An Extension of the Jerger Classification of Tympanograms for Ventilation Tube Patency—Specification and Evaluation of Equivalent Ear-Canal Volume Criteria

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Objective: **To determine ventilation tube (VT) patency, or presence of an eardrum perforation, where otoscopy is not available or corroboration is required, tympanometry may be used, with a firm acoustical rationale. However, published literature shows little evidence that tympanometric criteria for patency have been optimized or are in routine clinical use. A randomized trial of VTs in otitis media with effusion offered large case numbers, assessed by uniform protocol, to define and evaluate a tympanometric patency criterion.**

Design: **Children had been randomized to one of three interventions (VT insertion with or without adjuvant adenoidectomy and nonsurgical observation). The study examines 165 left and 171 right ears with functioning VTs and 103 left and 102 right noninserted ears, in children aged 3¾ to 7¼ yrs at first postintervention visit. Experienced otolaryngologists judged VT patency otoscopically. Measured equivalent ear-canal volume (Veq) was compared across the VT-inserted and the not-inserted groups, and also within the VT-inserted group between the pre- and postintervention visits. With otoscopy as reference, patency coding errors in both VT-inserted and not-inserted groups were analyzed as a function of Veq. Three methods of determining optimum cutoff were considered: equal error (cross-over point of the errors in each group), equated "cost" of error (maximum summed sensitivity and specificity), and minimum combined error (determined from the minimum of a polynomial fitted to the mean of the errors in each group). Cutoffs were evaluated in terms of classification accuracy against otoscopy after intervention.**

Results: **The between-group comparison gave cutoffs by the three methods at Veq ≥0.95 mL, Veq ≥1.10 mL, and Veq ≥1.33 mL, respectively, pooled to 1.13 mL. The same 1.13 mL was also found for the within-group comparison. The corresponding cutoffs for the pre- and postintervention difference in Veq occurred at 0.23, 0.44, and 0.39 mL, respectively, with a mean of 0.35 mL. Within the range studied, age did not influence Veq, nor the optimum Veq cutoff, but boys had significantly larger Veqs (by 0.09 mL) than girls. Raw Veq, pre- and postintervention Veq difference or a combination of these definitions differed little in accuracy of predicting otoscopic status.**

Conclusion: **In 3¾ to 7¼ years olds, the Veq criteria for VT patency, based on rigorous and transparent derivations, offer a supplementary information source for clinical practice, as well as a sole objective marker in research. We recommend for general use the pooled mean cutoff at Veq ≥1.13 mL, slightly higher than the 1.00 mL in the literature. The pooled pre- and postintervention difference Veq criterion was slightly lower than the 0.4 mL of Shanks et al. However, the extra effort in its use, alone or in combination with raw Veq, was not justified. Given the wide (flat-bottomed) error functions, users have the option of declaring slightly lower or higher cutoffs, reflecting differing "costs" on the two types of errors, e.g. penalizing false "patent" decisions more heavily.**

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INTRODUCTION

The Issue and Potential Value of a Solution

In assessment of otitis media (OM), and particularly of OM with effusion (OME), the middle ear's mobility and pressure are fundamental, as is any eardrum perforation. Jerger (1970) offered the first widely accepted classification system for traces from tympanometry, a then new technique but now long-established. There have been subsequent modifications e.g., Zielhuis et al. (1990) giving the "Modified Jerger" of Table 1, used in this article. Most contemporary clinical studies (De Melker, 1992; MRC Multicentre Otitis Media Study Group, 2001a; Moody, et al., 1998; Rovers, et al., 2001; Sakaguchi, et al., 1994) use this in preference to other modifications suggested (e.g. Anteunis, et al., 2000; Fiellau-Nikolajsen, et al., 1980; Maw and Herod, 1986).

Ventilation tubes (VTs, also known as tympanostomy tubes, pressure equalization tubes-PETs-or grommets) are the main treatment for OME. Patency of the tube is relevant to its efficacy, because a blocked tube approximates no tube at all from the therapeutic point of view. For example, blockage

MRC ESS in Childrens' Middle Ear Diseases, Cambridge, UK. (see Appendix).

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TABLE 1. Modified Jerger Classification of tympanograms as described by Zielhuis et al. (1990), defined on children aged 1–7 yrs

For use on ears with no perforation or with ventilation tubes (VTs) inserted

Type A: MEC ≥0.2 mL and MEP >−100 da Pa
Middle ear admittance at or above 0.2 mL and middle ear pressure above −100 da Pa

Type C1: MEC ≥0.2 mL and −200 < MEP ≤ −100 da Pa
Middle ear admittance at or above 0.2 mL and middle ear pressure higher than −200 da Pa but no higher than −100 da Pa

Type C2: MEC ≥0.2 mL and −400 < MEP ≤ −200 da Pa
Middle ear admittance at or above 0.2 mL and middle ear pressure higher than −400 da Pa but no higher than −200 da Pa

Type B: MEC <0.2 mL or MEP ≤−400 da Pa
Middle ear admittance below 0.2 ml or middle ear pressure at or below (i.e. more negative than) −400 da Pa

MEP, middle ear pressure; MEC, middle ear compliance (or peak-compensated static acoustic admittance).

may permit reaccumulation of fluid and conditions more favorable to continued survival of bacteria in the middle ear. Tympanometry permits a physical test of patency: if a seal is obtainable, a high value for the volume (Veq) will be recorded for a patent tube. (Hereafter we use the term "volume" to express the acoustically inferred volume of the ear canal and, where a patent grommet or perforation exists, some contribution also from the volume of the middle ear space.) Healthcare after VT placement usually includes a check for any discharge, which might indicate infection and some form of patency check, usually by otoscopy and pneumatic otoscopy, but not necessarily full tympanometry. Where the otoscopist is skilled and/or carries the clinical responsibility, efficiency considerations might lead the clinical pathway to by-pass tympanometry, particularly if the tube shows no evident signs of blockage. However, even if not all circumstances call for tympanometry, having a specified optimum procedure is useful. For patency or perforation there are two general and two particular reasons for having a tympanometric criterion to supplement otoscopy. First, in cases of doubt, clinicians may need to pool information from more than one procedure (e.g., otoscopy and tympanometry), but if each has a dichotomous decision criterion, this still needs to be well defined. Second, in research, objective measures may be required, to counteract biases such as the incentivized belief that therapy must be successful. Third, the clinical pathway may not include a skilled otoscopist (e.g., in affordable healthcare systems for much of the world's population, or if geography dictates that postsurgical follow-up should occur in primary care, or if the context is screening). Fourth, in individual cases the eardrum may not be visible, e.g. where debris sits in the ear canal or where the tube is angled away from the examiner's view. Thus an addition to the Jerger coding system, an evidence-based cutoff for defining a patent VT or perforation, should be of value.

Simple classification of tympanograms from middle ear pressure and maximum admittance can be misleading about patency of VTs or perforations. (Hereafter we use "patency" to include the presence of a natural perforation.) A flat tympanometric trace can occur in any of four states: (a) a near-normal tympanic membrane accompanied by fluid presence (the basic interpretation of a Type B tympanogram, but not precluding a recently extruded tube), (b) the same, with a tube in place but blocked, (c) a functioning tube, or (d) a perforation. Veq, when measurable, provides at least rough confirmation of patency, because the effective volume becomes that residing between the probe and the eardrum plus a proportion (determined by the aperture) of the middle ear cavity (between the eardrum and the extremities of the mastoid airspace and Eustachian tube). A high Veq combined with a flat trace should therefore be interpreted as a large volume of air rather than TM immobility, and so not be erroneously coded as a type B tympanogram. However, the ability to record a Veq measure relies on obtaining a retrotympanic seal. Many instruments will typically not permit a reading in patent eardrums, as the pressure response is similar to that with no seal. The use of "no-seals" in patency decisions is discussed later. We therefore addressed the reduction of ambiguity of interpretation of a flat tympanogram where a ventilation tube may be present and, if so, may be patent, in the large proportion of ears where a tympanometric seal permitted Veq recordings.

The foregoing complexities go some way to explaining the conflicts between messages from the available literature on normative values for Veq measures in children. Margolis and Heller (1987) reported a 90% range for Veq of 0.4 through 1.0 mL for 50 otologically normal children ranging from 2.8 through 5.8 yrs. Shanks et al. (1992) reported a 90% range of 0.3 to 0.9 mL for 334 children between the ages of 8 weeks and 6.7 yrs awaiting grommet insertion. Haapaniemi (1996) gave a 90% range of 0.4 to 0.9 mL for a group of 312 otologically normal children aged 6 to 9 yrs. De Chicchis et al. (2000) gave a mean ± SD of 0.71 ± 0.26 mL for a group of 4- to 5-yr olds, representing the upper of five age-groups formed from 221 children with normal middle ear function. The upper end of the 90% range (i.e., 95th percentile) for this age group would therefore be 1.23 mL. The lowest of the five age-groups in the De Chicchis study (6 to 12 mo) gave 0.49 mL (±0.14 mL), hence a much lower value at 0.77 mL for the upper limit. Veq for this and the 1 to 2 yr age

groups was significantly lower than for the upper age group, but from age 2 through 5 yrs, Veq did not differ significantly. Based on these conflicting pointers, an audiologist might choose a cutoff value between 0.9 and 1.2 mL. A considerable margin of uncertainty remains, and the 5% of cases beyond the 95th percentile in unoperated children are still likely to be misclassified as having a perforation, (undesirably high, as none were recorded in the Haapaniemi study.) The principles of statistical decision theory (and its application to signal detection), deal with the inevitably incorrect categorizations on either side of any cutoff, and aid the specification of an optimum cutoff by considering the "cost" or risk of each type of error, as well as their probabilities. This risk consideration applies when setting a general cutoff value and when applying it to individuals, for example where other information may also be present. A relatively high cutoff yields more certainty that patency is not over-assigned, but less certainty that true patency will be detected. This raises two practical questions: (1) With flat traces, how wide is the zone of uncertainty where further information would be required to distinguish between (a) the presence of fluid behind a large external ear canal and (b) a patent tube? (2) Given that Veq measures can be affected by age-determined anatomical volumes (both those in front of and behind the eardrum), would information on preinsertion Veq narrow this zone of uncertainty? The consideration of costs of error-types can be problematic, because of absence of data or conflicting value perspectives, so narrowing of the uncertainty remains a core aim in reducing the need for rigorous cost information.

We have found only two published papers directly addressing tympanometric patency information. Shanks et al. (1992) examined Veqs in children both before and after insertion of ventilation tubes. To explore relative and absolute elements in a decision about patency, they compared a cutoff in volume (Veq $\geq$1.0 mL) with a cutoff in pre- and postsurgery difference in Veq (difference $\geq$0.4 mL). They did not specify exactly how they arrived at their recommended cutoff of 1.0 mL. Only for children below 4 yrs, which range spans an appreciable range of head sizes, was there any advantage in taking preintervention Veq into account. Wilber and Feldman (1976) ascribed Veq values above 1.5 through 2.0 mL to patent tubes. For ears with blocked VTs in the contralateral ear, they offered a between-ear difference in Veq of 0.5 mL as a criterion of patency, but they gave few details of population and methods, and their approach only applies to the generally small proportion of the caseload with one ear of clear nonfunctioning status. Surprisingly, in the context of tube patency, we have been able to trace only one paper citing either of these former contributions (Brookhouser, 1998). This does not necessarily imply that a useful application of tympanometry has been lost from practice, which surveys of practice would be required to clarify. There are a number of possible reasons why the problem has not been systematically addressed or regularly reported, including interprofessional issues, an impression that the problem had been solved adequately for practice, or lack of appreciation of the need to demonstrate optimal derivation on a large sample.

Use of Relevant Data Base to Improve Specification of Criterion

Our clinical trial in OME required a well-documented objective criterion of tube patency and the large sample also permitted the reliable derivation of a cutoff in a transparent way. It also offered the opportunity to estimate cutoffs independently on randomized (therefore statistically indistinguishable) groups of children both with and without VTs inserted, and hence a quantitative within-subjects replication (pre/post) of results from a between-subjects contrast. We could also address certain issues of generalizability and correspondence with otoscopic judgment of patency, which Shanks et al. (1992) did not.

Materials and Methods

Participants

The UK Trial of Alternative Regimens for Glue Ear Treatment (TARGET) is a randomized controlled trial (RCT) of effectiveness of the placement of ventilation tubes, with/without adjuvant adenoidectomy, relative to nonplacement or delayed placement (MRC Multicentre Otitis Media Study Group, 1999, 2000, 2001). Eleven ENT departments in the United Kingdom provided randomized data for present analyses (see Appendix for list of centers and contributorship). For the TARGET trial, children aged 3¼ through 6¾ yrs on a first visit with no previous history of ear surgery qualified for randomization if, on each of two qualifying visits separated by 3 mo, they had tympanogram combinations of B+B or B+C2 (Table 1) and a better-ear hearing level, averaged across 0.5, 1, 2, and 4 kHz, of $\geq$20 dB. The UK healthcare system has a high degree of gatekeeping by general medical practitioners and community pediatricians, so ENT caseloads in OME are older and more severely affected than the typical caseloads seen in more interventive healthcare systems (cf. Paradise, et al., 2001; Sabo, et al., 2003). A total of 376 children meeting these age, hearing and

tympanogram criteria, and available for follow-up, were randomized at their second visit to one of three interventions: further watchful waiting control, ventilation tube insertion alone, or VT with adjuvant adenoidectomy. A further 56, with better-ear hearing >40 dB HL, were nonrandomly assigned to receive VTs (30 also with adenoidectomy) on the otolaryngologist's judgment and followed up; these 432 (376 + 56) cases constitute the reference sample, a well-characterized set for deriving a categorization formula.

At each visit, children received audiometry, tympanometry, and otoscopy, as well as a variety of questionnaires. Full tympanometric and otoscopic data were available from 268 left ears and 273 right ears of those children who attended the first postrandomization visit, 3 mo after randomization. (Analyses were performed on individual ears, rather than summing left and right ears, to avoid erroneously inflating the degrees of freedom by combining nonindependent data.) Separation of ears gave useful general replication via 165 and 103 functioning and noninserted left ears, respectively, and 171 and 102 functioning and noninserted right ears, respectively. Those not included were 42 left and 43 right ears that were either blocked, infected, extruded or not seen, and 56 left and 50 right ears with missing tympanometry data (nearly all of which were accompanied with a statement from the audiologist indicating patent grommet or "no seal"). These cases underline the clinical importance of the "no-seal" issue, but cannot assist the present optimization of Veq cutoff. The 165 functioning and 103 noninserted left ears and 171 functioning and 102 noninserted right ears correspond to 366 cases used from the core data. The remaining 66 cases of the 432 are 52 who did not attend the first +3 mo follow-up and 14 for whom no tympanometry or otoscopy form was completed. The cases available for pre- and postanalysis were obviously only those two-thirds of the 432 children who were allocated to one of the two treatment arms and who actually received VTs shortly afterwards.

The core data were analyzed at two time-points: the second qualifying visit where randomization took place (termed the "preintervention" timepoint for this study) and the first postintervention visit 3 mo later. Two types of comparison were made:

1. Between-groups comparison of Veq at the first postintervention visit, comparing ears known not to have received a VT with inserted ears judged functioning by otoscopy.
2. Within-groups comparison of Veq in ears that received VTs, comparing Veq at the postintervention visit with Veq in the same ears preintervention.

All study children had met the crucial TARGET trial inclusion criteria preintervention in which the chief relevant restriction was average of ≥20 dB HL in the better ear (0.5 through 4.0 kHz), and 44% of nonsurgically managed children continued to meet these criteria at the first postintervention visit.

Calibration

Tests were performed in sound-treated rooms conforming to BS EN ISO 8253–1 (1998). In addition to daily calibration checks on tympanometers and audiometers, to meet the trial's requirements for not losing data, centers performed full calibration at the start, annually and at the end of the study, to standards BS EN ISO 389-1 (2000), BS EN ISO 389-3 (1999), and BS EN 61027 (1993).

Audiometry Protocol

Thresholds for warble tones (±5 Hz of the center frequency) presented at 0.5, 1, 2, and 4 kHz through headphones were estimated using method A of the British Society of Audiology's Recommended Procedure (Anonymous, 1981). Play audiometry techniques were used for the younger children (less than about 5 yrs). The raw thresholds were stored on a Microsoft ACCESS data base and the average hearing level (HL) of 0.5, 1, 2, and 4 kHz for each ear was calculated.

Tympanometry Protocol

On each of the 11 sites, tympanometry was performed with one of three types of diagnostic instrument, a Kamplex KA9, a GSI 33, or a GSI 1723 (this last used in just one center). For children who had received ventilation tubes, the use of tympanometry was first authorized as safe by the otolaryngologist. The tympanogram swept from +200 daPa to −400 daPa at a sweep rate of 50 daPa/s, using a probe tone of 226 Hz. For children not having received VTs and showing flat traces, the tympanogram was repeated in the pressure range of +200 through −600 daPa. Middle ear pressure, peak-compensated static acoustic admittance, volume (Veq) and tympanogram gradient were recorded. Veq was taken as the admittance at +200 daPa. The original traces were additionally supplied from all but one of the 11 collaborating hospitals, so further checks enabled any inconsistencies between printed values and trace shape to be eliminated (e.g., a spike occurring from patient movement). Where the audiologist was not able to obtain a seal, (s)he was required by the protocol to note this as distinct from "not performed

for some other reason." The four parameters were stored in the data base and each tympanogram was initially classified according to the Modified Jerger classification (Table 1).

Flat traces were initially coded as Type B, regardless of Veq. Following the coding exercise described in Definitions 1 to 3 (described later), these were subsequently recoded to:

1. (True) Type B-representing a fluid-filled ear from a tympanogram with an intact tympanic membrane (either healed or blocked postinsertion, or one which had not been inserted) and,
2. "Type F"- representing the presence of a functioning tube (or a perforation).

A "no seal" response occurred in approximately one in six VT-inserted ears, as opposed to 1 in 60 ears that were not inserted. This strong relative risk (10.0), argues for routine assignment of "no-seal" as patent in ears known to have received VTs. ("No seal" is not the best term for the raw reading from the instrument, because in the majority of instances here it is not literally true; further interpretation is required.) Such ears were therefore also coded as examples of Type F ("functioning") but, having no tympanometric data, can of course play no part in the present optimization of Veq cutoff. In the evaluation of classification definitions (results section), we combine "no seals" with ears coded as Type F, via the classification rules developed under Definitions 1 to 3 (described later); together these make up the full set of ears with functioning VTs.

Otoscopy Criterion

Otolaryngologists coded various properties of the tympanic membrane from a static view with an otoscope or otomicroscope on a data recording form (MRC Multicentre Otitis Media Study Group, 2001b) previously developed by consensus among the participating otolaryngologists. The tube status (where inserted/seen) was coded as "functioning," "extruded," "blocked," or "infected." For certain analyses, the latter three labels are combined to form a dichotomy "functioning" versus "nonfunctioning". The otoscopy score is used here as a calibration metric for where a cutoff should occur, rather than general validation (see Discussion). It is perfectly consistent to use an imperfect measure (here otoscopy, which is partly subjective) to confirm the relevance and fix the appropriate mean cutoff values in a further measure (here tympanometry). This permits translation of the direct interpretive insight in the otoscopic domain over to the objective domain of tympanometry.

Results

Distributions of Volume in Nonoperated Ears

For the randomized nonsurgical control group, the means (and SDs) for the Veqs at the 3-mo follow-up visit were 0.63 mL (SD = 0.20 mL) and 0.64 mL (SD = 0.19 mL) for 103 left and 102 right ears, respectively. For the VT-inserted ears, the mean preintervention Veqs from the point of randomization were 0.63 mL (SD 0.27 mL) and 0.65 mL (SD 0.26 mL) for the 194 left and 197 right ears, respectively. There was no significant difference between the ears for either the preintervention data or the postintervention control data ($p > 0.1$ for each comparison). The two comparisons provide highly similar results, and compare well with Shanks et al.'s (1992) value of 0.6 mL from a similar age range. The 90% ranges (0.3 to 1.0 mL and 0.2 to 1.1 mL for the nonsurgical control and preintervention surgical groups' data, respectively) are similar to those reported in the literature for similar age ranges (De Chicchis, et al., 2000; Haapaniemi, 1996; Margolis and Heller, 1987; Shanks, et al., 1992—details in introduction).

Three Definitions of Patency Tested on the Data

The following three types of definition are compared for determining patent VT tubes by tympanometry. All would be clinically feasible, but the higher complexity of the third would have to be justified by higher precision and/or generality.

1. A cutoff for Veq, based on between-groups randomized comparison, above which an ear would be categorized as having a patent VT (type F).
2. A definition where the preintervention Veq (where available) is used to calculate a pre- and postsurgery difference, beyond which an ear would be categorized as having a patent VT.
3. A two-step definition, with the first step based on (a) and the second on (b), creating first a marginal zone between an upper and lower cutoff for absolute Veq, within which a cutoff based on pre- and postsurgery difference in Veq is applied only in a percentage of cases.

Definition 1: The between-groups single cutoff for absolute veq • Figure 1 shows the frequency distributions for Veq in right* ears at the +3-mo follow-up: (a) where no ventilation tubes were in-

*Very similar results were obtained for the left ear and can be made available. A total of 161 left ears were coded as functioning by otoscopy and 103 were not inserted.

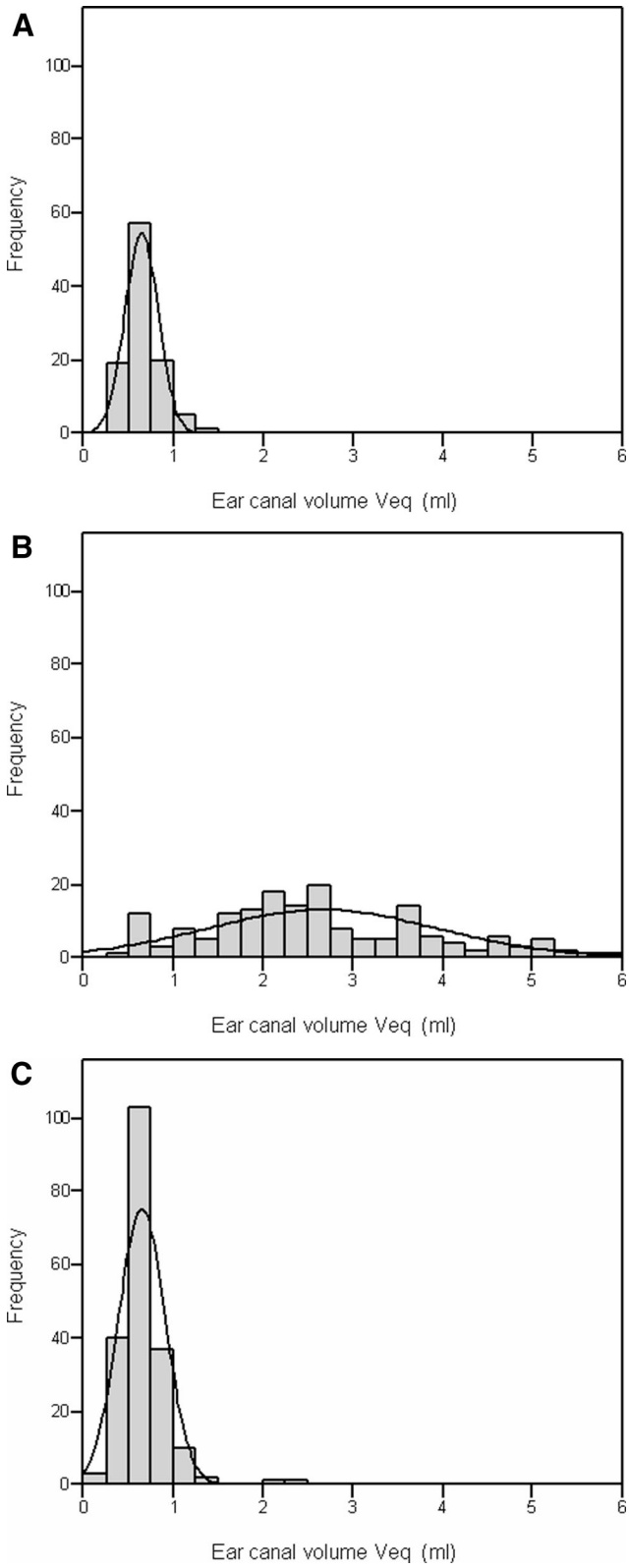

Fig. 1. Veq distributions for right ears at first follow-up visit (A and B) and at preintervention (C).

serted ($N = 102$), and (b) where tubes were inserted and furthermore were judged as "functioning" on otoscopy ($N = 171$). In the inserted ears (Fig. 1b), the distribution is wide; this is because the volume being measured is higher and has three chief components (i.e. the external ear canal and the middle ear space and the degree of coupling between these) hence three sources of individual variation. The relatively high bar for values between 0.5 and 0.75 mL may represent a few cases where only the external ear-canal volume is being measured (e.g. blocked cases that were incorrectly identified at otoscopy). For comparison with Shanks et al. (1992), the second histogram (b) was also compared with the histogram of preintervention Veqs (c) for children ($N = 197$) randomized to receive VTs. The overall N was higher for (c) than for (a), but the distributions' shapes and the degree of overlap with (b) differed little.

We calculated the number of errors incurred by various choices of cutoff ranging from 0.3 to 3.0 mL, in 0.05 mL intervals. Below or above this range, there is virtually no chance of coding errors, as Figure 1 confirms. Figure 2 shows a plot of the two types of errors in tympanometric coding (using SPSS, 2003, Version 12). Errors that code as "type B" ears with a VT described functioning by otoscopy (i.e. false-positives; dashed line) are plotted against errors that code as "type F" those ears known not to have been inserted (i.e. false-negatives; dot-dashed line). Noninserted ears are taken from postintervention control data in this figure, but the number of errors differed little when taken from preintervention data. The mean of the two types of error was also plotted (dotted line).

We examined three possible methods to finding the optimum cutoff for Veq from these errors:

1. By taking the point where the two types of error are equal (equal error, cross-over in Fig. 2).
2. By maximizing the sum of sensitivity and specificity in detecting a nonfunctioning VT (equal cost of error types).
3. By fitting low-order polynomials to the mean error through the range of Veq values, and taking the minimum value of the function (minimized overall error).

Table 2 gives the values for each method and an average Veq cutoff. The equal cost method (2), suggesting a cutoff of Veq $\geq$1.10 mL, corresponds to a sensitivity of 88.4% and specificity 97%. For method (3), cubic functions (solid lines) provided the best fit, having more flexibility in fitting asymmetry and sharp corners. Some asymmetry should be expected from the evidently unequal variance of the distributions in Figure 1, so it is not surprising that cubic

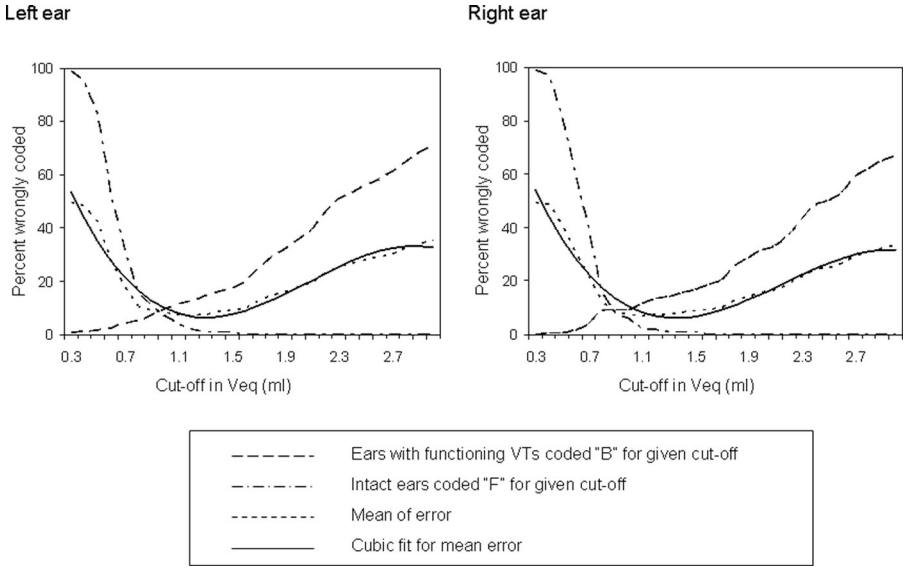

Fig. 2. Percentage error for 28 Veq cutoffs for left and right ears from assigning: (i) code "B" to ears judged "functioning" by otologist (dashed), (ii) code "F" to ears known not to have been inserted (dot-dashed). Mean error (dotted) and its cubic fit (solid) are also given. Approximately 165 left and 171 right ears were otoscopically labeled functioning and 103 left and 102 right ears were not inserted. Error types (i) and (ii) are most likely when Veq is set too high and too low respectively.

functions fitted the asymmetric nature of the data considerably better than did quadratics [cubic R^2 = 0.95 (L) and 0.96 (R), versus quadratic R^2 = 0.72 (L) and 0.77 (R)]. By solving the differentiated functions, minima were obtained at 1.30 mL (L) and 1.36 mL (R). Small asymmetries like this do appear in large data sets. There is no obvious anatomical or physiological reason why the two ears should have different volume characteristics, so the habits of probe placement by chiefly right-handed testers may be the origin of this very small discrepancy. For realistic clinical implementation, the result from this method is rounded to 1.33. Averaging this estimate with those from the other two methods, *Definition 1 gives a Veq cutoff of 1.13 mL, at or above which patency can be assumed.*

To demonstrate robustness and reliability a similar exercise was conducted making use of the available preintervention data to provide the noninserted cases. The results, as expected, were very similar, with pooled estimate Veq cutoff also of 1.13 mL across the three determinations. Thus we show identical pooled cutoffs for between- and within-subject comparisons when using the same definition.

Definition 2: A single cutoff for pre- postintervention difference • The difference between pre- and postintervention Veq provides the second possible patency indicator. This differencing offers the possibility of narrowing variability by reflecting pre- and postcorrelation across individuals, but the resulting comparison, as for the raw Veq in Definition 1, remains on a between-groups basis, i.e. between VT inserted and not-inserted ears. The pre- and postintervention difference in Veq was available for 116 left and 121 right functioning ears and 77 left and 77 right not-inserted ears having tympanometry and otoscopy at both pre and postintervention visits. Figure 3 shows the two types of error (coding as "type B" those ears with a VT described functioning by otoscopy, and coding as "type F" ears known not to have been inserted) plotted for 16 cutoffs, again as dashed and dot-dashed lines, respectively. The mean of the two types of errors is also shown (dotted line). Reduction of individual differences in absolute Veq values by differencing should lead to a

TABLE 2. Cutoff for Veq above which a perforation or patent VT can be validly attributed

Method	Left Ear			Right Ear			Mean L and R
	M	F	Mean	M	F	Mean	
Equal errors	1.00	1.00	1.00	1.00	0.80	0.90	0.95
Equal cost of error max (sensitivity + specificity)	1.20	1.00	1.10	1.10	1.10	1.10	1.10
Min error (cubic fit)	1.34	1.26	1.30	1.38	1.33	1.36	1.33
Pooled estimate of three methods	1.18	1.09	1.13	1.16	1.08	1.12	1.13

Cutoffs resulting from comparing Veq in ears with functioning VTs (165 left and 171 right) against not-inserted ears postintervention (103 left and 102 right) (see Fig. 2). For Veq cutoffs given in 0.05 mL increments, two types of error (of wrongly coding each otoscopic state—functioning and nonfunctioning) were found. Balancing the two types of error was achieved by three methods of determining an optimum Veq (see Results—Definition 1). The equal-errors approach codes more nonfunctioning ears as having a functioning VT, compared with the other approaches. Conversely minimum error (cubic fit) is more conservative, coding fewer nonfunctioning ears as functioning compared with the other approaches. The cutoff can be selected according to acceptability of the resulting balance of errors of the two types, or an average of the three methods can be used.

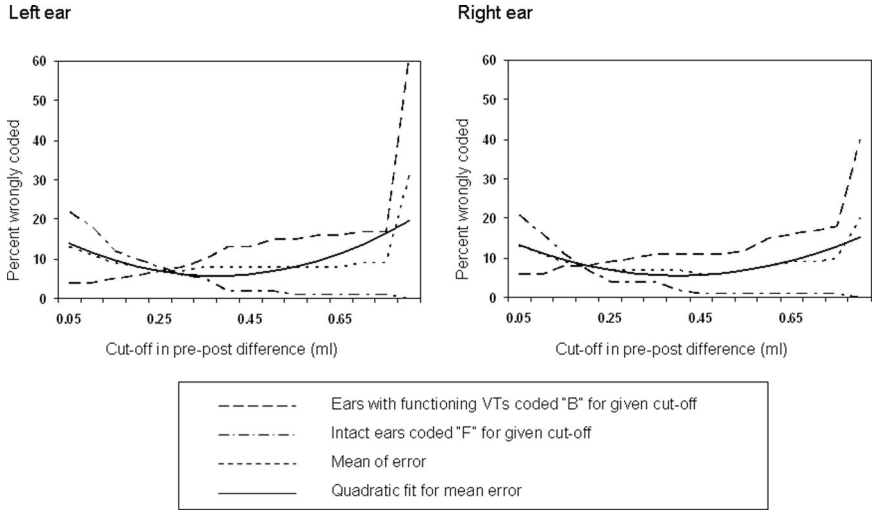

Fig. 3. Percentage error for 16 cutoffs in pre- and postintervention difference in Veq for left and right ears from assigning (i) code "B" to ears judged "functioning" by otologist (dashed), (ii) code "F" to ears known not to have been inserted (dot-dashed). Mean error (dotted) and its cubic fit (solid) are also given. Approximately 116 left and 121 right ears were otoscopically labeled functioning and 77 left and 77 right ears were not inserted. Error types (i) and (ii) are most likely when Veq is set too high and too low respectively.

narrower and less flat-bottomed distribution, and this is indeed seen. As a consequence, a quadratic function gives a preferable fit (i.e. the linear and quadratic terms had highly significant coefficients). All the coefficients became degraded in the cubic fit, an issue not met in the absolute approach of definition 1. This evident overfitting when spending additional degrees of freedom made the R^2 values a poor guide to the best model [Cubic: $R^2 = 0.54$ (L) and 0.76 (R); Quadratic: $R^2 = 0.46$ (L) and 0.74 (R)]. The quadratic fits (solid line) give minima of 0.376 and 0.404 mL for the left and right ears, respectively, an average of 0.390 mL. Pooling these cutoffs with those found by equal-error and equal-cost methods (Table 3) gives a pooled estimate for best cutoff in the pre- and postintervention difference of 0.351 mL.

Definition 2 implemented on our 2-group data would therefore assign patent tube status (type F tympanograms) to ears with pre- and postintervention Veq differences at or exceeding 0.35 mL, a little lower than the value of 0.4 mL recommended by Shanks et al. (1992).

Definition 3: A two-step (Zoom-In) definition • Efficiency in use of data can be promoted by defining a marginal or uncertainty zone for the result in a first-stage (simple) procedure, and concentrating further data or analysis there. Using Definition 1, such a zone was defined by a minimum of 0.9 mL and a maximum of 1.4 mL, i.e. the limits of the flat bottom of the error function (Fig. 2). In our data, this embraces 31 left and 24 right hard-to-classify ears. Here, additional use of the pre- and postintervention difference should introduce scaling for anatomical differences and so boost accuracy. Formally stated, Definition 3 involves a two-step rule for classifying a tympanogram:

Step 1

If $Veq \geq 1.4$ *Label as "Type F";*

If $Veq < 0.9$ *Label as "Type B"*

Step 2

If $0.9 \leq Veq < 1.4$, *examine the pre-post intervention difference,*

If pre-post difference ≥ 0.35, *Label as "Type F"*

If pre-post difference < 0.35, *Label as "Type B"*

TABLE 3. Cutoff for pre- and postintervention difference in Veq (mL) above which a perforation or patent VT can be validly attributed

Method	Left	Right	Mean
Equal errors	0.250	0.200	0.225
Equal cost of error max (sens + spec)	0.350	0.525	0.4375
Min error (Quadratic fit)	0.376	0.404	0.390
Pooled estimate of three methods			0.351

Cutoffs resulting from comparing pre- and postintervention difference in Veq for ears with functioning VTs (116 left and 121 right) against not-inserted ears (77 left and 77 right) (see Fig. 3). For cutoffs in pre- and postintervention difference given in 0.05 mL increments, again two types of error were found and balanced via three methods of determining an optimum cutoff (see Results—Definition 2). The equal-errors approach again codes more nonfunctioning ears as having a functioning VT, compared with the other approaches but the equal cost approach here makes least errors that code functioning ears as nonfunctioning. The cutoff adopted can be selected according to acceptability of the balance of errors of the two types or an average of the three methods can be used.

Evaluation of Alternative Definitions Against Otoscopy when Uncertainty is High

The uncertainty for real decisions about patency is highest in the period when tubes typically fall out. Therefore, our 6-mo postrandomization data (i.e. about 5 mo posttube insertion) offers a realistic and stringent validity test of the derivation. Using logistic regression, we compared the following six Veq cutoffs for defining patency as predictors of otoscopic status: (i) Veq ≥1.0 mL, advised by Shanks et al. (1992), which is also a central value of Veq cutoffs presented in the literature (see introduction); (ii)–

TABLE 4. Extra percent correct classification from six tympanogram criterion options (i.e. above that achieved by assigning all cases to nonfunctioning) in a logistic regression to predict otoscopy ("functioning" or "nonfunctioning*")

Ear	Percent non-functioning	From literature Veq ≥1.0	Definition 1 Veq ≥1.13	Definition 2 DIFF ≥0.35	Definition 3 2-step	Equal error Veq ≥0.95	Minimum error Veq ≥1.33
Left	58.9	+29.7	+31.1	+30.0	+29.7	+28.2	+30.7
Right	54.5	+36.4	+36.4	+36.0	+36.0	+35.7	+35.7

Data are from 6 mo postrandomization. Entry of the tympanometric independent variable is significant for all definitions ($p < 0.001$). Definition 1 represents the average of the three methods of determination of Veq cutoff but, as it is very close in magnitude to the equal cost method (Veq ≥ 1.10 mL), it can also be used with the last two columns to compare performance of individual methods.

** "Nonfunctioning" includes all states scored other than "functioning" on the otoscopy score sheet, i.e., "blocked", "extruded", "infected," and "none inserted."*

(iv) the three definitions described above; (v) Veq ≥0.95 mL (equal error); and (vi) Veq ≥1.33 mL (minimum error). These later two cutoffs were included separately from the definitions in which they are averaged, as each lay close to each extreme of the flat-bottomed error function. For all these comparisons, where the audiologist had interpreted "no seal" as due to a patent VT, these ears were also coded "functioning." The logistic regressions predicted the dichotomized otoscopy code (functioning versus nonfunctioning) from the similarly dichotomized tympanogram classification [(functioning versus nonfunctioning, i.e. F or "no seal" versus (B, A, C1, or C2)]. We used cases with no missing data in the variables of present interest at each visit.

Table 4 shows the increase in percent correct classification performance, as revealed by the respective logistic regressions in comparison with that available from the initial null model, i.e., an initial labeling of all cases as "nonfunctioning." All methods show a material advantage over the null model. Compared with using the Veq ≥1.0 mL cutoff, there is a slight advantage seen in the left ear for the Veq criterion being placed at the mean of the three methods (Definition 1), but no advantage in either ear for using Definitions 2 or 3, so the added sophistication is not worthwhile. For the right ear, although no advantages over using Veq ≥1.0 mL are seen at 6 mo, when fewer patent VTs are present in the later +12 mo visit (not shown), all three definitions perform more accurately than this literature-based cutoff.

Effect of Age and Sex on Applicability of Coding Rules

Only slight correlations (Pearson) were found between preintervention age and Veq [$r = 0.098$, $p = 0.055$ (L); $r = 0.059$, $p = 0.247$ (R); $N = 389$], in our sample of children aged 3¾ through 7¼.

At randomization, the 190 boys with valid Veq measures had significantly greater mean Veq values than the 199 girls (mean difference = 0.09 mL, SD = 0.53 mL, $t = 3.582$, $p < 0.001$ for the left ear and mean difference = 0.08 mL, SD = 0.57 mL, $t = 3.452$, $p < 0.001$ for the right ear). The mean cutoff for a patent tube on aggregated data was Veq ≥1.33 mL to two decimal places. Disaggregating by sex yields cutoffs under Method 3 (minimizing the mean errors) of 1.26 mL for girls and 1.34 mL for boys (left ear) and 1.33 mL for girls and 1.38 mL for boys (right ear). Reaggregating over ears, this method of determination would give gender-specific cutoffs of 1.30 mL (girls) and 1.36 mL (boys). Thus while sex-disaggregated data are more precise, aggregation introduced no systematic error, 1.33 being the mean of 1.30 and 1.36.

For the other two methods, the difference of approximately 0.1 mL from the mean for either gender is seen (Table 2) occasionally, because the increment of determination (0.05 mL) is as large as half the apparent difference. Nevertheless, on applying these differences where found, the estimates for cutoff, pooled across the three calculated values, are 1.1 mL (girls) and 1.2 mL (boys). Such a sex difference is also seen in the 6- to 7-yrs old data of Shanks et al.

DISCUSSION

Overall, there is satisfactory agreement between the methods in accuracy of predicting otoscopy and so the results support general use of the pooled estimate from the three methods. Under none of the three definitions (using raw Veq, pre- and postintervention difference and a combination) do the average cutoffs materially out-perform the others in practice, although a slight advantage was seen for using Veq ≥1.13 alone as criterion (Table 4). Values near the extremes of the flat-bottomed error function did not classify quite so well as more central values. The option of gearing a cutoff within the range of most uncertainty, e.g. according to clinical "costs" and values of the two types of error remains; however, this would be difficult to put fully into practice because of the lack of a clear value framework to judge such costs. We imagine that users will prefer to reduce error in other ways, e.g. by undertaking repeat measurements, in the few cases where the obtained value is in the uncertainty region spanned by our three estimates.

Strengths and Limitations of this Sample for Defining Veq Indicative of Patency

Scale and systematic approach • The study is more detailed and explicit than any other so far reported on the topic. Our 90% normative ranges are comparable with those in the literature (De Chicchis, et al., 2000; Haapaniemi, 1996; Shanks, et al., 1992). On the pre- and postintervention difference, as derived for resolving ambiguities in the marginal region, our cutoff differs only slightly from the value recommended by Shanks et al. (1992). However for the optimum cutoff for absolute Veq, which is feasible in all circumstances, we are led to recommend toward the higher end of the range of values from the literature, particularly when using the equal cost and minimum error methods. We have determined Veq cut-off using three methods (equal error, equal cost, and minimum error) for three definitions: raw Veq, pre- and postintervention difference and a two-step combination of these. The similarities of result over the various definitions and methods in predicting otoscopic status demonstrate an overall robustness and generalizability of the findings. Furthermore, we were able to demonstrate robustness in the raw Veq definition by using within-subject preintervention data as control as an alternative to the same-occasion control data. These two comparisons yielded identical cutoff values in our data, so high confidence can be attached to the estimate we obtain of 1.13 mL, compared with the central tendency for various previously reported data.

Possible bases for high cutoff • Shanks et al. (1992) reported using insert tips, which could be expected to give a smaller Veq, so we have examined whether our higher cutoff might be due to the type of probe tip. Because our protocol allowed transfer to screening mode in difficult-to-test cases, a screening tip would have been used in some cases. For the purposes of the trial, it was not necessary to record the occasions when screening mode was used, so we cannot give an accurate adjustment or set of exclusions for this. However, the data we use are from the third visit, by which point children were older and accustomed to testing, and from regular discussions on progress with the audiologists in the centers, we know that intolerance of probe was rare overall (certainly $<5\%$), as would be expected from the minimum age at the third visit being 3¾ yrs. Insofar as our estimate for cutoff with two methods is higher than that of Shanks et al. (1992), type of tip does not offer an adequate explanation.

Otoscopy as criterion • Otoscopy provides the criterion for where cutoffs in Veq values should be placed but is not a validator in the general sense. Although we do not have dual-otoscopist corroboration, we can use the clearest cases with extreme Veq values (for which there is not a particular otoscopic correlate) to provide a general marker for quality of the otoscopy. This was done for the first postintervention visit with no record-based information to hand at time of otoscopy. To obtain this, we focused on the otoscopy codings for those ears most likely to have a functioning tube (Veq >2.0 mL). For the 107 left and 120 right ears thus identified as extreme, 104 (left, 97.2%) and 116 (right, 96.7%) were judged "functioning." One right ear was reported "blocked" and one left ear "not seen." There remained two left and three right ears, which were judged as "extruded." This does not necessarily imply any overall inconsistency with the tympanometric Veq. A small number of such inconsistencies is always to be expected, as a temporary perforation must exist immediately after extrusion but before healing, so with prescheduled visits, this would be seen in a few cases. These supplementary data show that the standard of otoscopy was generally high.

Choice of Techniques for Clinical and Research Work

The confirmation of relevance and determination of appropriate cutoffs reported here is not a validation study as usually understood or required and it does not presuppose that otoscopy is universally "better" or worse than tympanometry for the purpose in hand. Pneumatic otoscopy is very uncommon in the UK because of the availability of tympanometry in secondary and intermediate care clinics and absence of generalist pediatricians in primary care. It was not required for completion of the otoscopy coding form. We therefore have no data on how, where available, pneumatic otoscopy might fit into patency ascription, clinically or in research. Clearly the expected lack of eardrum movement on pressure change when a tube is patent makes this a promising candidate, and many of the points made favoring tympanometry as one useful information source would apply equally to pneumatic otoscopy. For circumstances where a skilled otoscopist can be guaranteed, the emergence of this further information without a switch to separate instrumentation could give pneumatic otoscopy an efficiency advantage. In other circumstances, absence of a separate technique and need for a skilled otoscopist could be a disadvantage. More generally, there are two advantages in maintaining two broadly equivalent clinical techniques for a single purpose: (a) the ability to substitute, should one be unavailable for practical reasons; (b) the ability to reduce error by pooling the two methods where the demand for precision justifies this (e.g. in research). The opti-

mum type of formula (e.g. simple versus conditional) for such pooling is strictly outside the present scope, as is discussion of the particular clinical pathways according to which either class of information would be considered primary and the other as the "tie-breaker."

Cost Considerations in Using Classification Error Functions

The error curves plot two types of errors: those that mis-code as type F some cases known not to have received VTs (i.e. the state we can be most sure about) and those that mis-code as type B ears judged by otoscopy to be functioning. On the patient's perspective, to fail to detect that a tube is currently not functioning could be considered the more serious of the two error types—complacency about the fact of recent treatment, and missing a predictor of the return of OME. A high criterion for the Veq is conservative in declaration of patency, so adopting a higher value compared with Shanks et al. (1992) (e.g. as in average or the equal or minimum cost methods) avoids such complacency. However, except for cases with the most highly recurrent acute otitis media or with serious comorbidities justifying a clinically more aggressive (preventive) approach, the justification for reinsertion or treatment may depend not only on the fact of nonfunctioning or extruded tubes, but largely on hearing level or on evidence of return of infection (e.g. from otorrhea). The immediate implication of blockage or extrusion will therefore usually be continued observation. Mislabeling a patent tube as blocked also carries costs and risks. We leave it to others closer to these decisions on a routine basis to determine whether the risks and costs are now worth quantifying, what their values should be, and the implications e.g. in terms of scheduling reappointments.

Conditioned Cutoff Values for Age, Sex, and Particular Ear

We have shown mean Veq to be larger in boys than girls by 0.1 mL, pooled across the three methods. We believe the difference is real and simple to apply, rounding to 1.1 mL for girls, unaltered from that for the total sample to 1 decimal place, and 1.2 mL for boys. The practical advantage of using a sex-specific cutoff would be small, partly because of the flat-bottomed functions, but the ease of adding just an extra 0.1 mL to the criterion for boys provides a simple and memorable rule. We found no significant age effect in our sample. Studies which did report age effects (De Chicchis, et al., 2000 and Shanks, et al., 1992) spanned a younger range of age. We found only a very small, and nonsignificant, difference between the ears in this study, so the cutoffs can be applied to either ear. In sum, we do not find compelling evidence for the added complexity of supporting differing clinical criteria according to age, sex or ear.

Interpretation of Nonsealable Ears

In our data, one in six VT-inserted ears were not sealable compared with 1 in 60 noninserted ears. In the intact ears, although generally lack of seal might be due to poor probe placement, we cannot rule out the possibility of a perforation, particularly as the sample is one with an OM history (recurrent acute otitis media often preceding OME). Furthermore, the audiologists were all experienced in pediatric testing. In ears known to have been inserted, whether it be due to equipment cutout at large Veq or failure to seal at the Eustachian tube, we see no reason to question the usual clinical interpretation, i.e. as patent tube or perforation. Thus, from our data, for every 60 ears tested, 10 seal failures can typically be expected, with 0 or 1 of these probably because of poor probe placement and 9 or 10 because of patent VT or perforation at the tympanic membrane. An apparent "no-seal" in an ear known to have been inserted can be reasonably attributed to a functioning tube.

Relevance of Research Findings to Alternative Instrumentation

In recent years measures of wideband energy reflectance have been shown to be good indicators of presence of middle ear effusions (Keefe and Simmons, 2003; Piskorski, et al., 1999). There is every reason to believe that principles of the type developed here for the appropriate clinical use of new information will also apply to measures from such novel instrumentation that may lift the general level of precision or convenience. We did not have these measures available in the TARGET data, but can encourage further research applying these principles to new measures influenced by patency in operated or perforated ears. Until such work has been completed and shown to be applicable in routine clinical practice, the comparison of Veq from standard 226 Hz tympanometry against the cut-offs presented here offers a useful contribution to accurate determination of VT patency.

Conclusions

We have adopted a rigorous and transparent approach, based on derivations in a large sample on a core age group, to minimizing errors in the tympanometric classification of ventilation tube pa-

tency. The same principles apply to younger and older children, and age effects are not strong, but the values given here may not be optimal for very young children, where lower cutoffs could be more appropriate—a topic for further research.

1. For clinical follow-up and epidemiological studies seeking efficient characterization of children in respect of middle ear disease, we propose addition of "Type F" to the modified Jerger classification. In children aged 3¾ through 7¼ yrs, an appropriate cutoff signifying patency (determined from an average of three methods) would be ≥1.13 mL in equivalent volume (Veq).
2. A more conservative approach to classifying patency (i.e. one in which a nonfunctioning VT is less likely to be missed) can be achieved by taking a slightly higher cutoff of Veq ≥1.2 mL (as indicated by equal-costs method) or even Veq ≥1.3 mL (minimized mean error method). It is not evident that cost/risk considerations could ever be strong or unidirectional enough to justify a cutoff outside this range.
3. Despite reasoned expectation from the reduced variability seen with paired before/after measures in individuals, the improvement in classification accuracy from definitions that additionally take the preintervention Veq into account is small. It is not clinically worthwhile in our age range. Uncertainty within the range of our three estimates (0.95 to 1.33 mL) could be partly, and more appropriately, resolved by repeat measurement.

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APPENDIX

MRC Multicentre Otitis Media Study Group

The group does not have a formal constitution; regular meetings of the core staff and collaborating consultants were only held during the conduct of the trial in the mid-1990s. This list satisfies editorial requirements for specified authorship, plus the governance and human resource requirements for acknowledged contributorship. The analyses reported here were conducted by JM Higson and the paper was written by her and MP Haggard.

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REFERENCES

Anonymous. (1981). Recommended procedures for pure-tone audiometry using a manually operated instrument. *Br J Audiol*, *15*, 213–216.

Anteunis, L. J. C., Engel, J. A. M., Hendriks, J. J. T., et al. (2000) Otitis media with effusion algorithms and the associated hearing loss in infants 0–2. In L.J.C. Anteunis, J.A.M. Engel (Eds.), *Maastricht Otitis Media with Effusion Study (MOMES)*, *A prospective longitudinal study in infants from 0 to 2 years* (Chapter 10: 141–154). Drukwerk. Maastricht.

BS EN 61027. (1993). Instruments for the measurement of aural acoustic impedance/admittance.

BS EN ISO 8253-1. (1998). Acoustics. Audiometric test methods. Basic pure tone air and bone conduction threshold audiometry.

BS EN ISO 389-1. (2000). Acoustics. Reference zero for the calibration of audiometric equipment. Reference equivalent threshold sound pressure levels for pure tones and supra-aural earphones.

BS EN ISO 389-3. (1999). Acoustics. Reference zero for the calibration of audiometric equipment. Reference equivalent threshold force levels for pure tones and bone vibrators.

Brookhouser, P. E. (1998). Use of tympanometry in office practice for diagnosis of otitis media. *Pediatr Infect Dis J*, *17*, 544–551.

De Chicchis, A. R., Todd, N. W., & Nozza, R. J. (2000). Developmental changes in aural acoustic admittance changes. *J Am Acad Audiol*, *11*, 97–102.

De Melker, R. A. (1992). Diagnostic value of microtympanometry in primary care. *Br Med J*, *304*, 96–98.

Fiellau-Nikolajsen, M., Falbe-Hansen, J., & Knudstrup, P. (1980). Adenoidectomy for middle ear disorders: a randomized controlled trial. *Clin Otolaryngol*, *5*, 323–327.

Haapaniemi, J. J. (1996). Immitance findings in school-aged children. *Ear Hear*, *17*, 19–27.

Jerger, J. (1970). Clinical experience with impedance audiometry. *Arch Otolaryngol—Head Neck Surg*, *92*, 311–324.

Keefe, D. H., & Simmons, J. L. (2003). Energy transmittance predicts conductive hearing loss in older children and adults. *J Acoust Soc Am*, *114*, 3217–3238.

Margolis, R. H., & Heller, J. W. (1987). Screening tympanometry: criteria for medical referral. *Audiology*, *26*, 197–208.

Maw, A. R., & Herod, F. (1986). Otoscopic impedance and audiometric findings in glue ear following adenoidectomy and tonsillectomy. A prospective randomized study. *Lancet*, *1*, 1399–1402.

Moody, S. A., Alper, C. M., & Doyle, W. J. (1998). Daily tympanometry in children during the cold season: association of otitis media with upper respiratory tract infections. *Int J Pediatr Otorhinolaryngol*, *45*, 143–150.

MRC Multicentre Otitis Media Study Group. (1999). Sensitivity, specificity and predictive value of tympanometry in predicting a hearing impairment in otitis media with effusion. *Clin Otolaryngol*, *24*, 294–300.

MRC Multicentre Otitis Media Study Group. (2000). Influence of age, type of audiometry and child's concentration on hearing thresholds. *Br J Audiol*, *34*, 231–240.

MRC Multicentre Otitis Media Study Group. (2001a). Surgery for persistent otitis media with effusion: generalizability of results from the UK trial (TARGET). Trial of Alternative Regimens in Glue Ear Treatment. *Clin Otolaryngol*, *26*, 417–424.

MRC Multicentre Otitis Media Study Group. (2001b). Pars tensa and pars flaccida retractions in persistent otitis media with effusion. *Otolaryngol Neurotol*, *22*, 291–298.

Paradise, J. L., Feldman, H. M., Campbell, T. F., et al. (2001). Effect of early or delayed insertion of tympanostomy tubes for persistent otitis media on developmental outcomes at the age of three years. *N Engl J Med*, *344*, 1179–1187.

Piskorski, P., Keefe, D. H., Simmons, J. L., et al. (1999). Prediction of conductive hearing loss based on acoustical ear-canal response using a multivariate clinical decision theory. *J Acoust Soc Am*, *105*, 1749–1764.

Rovers, M. M., Krabbe, P. F. M., Straatman, H., et al. (2001). Randomized controlled trial of the effect of ventilation tubes (grommets) on quality of life at age 1–2 years. *Arch Dis Childhood*, *84,* 45–49.

Sabo, D. L., Paradise, J. L., Kurs-Lasky, M., et al. (2003). Hearing levels in infants and young children in relation to testing technique, age group, and the presence or absence of middle-ear effusion. *Ear Hear*, *24*, 38–47.

Sakaguchi, M., Taguchi, K., Ishiyama, T., et al. (1994). Tympanometric changes following acute otitis media in Japanese children. *Eur Arch Otorhinolaryngol*, *251*, 113–116.

Shanks, J. E., Stelmachowicz, P. G., Beauchaine, K. K., et al. (1992). Equivalent ear canal volumes in children pre- and post-tympanostomy tube insertion. *J Speech Hear Res*, *35*, 936–941.

SPSS for Windows. (2003). Rel. 12.0.0. Chicago: SPSS Inc.

Wilber, L., & Feldman, A. (1976). The middle ear measurement battery. In A. Feldman, L.A. Wilber (Eds.), *Acoustic impedance and admittance: the measurement of middle ear function* (pp. 345–377). Baltimore: Williams & Wilkins.

Zielhuis, G. A., Rach, G. H., & Van den Broek, P. (1990). The occurrence of otitis media with effusion in Dutch preschool children. *Clin Otolaryngol*, *15*, 147–153.