Evaluation of Middle Ear Function in Young Children: Clinical Guidelines for the Use of 226- and 1,000-Hz Tympanometry

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Hypothesis: The aims of the study were to evaluate tympanometry with regard to age and classification system using two probe-tone frequencies and to provide clinical guidelines.

Methods: Six subject groups were included in the evaluation: (1) neonatal intensive care unit babies, (2) children younger than 3 months, (3) children 3 to 6 months old, (4) children 6 to 9 months old, (5) children 9 to 32 months old, and (6) adults. Hearing of all subjects was screened by means of auditory brainstem responses, transient-evoked otoacoustic emissions, or behavioral audiometry. Tympanograms, recorded with probe-tone frequencies of 226 and 1,000 Hz, were classified according to shape and middle ear pressure. Additionally, 1,000-Hz tympanograms were classified based on the Vanhuysse model of tympanometric shapes. Furthermore, tympanometric parameters equivalent ear canal volume, admittance value at +200 daPa, middle ear admittance, tympanometric peak pressure, and tympanometric width were calculated for each tympanogram.

Results: For clinical purposes, the visual admittance classification system was more suitable than the Vanhuysse model. Furthermore, in children younger than the age of 3 months, 1,000-Hz tympanometry was easier to interpret and more reliable than 226-Hz tympanometry. From the age of 9 months, 226-Hz tympanometry was more appropriate. In children between 3 and 9 months, the reliability of tympanometry was independent of probe-tone frequency. A two-stage evaluation with a 1,000- to 226-Hz tympanometry sequence was preferred because this reduced the total number of tests.

Conclusion: The current study provides normative data and age-related guidelines for the use of tympanometry in clinical practice. These results have led to a successful implementation of 1,000-Hz tympanometry in neonatal hearing assessment.

Key Words: Admittance—Infants—Middle ear—Probe-tone frequency—Tympanometry.

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In the last few years, audiologic clinicians have been faced with a very young patient population due to neonatal hearing screening programs. It is of great importance that the hearing of the referred infant can be accurately assessed as soon as possible to provide adequate rehabilitation. As middle ear dysfunction may confound the interpretation of test results, it is crucial to distinguish conductive from sensorineural hearing loss. Moreover, in young children, the incidence of middle ear problems is very high. Approximately 70 to 90% of all children are affected by otitis media with effusion at some time before school age and more than 50% in their first year of life (1,2). Recurrent otitis media with effusion can result in

mild to moderate hearing loss because persistent middle ear fluid decreases the mobility of the tympanic membrane and ossicles. This (temporary) hearing impairment may have consequences on the development of speech, language, and cognitive skills.

Tympanometry is an objective and adequate test in detecting middle ear problems and is used in hearing screening at a young age. Conventional 226-Hz tympanometry is accepted as the criterion standard to distinguish conductive from sensorineural hearing loss in adults and older children, but it is known to have little sensitivity in newborns (3,4). Furthermore, it produces differently shaped tympanograms in infants compared with adults and older children (5–7).

Developmental changes in the external and middle ear structures during the first months of life significantly affect the ear canal impedance and reflection coefficient responses (7,8). Middle ear compliance is lower and resistance is higher in infants compared with adults, and less power is transferred into the middle ear. Moreover,

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the resonant frequency of the tympanic membrane is much lower in children. Hence, the middle ear evolves from a mass-dominated to a stiffness-dominated system (7,9). Therefore, tympanometry in young children would be more effectively measured at probe-tone frequencies higher than 226 Hz (10). However, despite these findings and several studies revealing erroneous results in 226-Hz tympanometry in infants (3,9–11), the change to a higher probe-tone frequency was not fully put into clinical practice because of difficulties in interpreting tympanograms and controversial suggestions with regard to probe-tone frequency in relation to age (7,9,12,13).

However, the amount of research on high-frequency tympanometry has increased in the last few years. Several researchers have suggested the Vanhuysse model of tympanometric shapes (14) to interpret tympanometric patterns in children (6,7,12,15). Furthermore, other researchers have created their own methods to classify high-frequency tympanometry in children (11,12,16,17). For example, Baldwin (17) proposed a classification system based on identifying positive versus negative peaks above a baseline between +200 and –400 daPa. Finally, some researchers have evaluated high-frequency tympanometry by means of a simple visual admittance classification method (17–19). Kei et al. (18) and Margolis et al. (19) evaluated 1,000-Hz tympanometry in neonates and presented normative data.

Despite numerous studies indicating the relevance of high-frequency tympanometry, to our knowledge, clear clinical guidelines are not yet at hand. In the current study, 226- and 1,000-Hz tympanometry were performed in young children between birth and 32 months. A first objective was to determine the classification system of preference for 1,000-Hz tympanometry. A second objective was to evaluate tympanometry at probe-tone frequencies of 226 and 1,000 Hz in relation to age. Finally, a third objective was to propose a straightforward and effective protocol that can serve as a guideline in clinical practice.

MATERIALS AND METHODS

Subjects

In total, 110 children between birth and 32 months and 15 adults participated in this study. Participants' ears that fulfilled at least one of the following inclusion criteria were assigned to six different groups depending on age (Table 1):

- 1) normal click-evoked auditory brainstem response (ABR) patterns at 70 and 80 dB peak sound pressure level (median corrected age at time of testing, –1 mo);
- 2) transient-evoked otoacoustic emissions (TEOAEs) present in at least three of five frequency bands (median age, 7 mo);
- 3) behavioral hearing thresholds 20 dB hearing loss or less at octave frequencies between 500 and 4,000 Hz (median age, 22 yr).

Data of 131 ears were included for further analyses. In these ears, middle ear problems were assumed to be nonexistent.

TABLE 1. The six different age groups, with corresponding age range and number of tested ears

Group	Age range	No. ears (n = 131)
NICU	–4 wk ≤ x ≤ 6 wk	28
0–3 mo	0 mo ≤ x < 3 mo	15
3–6 mo	3 mo ≤ x < 6 mo	15
6–9 mo	6 mo ≤ x < 9 mo	15
9–32 mo	9 mo ≤ x ≤ 32 mo	28
Adults	17 yr ≤ x ≤ 27 yr	30

For further analyses, the NICU group and the 0- to 3-month-old group, as well as the 3- to 6-month-old group and the 6- to 9-month-old group, were clustered together, creating 4 age groups: younger than 3 months (n = 43), 3 to 9 months (n = 30), 9 to 32 months (n = 28), and adults (n = 30).

Furthermore, tympanometric data of 33 additional ears, with TEOAE results showing signal-to-noise ratios (SNRs) of 0 dB or less in all frequency bands, were evaluated in more detail. Because this criterion was set to be very strict, negative TEOAE screening results were assumed to be caused by middle ear dysfunction, rather than noisy test situations. Moreover, the chance that TEOAEs were absent because of sensorineural hearing loss was limited as all these children passed the neonatal hearing screening (Automated-ABR) and had no history of hearing problems.

This research project fitted within the neonatal hearing assessment program at the Ear, Nose, and Throat (ENT) Department of UZ Leuven. At the neonatal intensive care unit (NICU), hearing screening is performed by means of ABR in all infants by experienced audiologists. Furthermore, TEOAE recordings are standardly performed as a part of the follow-up after neonatal hearing screening in Flanders. This research project was approved by the Committee of Medical Ethics of Clinical Research of K.U.Leuven and was in accordance with the Helsinki Declaration. Informed consent was obtained from a parent of each child to conduct the audiologic tests.

Test Procedure

The hearing status of all adults was evaluated by means of behavioral audiometry. Thresholds were obtained with a clinical audiometer (Madsen Electronics Orbiter 922; Minneapolis, MN, USA) and TDH-39 headphone (GN Otometrics, Taastrup, Denmark). In children, TEOAEs, ABR recordings, or behavioral thresholds were obtained before tympanometry. TEOAEs were recorded with the Otodynamics ILO292 (Otodynamics, Ltd., Hatfield, Herts, U.K.). TEOAEs were considered present if the SNR exceeded 6 dB in at least three of five frequency bands. ABR measurements were performed with a Madsen ERA 2260 brainstem evoked response audiometer (GN Otometrics). Behavioral audiometry was performed in free-field conditions by means of visual reinforcement audiometry.

In the same test session, tympanograms were recorded with a MADSEN OTOflex 100 middle ear analyzer (GN Otometrics). Tympanometric data were obtained with probe-tone frequencies of 226 and 1,000 Hz in random order. Ear canal pressure was swept in a positive-to-negative direction from +200 daPa to –400 daPa at a pump speed of 500 daPa/s.

The following parameters were calculated for each tympanogram: equivalent ear canal volume (ECV), admittance value at +200 daPa (Y_{+200}), middle ear admittance (Y_{ME}), tympanometric peak pressure (TPP), and tympanometric width (TW). Shape and middle ear pressure of all recorded tympanograms

were evaluated, and tympanograms were classified into different categories.

Classification

Visual Admittance Classification

Both 226- and 1,000-Hz tympanograms were evaluated based on the visual admittance classification system of Liden (20) and Jerger (21). Tympanograms were classified into five categories according to shape and middle ear pressure (Table 2).

In case of a double-peaked tympanogram, TPP was measured at the dip of the tympanogram. Similar to the study of Calandruccio et al. (15), middle ear admittance was calculated as follows:

$$Y_{ME} = \sqrt{(B_{tip} - B_{tail})^2 + (G_{tip} - G_{tail})^2}$$

with Y_{ME} = middle ear admittance; B_{tip}/G_{tip} = susceptance (B)/conductance (G) at the tip of the tympanogram (dip or peak); and B_{tail}/G_{tail} = susceptance (B)/conductance (G) at +200 daPa.

Vanhuyse Model

A second classification system was based on the Vanhuyse model of tympanometric shapes (14). In this model, two separate tympanograms for susceptance (B) and conductance (G) are presented instead of a single admittance tympanogram. Four normal types are defined: 1B1G, 1B3G, 3B3G, and 5B3G.

Statistical Analyses

Statistical analyses were performed with SPSS software. To check the reliability of tympanometry with regard to both probe-tone frequencies, intrasubject evaluations were applied by means of McNemars χ^2 tests. One-way analysis of variance statistics were performed for significance testing of the differences among age groups. Within each group, the effect of probe-tone frequency on the tympanometric parameters was evaluated with paired-sample t tests. Bonferroni correction was applied to correct for the problem of repeated testing.

RESULTS

In the first analysis, test results were evaluated for all age groups. However, results were similar in the NICU

TABLE 2. Tympanogram types according to the visual admittance classification system based on Liden (20) and Jerger (21) for both 226- and 1,000-Hz probe-tone frequencies

226 Hz	1,000 Hz	Description
A	1	Tympanogram with a single peak and TPP around 0 daPa
B	2	Flat sloping tympanogram (no distinct peak, $Y_{ME} < 0.2$ mmho and/or $TW \geq 200$ daPa)
C	3	Tympanogram with a single peak and TPP < -150 daPa
D	4	Double-peaked tympanogram with TPP around 0 daPa
Du	4u	Double-peaked tympanogram with TPP < -150 daPa (under pressure)

FIG. 1. The distribution of 226-Hz tympanogram types according to the visual admittance classification system for 4 age groups.

group and the 0- to 3-month-old group, as well as in the 3- to 6-month-old group and the 6- to 9-month-old group. Therefore, data were clustered to create four different age groups, making test results clearer and statistical analyses more powerful (Table 1).

Distribution of Tympanogram Types

Figures 1 and 2 depict the distribution of tympanogram types according to the visual admittance classification system with a 226- and a 1,000-Hz probe tone, respectively. For 226-Hz tympanometry, the proportion of single-peaked tympanograms increased with age, with type A representing 100% of the tympanograms in adults. Conversely, the proportion of double-peaked tympanograms decreased with age to 0% from the age of 9 months. Remarkably, there was a rather high prevalence of flat sloping tympanograms in all child groups. For 1,000-Hz tympanometry, a reversed effect was found: the proportion of single-peaked tympanograms decreased with age, whereas the proportion of double-peaked tympanograms increased with age. Moreover, the use of a 1,000-Hz probe-tone frequency lowered the prevalence of flat sloping tympanograms in the child groups.

Figure 3 shows the distribution of 1,000-Hz tympanograms according to the Vanhuyse model. The proportion of 1B1G tympanograms decreased with age. In the younger than 3-month-old age group, Types 1B1G and 3B1G were mainly found (together, 91%). From the age of 9 months, the distribution of the different tympanograms became more complex. Type 3B3G was very

FIG. 2. The distribution of 1,000-Hz tympanogram types according to the visual admittance classification system for 4 age groups.

FIG. 3. The distribution of 1,000-Hz tympanogram types according to the Vanhuyse model of tympanometric shapes (14) for 4 age groups.

rare in children, but was found in 30% of the cases in adults. Finally, in two cases, an abnormally shaped tympanogram was found, namely, a 5B1G tympanogram. All of the 1B1G tympanograms corresponded to a single-peaked tympanogram in Figure 2, whereas the 3B3G and 5B3G tympanograms all resulted in double-peaked tympanograms. The proportion of 3B1G tympanograms that corresponded with a single-peaked tympanogram decreased from 100% in the younger than 3-month-old age group to 56% in adults.

Type Change With Test Frequency

The distributions of the tympanogram types according to the visual admittance classification system were converted into a dichotomous distribution with a pass-fail criterion. Type A and Type 1 tympanograms were considered as pass results, whereas all other types were considered as fail results. Type D and Type 4 tympanograms were considered as fail results because double-peaked tympanograms can result from both normal and pathologic ears (21). Results of the dichotomous distribution are shown in Table 3 for every test group separately.

In children younger than 3 months, 1,000-Hz tympanometry performed significantly better in evaluating the middle ear system (91% pass results using 1,000 Hz versus 35% using 226 Hz; McNemar, $p < 0.001$). Moreover, the use of 226-Hz tympanometry resulted in 58% false fail results. On the other hand, in children older than 9 months and adults, 226-Hz tympanometry was more reliable (75 to 100% pass results using 226 Hz, respectively; McNemar, p always < 0.001), whereas 1,000-Hz tympanometry gave up to 63% erroneous fail results. Finally, in children between 3 and 9 months, there was no significant difference in reliability between 226- and 1,000-Hz tympanometry (70% pass results using 1,000 Hz versus 57% using 226 Hz; McNemar, $p = 0.424$). This implies that both probe-tone frequencies should be considered to evaluate the middle ear system. In case of a fail result using one probe-tone frequency, a second test should be performed using the other probe-tone frequency. A 1,000- to 226-Hz tympanometry sequence was preferred over a 226- to 1,000-Hz tympanometry sequence because this sequence reduced the total number of tests (13 versus 9 ears, in which a

second test would have to be performed if starting with 226 or 1,000 Hz, respectively).

Tympanometric Parameters

Normative Data

Table 4 shows an overview of median, 5th and 95th percentile for Y_{+200} , Y_{ME} , TPP, and TW. Based on the findings above, for children younger than the age of 3 months, only 1,000-Hz normative data are shown. For children older than 9 months and adults, only 226-Hz normative data are presented. Finally, for children between 3 and 9 months, both 226- and 1,000-Hz normative data are shown. No significant differences existed between the 3- to 9-month-old group and the 9- to 32-month-old group with regard to all different parameters with a 226-Hz probe tone (analysis of variance, p always > 0.05).

Equivalent Ear Canal Volume

In 226-Hz tympanometry, ECV is directly derived from Y_{+200} . However, when a different probe-tone frequency is applied, an equivalent baseline volume (EBV) is calculated in the following way:

$$EBV = (226/f_p) * Y_{+200}$$

with f_p = the applied probe-tone frequency.

This is equal to ECV in a purely compliant system (23).

An effect of probe-tone frequency was evaluated in all age groups separately. In the younger-than-3-month-old age group, there was a significant difference between ECV and EBV (t test, $p < 0.001$). On the contrary, there were no significant differences between ECV and EBV in all the other groups (t test, p always > 0.05). These results imply that the middle ear changes into a compliant system from the age of 3 months.

Failed TEOAEs

In 33 additional ears, 12 ears from children between 3 and 9 months and 21 ears from children older than 9 months, TEOAE results showed SNRs of 0 dB or less in all frequency bands. Tympanometric data were evaluated in more detail. Overall, results revealed a very high prevalence of fail results according to the dichotomous distribution, with 92% fail results for 226- and 1,000-Hz

TABLE 3. The dichotomous distribution of tympanogram types for four age groups and both probe-tone frequencies

		1,000 Hz							
		<3 mo		3-9 mo		9-32 mo		Adults	
		Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail
226 Hz	Pass	14	1	12	5	9	12	11	19
	Fail	25	3	9	4	0	7	0	0

Fail indicates Types B, C, D, Du/Types 2, 3, 4, 4u; Pass, Type A/Type 1.

TABLE 4. Normative data for tympanometric parameters Y_{+200} , Y_{ME} , TPP, and TW

Probe tone	Age group		Y_{ME} (mmho)	Y_{+200} (mmho)	TPP (daPa)	TW (daPa)
1,000 Hz	<3 mo	Pc 5	0.34	0.58	-96	89
		Median	0.95	1.11	7	133
		Pc 95	2.66	1.82	86	184
	3-9 mo	Pc 5	0.78	1.40	-126	102
		Median	1.88	1.97	-52	132
226 Hz	3-9 mo	Pc 95	3.55	3.07	13	174
		Pc 5	0.22	0.35	-91	94
		Median	0.32	0.56	-37	142
		Pc 95	0.49	0.74	49	192
		Pc 5	0.22	0.38	-237	68
	9-32 mo	Median	0.33	0.54	-46	123
		Pc 95	0.82	0.74	50	173
		Pc 5	0.39	0.60	-9	43
	Adults	Median	0.77	0.82	13	69
		Pc 95	2.22	1.02	25	111

Data of flat sloping tympanograms (Type B/Type 2) were excluded from this overview. Data of tympanogram Types C, Du/Types 3, 4u were not included for the calculation of TPP.

tympanometry in the 3- to 9-month-old group (8% pass results, Type A using 226 Hz, Type 1 using 1,000 Hz [$n = 1$]) and 90% fail results for 226-Hz tympanometry in the 9- to 32-month-old group ($n = 19$). These data may indicate a good sensitivity of tympanometry for detecting middle ear problems in these age groups.

DISCUSSION

Clinical Guidelines

Classification

Several methods for classifying tympanometric patterns have been suggested before, but the preference for a specific classification system remained controversial. Therefore, a first aim of this study was to evaluate 1,000-Hz tympanometry with regard to two classification methods: a visual admittance classification system and the Vanhuyse model.

The Vanhuyse model was shown to be suitable for identifying 1,000-Hz tympanograms in children. In the current study, 99% of the child tympanograms can be classified. Moreover, the distribution of tympanogram types according to the Vanhuyse model showed similar results compared with a recent study of Calandruccio et al. (15). In both studies, an equal distribution of 1B1G and 3B1G types in the youngest children changed into a distribution with predominantly 3B1G types in adults. However, using the Vanhuyse model, the interpretation of tympanometric patterns is more complicated compared with the simple visual admittance classification method. Moreover, by merely looking at susceptance (B) and conductance (G) patterns, middle ear pressure and the extent of tympanic membrane movement are not taken into account. These constraints make the Vanhuyse model less applicable to clinical hearing assessment.

Conversely, the use of a visual admittance classification system can be recommended based on our study. With this classification method, the prevalence of 1,000-Hz Type 1 tympanograms was 91% in the younger-than-3-month-old age group. This percentage corresponded well with the results of Kei et al. (18), showing a prevalence of 92% single-peaked tympanograms in neonates. In a study of Margolis et al. (19), 91% of the tympanograms were considered as normal. However, a study of Baldwin (17) showed that, in children younger than the age of 21 weeks, the percentage of normal tympanograms was only 71%. The difference in prevalence may partially be due to the age range of the children included in the study of Baldwin (17), as opposed to the 0- to 3-month range in the current study, because the proportion of Type 1 tympanograms decreased with age (Fig. 3).

Age

Tympanometry has proven its importance in detecting effusion and other middle ear problems. However, clear age-dependent guidelines toward appropriate probe-tone frequency in children between birth and 2 years are currently not available. Although the use of a 226-Hz probe tone in children younger than 7 months is said to be invalid (3,4,8), few researchers have validated tympanometry within this age group. Baldwin (17) concluded that 226-Hz tympanometry was unreliable in children younger than 21 weeks, and that 1,000-Hz tympanometry should be applied. In the studies of Kei et al. (18) and Margolis et al. (19), 1,000-Hz tympanometry was validated in neonates. However, in none of these studies were age effects evaluated. In a study of Calandruccio et al. (15), multifrequency tympanometry was performed in children between 4 weeks and 2 years, yet no suggestions toward probe-tone frequency in relation to age were made.

The currently presented data provide age-related guidelines for tympanometry in clinical practice. In this study, 1,000 Hz was shown to be the most appropriate probe-tone frequency in children younger than 3 months. However, 1,000-Hz tympanometry remained clinically important until the age of 9 months. For clinical purposes, the following test protocol is suggested:

- 1) for children younger than 3 months, always perform 1,000-Hz tympanometry to evaluate middle ear functioning (current study, 91% pass results; 9% fail results: Types 2 [$n = 3$] and 4 [$n = 1$]);
- 2) for children between 3 and 9 months, perform a two-stage evaluation of the middle ear: a) 1,000-Hz tympanometry and b) 226-Hz tympanometry in case of fail result in a (current study, 87% pass results after a two-stage evaluation; 13% ($n = 4$) fail results: Types 2-4 using 1,000 Hz, all type B using 226 Hz); and
- 3) from 9 months on, always perform 226-Hz tympanometry (current study, 75-100% pass results; in children 9-32 mo, 25% fail results: Types B [$n = 4$] and C [$n = 3$]).

Normative Data

Overall, the currently presented normative data were similar to results reported in association with previous studies.

For the younger-than-3-month-old group, the 90% range for Y_{ME} data (0.34–2.66 mmho) was slightly higher, but comparable to the 90% range of Y_{ME} data from Calandruccio et al. (15) for a 4- to 10-week group (0.20–2.26 mmho). Moreover, median Y_{+200} results were comparable [0.95 mmho in our study versus 1.07 mmho in Calandruccio et al. (15)]. Furthermore, the 90% range for our TPP data fell within the 90% range for the TPP data of full-term children in the study of Margolis et al. (19). However, comparing our Y_{ME} results with results of Kei et al. (18) and Margolis et al. (19) was disputable because Y_{ME} was not calculated in those studies. Instead, static admittance values were presented to indicate the peak-to-tail difference in admittance value.

For the 3- to 9- and 9- to 32-month-old groups, it was more difficult to compare our Y_{ME} data with Y_{ME} data of Calandruccio et al. (15) because age groups were not the same. However, a gross comparison can be made by combining their 11- to 19- and 20- to 26-week-old groups on the one hand and their 6- to 12-month-old and 2-year-old groups on the other hand. This revealed comparable 90% ranges for Y_{ME} and Y_{+200} data for both age groups.

According to Holte et al. (7), there is a growing contribution of compliant elements in the first 4 months of life. The results of the present study were in accordance with this result because ECV was equal to the calculated EBV from the age of 3 months, indicating that the middle ear system is functioning as a compliant system.

CONCLUSION

The results from the present study provide clear guidelines for the use of tympanometry in clinical practice. Until the age of 3 months, 1,000 Hz was shown to be the probe-tone frequency of choice. Currently, 1,000-Hz tympanometry has been successfully implemented in the neonatal hearing assessment program of the ENT Department of UZ Leuven. This implementation has provided the possibility to differentiate between conductive and sensorineural hearing loss at a very young age and has led to a more complete hearing diagnosis.

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