Background: Eustachian tube (ET) dysfunction is a common but poorly understood cause of patient symptoms, and an important aetiological factor in the development of middle ear pathology. Despite this, there are no specific tests of ET function in widespread clinical use and no identified ‘gold standard’ with which to diagnose the disease.

Objective: This review aims to review the literature to identify currently available tests of ET function and, where possible, report on their accuracy.

Type of review: Narrative systematic review.

Search strategy: MEDLINE, EMBASE, Biosis and the Cochrane library were searched and reference lists reviewed for relevant articles.

Evaluation method: Tests in included studies were required to measure a physiological function of the ET, or play a role in the diagnosis of poor ET function. Significant variation in demographic characteristics, disease presentation and severity, and technological approaches only permitted narrative systematic review.

Results: While many tests of ET function have been developed, with some in routine clinical use, all have significant limitations. Published accuracy data are limited and of differing quality due to the variability in comparative tests, and the spectrum of otological disorders associated with ET dysfunction.

Conclusions: Currently, no single test could be considered a ‘gold standard’ for the diagnosis of ET dysfunction, but there is some evidence that diagnostic accuracy can be improved by combining the results of different objective tests and patient-reported outcome measures. Further development of ET function tests is required to facilitate the accurate diagnosis of patients and allow outcome reporting for new interventions.

Background

The eustachian tube (ET) performs three primary functions: gas transfer and pressure equalisation between the nasopharynx and middle ear; clearance of mucus from the middle ear; and prevention of sound or fluid reflux from the nasopharynx. Although the ET is normally closed in a healthy individual, these actions are permitted when the cartilaginous portion of the tube is momentarily pulled open during swallowing by paratubal muscles. In individuals suffering from eustachian tube dysfunction (ETD), the tube opening may be obstructed, resulting in the typical complaints of ear fullness, muffled hearing, ‘popping’ sounds or tinnitus. Less frequently, the ET may be permanently patulous, resulting in the symptoms of aural pressure or autophony.

ETD has an estimated prevalence of 0.9% in the UK adult population and has been suggested as a causal factor in many ear pathologies. There have been many attempts to develop objective tests for ETD, but despite work over a number of decades, no single test has been found to be a reliable diagnostic tool. Currently, a number of treatments are in development that more directly address the underlying cause of ETD by improving the function of the eustachian tube, and to trial and validate these techniques, a better understanding of available tests for ETD and their sensitivity and specificity is required. Wider adoption of ‘standard’ tests and outcome measures would allow comparison of results between the many groups researching this area.

Objective

To provide a comprehensive review of currently available clinical tests of eustachian tube function and to report published accuracy data where available.

Type of review

Narrative systematic review.
Search strategy

The following databases were searched in October 2014 for articles published between database inception and October 2014: MEDLINE, EMBASE, Biosis and the Cochrane library. Additional articles were retrieved from reference lists in books, reviews and primary studies, and relevant websites were searched. The literature search used the following terms: ‘eustachian’ (and synonyms ‘auditory tube’ and ‘pharyngotympanic tube’) combined with ‘test’, ‘measure’, ‘function’, ‘accuracy’, ‘outcome’, ‘questionnaire’, ‘tool’ and ‘validated’. Each of the tests identified was then used as a search term to search for related papers. English language articles only were included unless an English translation was available, or the author could provide the required data.

Study evaluation method

For inclusion in this review, tests were required to measure a physiological function of the ET (such as opening or pressure equalisation) or play a role in the diagnosis of poor ET function. Results from earlier work that has been superseded by technical development of the same technique were omitted for reasons of clarity and clinical relevance. Clinical data were not an absolute requirement to enable inclusion of emerging techniques that may have future clinical benefit. Articles were excluded if the study inclusion criteria and characteristics of the population under investigation were not clear.

The primary outcome of interest was the accuracy (sensitivity and specificity) of the ET function tests. This was directly obtained or derived from published data. Where case–control accuracy data were unavailable, data on the detection of tube function in healthy or ETD case populations in isolation were analysed. Particular attention was paid to heterogeneity of patient inclusion criteria, as ETD has a number of manifestations with no clear index test to assign patients. A meta-analysis would be performed if there were sufficient comparable data on a clinical test from different trials.

Results

Significant variation in demographic characteristics, disease presentation and severity, and technological approaches only permitted narrative systematic review. The review has been based on the best evidence available – for most of the tests of ET function, this represents a retrospective case–control trial. A flow diagram describes the results of the search strategy (Fig. 1). A basic description of each test is included, with more detailed technical descriptions found in the cited references. The risk of bias is high in many studies due to the choice of initial diagnostic criteria for ETD and also from test interpretation in the context of known patient groups.

Tests of ET function can measure either passive tubal opening, where the tube is usually opened by a high pressure, or active tubal opening, which is usually elicited by asking the patient to swallow or make a ‘k’ sound. Patulous ETD is less common than obstructive ETD, and there are fewer tests described in the literature. Table 1 provides a summary of the tests included in this review.

Manometric tests are most widely used, and many institutions already possess some of the required equipment. An important consideration when selecting these tests is the state of the patient’s TM as some tests require it to be intact or perforated. This is summarised in Table 1.

Initial assessment and questionnaires

Although the patient history will focus on otorhinolaryngology-related symptoms, a wider assessment is required to look for potential causes of ETD, such as weight loss which can result in a patulous ET.

Recently, McCoul et al. developed the ETDQ7, a disease-specific instrument to assess symptoms related to ETD in adults. Discriminant validity was demonstrated via a retrospective case–control analysis. Fifty adult individuals were included as ETD cases based on findings of a retracted or poorly mobile tympanic membrane on pneumatic otoscopy, along with characteristic symptoms, a history of recurrent or persistent middle ear effusion, the inability to equalise

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Fig. 1. Search strategy flow diagram.
middle ear pressure, or abnormal tympanometric findings. Significant questionnaire response differences were found between the case and control groups, and by retrospectively calculating an optimal cut-off score for their own patient cohort, a sensitivity and specificity of 100% and 100% was possible. A German translation of the ETDQ-7 has been trialled in a German population that included 100 otologically healthy participants and 43 ETD cases based on similar inclusion criteria that also included a poor response to Valsalva. The sensitivity and specificity in this group using

### Table 1. Summary of tests of eustachian tube function

<table>
<thead>
<tr>
<th>Test</th>
<th>TM</th>
<th>OME</th>
<th>ETD ‘case’ group</th>
<th>Reported Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pneumatic otoscopy</td>
<td>Intact Yes*</td>
<td>N/A for ETD</td>
<td>N/A diagnostic accuracy for ETD</td>
<td>Sensitivity 94%, Specificity 80% for OME&lt;sup&gt;17&lt;/sup&gt;</td>
</tr>
<tr>
<td>Valsalva (witnessed)</td>
<td>Intact No</td>
<td>N/A</td>
<td>85% +ve in healthy individuals&lt;sup&gt;19&lt;/sup&gt;</td>
<td>Sensitivity 94%, Specificity 95% for OME&lt;sup&gt;17&lt;/sup&gt;</td>
</tr>
<tr>
<td>Toynbee (witnessed)</td>
<td>Both No</td>
<td>N/A</td>
<td>79% +ve in healthy individuals&lt;sup&gt;19&lt;/sup&gt;</td>
<td>N/A for ETD</td>
</tr>
<tr>
<td>Tympanometry</td>
<td>Intact Yes*</td>
<td>N/A for ETD</td>
<td>Meta analysis, OME diagnosis</td>
<td>Sensitivity 94%, Specificity 95% for OME&lt;sup&gt;17&lt;/sup&gt;</td>
</tr>
<tr>
<td>Tympanogram Valsalva</td>
<td>Both No</td>
<td>VTs inserted to treat OME or ETD symptoms alone</td>
<td>Sensitivity 55%, specificity 85%&lt;sup&gt;32&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Tympanogram Toynbee</td>
<td>Both No</td>
<td>N/A</td>
<td>Sensitivity 72%&lt;sup&gt;33&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Tympanogram sniffing</td>
<td>Both No</td>
<td>VTs inserted to treat OME or ETD symptoms alone</td>
<td>Sensitivity 52%, specificity 51%&lt;sup&gt;32&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Nine step test</td>
<td>Intact No</td>
<td>N/A</td>
<td>Detects ET opening in 81% of healthy ears&lt;sup&gt;45&lt;/sup&gt;</td>
<td>+ve pressure: Sensitivity 75%, specificity 65%</td>
</tr>
<tr>
<td>Inflation-deflation test</td>
<td>Perf. No</td>
<td>VTs inserted to treat OME or ETD symptoms alone</td>
<td>−ve pressure: Sensitivity 73%, specificity 58%&lt;sup&gt;32&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Forced response test</td>
<td>Perf. No</td>
<td>VTs inserted to treat OME or ETD symptoms alone</td>
<td>Sensitivity 79% Specificity 58%&lt;sup&gt;32&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Patulous tube test</td>
<td>Both No</td>
<td>Characteristic symptoms and endoscopy</td>
<td>Sensitivity 75%, Specificity 97%&lt;sup&gt;47&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Sonotubometry</td>
<td>Both Yes</td>
<td>N/A</td>
<td>Detects opening in 63–90% healthy adults&lt;sup&gt;50,51&lt;/sup&gt;</td>
<td>Detects opening in 37–80% healthy children&lt;sup&gt;50,51&lt;/sup&gt;</td>
</tr>
<tr>
<td>Tubomanometry</td>
<td>Both Yes</td>
<td>‘Chronic serous otitis media’ (not otherwise specified)</td>
<td>Sensitivity 74.2% specificity 65.6% for identifying openings in healthy ears&lt;sup&gt;49&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>ETDQ-7 questionnaire</td>
<td>n/a</td>
<td>n/a</td>
<td>‘Ideal’ of Sensitivity 100%, specificity 100%&lt;sup&gt;6&lt;/sup&gt;</td>
<td>Detects opening in 91% of swallows in a non-ETD cohort and in 47% of swallows in ETD&lt;sup&gt;53&lt;/sup&gt;</td>
</tr>
<tr>
<td>Test Combinations</td>
<td>Forced-response + inflation-deflation + Valsalva + sniffing test</td>
<td>VTs inserted to treat OME or ETD symptoms alone</td>
<td>Sensitivity 95% specificity 83%&lt;sup&gt;32&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>
McCoul’s cut-off figure were found to be 91% and 95%, respectively. Although the results from these small samples seem very promising, the questionnaire cannot yet be considered validated as a diagnostic tool. To be useful, it must first be prospectively applied in a population of patients with varied otological disorders, rather than clearly discrete groups of cases and controls. Furthermore, it has not been trialled in children, and correlation with existing objective tests of ETD is variable. In the absence of developed objective clinical tests, once further developed, such patient-reported measures could be an important asset when considering the development of tools for both diagnosis and outcome assessment.

Otoscopy

The most important aspect of the clinical examination is otoscopy. Some of the more noticeable features suggestive of ETD include a middle ear effusion, or TM retraction. Retraction can be graded using systems such as those suggested by Sade and Tos to allow documentation and follow-up assessment. Fullness or retraction are often first seen in the posterosuperior portion of the pars tensa and pars flaccida because they are most compliant. Pneumatic otoscopy provides a simple and quick assessment of middle ear pressure and TM mobility. It has proved a relatively accurate test for middle ear effusions, with a sensitivity and specificity of 94% and 80%, respectively; however, the technique is operator dependant, and it is not possible to assess middle ear pressure. Attempts have been made to quantify TM movement in video pneumatic endoscopy, but this is not well developed.

As an alternative, while performing otoscopy the patient can be asked to perform a Valsalva (forcibly exhaling against a closed mouth and nose pinched closed) or Toynbee (swallowing with the nose pinched closed) manoeuvre, whilst the TM is visualised. Both the patient’s subjective opinion of aural pressure change and observer-witnessed movement of the TM suggest patency of the ET. However, up to one-third of healthy individuals will fail this test, and as discussed later, techniques where patients induce nasopharyngeal pressure changes lack consistency.

While otoscopy findings such as TM retraction or movement on pneumatic otoscopy provide some information on middle ear pressure and ET patency, it is an insensitive measure of current physiological performance of the ET.

Manometric tests

Manometric tests are a collection of tools designed to define the ventilatory and pressure equalisation abilities of the ET. An important consideration when selecting a manometric test is whether or not the TM is intact, and so unlike sonotubometry or tubomanometry discussed later, testing diverse presentations or pre- and post-operative patients may not be possible with the same manometric test.

One of the simplest manometric tests is tympanometry, which is part of immittance audiometry testing and provides an indirect measure of ET function by measuring middle ear pressure. Middle ear pressure has a theoretical mean value of zero (atmospheric pressure) if the ET is functioning normally, with a 95% range in normal subjects of -20 to
+20 daPa. However, many studies have found middle ear pressure to be slightly negative even in healthy ears\textsuperscript{21,22} and pressures from −50 to +50 daPa can be considered normal in adults, and even lower pressures in children may have little clinical significance.\textsuperscript{21}

Tymanometry is widely described\textsuperscript{23} and one of the few tests of ETD in regular clinical use. This test is particularly effective in detecting middle ear effusions,\textsuperscript{24} with a reported sensitivity and specificity of 94\% and 95\%,\textsuperscript{17} respectively. There are limited published accuracy data for the use of tymanometry as a diagnostic test for ETD not associated with OME.\textsuperscript{25} Tymanometry and a simple classification system proposed by Jerger\textsuperscript{26} frequently been used as an outcome measure in studies investigating treatments for ETD.\textsuperscript{27–29} However, the technique has a number of limitations for detecting ETD, as a tympanogram will often appear normal in patulous ETD.\textsuperscript{2} A single measure of middle ear pressure does not provide information on ET opening, and middle ear pressures measured by tymanometry can vary considerably over the course of a few hours.\textsuperscript{30} Gaihede et al. examined the test–retest reliability of tymanometry and found that repeated measurements over a short period could increase TM compliance, but that middle ear pressure showed good agreement between measurements,\textsuperscript{31} and so fluctuating values must be assumed to reflect true middle ear pressure changes.

To detect active ET opening, or force passive ET opening, various tests have been developed. The simplest use basic tympanometry equipment to look at patient-induced pressure changes in the middle ear while the patient performs a forcible ‘sniff’, a Valsalva or Toynbee manoeuvre. If the ET opens, Valsalva and Toynbee manoeuvres will usually induce a relative increase or decrease in pressure in the middle ear, respectively, which can be measured with tympanometry. Doyle et al.\textsuperscript{32} compared ETD and control groups, calculating a sensitivity and specificity of 55\% and 85\% for Valsalva and 52\% and 51\% for the sniffing test. YüceTürk et al.\textsuperscript{33} found Toynbee had a sensitivity of 72\% for detecting chronic otitis media, but given the both positive and negative pressure phases in the nasopharynx, it can be harder to interpret middle ear changes.\textsuperscript{20} It has been demonstrated that the increase or decrease in nasopharyngeal pressures during the sniff, Toynbee or Valsalva tests are very variable between patients,\textsuperscript{20} and the pressure achieved is related to frequency of detected ET opening.\textsuperscript{34}

‘Tubo-tymano-aerodynamic-graphy’(TTAG) is a variant of the objectively assessed Valsalva, Toynbee or sniff. In addition to an ear probe detecting middle ear pressure changes, a nasal probe allows an assessor to determine whether the patient-induced nasopharyngeal pressure change is adequate.\textsuperscript{35} These tests rely on passive ET opening due to a pressure differential, rather than the more physiological active muscle function. TTAG is used as a test of ET function, in some units, with evidence that the characteristic shape of the middle ear pressure trace can indicate different ETD pathologies.\textsuperscript{35,36} However, good quantitative data on accuracy are lacking in English language articles.

To overcome the variability of patient-induced pressure tests, a series of formal manometric tests are in use whereby the applied pressure is carefully controlled. The most commonly performed are the inflation–deflation test, the forced response test and the ‘nine-step’ test, with the first two suitable for perforated TMs and the last only possible if the TM is intact.

The inflation–deflation test is primarily a measure of active ET function, although passive opening can be measured. A positive pressure is applied to the middle ear via a sealed probe in the ear canal, and this is increased either to a defined point (typically 100 –300 mm H$_2$O),\textsuperscript{32,34,37,38} or until the ET passively opens.\textsuperscript{2,35} The patient is then asked to swallow repeatedly until no further middle ear pressure changes are detected, and the ‘residual pressure’ plateau is reached. The procedure is then repeated by applying a negative pressure of similar magnitude. The residual pressure and number of swallows required to reach it are recorded. Figure 2 demonstrates the apparatus required. Healthy adults were found by Swarts et al.\textsuperscript{34} to equilibrate 83\% of the applied positive inflation pressure and 67\% of the applied deflation pressure. Good reproducibility has been reported in children.\textsuperscript{37} The reported sensitivity and specificity of the inflation–deflation test in assigning patients to an ETD group is 75\% and 65\% for applied over-pressure and 73\% and 58\% for applied under-pressure measurements.\textsuperscript{32}

The forced response test is primarily a test of passive ET opening, which requires a TM perforation or ventilation tube without otorrhoea. A sealed probe in the external auditory canal is used to increase middle ear pressure until the ET is forced open. Air delivery is continued in an attempt to establish a stable middle ear pressure due to a steady flow out via the ET.\textsuperscript{34,39,40} If the air flow is stopped, the pressure at which the ET closes can be recorded and used as an outcome variable along with the tube opening pressure, steady state pressure and calculated resistances. The test can be performed at different air flow rates, and swallowing during the steady state period can provide further information on active ET function and the effect this has on tubal resistance.\textsuperscript{41} Using a derived measure of ‘dilatory efficiency’, Doyle et al.\textsuperscript{32} found a sensitivity and specificity of 79\% and 58\% in assigning patients to an ETD group. There is considerable interindividual variation, which is more pronounced in those with ETD, and the reproducibility of sequential measurements with the forced response test has been questioned in both adults\textsuperscript{42} and children.\textsuperscript{37}
The nine-step test is a version of the inflation–deflation test developed by Bluestone to test active ET function in the presence of an intact TM and dry middle ear. By varying external canal pressures, both positive and negative middle ear pressures can be induced. A modification was introduced by Givens et al. who used a bivariate assessment technique analysing both changes in the middle ear pressure and the compliance of the TM.

Using the nine-step test, ET opening can be recorded in 81% of healthy individuals during swallowing. Seifert et al. found significant differences in detectable pressure changes when 200 mm H₂O and 400 mm H₂O were applied to the ear canal, suggesting a reason why results from healthy individuals in different study protocols vary. Interestingly, Adali et al. found that dry swallowing was more effective than wet swallowing (swallowing water) at equalising middle ear pressure using the nine-step test. The differing characteristics of dry and wet swallows have been noted by other investigators using other tests, including Finkelstein et al. who noted the differing techniques generated different shaped nasopharyngeal pressure waves.

Through the combination of four manometric test parameters (Valsalva, ET opening pressure, dilatory efficiency in the forced response test and positive pressure equilibrated in the inflation deflation test), Doyle et al. reached an overall sensitivity and specificity of 95% and 83% for assigning ears to an ETD group.

Tympanometry also has a role as an objective test of patulous ET. If a continuous trace of ear canal pressure is recorded, a respiratory-synchronous compliance pattern can be seen, and exaggerated by closing the mouth and one nostril while breathing forcefully. McGrath et al. found this test to have a sensitivity and specificity of 75% and 97% for identifying patulous ETs.

**Sonotubometry**

Sonotubometry (STM) measures the function of the ET using sound and has been explored as a method for ET function testing for many years, Politzer having first reported the phenomenon of sound transmission via the ET in 1865. A sound source is applied to the nostril, and a sensitive microphone placed in the external auditory canal. The patient is asked to swallow, and if the ET opens, an increased sound level can be detected in the ear canal. Figure 3 illustrates the set-up for this test, and Fig. 4 demonstrates the results that could be obtained from sonotubometry when compared to inflation–deflation testing. Although usually performed at atmospheric pressure, the nasopharyngeal pressure may be varied, or the procedure performed in a pressure chamber. If performed at atmospheric pressure, sonotubometry is one of the few tests to be able to detect ET opening under physiological pressure conditions in the nasopharynx and middle ear.

Using STM, the rate of detectable ET opening with swallowing varies between studies with a reported range of 63–92% in healthy adults and 37–80% in healthy children. The rate of ET opening with swallowing in diseased patients appears lower, with a rate of 47% in adults with ETD, and 27–29% in children with OME. Most studies...
have not correlated these rates to another measure of tube opening. However, Swarts et al. used white-noise signal STM simultaneously with tympanometric methods to confirm ET opening and found that STM had a sensitivity and specificity of 74.2% and 65.6% for identifying ET openings in healthy individuals.

Although widely applicable, the efficacy of STM when a middle ear effusion is present is debated, with one study suggesting STM has a predictive rate for OME in children of 85%. In an attempt to test the validity of the testing method, van der Avoot et al. tested 33 children with OME before and after ventilation tube insertion as well as 61 otologically healthy children. They found no difference in tube opening between the post-operative group and controls, but reduced opening in the OME group prior to surgery. It is not known whether these findings are a genuine

Fig. 3. Diagram of the equipment set-up for sonotubometry. A sound stimulus applied to one or both nostrils can be detected in the external ear during eustachian tube opening. Usually, commercially available sound recording equipment has been used connected to a computer running bespoke software.

Fig. 4. Representative diagram of the results obtained for sonotubometry and inflation–deflation testing, demonstrating the effect of swallowing. These idealised results represent a healthy individual with a TM perforation. The black rectangles indicate periods of induced positive or negative pressure, and middle ear pressure equalisation can be seen via sequential swallows, until a residual pressure is reached. The sonotubometry traces represent sound pressure detected in the external ear after significant digital filtering.
reflection of ET opening or simply the dampening effect of the effusion on sound transmission.

As well as differences in opening frequency, the average amplitude of the openings with STM is different in healthy and pathological ears. As such, other quantifiable elements of the sound signal ‘shape’ have been used to differentiate adults with a history of otitis media from those that do not.

STM provides a more physiological and non-invasive method of testing active tubal opening than those where pressure is induced, with the added benefit of being simple to perform and suitable for both intact and perforated TMs. However, a weakness will always remain that sound transmission (unlike pressure equalisation) is not a normal function of the ET, and the frequency of tube opening can only provide a limited assessment of overall physiological function. In fact, the most repeatable finding with STM has been that 10–20% of healthy individuals do not have detectable opening during swallowing, which limits the use of STM as a stand-alone test of ETD. STM may be more useful when combined with another test of ETD. Mcbride et al. compared the nine-step test with sonotubometry and found 78% agreement between the two techniques with a combined ability to detect tubal functioning in 96% of normal ears.

**Tubomanometry**

Tubomanometry (TMM) was first described by Estève in 2001, although a similar procedure was previously described by Moon et al. in 1983. The patient is positioned seated with a tight-fitting pressure receiver in the external auditory canal, and a nasal applicator held tightly in place to allow the production of a defined pressure in the nasopharynx (Fig. 5). The patient is asked to swallow, and this movement triggers the delivery of a synchronous pressure increase in the nasopharynx, typically to a pressure of 30, 40 or 50 mbar (approximately 300, 400 and 500 mm H₂O). TMM is, therefore, a test of both active and passive tubal opening at different pressures.

Recordings of the pressure change within the nasopharynx and middle ear (as transmitted through TM movement or a perforation) are compared digitally. From these data, two variables are used in ET assessment: the first is simply if, and at what applied pressure, there is a middle ear pressure increase consistent with ET opening; the second is a measure of the latency between the swallow-triggered nasopharyngeal pressure application and the ET opening. Initial work suggested that the test was able to diagnose an ETD cohort with a sensitivity of 49% and specificity of 93% for opening threshold measurements, and a sensitivity of 87% and specificity of 67% for latency measurements.

To date, the use of TMM has been limited and further work is required to validate it as a measure of ETD, although it has been recently used in a measure combining patient symptoms and TMM results. The ‘eustachian tube score’ was developed by Schroder et al. and combines three measures from TMM, along with patient-reported Valsalva and Toynbee outcomes over the preceding month. This has a reported sensitivity and specificity of up to 91% and 86%. By combining this score with data from tympanometry and objective Valsalva, the team improved the sensitivity and specificity to 96% and 96%.

![Fig. 5. Diagram of the equipment set-up for tubomanometry. A nasopharyngeal pressure of defined value is induced at a point triggered by swallowing, and the resultant change in middle ear pressure is measured to indicate eustachian tube opening. A commercial system is available.](image-url)
**Endoscopy**

Initial endoscopic examinations of the Eustachian tube were focussed on confirming patency, with techniques described for examining the tube via both transtympanic and transnasal approaches. More recently, slow motion video endoscopy has been used to visually assess ET function. A correlation between the tubal appearance during swallowing and tympanometric assessments of ET function has been shown, and efforts have been made to quantify dilatory movements at the ET orifice in healthy and ETD groups. With further development, slow motion video endoscopy may become a useful addition to ET tests, particular in groups such as cleft palate patients where tubal dysfunction is more likely to be secondary to movement and anatomical abnormalities.

**Evolving techniques**

Two new techniques are under development with the aim of providing a non-invasive method of continuously recording of TM movement secondary to pressure variations under physiological conditions. Optotensometry is being developed for this purpose by Zehlicke, but has currently only been demonstrated to work in a laboratory model. Another approach trialled in a cadaver model has been to attach a film patch with integrated strain gauge to the tympanic membrane.

**Radiological imaging**

Functional imaging of the eustachian tube is in the early stages of development, and to date, computed tomography (CT) has been the most widely used modality. Using multplanar reconstruction in upright seated patients, Kikuchi et al. were able to visualise a continuous hyperlucency from the pharyngeal to the tympanic orifices in patients with patulous ETD, and comparing a control group reported a 79% sensitivity and 100% specificity for the technique. More advanced CT systems have allowed functional imaging of ET movements during sniffing, and using cine CT, McDonald et al. have been able to image the passage of an air bolus through the ET. In a small trial, this was seen in normal subjects but found to be absent in ETD patients, an interesting finding that may explain why multiple swallows are required to equalise middle ear pressure in manometric testing and why sonotubometry is negative in some individuals with normal ET function.

Magnetic resonance imaging has been used less frequently, and although the opening of the ET during a Valsalva manoeuvre is assessable on MRI, overall the technique lacks development and anatomical imaging of the cartilage is poor. Scintigraphy has also been proposed as a test of ET ventilatory function, with transfer of radioisotope along the ET in 70% of normal individuals. Significant differences are detectable on isotope scans between controls and ears with ETD, but so far, this has only been exploited as a research tool.

**Electromyography**

The eustachian tube is passively closed at rest, but during swallowing, yawning or sneezing, it is opened by the action of paratubal muscles, the tensor veli palatini (TVP) and levator veli palatini (LVP). There remains some debate regarding the relative roles of TVP and LVP in eustachian tube opening, but deficiencies in their action are likely the cause of ETD in cleft palate patients, and possibly in other subgroups. Electromyography (EMG) recordings from the paratubal muscles have been used to investigate ET function. In healthy individuals, Alper et al. compared sonotubometry and videendoscopy findings to EMG recording and found that TVP but not LVP peak activity was associated with peak ET opening.

Some studies have investigated whether a muscle weakness can be demonstrated in ETD patients without a known cause of muscle dysfunction such as cleft palate. Sapci et al. used EMG to look at TVP activity and found no difference between patients in an ETD group and controls, although contradictory results from a smaller study suggested ipsilateral LVP weakness on EMG recordings in some patients with unilateral ETD.

**Tests of middle ear clearance and reflux prevention**

Most patient symptoms and pathological sequelae arising from ETD are caused by poor atmospheric pressure equalisation of the middle ear due to inadequate ET opening. The ET also plays an important role in draining the middle ear of mucus and protecting the middle ear from the reflux of liquid and sound from the nasopharynx. Failure of the protective function of the ET is thought to be related to the pathogenesis of otitis media and has been assessed radiologically by looking for evidence of contrast refluxing up the ET from the nasopharynx. Mucociliary and muscular clearance has been assessed in various ways including instilling fluorescein, methylene blue or contrast agent into the middle ear and looking for its presence in the nasopharynx, or waiting for the patient to taste saccharin placed at the tympanic end of the ET via a TM perforation. Tests designed to determine the ET functions of middle ear drainage and reflux protection have not entered routine clinical use.
Issues with test trial design

Despite development over many decades, there are only a limited amount of published data reporting the sensitivity and specificity of ET function tests, and this is probably due to the complexity of validating the outcome measures. The first hurdle is in defining the ETD population to be tested. This has been achieved either by including only a specific subgroup of patients with ETD, such as those with middle ear effusions or dry perforations and CSOM, or by relying on expert opinion, patient symptoms, otoscopy, basic tympanogram findings or other tests that individually may not be effective measures of ETD. The ‘case’ group characteristics of included studies are summarised in Table 1. This method of case inclusion has resulted in a patchwork of patient groups who are difficult to compare, as noted in reviews of ETD treatments.5

Another weakness of the published test accuracy trials is that all have been completed using the ‘two-gate’ design, in which the test is applied to known case and control groups. In a ‘single-gate’ design, a group of patients of unknown disease status undergoes the test in question and a reference test to which the results are compared. This provides a much better representation of the true way in which the test will be used by including a full spectrum of disease, whereas the pre-selection used in the two-gate method tends to overestimate test accuracy.74

ET opening is often used as a marker for ET function, but the fact the tube opens is not a true marker of physiological function, as demonstrated by the extreme case of patulous ETD. The use of ET opening as a surrogate marker of function suffers from the weakness that the ET appears not to open for every swallow, meaning a high number of repetitions may be required to get a reliable result in tests of active function.

Due to the heterogeneity of methods, case inclusion criteria, and frequently, the use of ET tests only within single centres or specialist interest groups, results are limited to small sample numbers that cannot easily be combined or compared. Also the need for an intact or perforated TM and incompatibility with a middle ear effusion remains an issue with many tests (summarised in Table 1). Because of the difficulties surrounding ET function tests, commercially available equipment is limited and the only test in current widespread use is the tympanogram.

The literature review has revealed not only that studies into ET test accuracy in this field are infrequent, but also that analysis of the studies is limited by poor reporting. The STARD initiative has proposed standards for the reporting of diagnostic accuracy studies,75 and if adopted in the way that CONSORT has been for randomised controlled trials, the initiative may improve both the quality of future studies and the ability to assess methodology.

Conclusions

There is a wide range of tests of ET function, and currently, none can be considered a ‘gold standard’. Although many tests are reported to determine ET function with a reasonable degree of accuracy, it is likely that the optimal assessment tool for the complex spectrum of ETD disorders lies in a combination of objective clinical tests and patient-reported measures. Further improvement, validation and comparison of tests of ET function may allow a standard testing regime to be adopted in ETD-related research, allowing the comparison of outcomes between different trials.

Keypoints

- The use of accurate methods of assessing Eustachian tube function has been identified as a key priority in research into treatments for Eustachian tube dysfunc-
- Over the last decade, new data have been published on Eustachian tube function tests, and new techniques have been developed.
- Many tests are based on manometric assessments, although sound transmission, electromyography and imaging have also been explored.
- However, good-quality test accuracy studies are lacking, and those that have been performed are difficult to compare due to heterogeneous and poorly defined inclusion criteria.
- By combining clinical tests of Eustachian tube function with each other, or with patient-reported measures, accuracy can be improved.

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