components cannot be extracted as readily. The contribution from individual middle ear components is subtle and may not always be in the same direction.

Θ_Y gives information on the contribution of the acoustical components to the overall response. While the magnitude of Y indicates the overall state of the system, it cannot by itself indicate the individual contributions. A low Θ_Y indicates a relatively greater contribution of conductance to the overall response, while a high value of Θ_Y indicates a relatively greater contribution from susceptance. A Θ_Y of 45° would indicate an equal contribution from both components. A Θ_Y of 0°, occurring when mass susceptance and compliant susceptance cancel each other out, indicates that the system is at resonance; the response of the system at this frequency will be wholly determined by its conductance. A Θ_Y greater than 45° indicates that the system is dominated by stiffness compliance; that is, the response of the system is determined predominantly by its stiffness; its conductance and mass compliance will contribute less. With increasing stimulating frequency, Θ_Y eventually becomes negative when mass susceptance begins to dominate the system response.

Despite the apparent utility of Θ_Y, it has not found common clinical use. There is no a priori reason why the measure could not be included in clinical tympanometric equipment in the same way that the amplitude of Y is routinely reported. This lack

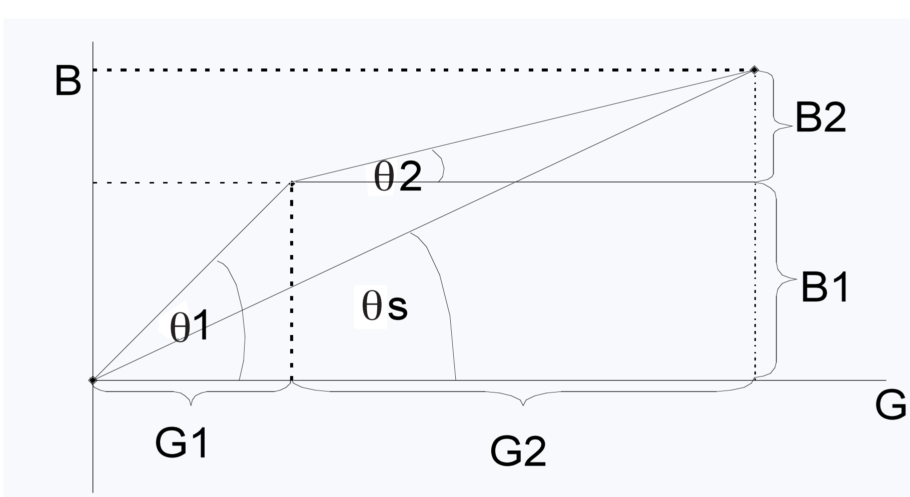

Figure 2. Graphical representation of two acoustic systems acting in parallel.

may be due in part to a number of factors. The complexity of the underlying concepts may obscure their utility. The focus of audiological assessment in the past, to identify otologically significant pathology, may also have contributed to almost exclusive focus on the amplitude of *Y*.

Tympanometric assessment in the 1970s focused almost exclusively on the detection of otologically significant middle ear conditions. Indeed, otological opinion was not always favorable toward tympanometry in its early days; a not uncommon opinion was that tympanometry is no better at detecting certain abnormal middle ear conditions than is a trained otologist. This opinion persists to this day (Cinamon and Sade, 2003). Some of this antipathy arises from nonexact interpretation of tympanometry, such as confusion of peak pressure with middle ear pressure, a pitfall of tympanometry that was described by Van Camp et al (1986).

In part, the tendency to adopt a simplistic view of tympanometry may be due to the limited success routine tympanometry has enjoyed in accurately identifying certain middle ear pathologies, such as otosclerosis (Lilly, 1984). In contrast, the general success of tympanometry in identifying middle ear effusion and its variants through the use of the Jerger tympanometric types classified by peak pressure and *Y* has tended to overshadow the potential usefulness of tympanometry for other types of pathology. There has been no routine widespread clinical use of other tympanometric measures that might have allowed stronger links to particular middle ear conditions to be identified. A tendency for errors of interpretation to become ingrained in clinical thinking may also have helped create this limited effectiveness.

Despite the a priori inherent interest in Θ_Y,[1] there appear to be very few studies in the literature that have utilized it. Vlachou et al (2001) showed that Θ_Y continues to change in children following acute otitis media even after the magnitude of Y has returned to normal. In their study, they utilized delta theta ($\Delta\Theta$), which is produced by the multifrequency tympanometry procedure of the Grason-Stadler middle ear analyzers. $\Delta\Theta$ appears to have been first described by Funasaka et al (1984) and further evaluated by Lilly (1984), who describes $\Delta\Theta$ as the "phase angle of sound pressure in the EAM [external auditory meatus] at ambient air pressure minus the phase angle measured with an air pressure of -200 daPa in EAM" (figure 9, p. 306). The Grason-Stadler implementation replaces the ambient pressure measurement with peak pressure. Lilly's (1984) procedure produces a range of positive values, but the values produced by the Grason-Stadler middle ear analyzers are negative, suggesting that the arithmetic is reversed. The measure is not intuitive and, until Vlachou et al's (2000) study, appears to have been largely overlooked.

Creten et al (1981) have discussed the diagnostic significance of "phase-angle" tympanograms, where Θ_Y is plotted against ear canal pressure. They also presented "phasor" diagrams, resulting from plotting *B* against *G* for varying ear canal pressures. Their results, however, did not provide compelling reason to adopt either measure, and little evidence exists that they have found much use in the intervening years. Lilly (1984) suggested that phase-angle tympanograms, as a suite of tympanograms including *Y, B*, and *G*, plotted against probe frequency, would assist in isolating the influence of tympanic membrane scarring on the tympanometric response. Such an analysis may well prove beneficial in describing middle ear status, but the sophisticated demands of this approach, together with a general clinical focus on middle ear effusion that was satisfied more simply by the Jerger types, has meant that no commercially available equipment today is capable of easily providing this information.

The present study sets out to discover more information about the relatively simple parameter Θ_{Y226} (that is, the phase angle of *Y* obtained with a 226 Hz probe tone), such as its distribution in a clinical population and its relationship to some other audiometric measures, including the underutilized measure of middle ear resonant frequency.

METHOD

A retrospective search of clinical records from the first author's practice was made for patients meeting the criteria for inclusion in this study.[2] To qualify, the records simply needed to include conventional

Table 1. Conventional Tympanometric Variables Used in This Study

ECV	ml	Equivalent canal volume is the effective volume of air between the probe tip and the tympanic membrane at a canal pressure of +200 daPa (relative to atmospheric pressure).
PP_{pn}	daPa	Peak pressure read from the positive-to-negative pressure sweep trace. This is the pressure corresponding to the positive extremum of the tympanogram.
Y_{pn}	ml	Peak compensated middle ear admittance read from the positive-to-negative pressure sweep trace.
TW	daPa	"Tympanic width" (de Jonge, 1986)* is a representation of the "peakedness" of the tympanogram
Gradient	ml	The "peakedness" of the tympanogram calculated according to the ratio method developed by Paradise in 1976 (de Jonge, 1986)†

*de Jonge (1986) gives "tympanic width" (dP) as the "pressure range … encompassing the half-amplitude points on either side of the tympanogram peak" (p. 300). †de Jonge (1986) showed that this measure, G_{ratio}, correlates with static admittance, adding little to other information provided by tympanometry. His G_{dp}, described in the same paper and correlating poorly with static admittance, has become more widely utilized now as "tympanometric width."

tympanometry, multicomponent tympanometry, and multifrequency tympanometry.

Data had been collected as part of the clinical investigation of patients from 1998–2003 who presented with a variety of complaints. Patients were excluded whose records did not contain the minimum data set required for inclusion in this study. This included: pure-tone audiometry, conventional tympanometry, multicomponent tympanometry, multifrequency tympanometry, and ipsilateral broadband stapedius reflex threshold.

These data were recorded as part of the clinical assessment, and the resulting population cannot therefore be considered to be randomly selected. However, they do represent a reasonable sample of presenting complaints in a general audiology practice.

Pure-tone audiometry was carried out in a sound-treated room meeting the New Zealand standards using a Beltone 2000 clinical audiometer maintained in current calibration. Conventional tympanometry was performed early in the study with a Grason-Stadler 33 (GSI33) Type II middle ear analyzer and, later, with a Grason-Stadler TympStar middle ear analyzer. Equipment was maintained in calibration. Compensated admittance tympanograms were obtained with a positive-to-negative pressure sweep at a rate of 200 daPa/sec, using a 226 Hz probe tone and a starting pressure of +200 daPa.[3] Where necessary, the extended pressure range was utilized to identify pressure peaks below -400 daPa. This measure yielded the variables given in Table 1.

Multicomponent tympanometry was carried out using a 226 Hz probe tone with a negative-to-positive pressure sweep at a rate of 50 daPa/sec from a starting pressure of -400 daPa; where necessary, a starting pressure of -600 daPa was used in order to delineate the peak pressure. The negative starting pressure was chosen following recommendations of Shanks (1984) showing that this starting pressure gives the best estimation of ear canal volume; clinical experience also shows that it reduces the incidence of artefactual negative conductance values. Conductance (G) and susceptance (B) components were recorded. This measure yielded the variables in Table 2.

Peak pressure was defined as the pressure corresponding to the positive extremum of the tympanogram. At low probe frequencies, the compliance tympanogram typically has only one such point. For most multicomponent tympanograms, the extrema of the conductance and susceptance traces corresponded very closely, but in some cases they differed. In these cases, peak pressure was defined as the pressure corresponding to the positive extremum of the conductance trace. This necessarily introduced an error in some records as the recorded value for susceptance was not maximal. However, the effect on the calculated Θ_Y was very small and was considered to be insignificant on the total data set.

Multifrequency tympanometry was performed according to the standard protocol recommended by the equipment manufacturer. This consisted of an initial frequency sweep, at 50 Hz intervals from 0.2 to 2 kHz, of the probe tone while the applied ear canal pressure was maintained at +200 daPa. This was followed by a noncompensated compliance tympanogram using a pressure sweep from +200 daPa to -400 daPa with a 226 Hz probe tone. Following

Table 2. Multicomponent Variables Used in This Study

G_{-350}	mmho*	Conductance recorded at the negative tail
B_{-350}	mmho	Susceptance recorded at the negative tail
G_P	mmho	Conductance recorded at the peak pressure
B_P	mmho	Susceptance recorded at the peak pressure
G_C	mmho	Compensated conductance ($G_C = G_P - G_{-350}$)
B_C	mmho	Compensated susceptance ($B_C = B_P - B_{-350}$)
θ_Y	degrees	The calculated polar phase angle of the components *B* and *G* as detailed above

*The Systéme Internationale unit for these quantities is not named. The quantities are defined as $\frac{m^3}{Pa.s}$. The practical unit is given as $\frac{m^3.10^{-9}}{Pa.s}$. In the cgs system, the units are named "mho" and the practical unit is given as "mmho," defined as $\frac{cm^5.10^{-3}}{dyne.s}$ (van Camp et al, 1986).

this, a further probe-tone frequency sweep in 50 Hz steps across the same frequency range was carried out at peak pressure, leading to a display of ΔB and $\Delta\theta$ across the measured frequency range. Middle ear resonant frequency was identified as $\Delta B = 0$, where the ΔB versus probe frequency crossed the zero line. The probe tone was then set to the nearest 50 Hz step, and a further uncompensated tympanogram was run from +200 daPa to -400 daPa at a rate of 50 daPa/sec to produce the "response at resonance." This yielded the variables in Table 3.

The ipsilateral broadband stapedius reflex threshold was obtained in the standard manner. Ear canal pressure was maintained at or near peak pressure, and broadband stimuli were presented ipsilaterally at 5 dB steps to elicit the reflex. The reflex threshold was taken as the lowest stimulus intensity to elicit a reflex amplitude of 0.02 ml or greater, shown as the variable *Ipsi BBART* in dB SPL. The reflex was also recorded as simply being present or absent.

From the multicomponent tympanometry, peak conductance (G_P) and susceptance (B_P) were measured with the equipment cursor and recorded in the printout. Conductance (G_T) and susceptance (B_T) values were also obtained at or near -400 daPa (G_{-350} and B_{-350}, respectively), where the traces became asymptotic. θ_{Y226} was then calculated in a computer spreadsheet, based on the following formulae adapted from Van Camp et al (1986):

1. $B_c = B_p - B_{-350}$
2. $G_c = G_p - G_{-350}$
3. $Y_c = \sqrt{(B_c^2 + G_c^2)}$
4. $\theta y_c = tan^{-1}(B_c / G_c)$
5. $R_c = G_c / (B_c^2 + G_c^2)$
6. $X_c = -B_c / (B_c^2 + G_c^2)$
7. $Z_c = \sqrt{(X_c^2 + R_c^2)}$
8. $\theta_{ztc} = tan^{-1}(X_c / R_c)$
9. $\theta_{yc} = -\theta_{zc}$

The MS™ Excel implementation of this calculation is given in the Appendix. Essentially the process consists of entering the peak values of *B* and *G* (B_P and G_P) and the tail values (B_{-350} and G_{-350}).[4]

θ_Y can be calculated for any pair of measurements of *B* and *G*. Although this study is primarily concerned with *compensated* θ_Y, where the effects of air in the ear canal have been subtracted from the peak response, it also presents data on *ear canal* θ_Y, obtained from calculations on B_{-350} and G_{-350} at a negative pressure loading on the drum of a nominal -350 daPa, and *peak* θ_Y, obtained from B_P and G_P at tympanometric peak pressure.

Because this calculation is based on compensated *B* and *G*, it could be used at different

Table 3. Multifrequency Variables Used in This Study

Resf	kHz	Middle ear resonance frequency as defined above
Width	daPa	The pressure difference between the outermost extrema of the "response at resonance" as outlined above
$\Delta\theta$	Degrees	The change in θ observed with a 226 Hz probe tone and θ observed with the resonant frequency as outlined above

Table 4. Presenting Complaints

Presenting Complaint	N	Presenting Complaint	n
Hearing concerns	80	Autophony	2
Tinnitus	57	Facial neuralgia	1
Otalgia	8	Discomfort	1
Blockage	6	Distortion	1
Trauma	5	"Thick head"	1
Hyperacusis	5	Barotrauma	1
Rotatory vertigo	5	Fullness	1
Unilateral deafness	4	Reverberation	1
Acoustic shock	2	Virus	1
Balance problems	2	Middle ear	1
Sudden deafness	2	Not recorded	5

Note: The total complaints exceed the study *n* due to some patients having more than one complaint.

probe frequencies, at least below 1 kHz, as it allows the calculation of differing values of the components in the middle ear and ear canal. Above 1 kHz, uncontrollable phase differences between the ear canal and the drum mean the model becomes increasingly less valid.

RESULTS

195 records met the selection criteria. 100 records were from males, 95 from females. Some ears did not include all variables and were excluded from correlation tables; 364 ears were included in the final analysis. Presenting complaints are given in Table 4. Ages ranged from 2–80 years (mean = 47, sd = 14.97).

THETA

The distribution of compensated θ_Y for left and right ears was obtained separately. The means and standard deviations from the left (mean = 66.67°, sd = 8.97) and right (mean = 67.53°, sd = 6.53) ears were subjected to a paired two-tailed t-test, which was not significant (t = 0.183014). As a result, the data from each ear were combined, giving a grand mean of 67.10° (sd = 7.85). The resulting distribution, shown in Figure 3, was fairly symmetrical about the mean but with a mild preponderance of extremely low values over extremely high values.

The details of the distribution of the ear canal, peak, and compensated θ_Y are presented in Table 5, and their distributions are given in Figure 4.

Figure 5 gives the details of the acoustical model obtained from the data in this study. There is, on average, a 10° variation between the ear canal acoustical model and that of the middle ear.

Figure 6 shows the distributions of Y_c, G_c, and B_c, together with Y_{pn} (peak compensated middle ear admittance). The distributions all have a marked positive skew. The distribution of G_c shows greater kurtosis and is

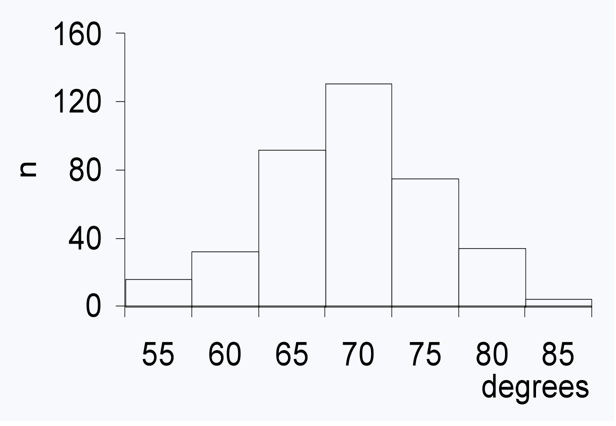

Figure 3. The distribution of θ_Y amalgamated from left and right ears.

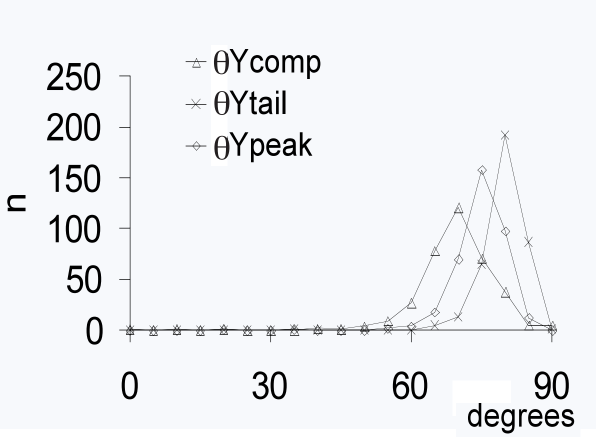

Figure 4. The distributions of compensated θ_Y (θ_Y comp), ear canal θ_Y (θ_Y tail), and peak θ_Y (θ_Y peak).

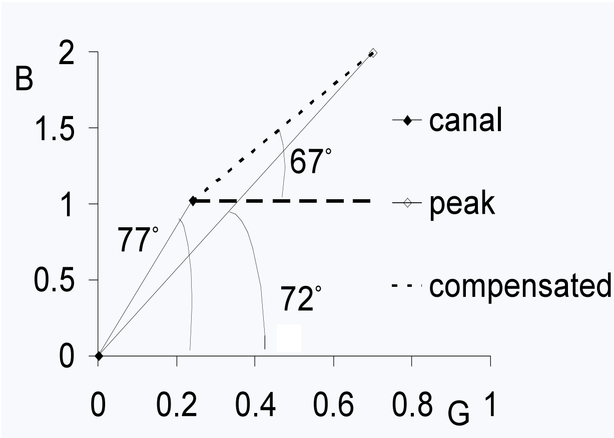

Figure 5. Graphical representation of the mean components of the external and middle ear acoustic systems obtained from this study.

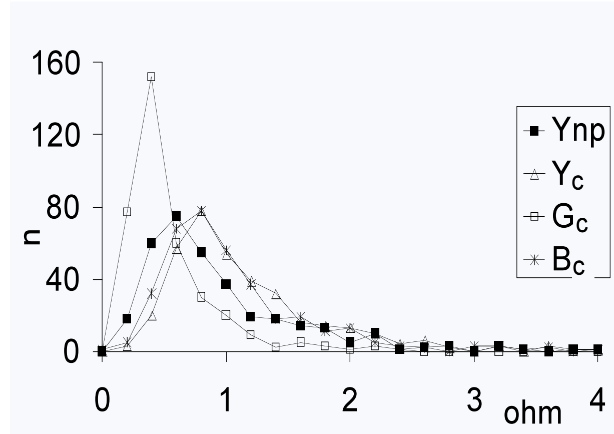

Figure 6. Distributions of measured B_c, G_c, and Y_{np}, and calculated Y_c.

Table 5. Details of the Distributions of θ_Y

	Ear canal θ_Y	Peak θ_Y	Compensated θ_Y
Mean	77	72	67
Mode	79	76	72
Median	78	73	68
Range	32–85	20–83	90–86
SD	4.66	6.05	12.07

Note: θ_Y is rounded to the nearest whole degree.

offset distinctly from the other variables that display a remarkable degree of overlap.

Correlations between the study variables in each pair of ears are shown in Table 6. Because the sample size is quite large, there is an increased chance of randomly significant relationships, and significance was set at $p < .001$ to reduce this risk (Paul Jose, pers. comm., 2005). All of the diagonal cells (bolded in Table 3) exceeded this level of significance; those with the double asterisks were particularly strongly related. Slightly weaker

Table 6. Left/Right Variable Correlations

	R ECV	R PP$_{pn}$	R B$_c$	R G$_c$	R Y$_c$	R θY$_c$	R Res.f	R Δθ	R Width	R TW	R Gradient
L ECV	**0.66****	0.09	0.14	0.13	0.14	-0.09	-0.09	0.10	0.01	0.02	-0.06
L PP$_{pn}$	0.04	**0.56****	0.14	0.09	0.13	0.17	-0.02	-0.06	-0.15	-0.29*	0.19
L B$_c$	0.16	0.13	**0.67****	0.62*	0.67**	-0.10	-0.27*	-0.52*	-0.07	-0.37*	0.33*
L G$_c$	0.21	0.12	0.55*	**0.57***	0.56*	-0.27*	-0.31*	-0.41*	-0.11	-0.31*	0.29*
L Y$_c$	0.18	0.13	0.67**	0.63**	**0.67****	-0.15	-0.30*	-0.52*	-0.08	-0.38*	0.33*
L θY$_c$	-0.12	0.05	-0.01	-0.10	-0.03	**0.33***	0.10	-0.02	0.10	-0.03	-0.05
L resf	0.01	0.00	-0.23*	-0.20	-0.23*	0.09	**0.53***	0.30*	0.02	0.08	-0.11
L Δθ	0.07	0.00	-0.39*	-0.26*	-0.37*	-0.05	0.23*	**0.67****	0.09	0.31*	-0.27*
L Width	-0.04	-0.17	-0.13	-0.05	-0.12	-0.14	-0.10	0.16	**0.34***	0.36*	-0.36*
L TW	0.06	-0.25*	-0.33*	-0.23*	-0.31*	-0.14	0.04	0.40*	0.25*	**0.55***	-0.43*
L Gradient	-0.09	-0.15	0.23*	0.18	0.22*	-0.03	-0.05	-0.36*	-0.18	-0.36*	**0.31***

Note: Diagonal entries are bolded. * p << 0.001; ** particularly strong relationships

Table 7. Grouped Correlations between Components

	ECV	PP$_{pn}$	B$_c$	G$_c$	Y$_c$	θY$_c$	Res.f	Δθ	Width	TW	Gradient
Age	0.07	-0.11	0.12	0.18	0.14	-0.17	-0.15	-0.13	0.05	0.02	0.07
ECV		0.09	0.25*	0.25*	0.25*	-0.13	-0.05	0.12	0.06	0.12	-0.12
PP$_{pn}$			0.11	0.07	0.10	0.11	0.04	0.04	-0.19	-0.36*	0.09
B$_c$				0.87**	0.99**	-0.02	-0.34*	-0.61*	-0.18	-0.47*	0.41*
G$_c$					0.93**	-0.38*	-0.35*	-0.46*	-0.10	-0.33*	0.33*
Y$_c$						-0.11	-0.35*	-0.59*	-0.16	-0.44*	0.40*
θY$_c$							0.16	-0.10	-0.12	-0.22	0.07
Res.f								0.41*	0.02	0.10	-0.06
Δθ									0.21*	0.52*	-0.44*
Width										0.51*	-0.42*
TW											-0.70*

* p << 0.001; ** particularly strong relationships

interear correlations were obtained for θ_Y, *Resf* (middle ear resonant frequency), *Width* (pressure difference between the outermost extrema of the "response at resonance"), *TW* (tympanic width), and *Gradient* ("peakedness" of the tympanogram).

Correlations between the variables amalgamated from each ear are given in Table 7. Very strong relationships are again indicated by double asterisks. The relationships between Y_c, G_c, and B_c, with correlations exceeding 0.87, appear virtually deterministic. This very strong grouping dominates the data set.

Of particular interest to this study are the correlations with θ_Y. There is a significant positive correlation with G_c and a significant negative correlation with *TW*.

Among the other study variables, strong negative relationships were noted between $\Delta\theta$ and Y_c and B_c, and *TW* and *Gradient*. Slightly weaker negative correlations were obtained between *Gradient*, *Width,* and $\Delta\theta$, and between *TW* and PP_{pn} (peak pressure), G_c, B_c, and Y_c. Positive correlations were noted between *ECV* (equivalent canal volume), G_c, B_c, and Y_c, and between *Gradient* and G_c, B_c, and Y_c. This latter finding has been commented on before, for instance, de Jonge (1986).

A factor analysis of the variables in Table 7 produced three factors accounting for 63% of the observed variance. The variable communalities are given in Table 8.[5] The factor loadings are shown in Table 9.

Factor 1 loaded very heavily positive on B_c, G_c, and Y_c, and negatively more lightly on $\Delta\theta$, *TW, Resf,* and *Width*. The loadings of B_c, G_c, and Y_c are very high (0.893–0.929). The second factor loads positively on *Gradient* and θ_Y, B_c, and Y_c, with negative loadings on *Width, TW,* and *ECV*. The third factor loads negatively on PP_{pn}, *Resf*, $\Delta\theta$, and *ECV*, and positively on *Age*.

The factors are not easily interpretable but show that θ_Y (given as θY_c in Table 6), loading significantly on Factor 2, relates differently to the data set from G_c, B_c, and Y_c, which load on Factor 1.

Table 8. Communalities of the Study Variables

Communalities			
Variable		Variable	
Age	0.250	θY_c	0.375
ECV	0.617	Resf	0.387
PP_{pn}	0.573	$\Delta\theta$	0.713
B_c	0.895	Width	0.450
G_c	0.893	TW	0.819
Y_c	0.929	Gradient	0.624

Table 9. Varimax Rotated Factor Loadings Extracted from the Study

Variable	Factor 1	Factor 2	Factor 3
Age	0.212	-0.094	0.443
ECV	0.522	-0.420	-0.411
PP_{pn}	0.166	0.220	-0.705
B_c	0.880	0.340	0.066
G_c	0.928	0.120	0.129
Y_c	0.915	0.291	0.088
θY_c	-0.360	0.448	-0.212
Res.f	-0.413	-0.060	-0.462
$\Delta\theta$	-0.428	-0.591	-0.425
Width	-0.052	-0.631	0.221
TW	-0.282	-0.845	0.158
Gradient	0.248	0.748	0.054

Note: Rotation completed in eight iterations. Rotation was normalized.

EAR CLASSIFICATION

Because Y_c and θ_Y are not significantly correlated, it is possible to use their distributions to classify ears according to their position in each of the variables. Low, normal, and high value ranges of each variable were established. For Y_c the commonly accepted normal range (0.3–1.5 mmho) was used. This range is used with conventional admittance tympanometry to identify tympanograms with abnormally high or low compliance. The normal range for θ_Y was set as the mean ±1 sd (59–76°). This produced the 3x3 grid shown in Table 10. The number of ears falling into each cell varied from 1 to 245, making interpretation of ear characteristics in some cells weak. However, it was possible to discern some interesting patterns.

Table 10. Number of Ears by θ_Y x Y_C Distributions

	θ_Y			
Y_c	Low	Normal	High	Σ
Low	1	47	1	49
Normal	22	245	27	294
High	2	15	4	21
Σ	25	307	32	364

Key: Cell identifiers

1	2	3
4	5	6
7	8	9

SUSCEPTANCE AND CONDUCTANCE

Figure 7 shows B_c and G_c means in each cell. Each cell is identified by the key given in Table 10. The data in this figure illustrate the relationship between the four variables, reinforcing the correlations presented above. In cells 1–3, the top row of the grid defined as high Y_c, B_c is above the sample median value; it is at the sample median in the middle row and below the sample median in the bottom row. Similarly, there is a progressive reduction in the value of G_c across the columns. These systematic relationships suggest that, in this population, Y_c is largely determined by B_c, while Θ_Y is largely determined by variations of G_c.

The multicomponent traces obtained showed some variation of form. In the large majority, *G* and *B* components varied similarly across the measured pressure range. Smaller numbers showed a discrepancy between peak pressure of the two traces, while others showed variations of *G* that were not mirrored in *B*. These variations were examined but revealed no systematic relationship with Θ_Y.

MIDDLE EAR RESONANT FREQUENCY

The distribution of *Resf* was amalgamated for left and right ears. The distribution is given in Figure 8 (mean = 1.08 kHz, sd = 0.34).

Mean *Resf* in the nine cells of Table 10 showed a significant increase from cells 1 to 9 ($r = 0.93$, $F = 42.28$, $p < .001$). The relationship is shown in Figure 9. In this data set, low Y_c values are associated with low Resf, and high Y_c values are associated with high *Resf*.

The ΔB traces were sorted visually into three main groups defined by the steepness of the zero-crossing section. No systematic relationship with Θ_Y was found in this data set, and this classification was not explored further in this paper.

Δθ

$\Delta\theta$ traces are produced by the equipment as part of the multifrequency examination; variations in $\Delta\theta$ traces were noted but were

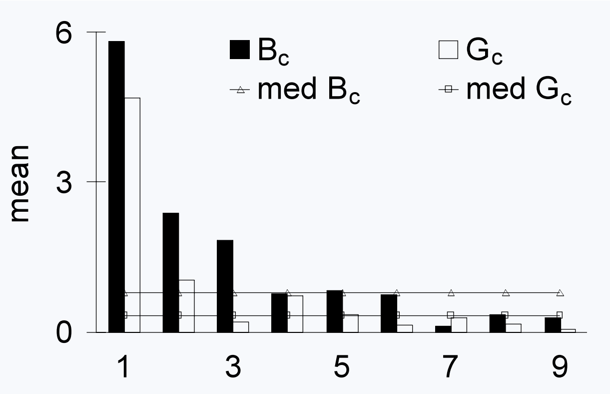

Figure 7. Mean B_c and G_c in each cell with sample median B_c (Bmed) and G_c (Gmed) values. Note: the number of ears in each cell is not equal (refer to Table 7).

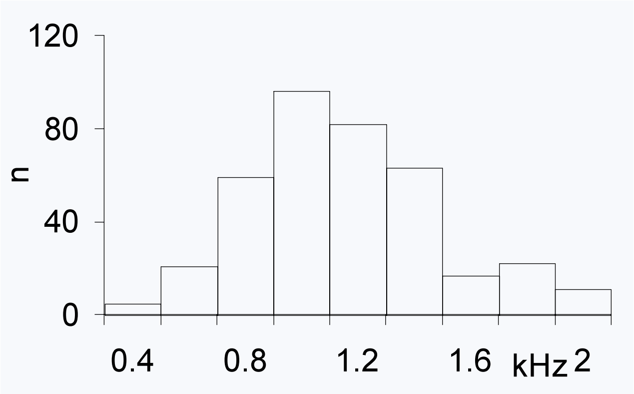

Figure 8. The distribution of middle ear resonant frequencies amalgamated for left and right ears.

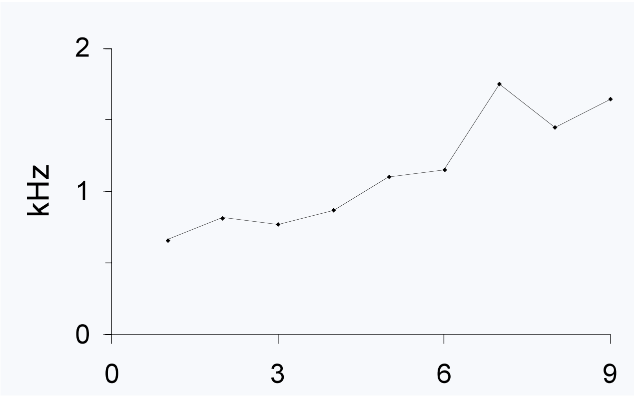

Figure 9. Mean resonant frequency (*Resf*) in each cell.

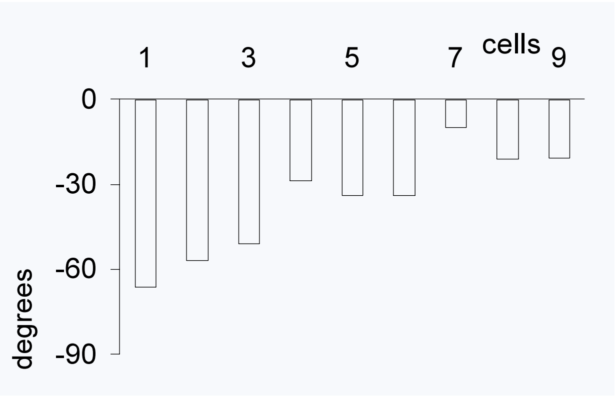

Figure 10. Mean $\Delta\theta$ in each cell.

not evaluated in this study. Instead, following the process of Vlachou et al (2000), $\Delta\theta$ at resonant frequency was recorded.

The distribution of $\Delta\theta$ across cells of Table 10 is noted in Figure 10. $\Delta\theta$ shows a systematic reduction across the rows of Figure 7; it is largest in cells 1, 2, and 3, moderate in cells 4, 5, and 6, and smallest in cells 7, 8, and 9.

AGE AND GENDER INTERACTION ON θ_Y

The data were examined for any age and gender effects. The data were ordered according to age and gender, and mean θ_Y was calculated for each decade. The results are shown in Table 11.

There appears to be a weak decline in θ_Y with increasing age, with higher θ_Y values found in young females. In contrast to males, who showed tendency for a nonsignificant increase with age in both B_c (t = 0.77, p = 0.48) and G_c (t = 0.53. p = 0.62), the female subgroup showed a tendency for declining B_c (t = -1.43, p = .21) and a stronger increase of G_c (t = 3.61, p = .02) with increasing age.

DISCUSSION

The data presented above demonstrate that θ_Y does meet the basic requirements of a useful measurement, in that it has a reasonably symmetrical distribution with no significant floor or ceiling effects and that it is not systematically correlated to other common measures. While there is a significant negative correlation with G_c, there is no correlation with B_c. The present data suggest that Y_c is determined largely by B_c, while θ_Y is determined largely by G_c. However, knowledge of the amplitude of G_c by itself is not particularly useful as it is correlated strongly with the amplitude of B_c; that is, ears with large G_c almost always have large B_c. However, an ear-by-ear examination of the relationship of these two parameters given by θ_Y does reveal unique and potentially useful variation.

The correlation of ear canal volume with G_c, B_c, and Y_c is puzzling. Calculation of these parameters is made by subtracting their base values obtained with an apparently asymptotic pressure loading on the tympanic membrane from the peak values obtained with zero pressure loading on the tympanic membrane. The most probable explanation is that, even with the asymptotic pressure loading, middle ear impedance is not driven to infinity, and the asymptotic measures have some contamination from middle ear status. When the base values are subtracted from the peak values, this "contamination" remains, possibly giving rise to the relatively weak correlations observed.[6] The small 10° discrepancy between the elements of the acoustical system model presented in Figure 5 also suggests that the acoustical model may not fully describe the status of the outer and middle ear systems.

Establishing the clinical utility of θ_Y is beyond the scope of this study, but the measure has intuitive interest, giving access as it does to the relationship between energy-dissipating (resistance or conductance) and energy-storing (reactance

Table 11. Distribution of Male and Female Ears in Decade Age Bins, with Corresponding Mean θ_Y.

	M		F	
Age bin	N	θY	n	θY
<=10	4	67.81	2	74.48
11–20	8	73.45	4	75.34
21–30	19	64.48	20	69.12
31–40	30	67.01	32	69.48
41–50	48	67.25	34	66.24
50–60	60	65.53	46	66.27
60–70	14	66.22	22	68.22
>=71	7	69.45	14	64.14
n	190		174	

Note: Some incomplete records were not included in this analysis, accounting for the reduced *n*.

or compliance) components of the middle ear acoustic system. Although Θ_Y may not be as intuitive a measure as the magnitude of the admittance vector, it may be helpful in revealing subtle aspects of middle ear function more sensitively than does admittance. Its communality in the current data set (0.375) is similar to that of middle ear resonant frequency (0.387), suggesting a similar degree of utility between the two measures.

There appears to be a relationship between the cell types described in Table 10 and middle ear resonant frequency, ΔB and $\Delta\Theta$. These latter two measures appear to be unique to the Grason-Stadler middle ear analyzers and are not at all intuitive. $\Delta\Theta$ is mentioned by Lilly (1984), but the Grason-Stadler presentation is different from his. While identification of middle ear resonant frequency as $\Delta B = 0$ seems to work pragmatically, the logic is obscure. Middle ear resonant frequency is defined as the frequency where $B_c = 0$ and where, necessarily, $\Theta_Y = 0$. It would be expected from simple logic that $\Delta\Theta = 0$ at resonant frequency, but this is not the case. Nevertheless, there appears to be an interesting relationship with the present study variables that might reward further investigation.

The dominance of admittance amplitude on the data set helps to explain why it has tended to occupy the focus of clinical tympanometry for the past 30 years. This focus, however, may have resulted in other parameters being overlooked, which may help to increase the sensitivity of the measure to middle ear status. The current data suggest that the use of Θ_Y together with Y_c can increase the sensitivity by identifying as abnormal ears that are within the normal range on Y_c but that show either a higher or lower Θ_Y. By examining the contributory values of G_c and B_c to abnormal values of Θ_Y, it is possible to determine whether an abnormality is due to, for instance, elevated G_c and reduced B_c. This appears to offer a more sensitive identification of middle ear status, but the ultimate clinical utility can only be determined in clinical usage. While it is true that normative ranges of G_c and B_c have been available for many years, they have not found much use in routine clinical tympanometry. This may possibly be due to the strong correlation between them and the difficulty in evaluating the relative variation of their magnitudes; Θ_Y offers a way to determine whether their relationship falls within a normal range or not.

Traditional tympanometry has been found to be sensitive to middle ear pathology such as middle ear effusion-type conditions, ossicular chain disruption, and tympanic perforation and scarring, but there remain significant areas of pathology, especially those involving the more medial components of the ossicular chain and possibly the middle ear muscles, to which it is insensitive. Measures to increase the sensitivity of the technology have included multicomponent and multifrequency tympanometry but have largely overlooked Θ_Y. Because Θ_Y is not strongly correlated with admittance, it can be regarded as orthogonal to it, and this relationship can improve the sensitivity by identifying ears that may be normal on admittance but whose Θ_Y lies outside the normal range. Table 10 shows the distribution of ears from this data set that fall into the nine cells defined by low, normal, and high Y_c and low, normal, and high Θ_Y. Unsurprisingly, the addition of an orthogonal normal distribution identifies about a third of the ears as being abnormal. The small number of ears falling into cells 1, 3, 7, and 9 suggests that they may be of clinical interest but also makes it difficult to establish related characteristics.

The lack of a discernible pattern of presenting complaints or other findings across the nine cells is not entirely unexpected in a study of this nature. Had a simple relationship existed, it would almost certainly have been noted in earlier studies. It does not negate the potential usefulness of the Table 10 grid in evaluating middle ear status in clinical practice, but it does indicate a requirement for larger *n*'s in each of the outlying cells. It also indicates the difficulty in coding clinical findings and retrospectively grouping ears in this study.

The variations noted in this data set of the form of the multicomponent traces, ΔB versus frequency, and $\Delta\Theta$ versus frequency traces, offer possible additional areas of increasing the sensitivity of tympanometry. They represent a different type of examination of middle ear status that relies on the dynamics of the perturbed system under investigation rather than the static measures presented in this paper.

The variation of Θ_Y with age is mild but possibly more marked in females. There appears to be a weak tendency for young females to have higher Θ_Y values. It would be of interest to explore this relationship further.

Θ_Y describes the relationship between susceptance and conductance. This relationship has been shown in this study to be independent of admittance. Low values, for instance, of Θ_Y may reflect relatively elevated conductance or, conversely, relatively reduced susceptance. It is suggested that, in clinical use of Θ_Y, the values of B and G be examined against the range of values established in this study (1.02 and 0.45, respectively) to distinguish between these conflicting interpretations. Because the distributions of B_c and G_c are markedly skewed, it is not appropriate to use the mean and standard deviation to establish normal ranges; the median and semi-interquartile ranges give a priori expected ranges and are given in Table 12.

These figures correspond at their lower end to the 90% range cited by Shanks et al (1988). The upper limits given by those authors, however, are considerably higher than the upper limits obtained in the present study and probably reflect the skewed distribution of these measures; the 90% range may overestimate the clinical normal range.

The subjects in the present study were not selected for a negative otological history in this way and included many ears with abnormal traditional tympanometry. Nevertheless, the obtained distributions of B and G are very similar to those published by Wiley et al (1987), even though their subjects were carefully screened for normal pure-tone audiometry and negative otological history. This suggests that a simple examination of values of B and G is unlikely to identify abnormal middle ears.

The ultimate clinical utility of the interpretation of Θ_Y in terms of B_c and G_c will require larger populations, especially in the outlying cells 1, 3, 7, and 9 of Figure 10.

Table 12. Median and Semi-interquartile Range Values for B_c and G_c

	B_c	G_c
Median	0.67	0.26
Semi-interquartile range	0.30	0.16

Clinical series defined either by presenting problems or by audiological or otological diagnoses will also help determine the utility of the measure and promote a deeper understanding of the effect of middle ear status on auditory perception. The study by Vlachou et al (2000), although limited in its interpretation, illustrates that Θ_Y is sensitive to longitudinal changes in middle ear status during recovery from acute otitis media. Similar longitudinal studies utilizing multicomponent tympanometry may give more specific information.

A further use for more sensitive tympanometry, apart from documenting current status, would be to identify historic signs that might allow identification of a history of middle ear disease or trauma. Such a use would enhance studies of the relationship of auditory processing difficulties to an early history of otitis media, for instance, if there are reliable tympanometric signs. Details of early childhood middle ear disease may not always be available from a clinical history or from otoscopic examination.

Manufacturers of tympanometric equipment could help by making Θ_Y more accessible. An argument could be made for establishing multicomponent tympanometry as the clinical standard: it provides all of the information, and more, that is available from standard tympanometry; data collection takes no longer than standard tympanometry; and it offers a potentially more valuable view of middle ear status. Despite the calls in the early literature, Lilly (1984) and Shanks (1984) for instance, for the routine clinical use of more sophisticated clinical tympanometry, the vast majority of commercially available tympanometers continue to provide only Y, peak pressure, and occasionally tympanometric width. This situation reflects the predominant current use of tympanometry in the identification of middle ear effusion and its variants. This situation will not change until there is demand from audiologists for more sophisticated measures; this will not occur until the clinical utility of these measures has been demonstrated.

NOTES

1. Shanks et al (1988) suggested that, because θ is the only measure of the ratio of the two rectangular components, future research may show it to be a valuable immittance component.

2. The project was assessed and accepted by the IRB of the Central Michigan University.

3. This starting pressure was used in this study as it is the most commonly used in clinical practice. Data were also collected with a negative-to-positive sweep to evaluate tympanometric hysteresis but are not presented here.

4. Values of R and Z were also calculated and their distributions examined, but these results are not presented here.

5. *Communality* of a variable is the variance in that variable accounted for by all the factors. It is given by the squared multiple correlation for the variable as dependent using the factors as predictors. The communality measures the percent of variance in a given variable explained by all the factors jointly and may be interpreted as the reliability of the indicator.

6. It has been suggested (anonymous reviewer, 2006) that there may be a relationship between ear canal volume and the area of the tympanic membrane, and the area of the tympanic membrane and the amplitudes of G_c, B_c, and Y_c. This appears reasonable a priori, but the relatively weak correlations suggest that it may not be completely deterministic.

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Appendix

The following extract from an MS™ Excel spreadsheet shows the implementation of the formulae given in the Method section:

1		V	W
2		**Left**	**Right**
3	**B_p**		
4	**G_p**		
5	B_{-350}		
6	G_{-350}		
7	B_{comp}	=$V$3-$V$5	=$W$3-$W$5
9	G_{comp}	=$V$4-$V$6	=$W$4-$W$6
10	**Calculated values:**		
11	**Y**	=SQRT(($V$7^2)+($V$9^2))	=SQRT(($W$7^2)+($W$9^2))
12	**Th**	=1/(TAN($V$7/$V$9))	=1/(TAN($W$7/$W$9))
13	**Degree**	=DEGREES(ATAN($V$7/$V$9))	=DEGREES(ATAN($W$7/$W$9))
14	**R**	=$V$9/($V$9^2+$V$7^2)	=$W$9/($W$9^2+$W$7^2)
15	**X**	=-$V$7/($V$9^2+$V$7^2)	=-$W$7/($W$9^2+$W$7^2)
16	**Z**	=SQRT($V$15^2+$V$14^2)	=SQRT($W$15^2+$W$14^2)

B_p Peak *susceptance*

G_p Peak *conductance*

B_{-350} Reference *susceptance* at -350 daPa canal air pressure

G_{-350} Reference *conductance* at -350 daPa canal air pressure

B_{comp} Compensated *susceptance*

G_{comp} Compensated *conductance*

Y *Compliance*

Th *Theta* in radians

Degree *Theta* in degrees

R *Resistance*

X *Reactance*

Z *Impedance*