CHAPTER EIGHT

Diagnosis and Tests of Function

Eustachian tube function tests can distinguish between normal and abnormal function, but the most physiologic test is the status of the patient’s ears over time when the tympanic membranes are intact.

In this chapter, I describe the available diagnostic procedures and tests of the structure and function of the Eustachian tube system. In other chapters in this text, I briefly refer to many of these procedures in describing certain aspects of the anatomy, physiology, and pathophysiology of Eustachian tube function and dysfunction and the tubal system’s role in pathogenesis of otitis media and related diseases and disorders. In the following two chapters, I discuss the role of the Eustachian tube in management in which some of these tests have also been alluded to but not described in detail. The reader is advised to use this chapter as a reference for a more comprehensive description of the available diagnostic tests and procedures when reviewing these other chapters. As I discuss in this chapter, several of these tests are fairly accurate in distinguishing between normal and abnormal structure and function of the Eustachian tube system, but none are truly physiologic because most only measure a short period in an individual’s life and some are invasive. The most physiologic assessment of the function of the tubal system is to observe the status of the individual patient and his or her ears, when the tympanic membranes are intact, over a relatively prolonged period of time. The best test is how is the patient doing? But because some middle-ear diseases and disorders are relatively asymptomatic (silent), periodic evaluation of the patient is prudent.

The methods described are presented related to the access to the middle ear (intact vs nonintact tympanic membrane) because the testing will not be the same. Also, assessment of the nasopharyngeal end of the tube is dependent on the age and cooperation of the patient.

Methods to assess the ventilatory function of the system are readily available to the clinician and should be performed when indicated (described later). Also, function tests available for clinical and laboratory studies are presented. The ventilatory function is the most important of the three functions because adequate hearing depends on relatively equal air or gas pressure on both sides of the tympanic membrane being maintained. In addition, impairment of the pressure regulation function can result not only in middle-ear underpressures and symptoms of Eustachian tube dysfunction but also otitis media and certain related diseases (such as perforation of the tympanic membrane) and disorders (atelectasis or retraction pocket). Tests to assess the protective and clearance functions are also addressed.

History and Physical Examination

When assessing patients who have diseases and disorders related to the Eustachian tube system, a medical history related to the whole body is important because there are conditions that affect Eustachian tube function. For example, a history of recent weight loss could indicate a patulous Eustachian tube. Specific information on recurrent or chronic symptoms referable to the ears, nose, and throat is also important, such as pharyngeal, nasal, and sinus disease (allergy) that can affect the tubal system. In obtaining the history, it is important to determine the frequency, severity, and duration of otitis media and related diseases and disorders (signs and symptoms of Eustachian tube dysfunction, such as fluctuating hearing loss, otalgia, vertigo, and tinnitus, including popping and snapping sounds in the ear or autophony). Otologic symptoms during pregnancy, puberty, flying in airplanes, swimming, and diving (especially scuba diving) can be helpful.

The physical examination should include the ears, nose, and throat, even if the patient only has symptoms referable to the ears. In addition to the otoscopic examination, an examination of the nasopharynx may reveal the underlying pathology of the proximal end of the Eustachian tube system. After examination of the external ear and canal, the clinician may proceed to the most important part of the physical assessment, the otoscopic examination.

Pneumatic Otoscopy

Otoscopy, using a pneumatic attachment, to visually inspect the tympanic membrane is one of the simplest and oldest ways to assess the middle-ear end of the Eustachian tube system. The
appearance of a middle-ear effusion, the presence of high negative middle-ear pressure, or both, determined by a pneumatic otoscope, is presumptive evidence of Eustachian tube dysfunction. However, the type of impairment, such as functional or mechanical obstruction, and the degree of abnormality cannot be determined by this method. A reasonable assessment of middle-ear pressure is possible by proper use of the pneumatic otoscope. Moreover, a normal-appearing tympanic membrane is not evidence of a normally functioning Eustachian tube. For example, a patulous or semipatulous Eustachian tube may be present when the tympanic membrane appears to be normal, with normal mobility to pneumatic otoscopy. In addition, the presence of one or more of the complications or sequelae of otitis media (such as a perforation or atelectasis that can be seen through an otoscope) may not correlate with dysfunction of the Eustachian tube at the time of the examination because Eustachian tube function may have improved with growth and development.

Otoscope

For proper assessment of the tympanic membrane and its mobility, a pneumatic otoscope in which the diagnostic head has an adequate seal should be used. The quality of the otoscopic examination is limited by deficiencies in the designs of commercially available otoscopes. The speculum employed should have the largest lumen that can comfortably fit in the patient’s cartilaginous external auditory meatus. If the speculum is too small, adequate visualization may be impaired and the speculum may touch the bony canal, which can be painful. In most models, an airtight seal is usually not possible because of a leak of air within the otoscope head or between the stiff ear speculum and the external auditory canal; leaks at the latter location can be stopped by cutting a small section of rubber tubing and slipping it over the tip of the ear speculum (Figure 8–1).

Many otolaryngologists prefer to use a Bruening or a Siegle otoscope with the magnifying lens. Both of these instruments allow for excellent assessment of drum mobility because they have an almost airtight seal. A head mirror and lamp (Figure 8–2) or a headlight is necessary to provide light for the examination. The examination is most accurate with the use of an otomicroscope and a nonmagnifying lens on the otoscope (Figure 8–3). It is important to examine a patient who is suspected of having a patulous Eustachian tube while in the sitting position.

Inspection of the tympanic membrane should include evaluation of its position, color, degree of translucency, and mobility.

Tympatic Membrane Position

The normal eardrum should be in the neutral position, with the short process of the malleus visible but not prominent through the membrane (Figure 8–4). Mild retraction of the tympanic membrane usually indicates negative middle-ear pressure, an effusion, or both. The short process of the malleus and the posterior malleal fold are prominent, and the manubrium of the

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**Figure 8–1.** A pneumatic otoscope with a small segment of rubber tubing attached to the speculum tip to provide an adequate seal in the cartilaginous portion of the external auditory canal to facilitate assessment of mobility of the tympanic membrane. When middle-ear pressure is normal, pressing gently on the pneumatic bulb applies a small amount of positive pressure to the eardrum, which should move slightly inward (medially); on releasing pressure on the pneumatic bulb, the tympanic membrane will return to its original position.

**Figure 8–2.** A Bruening otoscope, with a pneumatic bulb attached, can assess the mobility of the tympanic membrane. The instrument can be used with the aid of a mirror and lamp or a headlight.
malleus appears to be foreshortened. Severe retraction of the tympanic membrane is characterized by a prominent posterior malleal fold and short process of the malleus and a severely foreshortened manubrium. The tympanic membrane may be severely retracted, presumably owing to high negative pressure in association with a middle-ear effusion. Fullness of the tympanic membrane is initially apparent in the posterosuperior portion of the pars tensa and pars flaccida because these two areas are the most highly compliant parts of the tympanic membrane. The short process of the malleus is commonly obscured. The fullness is caused by increased air pressure, effusion, or both within the middle ear. When bulging of the entire tympanic membrane occurs, the malleus is usually obscured, which occurs when the middle ear–mastoid system is filled with an effusion. A bulging tympanic membrane can be visualized in infants (who have no middle-ear effusion) during crying, which is indicative of positive pressure in the middle ear. Presumably, the positive pressure is related to insufflation of nasopharyngeal air into the middle ear; infants have short, floppy Eustachian tubes (see Chapter 4, “Physiology”). Smith and colleagues identified positive pressure tympanograms in infants who were otoscopically without middle-ear effusion.3

**Tympanic Membrane Appearance**

Normally, the tympanic membrane has a ground-glass appearance; a blue or yellow color usually indicates a middle-ear effusion seen through a translucent tympanic membrane. A red tympanic membrane alone may not be indicative of a pathologic condition because the blood vessels of the drum head may be engorged as a result of the patient’s crying, sneezing, or nose
blowing. It is critical to distinguish between translucency and opacification of the eardrum to identify a middle-ear effusion. The normal tympanic membrane should be translucent, and the observer should be able to look through the drum and visualize the middle-ear landmarks (the incudostapedial joint promontory, the round window niche, and, frequently, the chorda tympani nerve). When middle-ear effusion is present medial to a translucent drum, an air-fluid level or bubbles of air admixed with the liquid may be visible. An air-fluid level or bubbles can be differentiated from scarring of the tympanic membrane by altering the position of the head while observing the drum with the otoscope (if fluid is present, the air-fluid level will shift in relation to gravity) or by seeing movement of the fluid during pneumatic otoscopy. The line frequently seen when a severely retracted membrane touches the cochlear promontory will disappear (the drum will pull away from the promontory) if sufficient negative pressure can be applied with the pneumatic otoscope. Inability to visualize the middle-ear structures indicates opacification of the drum, which is usually the result of thickening of the tympanic membrane, an effusion, or both.

**Tympanic Membrane Mobility and Middle-Ear Pressure**

To visualize a retracted tympanic membrane (atelectasis and retraction pocket notwithstanding) or to assess the mobility of the tympanic membrane, using the pneumatic otoscope is one of the simplest ways to diagnose abnormal pressures within the middle ear, which can provide some insight into Eustachian tube function. However, pneumatic otoscopy is not a Eustachian tube function test.

Abnormalities of the tympanic membrane and the middle ear are reflected in the pattern of tympanic membrane mobility when first positive and then negative pressure is applied to the external auditory canal with the pneumatic otoscope. As shown in Figure 8–5, this is achieved by first applying slight pressure on the rubber bulb (positive pressure) and then, after momentarily breaking the seal, releasing the bulb (negative pressure) (Figure 8–6). When the tympanic membrane and middle ear are normal, forceful application of positive and negative pressure (deeply depressing and releasing the thumb on the rubber bulb) can be painful, especially in children because the tympanic membrane is overdistended. If the tympanic membrane does not move when slight pressure is applied, more pressure is applied. The presence of effusion, high negative pressure, or both within the middle ear can markedly dampen the movements of the eardrum. Figure 8–7 shows the relationship between applied positive and negative pressures. When the middle-ear pressure is ambient, the normal tympanic membrane moves inward with slight positive pressure in the ear canal and outward with slight negative pressure. The motion observed is proportionate to the applied pressure and is best visualized in the posterosuperior quadrant of the tympanic membrane. If a two-layered membrane or an atrophic scar (owing to a healed perforation) is present, mobility of the tympanic membrane can also be assessed more readily by observing the movement of the flaccid area.

### Hypercompliant Tympanic Membrane

Movement of the tympanic membrane to the applied pressure from the rubber bulb attached to the otoscope can determine, in general, whether there is relatively normal or abnormal pressure within the middle ear, a possible effusion, or both (Figure 8–8). A hypermobile eardrum is seen most frequently when the tympanic membrane is either atrophic or flaccid. If the mobility of the tympanic

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**TO OBTAIN POSITIVE PRESSURE**

1. Insert speculum with no pressure on bulb
2. Depress bulb

**FIGURE 8–5.** To determine the response of the tympanic membrane to applied positive pressure, the rubber bulb is first pressed gently, which should deflect the tympanic membrane medially.

**To Obtain Negative Pressure:**

1. Insert speculum with bulb depressed
2. Release bulb

**FIGURE 8–6.** To determine the response of the tympanic membrane to applied negative pressure, the rubber bulb is depressed and then released, which should deflect the tympanic membrane laterally. The movement of the tympanic membrane is proportionate to the degree of pressure exerted on the bulb until the eardrum has reached its limit of compliance.
middle-ear pressure is even lower, there may be only slight out-
ward mobility of the tympanic membrane because of the limit-
ed negative pressure that can be exerted through the otoscopes
currently in use (see Figure 8–8, frame 5). If the eardrum is
severely retracted, owing to extremely high negative middle-ear
pressure, application of maximum negative pressure with the
rubber bulb will not produce significant outward movement (see
Figure 8–8, frame 6).

It is possible, with some experience, to make a reasonable
estimate of the degree of negative pressure in the middle ear.
Comparing the otoscopist’s estimate with the tympanometric
measurement of middle-ear pressure, which is a relatively accu-
rate “gold standard,” can improve the otoscopist’s expertise (see
Tympanometry).

Positive Middle-Ear Pressure A tympanic membrane that
exhibits fullness will move to applied positive pressure but not to
applied negative pressure if the pressure within the middle ear is
positive and if gas, with or without an effusion, is present (see
Figure 8–8, frame 7). In such an instance, the tympanic mem-
brane is stretched laterally to the point of maximal compliance
and will not visibly move outward any farther to the applied neg-
ative pressure; it will move inward to applied positive pressure as
long as some air is present within the middle ear–mastoid air cell
system. Positive middle-ear pressure has been identified in
infants who had no middle-ear effusion,3 which is most likely
secondary to insufflation of nasopharyngeal air into the middle
ear during crying. When this system is filled with an effusion and
little or no gas is present, the mobility of the bulging tympanic
membrane is severely decreased or absent to both applied posi-
tive and negative pressure (see Figure 8–8, frame 8).

Patulous Eustachian Tube Despite mobility of the tympanic
membrane being normal to applied positive and negative pres-
sures with an otoscope, there can still be dysfunction of the
tubal system, such as when the patient has a patulous Eustachian
tube (too open). When this occurs, the observer should be able
to detect slight movement of the tympanic membrane synchro-

Negative Middle-Ear Pressure Normal middle-ear pressure is
reflected by the neutral position of the tympanic membrane as
well as by its response to both positive and negative pressures
(described above). In other cases, the eardrum may be retracted,
usually because negative middle-ear pressure is present. The
compliant membrane is maximally retracted by even moderate
negative middle-ear pressure and hence cannot visibly be deflect-
ed inward further with applied positive pressure in the ear canal.
However, negative pressure produced by releasing the rubber
bulb of the otoscope will cause a return of the eardrum toward
the neutral position if a negative pressure equivalent to that in
the middle ear can be created by releasing the rubber bulb (see
Figure 8–8, frame 4). This is a condition that can occur when gas,
with or without an effusion, is present in the middle ear. When
middle-ear pressure is even lower, there may be only slight out-
ward mobility of the tympanic membrane because of the limited
negative pressure that can be exerted through the otoscopes
currently in use (see Figure 8–8, frame 5). If the eardrum is
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tube (too open). When this occurs, the observer should be able
to detect slight movement of the tympanic membrane synchro-
nous with respirations. When attempting to diagnose this dysfunction of the tube, it is important to have the patient in a sitting position because a patulous tube is usually asymptomatic while in the recumbent position (sleeping). This phenomenon is due to congestion of the Eustachian tube secondary to venous engorgement of the tube; veins of the head and neck have no valves, in contrast to the extremities.

**Nasopharyngoscopy and Endoscopy of the Eustachian Tube**

Indirect mirror examination of the nasopharyngeal end of the Eustachian tube system is also an old but still important part of the clinical assessment of a patient with middle-ear disease. This is especially true in adults, in whom a neoplasm in the fossa of Rosenmüller may be diagnosed. The development of endoscopic instruments has greatly improved the accuracy of this type of examination (Figure 8–9). The flexible fiberoptic telescope has been used to examine the Eustachian tube from the nasopharyngeal and middle-ear end of the tube (Figure 8–10). Figure 8–11 shows a nasopharyngeal carcinoma as viewed with the endoscope.

Not only can certain aspects of the structure of the Eustachian tube be determined with the aid of currently available instruments, but some investigators have assessed Eustachian tube function. Yagi and colleagues used a fiberscope—a photoelectric device (phototubometry) to evaluate the patency of the Eustachian tube. Takahashi and colleagues used transtympanic endoscopy to examine the protympanic (osseous) portion of the Eustachian tube to determine the presence (and degree) or absence of inflammation. Poe and colleagues, using slow-motion videoendoscopy of the Eustachian tube, assessed tubal function in 44 adults and observed inflammation of the tube and patulous tube dysfunction.

**Imaging of the Eustachian Tube**

In the past, many investigators used radiographs (with and without contrast media) to evaluate the middle ear and Eustachian tube (see Radiographic Studies of Protective and Clearance Functions), but only recently has imaging technology been used to better define the anatomy and pathology of the tubal system. Magnetic resonance imaging (MRI) has been used to visualize the Eustachian tube and to assess the Eustachian tube anatomy and pathology of patients with nasopharyngeal carcinoma. Also, MRI has been used to evaluate inflammation of the middle-ear cleft in animals. It has more accurately identified the effect on the middle-ear cleft of experimentally induced (botulinum toxin A) functional obstruction of the Eustachian tube.

Computed tomographic (CT) scans have been used to assess clearance function of the Eustachian tube. Others have used CT scans to assess the tube in normal subjects, in those who had otitis media, and in patients with a patulous Eustachian tube. But these imaging studies were static assessments of anatomy and clearance function of the tube, whereas standard fluoroscopy with contrast provided more dynamic studies, such as those by Bluestone and Honjo and colleagues. In the near future, dynamic imaging should become available, which should provide greater insight into not only the anatomy and pathology of the tubal system but also its pressure regulation, protective, and clearance functions (see Chapter 11, “Future Directions”).

**Tests of Pressure Regulation Function of the Eustachian Tube**

In addition to the otoscopic examination, which includes assessment of middle-ear pressure using the pneumatic attachment,
FIGURE 8–9. Artist’s drawing of a flexible fiberoptic nasopharyngoscope inserted intranasally to examine the nasal cavities, nasopharynx, fossae of Rosenmüller, and pharyngeal orifices of the Eustachian tubes.

FIGURE 8–10. Photograph of the nasopharyngeal orifice of the Eustachian tube obtained with an endoscope.

FIGURE 8–11. Photograph of a nasopharyngeal carcinoma obtained with an endoscope.
there are tests that can assess the pressure regulation (ventilation) function of the Eustachian tube system. Some of the tests are employed when the tympanic membrane is intact (tympanometry), whereas others are used when there is a nonintact eardrum (forced-response test). Still others can be used irrespective of the integrity of the tympanic membrane (sonotubometry).

When the tympanic membrane is intact, the microlow technique or an impedance method (both of which require a pressure chamber), sonotubometry, sequential scintigraphy, microendoscopy, or directly inserting a balloon catheter into the cartilaginous Eustachian tube may be used. When the tympanic membrane is not intact, the forced-response test may be used. Sonotubometry is currently in use in routine research studies but is not yet available for clinical use. A new measurement of Eustachian tube mechanical properties using a modified forced-response test is currently being tested in animals and humans. Kumazawa and colleagues devised the using a modified forced-response test is currently being tested in research studies but is not yet available for clinical use.  A more accurate method of assessing changes in middle-ear pressure is tympanometry, but because the positive pressure created in the middle ear for such a test may only be momentary—inflation followed by immediate equilibration before tubal closing—the alteration in middle-ear pressure may not be visualized or recorded by tympanometry. When the tympanic membrane is not intact, the sound of the air entering the middle ear can be heard with a stethoscope or with the Toynbee tube (a rubber tube with an olive tip at either end, one for the patient’s test ear and one for the ear of the examiner). However, these methods are outmoded, and measurements are now made with a manometric system or tympanometry, preferably one equipped with a strip chart recorder.

Unfortunately, regardless of the testing technique or method of assessment, the Valsalva’s test results are not reliable indicators of Eustachian tube pressure regulation function. When positive, they indicate only an anatomically patent and probably distensible Eustachian tube. Indeed, without inflation of the middle ear during this test, no useful information concerning tubal function is obtained. Elner and colleagues found that 85% of 101 adults with normal ears had positive results on Valsalva’s test.

**Classic Tests**

Prior to the 1960s, most tests of the pressure regulation function of the Eustachian tube were, in reality, only assessments of the tubal patency. The classic methods of Valsalva, Politzer, and Toynbee for assessing the Eustachian tube are still in use today, as is catheterization of the Eustachian tube. But of these tests, the Toynbee, albeit crude, provides some insight into the patient’s Eustachian tube regulatory function. These tests are traditionally used when the tympanic membrane is intact, but some are used when the eardrum is not intact, such as Valsalva’s test.

**Valsalva’s Test**

The effect of high positive nasopharyngeal pressures at the proximal end of the Eustachian tube system can be evaluated qualitatively by Valsalva’s test. The test results are considered to be positive (normal) when the Eustachian tube and middle ear can be inflated by a forced expiration (with the mouth closed and the nose held by the thumb and forefinger) (Figure 8–12). The amount of overpressure thus created is variable and may be as much as 2,000 mm H₂O.

When the tympanic membrane is intact, the overpressure in the middle ear can be observed as a bulging tympanic membrane by visual inspection of the tympanic membrane with a pneumatic otoscope or, more precisely, with the aid of the otomicroscope and a nonmagnifying Bruening or Siegle otoscope. The tympanic membrane moves inward when positive canal pressure is applied, but outward mobility in response to applied negative canal pressure is decreased or absent if positive pressure is present within the middle ear.

A more accurate method of assessing changes in middle-ear pressure is tympanometry, but because the positive pressure
into the middle ear (see Chapter 9). However, the use of this method as a test or treatment is limited in children because it can be frightening and difficult to perform in the awake child.

**Toynbee Test**

In performing the Toynbee test, the subject is asked to swallow when the nose is manually compressed (Figure 8–15). This maneuver usually creates a positive pressure within the nasopharynx, followed by a negative pressure phase.\(^1\) If the Eustachian tube opens during the test, the middle-ear pressure changes; the way in which it changes is determined by the timing of the tubal opening and the nasopharyngeal pressure gradient.

Change in middle-ear pressure is assessed on the Toynbee test in the same way that it is assessed on Valsalva’s test. If negative pressure is present within the middle ear, the tympanic membrane will be retracted and will not move inward to applied positive pressure with the pneumatic otoscope. It will move outward to applied negative pressure if the pressure applied exceeds the negative pressure within the middle ear.

The test results are usually considered positive when there is an alteration in the middle-ear pressure. Negative middle-ear pressure after the Toynbee test or only momentary negative middle-ear pressure followed by normal middle-ear gas pressure usually indicates good tubal function because it shows that the Eustachian tube can open actively (the tensor veli palatini muscle contracts) and that the tubal structure is sufficiently stiff to withstand nasopharyngeal negative pressure.

When the tympanic membrane is intact, tympanometry can be used to assess the outcome of the test (Figure 8–16). However, some abnormal Eustachian tubes that are either patulous or have low tubal resistance may transfer gas from the middle ear into the nasopharynx during the Toynbee test (as they may with sniffing). The finding of only positive middle-ear pressure signifies tubal patency but does not have the same significance, as does even transitory negative pressure. When the tympanic membrane is not intact, the manometer of the immittance instrument can be observed to determine middle-ear pressure.

Unfortunately, the absence of any alteration in middle-ear pressure during the Toynbee test does not indicate poor Eustachian tube function. Zollner and Thomsen reported that 30% of the adults with negative examination findings had normal results on the Toynbee test\(^1\).\(^2\)\(^,\)\(^3\)

In the study by Elner and colleagues, the results of the Toynbee test were positive in 79% of normal adults.\(^3\)\(^8\) Cantekin and colleagues reported that only 7 of 106 ears (6.6%) of subjects (mostly children) who had had tympanostomy tubes inserted for otitis media could show positive results when given a modification of the Toynbee test (closed-nose equilibration attempt with applied negative middle-ear pressure of 100 or 200 mm H\(_2\)O).\(^4\)\(^4\) Likewise, in a series of patients, most of whom were older children and adults with chronic perforations of the tympanic membrane, only 3 of 21 (14.3%) passed the test.\(^4\)\(^4\) However, in children with a traumatic perforation of the tympanic membrane but who otherwise had a negative otologic history, 3 of 10 (30%) could pass the test.\(^4\)^\(^,\)^\(^4\) In the study by Bluestone and colleagues of “normal” children with traumatic perforations, six of seven children could change the middle-ear pressure, but none of the 21 ears of children who had a retraction pocket or a cholesteatoma showed pressure change.\(^4\)\(^5\) The test is of greater value in determining normal or abnormal Eustachian tube function in adults than it is in children. The test is still of considerable value because, regardless of age, if negative pressure develops in the middle ear during or following the test, the Eustachian tube function is most likely normal because the Eustachian tube actively opens and is sufficiently stiff to withstand nasopharyngeal negative pressure (it does not “lock”). If positive pressure is noted or no change in pressure occurs, the function of the Eustachian tube may still be normal, and other tests of Eustachian tube function should be performed.

**Tests of Pressure Regulation Function When the Tympanic Membrane Is Intact**

Eustachian tube function in individuals with intact tympanic membranes may be determined by manometry, tympanometry,
FIGURE 8–15. The Toynbee test of Eustachian tube function. Closed-nose swallowing results first in positive pressure in the nose and nasopharynx, followed by a negative pressure phase. When positive pressure is in the nasopharynx, air may enter the middle ear, creating positive pressure. During or after the negative pressure phase, negative pressure may develop in the middle ear, positive pressure may still be in the middle ear (no change in middle-ear pressure during negative phase), positive pressure may be followed by negative middle-ear pressure, or ambient pressure will be present if equilibration takes place before the tube closes. If the tube does not open during the positive or negative phase, no change in middle-ear pressure will occur.
or sonotubometry. A pressure chamber may or may not be necessary for testing.

**Pressure Chamber Methodology**

Middle-ear pressure is measured indirectly by the response to pressure changes in a pressure chamber. Decompression of the chamber creates relative positive pressure in the middle ear, whereas chamber compression results in relative negative pressure in the middle ear.

Investigation of Eustachian tube function by means of pressure chambers dates back more than a century to 1864, when Magnus first reported his findings on tubal function in a diving bell.46 By using rising external pressures, Magnus was able to make several observations:

- He confirmed Toynbee’s assumption that the Eustachian tube is closed under normal conditions.
- He realized the importance of deglutition for the opening of the tube.
- He noted that if the pressure difference between the middle ear and the bell became too pronounced (relative negative pressure in the middle ear), it could not be equilibrated by swallowing.

These findings were confirmed by Mach and Kessel when they conducted experiments in a primitive pressure chamber.47 Their chamber consisted of a wooden box in which the pressure could be varied between −200 and −140 mm H₂O with the aid of an organ pump. Since that time, pressure chambers have been used to test the function of the Eustachian tube. In 1958, Thomsen reported using a pressure chamber using tympanometry, which is described below.43

**Microflow Technique** Early volume displacement measurements of the tympanic membrane were done by means of closed manometry in the external ear, with simultaneous direct measurements of middle-ear pressure. This was abandoned as a clinical procedure because of the difficulties encountered in direct measurements, which were usually made by inserting a mandarin needle into the middle-ear cavity. Later, however, tympanic membrane displacements were recorded by use of microflow techniques. When the drum is moving, airflow is produced in the external ear canal. This flow is recorded by a flowmeter and then integrated to give quantitative measurements of volume displacement. Displacements as small as 1 µL have been recorded with up to 95% accuracy.

The microflow method was the only method used to assess normal Eustachian tube function quantitatively in adults who had intact tympanic membranes (see Chapter 4).38,48–50 This technique permits continuous recording of the volume deviation of the tympanic membrane resulting from changes in ambient pressure and changes in pressure within the middle ear. During the test, the tympanic membrane is in permanent and free contact with ambient air (Figure 8–17).

Under an otomicroscope, the subject is fitted with a catheter through a rubber disk inserted into the bony part of the ear canal. The rubber disk maintains an airtight seal with the canal walls. The air cushion between the tympanic membrane and the disk is connected to a sensitive flowmeter through the catheter; the other end of the flowmeter is open to ambient air. An identical flowmeter is connected to a reference volume simulating the air cushion volume between the tympanic membrane and the rubber disk seal. The signal from the reference flowmeter is subtracted from that of the ear canal flowmeter, compensating for the flow changes owing to compression or expansion of air in the pressure chamber. This corrected airflow rate is integrated to obtain the volume displacement of the tympanic membrane. Then, by changing the ambient pressure in the chamber, the tympanic membrane displacement as a function of middle-ear pressure is obtained.

In this way, this procedure calibrates the tympanic membrane as a pressure transducer so that after this measurement has been made, the subjects can be tested for their abilities to equilibrate various middle-ear pressures created by changes in...
chamber pressure. Within the elastic limits of the tympanic membrane (±150 mm H₂O pressure differential between the middle ear and ear canal), an accurate inflation-deflation test can be conducted. However, because this technique requires a pressure chamber and sophisticated equipment, it is practical only for use in research centers.

Tympanometry

Determination of middle-ear pressure and acoustic immittance using electroacoustic impedance equipment were introduced by Metz about 50 years ago.5 These same techniques have been used to perform tympanometry, which is the measurement of the acoustic driving-point immittance as a function of the static pressure in the canal. If low-frequency tones are used for the measurement, the static pressure that produces the maximal acoustic immittance is approximately equal to the gas pressure in the middle ear.

**Tympanometry in a Pressure Chamber**

Thomsen adapted the acoustic impedance method for use in a pressure chamber.43 He varied the chamber pressure and measured the percentage of absorption of a tone presented into the ear canal. He found that there was a fall in absorption as the pressure difference between the middle ear and the chamber was increased. The absorption reached a peak when the two pressures were identical. Unfortunately, Thomsen's technique failed to account for the change in middle-ear pressure caused by the measurement procedure. As the pressure in the chamber is varied (in search of maximal loudness or absorption), the tympanic membrane moves from its original position to a new position, thus changing the volume of the middle-ear cavity. However, according to Boyle's law, as the volume of the cavity changes, the pressure must also change. Thus, by knowing the volume displacement and "measuring" the final pressure, the original pressure can be deduced.

Bylander used tympanometry with a pressure chamber to evaluate Eustachian tube function in normal children.23 In this method, the resting middle-ear pressure is obtained from the initial tympanogram. Then the chamber pressure is lowered to −100 mm H₂O relative to ambient pressure, and a second tympanogram is obtained, verifying the relative overpressure in the middle ear. After this deglutition of the subject, a tympanogram is recorded to determine middle-ear pressure. The same procedure is repeated with 100 mm H₂O relative overpressure in the chamber to assess the subject’s ability to actively equilibrate relative underpressure in the middle ear. With use of this method, the inflation-deflation test was conducted on 50 children, and the results were compared with the results of tests that measured tubal function in adults. In this way, the first database for tubal function in otologically normal children was established.

Shupak and colleagues also used tympanometry inside a pressure chamber to assess the ability of naval scuba divers to equilibrate negative middle-ear pressure.52

**Using an immittance instrument to obtain a tympanogram is an excellent way of determining the status of the tympanic membrane–middle-ear system, and it can be helpful in assessing Eustachian tube function.**44 In 1973, my colleagues and I reported that tympanometry was an excellent method to detect middle-ear effusions in children after we compared it with otoscopy and the findings at myringotomy as the “gold standard” and found audiometry to be a poor test of the presence or absence of middle-ear effusion.55 (This report was selected as 1 of the 12 “classic” articles of the past 100 years for the centenary celebration of *Laryngoscope* and republished in that journal in 1996.)

There are several methods for the clinical evaluation of Eustachian tube function by tympanometry without the need of a pressure chamber. Each of these methods is based on an indirect determination of middle-ear pressure under various conditions. The pressure is, of course, obtained by finding the peak in the tympanogram. However, only relative qualitative information can be obtained by use of these methods. If the subject fails to induce pressure changes in the middle ear, tubal function...
cannot be evaluated. Therefore, no truly satisfactory clinical test is indicative of tubal function in subjects with intact tympanic membranes.

**Resting pressure.** When the tympanic membrane is intact, tympanometry is a reliable method to determine the middle-ear pressure in the absence of a severely distorted tympanic membrane. Figure 8–19 is a tympanogram of a patient with normal middle-ear resting pressure. But one test represents the middle-ear pressure only at one moment. A single measurement of normal resting middle-ear pressure does not necessarily indicate normal Eustachian tube function, but a measurement of negative middle-ear pressure is presumptive evidence of Eustachian tube dysfunction. Serial determinations are more indicative of the dynamics of tubal function in a single patient. Therefore, the chief drawback of this procedure is that it gives no indication of the pressure regulation function of the Eustachian tube under various conditions of induced middle-ear pressure. For this reason, the remaining tests using tympanometry were developed (see later in this section).

A resting pressure that is highly negative is associated with some degree of Eustachian tube obstruction, but the presence of normal middle-ear pressure does not necessarily indicate normal Eustachian tube function; a normal tympanogram is obtained when the Eustachian tube is patulous (see Patulous Eustachian Tube Test).

The presence of a middle-ear effusion or high negative middle-ear pressure determined by this method usually indicates impaired Eustachian tube function. Figure 8–20 is a tympanogram of a patient with high negative middle-ear resting pressure, which is indicative of obstruction of the Eustachian tube. (Such obstruction may be functional, mechanical, or both.) However, unlike the otoscopic evaluation, tympanometry is an objective way of determining the degree of middle-ear negative pressure. Unfortunately, assessing the abnormality of values of negative pressure is not so simple: high negative pressure may be present in some patients, especially children who are asymptomatic and who have relatively good hearing. In others, symptoms such as hearing loss, otalgia, vertigo, and tinnitus may be associated with modest degrees of negative pressure or even with normal middle-ear pressures. The middle-ear air pressure may depend on the time of day, season of the year, or condition of the other parts of the system, such as the presence of an upper respiratory tract infection. For instance, a young child with a common cold may have transitory high negative middle-ear pressure while he or she has the cold but may otherwise be otologically normal. The decision as to whether high negative pressure is abnormal or is only a physiologic variation should be made taking into consideration the presence or absence of signs and symptoms of middle-ear disease. If severe atelectasis or adhesive otitis media of the tympanic membrane–middle-ear system is present, the tympanogram may not be a reliable indicator of the actual pressure within the middle ear.

**Toynbee and Valsalva’s tests.** A method for measuring Eustachian tube function involves the Toynbee and Valsalva’s tests. This procedure gives a semiquantitative indication of the ability of the Eustachian tube to equilibrate established overpressures and underpressures in the middle ear. Figure 8–21 shows the sequence of steps in these tests. First, a tympanogram is obtained to determine the resting middle-ear pressure. Then the subject is asked to perform a Toynbee maneuver, which normally leads to negative pressure in the middle ear. If the maneuver is successful in inducing negative middle-ear pressure, then the subject is asked to swallow in an attempt to equilibrate the negative pressure. A third tympanogram is recorded to determine whether the equilibration was successful and, if so, to what degree. If the equilibration was not complete, the subject is asked to swallow repeatedly. A tympanogram is recorded between each swallow to monitor the progressive equilibration. The pressure remaining in the middle ear after several swallows is termed residual negative pressure. A similar approach is used...
FIGURE 8–19. Tympanogram that shows normal middle-ear resting pressure.

FIGURE 8–20. Tympanogram that shows high negative middle-ear pressure.

FIGURE 8–21. Tympanograms of the Toynbee and Valsalva's tests of Eustachian tube function when the tympanic membrane is intact.
with the Valsalva’s (or Politzer air bag) maneuver to test for the tube’s ability to equilibrate overpressure in the middle ear.

These combined tests are most significant if the subject is able to develop negative pressure within the middle ear during the Toynbee test and then is able to equilibrate the negative pressure to the initial resting pressure. This indicates excellent function of the Eustachian tube. However, inability to develop negative middle-ear pressure after the Toynbee test or positive intratympanic pressure after the Valsalva’s test does not differentiate between normal and abnormal tubal function. One obvious problem with these tests is that it is impossible to control the relative amounts of overpressure and underpressure generated in each individual. (In fact, some individuals fail to generate negative pressure during the Toynbee maneuver.) To overcome this difficulty, the following tests were developed:

**Holmquist’s method.** A test developed principally by Holmquist, it measures the ability of the Eustachian tube to equilibrate induced negative middle-ear pressures.\(^{39,60}\) The test procedure involves five steps:

1. A tympanogram is recorded to determine the initial middle-ear pressure.
2. A negative pressure is created in the nasopharynx by a pressure device connected to the nose, and the subject is asked to swallow to establish a negative pressure of about \(-200\) mm H\(_2\)O in the middle ear.
3. A second tympanogram is recorded to evaluate the exact negative middle-ear pressure achieved.
4. The patient is told to swallow repeatedly (if the tube opens, the pressure is equalized).
5. A third tympanogram is recorded to register the final middle-ear pressure.

Holmquist did not describe a similar procedure for testing equilibrating capacity with induced positive pressures. Siedentop and colleagues described the difficulties encountered in using this method and concluded that many subjects could not be tested by this method even though they had normal tympanic membranes and negative otologic histories.\(^{61}\)

**Patulous Eustachian tube test.** If a patulous Eustachian tube is suspected, the diagnosis can be confirmed by otoscopy or objectively by tympanometry when the tympanic membrane is intact.\(^4\) One tympanogram is obtained while the patient is breathing normally, and a second is obtained while the patient is holding his or her breath. Fluctuation of the tympanometric trace that coincides with breathing confirms the diagnosis of a patulous tube. Fluctuation can be exaggerated by asking the patient to occlude one nostril with the mouth closed during forced inspiration and expiration or by performing the Toynbee maneuver. When the tympanic membrane is not intact, a patulous Eustachian tube can be identified by the free flow of air into and out of the Eustachian tube by using the pump-manometer portion of the electroacoustic impedance bridge. These tests should not be performed while the patient is in a reclining position because the patulous Eustachian tube will close.\(^4\) If a patulous Eustachian tube is suspected, the diagnosis can be confirmed by tympanometry when the tympanic membrane is intact. One tympanogram is obtained while the patient is breathing normally, and a second is obtained while the patient holds the breath. The fluctuation in the tympanometric line should coincide with breathing (Figure 8–22). The fluctuation can be exaggerated by asking the patient to occlude one nostril with the mouth closed during forced inspiration and expiration or by the Toynbee test (Figure 8–23). Figure 8–24 shows the outcomes of normal testing compared with testing of an individual with a patulous Eustachian tube, in which a strip chart recording is used for the tympanometry. Others have also used a strip chart recording to identify a patulous Eustachian tube in patients.\(^{62}\)

**Bluestone’s nine-step test.** Another method of measuring Eustachian tube function is an inflation-deflation test developed by Bluestone,\(^{58}\) although the applied middle-ear pressures are limited in magnitude. This test is currently used in our clinics, as well as others, to test Eustachian tube function when the tympanic membrane is intact. The middle ear must be free of effusion. The nine-step tympanometry procedure (Figure 8–25) may be summarized as follows:

1. The tympanogram records resting middle-ear pressure.
2. Ear canal pressure is increased to \(+200\) mm H\(_2\)O with medial deflection of the tympanic membrane and a corresponding increase in middle-ear pressure. The subject swallows to equilibrate middle-ear overpressure.
3. While the subject refrains from swallowing, ear canal pressure is returned to normal, thus establishing a slight negative middle-ear pressure (as the tympanic membrane moves outward). The tympanogram documents the established middle-ear underpressure.
4. The subject swallows in an attempt to equilibrate negative middle-ear pressure. If equilibration is successful, airflow is from the nasopharynx to the middle ear.
5. The tympanogram records the extent of equilibration.
6. Ear canal pressure is decreased to \(-200\) mm H\(_2\)O, causing a lateral deflection of the tympanic membrane and a corresponding decrease in middle-ear pressure. The subject swallows to equilibrate negative middle-ear pressure; airflow is from the nasopharynx to the middle ear.
7. The subject refrains from swallowing while external ear canal pressure is returned to normal, thus establishing a slight positive pressure in the middle ear as the tympanic
membrane moves medially. The tympanogram records the overpressure established.

8. The subject swallows to reduce overpressure. If equilibration is successful, airflow is from the middle ear to the nasopharynx.

9. The final tympanogram documents the extent of equilibration.

The test is simple to perform, can give useful information regarding Eustachian tube function, and should be part of the clinical evaluation of patients with suspected Eustachian tube dysfunction. In general, most normal adults can perform all or some parts of this test, but even some normal children have difficulty in performing it. However, if any patient can pass some or all of the steps, Eustachian tube function is considered good.

The test has been used in clinical studies in our center. McBride and colleagues assessed Eustachian tube function in a normal population of 107 college-age subjects using two noninvasive methods, the Bluestone nine-step inflation-deflation test and sonotubometry (see Sonotubometry).26 The results showed a 78% agreement between the two methods when one test was performed, but the combination of the two tests identified 96% of the normal subjects as having tubal function. Other investigators have also used this test or a modification of it.63

**Tympanic membrane volume displacement.** A relatively new modification of the tympanometric method to assess the middle ear when the tympanic membrane is intact combines static compliance by tympanometric versus dynamic compliance of the pressure-volume relationship and other components of tympanometry.64 Although not strictly a test of Eustachian tube function, these investigators have assessed the biomechanical characteristics of the middle-ear system.

**Sonotubometry**

Conduction of sound through the Eustachian tube was first reported by Politzer.65 He observed that the sound of a tuning fork placed near the nose appeared to increase in amplitude during swallowing. He concluded that this sound must have been traveling through the Eustachian tube, which opens during swallowing. Politzer’s findings were soon forgotten, and it was not until 1932 that sound conduction through the Eustachian tube was reported again, this time by Gyergyay.66 He used various musical instruments to generate a sound that was introduced into the nose. He verified Politzer’s experiments but concluded that the Eustachian tube opens only intermittently during swallowing.

In 1939, Perlman studied sound conduction through the Eustachian tube by introducing a 500 Hz tone through a tube to the nostril of his subjects.67 By placing a microphone in the ear canal of his subjects and recording the test sound, he was able to detect tubal opening. His results provided some information on tubal opening time but were too varied to be useful. Little work was done until 1951, when Perlman repeated his earlier studies.41 This time, he reduced the tone frequency to 100 Hz, and by recording the output of the microphone, he was better able to assess the duration of tubal opening. He observed increases in sound pressure levels of up to 20 dB during swallowing. These measurements by Perlman were instrumental in the development of sonotubometry.

Elpern and colleagues used a 200 Hz tone as the sound source in experiments in Eustachian tube conduction of sound.68 They catheterized the Eustachian tube with a thin polyethylene tube to verify that the sound was presented only to the

![Figure 8–22. Tympanogram showing a trace of patulous Eustachian tube when the patient is breath-holding (steady line) and when breathing (wavy line), indicating that the tube is open at rest and transferring air from the nasopharynx to the middle ear.](image)

![Figure 8–23. Tympanogram showing wide fluctuations when the patient swallowed several times with the mouth and nose closed (Toynbee test), indicating that the patulous Eustachian tube was open, when compared with the resting tympanogram (steady trace).](image)
tube and were able to show that the sound indeed traveled through the Eustachian tube during swallowing.

In 1966, Guillerm and colleagues repeated Perlman's procedure using a 100 Hz tone but made one important modification.69 They varied the pressure in the nasopharynx with the aid of an air pump and recorded the sound conduction and pressure change in the middle ear through a Foley catheter that was sealed at the external ear canal. If the Eustachian tube opened during swallowing, both sound and pressure changes were recorded; conversely, if the tube did not open, neither was recorded. This procedure, known as sonomanometry, was used later by Venker and Pieraggi.70,71

Naunton and Galluser developed a Eustachian tube analyzer that used a 200 Hz tone to analyze the theoretical vector of the response.72 Satoh and colleagues conducted experiments using 1,930 Hz as the test frequency.73 Then, in 1975, Eguchi constructed a model of the Eustachian tube and conducted similar tests using 2,000 Hz.74

The selection of the test frequency had been somewhat arbitrary up to this point; each experimenter had chosen a frequency believed to overcome the technical difficulties of the measurement, but little thought had been given to selecting the frequency (or frequencies) at which the maximal amount of sound would be transmitted through the open Eustachian tube. All of the frequencies used were 2,000 Hz or below.

In 1977, Virtanen conducted experiments using a wide set of frequencies.75 He chose single tones at 1 kHz intervals between 1 and 20 kHz and found that sound conduction through the Eustachian tube appeared to be best at 6, 7, and 8 kHz. He also recorded the physiologic noise owing to swallowing and found it to be significant up to 5 kHz. This led him to conclude that recordings of sound conduction using test frequencies below 5 kHz were invalid because they are distorted by the physiologic noise of swallowing.

Pilot studies were conducted with use of white noise as the stimulus.75 When white noise is used, no a priori assump-
tions are made about which test frequencies are most suitable. The results of these pilot studies were in agreement with those of Virtanen. On the basis of these results, it appears that sound conduction may be a reliable test to indicate tubal function. We successfully used this noninvasive method to assess tubal opening in the human.

Figure 8–26 shows the system used in our laboratory for testing Eustachian tube function by sonotubometry, and Figure 8–27 shows the basic method to determine if tubal opening occurs. In a comparison study of normal volunteers, two noninvasive tests of tubal function when the tympanic membrane is intact were compared: the Bluestone nine-step inflation-deflation test and sonotubometry. The latter was considered to be more physiologic than the former, although both provided useful information. The sonotubometry method is currently used to study the effect of viral upper tract infections on the function of the Eustachian tube in adult volunteers in our center by Doyle and colleagues (see Chapter 6, "Pathogenesis").

Tests of Pressure Regulation Function When the Tympanic Membrane Is Not Intact

The pressure regulation function of the Eustachian tube system can be directly assessed when the tympanic membrane is not intact. Although not strictly physiologic because the middle ear is open, these tests can distinguish normal from abnormal function. Several tests have been developed over the years, but we use two tests in humans and animals that employ manometry: the inflation-deflation and the forced-response tests.

Modified Inflation-Deflation Test

When a perforation of the tympanic membrane or a tympanostomy tube is present, inflation-deflation tests to measure the ventilatory function of the Eustachian tube can be performed in the clinical setting with the pump-manometer portion of an electroacoustic immittance audiometer (see Figure 8–18) or a controlled syringe pump and manometer (Figure 8–28).

Figure 8–29 is a simplified explanation of the combined passive and active function test when positive pressure is applied to the middle ear (inflation). This test is similar to ascending in an airplane until the Eustachian tube opens passively. It involves the application of enough positive pressure to the middle ear to force the Eustachian tube open. The pressure remaining in the middle ear after passive opening and closing is termed the closing pressure. Further equilibration of pressure is by swallowing (an active function), which is the result of contraction of the tensor veli palatini muscle. When the muscle contracts, the lumen of the Eustachian tube is opened and air flows down the tube. The pressures can be monitored on a strip chart recorder. The pressure remaining in the middle ear after passive and active function is termed the residual positive pressure.

Figure 8–30 shows the deflation phase of the study, which is similar to descent in an airplane. Low negative pressure is
applied to the middle ear and is then equilibrated by active tubal opening. The pressure remaining in the middle ear after swallowing is termed the *residual negative pressure*.

In certain instances, the ability of the tube to open actively in response to applied low positive pressure is also assessed (Figure 8–31). This is similar to ascent in an airplane to an altitude lower than a pressure that would force the Eustachian tube open. The patient is asked to swallow in an attempt to equilibrate the pressure by active function.

Figure 8–32 shows the symbols employed and examples of results obtained in ventilation studies. Figure 8–32A shows the results of a typical study in a patient with normal Eustachian tube function. After passive opening and closing of the Eustachian tube during the inflation phase of the study, the patient was able to completely equilibrate the remaining positive pressure. Active swallowing also completely equilibrated applied negative pressure (deflation). Figure 8–32B shows the results of a typical study in a child who had had otitis media with effusion. The Eustachian tube passively opened and closed after inflation, but subsequent swallowing failed to equilibrate the residual positive pressure. In the deflation phase of the study, the child was unable to equilibrate negative pressure. Inflation to a pressure below the opening pressure but above the closing pressure could not be equilibrated by the active swallowing function.

Failure to equilibrate the applied negative pressure indicates locking of the Eustachian tube during the test. This type of tube is considered to have increased compliance or to be floppy in comparison with the tube with perfect function.1,84,92,93 A stiff tube will neither distend in response to high positive pressures nor collapse in response to negative pressures; however, a tube that lacks stiffness is collapsed, and this, in turn, results in functional tubal obstruction. The tube collapses even further and may lock entirely in response to negative pressures; it may not open in response to low positive pressure, but as pressure progressively increases, it opens and may ultimately distend.

The speed of the application of the positive and negative pressure is an important variable in testing Eustachian tube function with the inflation-deflation test. The faster the positive pressure is applied, the higher the opening pressure is. During the deflation phase of the study, the faster the negative pressure is applied, the more likely it is that the “locking phenomenon”
will occur. Figure 8–33 compares the locking of the Eustachian tube when extremely high negative pressure is applied to the middle ear during the deflation part of the test procedure with that of a tire pump attached to a stiff and collapsible tube and balloon. The stiffer the tubing, the less likely it is that the tubal lumen will lock when low and high negative pressures are applied (and distend when positive pressure is applied). However, when the tube is floppy, as in the human, especially in infants and young children, the tube will distend and lock even with low positive and negative applied pressures.

Figure 8–34 illustrates elements of the procedures and the symbols used in recording the results of ventilatory studies in the clinical setting with an immittance instrument when a strip chart recorder is not available (i.e., when the pressures are noted on the manometer). Figure 8–34A is similar to Figure 8–32A; in Figure 8–34, however, the tube did not open passively. Depending on the type of electroacoustic impedance bridge, the pump-manometer may not produce pressures greater than 400 mm H₂O. The mean opening pressure for apparently normal subjects with a traumatic perforation and negative otologic history reported by Cantekin and colleagues was 330 mm H₂O (± 70 mm H₂O). Many Eustachian tubes open at pressures above 400 mm H₂O, which is above the limit of the manometers used in the most commonly available bridges. Again, the opening pressure is dependent on the speed of the pump. Figure 8–34B demonstrates functional obstruction of the Eustachian tube. The diagnosis of total mechanical obstruction of the Eustachian tube (air cannot flow out of or into the middle ear) cannot be made if the pressures cannot be elevated above 400 mm H₂O.

During each equilibration, the time interval between each swallow should be approximately 20 seconds to avoid strain on the pharyngeal muscles. The subject should swallow “dry,” but patients with reduced function of the Eustachian tube may need water to swallow.

Figure 8–35 shows the procedures employed in assessing the ventilatory function of the Eustachian tube with the equipment illustrated in Figure 8–28. The results are based on a four-part test in the following sequence:

1. Active opening of the tube
2. Passive opening of the tube during open-nose swallowing
3. Active opening of the tube during closed-nose swallowing (Toynbee maneuver)
4. Valsalva’s test

These tests of ventilatory function are more complete and provide more information than the more simplified testing procedure.

Even though the inflation-deflation test of Eustachian tube function is not strictly physiologic, the results are helpful in differentiating normal from abnormal function. If the test results reveal passive opening and closing within the normal range, if residual positive pressure can be completely equilibrated by swallowing, and if applied negative pressure can also be equilibrated, the function of the Eustachian tube can be considered to be normal. However, if the tube does not open to 1,000 mm H₂O, one can assume that total mechanical obstruction is present. This pressure is not hazardous to the middle ear or inner ear windows if the pressure is applied slowly. An extremely high opening pressure (greater than 500 to 600 mm H₂O) may indicate partial obstruction, whereas a low opening pressure (less than 100 mm H₂O) would indicate a semipatulous Eustachian tube. Inability to maintain even a modest positive pressure within the middle ear would be consistent with a patulous tube (open at rest). Complete equilibration by swallowing of applied negative pressure is usually associated with normal function, but partial equilibration or even failure to reduce any applied negative pressure may or may not be considered abnormal because even a normal
**Figure 8–29.** Test of passive and active function of the Eustachian tube following application of positive middle-ear pressure. A, Analogous ascent in an airplane. B, Assessment of passive function. C, Closing pressure. D, Assessment of active function (swallowing). E, Strip chart recording showing an example of normal pressure tracing. Black circles represent swallows.

**Figure 8–30.** Deflation phase of Eustachian tube testing. A, Analogous descent in an airplane. B, Application of low negative pressure to the middle ear. C, Equilibration by active tubal opening. D, Strip chart recording showing an example of a normal tracing. Black circles represent swallows.
The test appears to be quite reliable over time when compared with the forced-response test (see Forced-Response Test). Manometric testing with the inflation-deflation and forced-response testing has been reported to vary between the right and left ears in children who had middle-ear effusion. Modifications and additions of the inflation-deflation test have been used by several investigators over recent years. Bunne and colleagues added the sniff test to forced opening, pressure equalization, and Valsalva measurements.

A patulous Eustachian tube can be assessed with either this type of manometric system or the pump-manometer portion of the tympanometer. Figure 8–36 shows that compared with a normal tube, when positive pressure is applied in the inflation phase of the test, no pressure is maintained in the middle ear (there is no opening pressure).

The other end of the spectrum of dysfunction is when positive pressure is applied to the middle ear and the tube fails to open even at 1,000 mm H₂O. This finding is indicative of total anatomic obstruction somewhere in the Eustachian tube system and signals the need to perform nasopharyngoscopy and imaging of the skull base because tumor may be the cause. Figure 8–37 shows the CT scans of a teenager who had multiple congenital cholesteatomas in the skull base obstructing the Eustachian tube.

**Forced-Response Test**  We originally used the forced-response test to evaluate tubal function in the rhesus monkey animal model for normal and abnormal middle-ear ventilation; the same procedure was then used in the assessment of tubal func-
tion in human subjects. The current equipment and method to test Eustachian tube function in laboratories and clinics use the forced response. The tympanic membrane must be nonintact, and the middle ear should be without evidence of middle-ear inflammation. Figure 8–38 shows the equipment currently used in our laboratory. In the laboratory, we have used this method not only in the monkey but also in the ferret, which showed the tubal response to be similar to the primate and human tube.

Briefly, this method enables the investigator to study both passive and active responses of the Eustachian tube. The active response is due to the contractions of the tensor veli palatini muscle, which displaces the lateral walls from the cartilage-supported medial wall of the tube. Thus, the clinician can determine whether tubal dysfunction is due to the material properties of the tube or to a defective active opening mechanism. During this test, the middle ear is inflated at a constant flow rate, forcing the Eustachian tube open. After the forced opening of the tube, the pump continues to deliver a constant airflow, maintaining a steady stream of air through the tube. Then the subject is instructed to swallow for assessment of the active dilatation of the tube.

The method is unique in that it eliminates the "mucous forces" in the Eustachian tube lumen that may interfere with the results of the inflation-deflation test when an attempt is made to assess the active opening mechanisms and the compliance of the tube. In this test, the passive resistance is assessed, and the active resistance is determined during swallowing. Patients with non-intact tympanic membranes as a result of chronic perforation or tympanostomy tubes can be distinguished from apparently normal subjects with traumatic perforations of the tympanic mem-

brane and negative otologic histories. The ratio of the passive and active resistance correctly differentiates a normally functioning Eustachian tube from an abnormally functioning one. But van Heerbeek and colleagues compared the forced-response test results with the pressure equalization test (inflation-deflation) in children who had tympanostomy tubes in

FIGURE 8–33. Application of positive and negative pressure in the middle ear during the modified inflation-deflation Eustachian tube function test is compared with a tire pump attached to stiff and floppy tubing and a balloon (see text).

FIGURE 8–34. Procedure and symbols used in describing ventilatory (inflation-deflation) studies when a strip chart recorder is not employed. Two illustrative examples (A and B) are shown.
place and concluded that the pressure equalization test was more reliable over time than the forced-response test because the latter showed a downward shift with repeated measurements.94

To more accurately ascertain the tissue mechanical properties responsible for Eustachian tube dysfunction, Ghadiali and colleagues at our center developed a modified forced-response test, which correlates experimental pressure and flow rate measurements with a standard engineering model of flow in a collapsible tube.99 Correlation between model and experimental data yielded quantitative measurements of Eustachian tube compliance and hysteresis in juvenile monkeys. These authors have used this test to investigate how various physical components, such as the mucosal surface condition and muscle tension, influence Eustachian tube mechanics.99,101–103 They concluded that the engineering-based measure of compliance is more accurate than current summary parameters (tubal compliance index) and that knowledge of how specific physical components alter Eustachian tube function may lead to improved treatments that target the underlying mechanical abnormality.

Figure 8–39 schematizes the forced-response test in a normal subject and compares the results with two response patterns that are commonly seen in association with defects in active dilatation. Figure 8–40 describes the testing procedure in a normal subject compared with a patient who had had chronic otitis media with effusion, in which the testing reveals constriction (as opposed to dilation of the lumen) of the Eustachian tube during swallowing. Studies in a large number of patients with tympanostomy tubes in place or perforations owing to otitis media revealed that all of the abnormal ears either had poor active function (as demonstrated by weak or absent dilation of the Eustachian tube during swallowing activity) or constricted during swallowing. As described in Chapter 5, “Pathophysiology,” this is a common abnormality identified by the forced-response test in older children and adults.104 Constriction of the Eustachian tube with swallowing was found to occur in most children with a cleft palate77 and has been attributed to opposing

Figure 8–35. Sequence of procedures employed in assessing many aspects of the ventilatory function of the Eustachian tube. A. Active tubal function. After a hermetic seal is obtained in the ear canal, 200 mm H2O pressure is applied in the middle ear (inflation). The subject is then instructed to swallow to equilibrate. The pressure remaining in the middle ear after five consecutive swallows without a pressure change is termed the residual positive pressure (SWA+). Then −200 mm H2O is applied in the middle ear (deflation) and the patient is instructed to swallow. The pressure remaining in the middle ear after this test is termed the residual negative pressure (SWA−). B. Passive and active tubal function. The middle ear is inflated with a constant flow of air until the tube spontaneously opens, at which time the syringe pump is manually stopped. The first passive opening of the Eustachian tube by middle-ear overpressure is termed the opening pressure (OP1). After discharge of air through the Eustachian tube, the tube closes passively without a further decay in middle-ear pressure. This pressure is called the closing pressure (CL1). The patient is then instructed to swallow for further equilibration. The residual pressure after passive closing and swallowing is termed CL1+. The minimal residual positive pressure is the lowest recorded pressure remaining in the middle ear after active and passive equilibration of middle-ear overpressure (lowest value of CL1+ and SWA+). C. The Toynbee test. Active function of the tube during closed-nose swallowing is assessed by applying a positive pressure of 200 mm H2O in the middle ear and manually compressing the unattached naris. The opposite naris is connected to the pressure transducer to record the nasal pressure that developed during closed-nose swallowing. The residual positive pressure remaining in the middle ear after closed-nose swallowing (TOY+) is determined. Next, the middle-ear pressure is reduced to −200 mm H2O. The residual negative pressure remaining in the middle ear after closed-nose swallowing (TOY−) is noted. D, Valsalva’s test. Passive opening of the Eustachian tube by nasopharyngeal overpressure is observed by instructing the subject to blow against the obstructed nares—Valsalva’s maneuver—while the middle-ear pressure is ambient. The nasopharyngeal pressure corresponding to the first detectable change in middle-ear pressure is taken as the nasopharyngeal opening pressure of the Eustachian tube. If a residual positive pressure remains in the middle ear after the termination of nasopharyngeal overpressure, equilibration is attempted by open-nose swallowing. Irrespective of Eustachian tube opening, the maximal pressure achieved in the nasopharynx is also noted. ME = middle ear; NP = nasopharynx.
muscle force. This test was also done with Native Americans as subjects; they showed low resistance of the Eustachian tube. The forced-response test result appears to be more indicative of the active function of the Eustachian tube than the inflation-deflation test outcome.

Assessment of Protective and Clearance Functions of the Eustachian Tube System

Despite pressure regulation function being the most important of the three physiologic functions of the Eustachian tube (for maintenance of optimal hearing), the protective and clearance functions are also important in maintaining the physiologic state. The clearance and drainage functions of the Eustachian tube have been assessed by a variety of methods in the past. By means of radiographic techniques, the flow of contrast media from the middle ear (tympanic membrane not intact) into the nasopharynx has been assessed by Welin, Aschan, Compere, Parisier and Khilnani, Bluestone, Bluestone and colleagues, Ferber and Holmquist, and Honjo and colleagues. Rogers and colleagues instilled a solution of fluorescein into the middle ear and assessed the clearance function by subsequently examining the pharynx with an ultraviolet light. Rogers and colleagues used a radioisotope technique to monitor the flow of saline solution down the Eustachian tube. Bauer assessed clearance by observing methylene blue in the pharynx after it had been instilled into the middle ear. Elbrønd and Larsen assessed middle ear–Eustachian tube mucociliary flow by determining the time that elapsed after saccharin had been placed on the mucous membrane of the middle ear until the subject reported tasting it. Unfortunately, all of these methods are qualitative and actually test Eustachian tube patency rather than measure the clearance function of the tube quantitatively.

Radiographic Studies of Protective and Clearance Functions

As described in detail in Chapter 5, abnormalities of the protective function are directly related to the pathogenesis of otitis media. This function has been assessed only by radiographic techniques20,84,112: and by a test that was a modification of a tubal patency test described by Wittenborg and Neuhauser.

The protective and clearance functions of the Eustachian tube have been assessed by a combined radiographic technique. Radiopaque material was instilled through the noses of patients so that the retrograde flow of the medium from the nasopharynx into the Eustachian tube could be observed. As described in Chapter 4, patients were considered to have normal protective function when radiopaque material entered only the cartilaginous portion of the Eustachian tube to the isthmus and did not enter the bony portion of the tube or middle-ear cavity during swallowing. The normal Eustachian tube protected the middle ear from the contrast material even when the liquid was under increased nasopharyngeal pressure during closed-nose swallowing. If, during the retrograde study, contrast medium traversed the entire Eustachian tube and refluxed into the middle ear during swallowing, the tube was considered to have increased distensibility and poor protective function. Figure 8–41 shows the fluoroscopy method used (see Chapter 4 and Chapter 5).

The effectiveness of the Eustachian tube in clearing the radiopaque medium instilled into the middle ear was taken as an indication of the effectiveness of the Eustachian tube in the clearance of secretions. Rapid and complete clearance of the medium into the nasopharynx was considered to indicate normal drainage function, whereas failure of the contrast material to drain from the middle ear into the nasopharynx indicated mechanical obstruction of the Eustachian tube; this was termed prograde obstruction to flow (see Figure 5–20). This was observed when there was middle-ear inflammation obstructing the osseous (protympanic, middle ear) portion of the Eustachian tube. In some patients, contrast material failed to enter the nasopharyngeal portion of the tube during the retrograde study when hypertrophied adenoids were present and in
infants with an unrepaired cleft palate. These abnormal functions of the tube were found in patients with otitis media and were not found in a small group of normal subjects.

**Mucociliary Clearance**

Mucociliary clearance has been investigated for the past 50 years using a variety of methods (Table 8–1). Clearance has been studied by instilling radiopaque material into the middle ears of children whose tympanic membranes were not intact, when the material entered the middle ear (intact tympanic membrane) from the nasopharynx, measured with radioisotopic methods (e.g., technetium 99m) and sequential contrast CT, and following insertion of foreign material into the middle ear of animal models. Following placement of foreign material in humans with perforations of the tympanic membrane, Sadé reported that the anterior half to two-thirds of the middle-ear cavity had the most active clearance properties. Such material will flow toward the middle-ear portion of the Eustachian tube and out the tube. This movement is related to ciliary activity that occurs in the Eustachian tube and parts of the middle ear; these ciliated cells in the middle ear are increasingly more active as their location becomes more distal to the opening of the Eustachian tube.

**Muscular Clearance**

In a series of elegant experiments employing cineradiography by Honjo and colleagues, the Eustachian tube was shown to “pump” liquid out of the middle ear in both animal models and humans. These investigators also studied both the mucociliary and muscular clearance in the cat using various viscosities of colored liquid and showed that when the volume of middle-ear liquid was small, the fluid was cleared by the mucociliary system. When the volume of liquid was large and of low viscosity, it was cleared by muscular activity. Highly viscous fluid was cleared by both ciliary and muscular clearance. Also,
FIGURE 8–39. Example of forced-response test: \( P_O \), \( P_A \) pressure (upper panel); \( Q_O \), \( Q_A \) flow (lower panel).

FIGURE 8–40. For the forced-response test, the middle ear is inflated at a constant airflow rate until the Eustachian tube is passively opened. The upper panel shows a typical normal response when airflow is then maintained until steady states in airflow through the tube and in middle-ear pressure are observed. The subject is induced to swallow, and the changes in steady-state pressure and flow are recorded. The pump is then turned off, and the tube is allowed to close passively. In general, an attempt is made to define the values of the forced response for three rates of constant airflow: 12, 25, and 48 cc/min. The passive resistance to airflow is determined by dividing the steady-state pressure by the concurrent airflow through the tube. Similarly, active tubal resistance is determined by dividing the steady-state pressure by the maximal airflow recorded during the induced tubal dilations that accompany each swallow.

The lower panel shows an abnormal response, which is indicative of constriction of the Eustachian tube during swallowing, which is a common pathophysiologic phenomenon identified in patients who have chronic and recurrent otitis media.\(^{104}\) \( P_A \) = active pressure; \( P_O \) = passive pressure; \( Q_A \) = active flow; \( Q_O \) = passive flow.
clearance time was affected by viscosity in the mastoid, but not the middle ear, and clearance was more effective in the tympanic cavity than in the mastoid.\textsuperscript{126}

**Clinical Indications for Testing Eustachian Tube Function**

**Diagnosis**

One of the most important reasons for assessing Eustachian tube function is the need to make a differential diagnosis in a patient who has an intact tympanic membrane without evidence of otitis media but who has symptoms that might be related to Eustachian tube dysfunction (otalgia, snapping or popping in the ear, fluctuating hearing loss, tinnitus, or vertigo). An example of such a case would be a patient who complains of fullness in the ear without hearing loss at the time of the examination—a symptom that could be related to abnormal functioning of the Eustachian tube or due to an inner ear disorder. A tympanogram that reveals high negative pressure (\(-50\) mm H\textsubscript{2}O or less) is strong evidence of Eustachian tube obstruction, whereas normal resting middle-ear pressure is not diagnostically significant. However, when the resting intratympanic pressure is within normal limits and the patient can develop negative middle-ear pressure following the Toynbee test or can perform all or some of the functions in the Bluestone nine-step inflation-deflation tympanometric test, the Eustachian tube is probably functioning normally. Unfortunately, failure to develop negative middle-ear pressure during the Toynbee test or an inability to pass the nine-step test does not necessarily indicate poor Eustachian tube function because many children who are otologically normal cannot actively open their tubes during these tests. Tympanometry is not only of value in determining whether Eustachian tube obstruction is present, it can also identify abnormality at the other end of the spectrum of Eustachian tube dysfunction, and the presence of an abnormally patent Eustachian tube can be confirmed by the results of the tympanometric patulous tube test.

Screening for the presence of high negative pressure in certain high-risk populations (children with known sensorineural hearing losses, developmentally delayed and mentally impaired children, children with a cleft palate or other craniofacial anomalies, Native American and Eskimo children, and children with Down syndrome) appears to be helpful in identifying those individuals who may need to be monitored closely for the occurrence of otitis media.\textsuperscript{127}

Tympanometry appears to be a reliable method for detecting the presence of high negative pressure as well as otitis media with effusion in children.\textsuperscript{128,129} The identification of high negative pressure without effusion in children indicates some degree of Eustachian tube obstruction. These children and those with middle-ear effusions should have follow-up serial tympanograms because they may be at risk of developing otitis media with effusion.

However, the best methods available to the clinician today for testing Eustachian tube function are the Bluestone nine-step inflation-deflation test, when the eardrum is intact, or, when not intact, the inflation-deflation test. A perforation of the tympanic membrane or a tympanostomy tube must be present to perform the latter test. The test uses the simple apparatus described earlier, with or without the impedance audiometer pump-manometer system. This test will aid in determining the presence or absence of a dysfunction and the type of dysfunction (obstruction vs abnormal patency) and its severity when one is present. No other test procedures may be needed if the patient has either functional obstruction of the Eustachian tube or an abnormally patent tube. However, if there is a mechanical obstruction, especially if the tube appears to be totally blocked anatomically, then further testing may be indicated. In such instances, CT of the nasopharynx–Eustachian tube–middle-ear region can be performed to determine the site and cause of the blockage, such as a cholesteatoma or tumor. In most cases in which mechanical

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Original radiographic method used to determine flow of radiopaque media into the Eustachian tube (retrograde flow) from the nasopharynx and flow or dye from the middle ear into the Eustachian tube (prograde flow). The patient is in the submental-vertex position. Reproduced with permission from Bluestone CD.\textsuperscript{20}}
\end{figure}
obstruction of the tube is found, inflammation is present at the middle-ear end of the Eustachian tube (osseous portion), and this usually resolves with medical management, middle-ear surgery, or both. Serial inflation-deflation studies should show resolution of the mechanical obstruction. However, if no middle-ear cause is obvious, other studies should be performed to rule out the possibility of a neoplasm in the nasopharynx.

**Eustachian Tube Function Tests Related to Management**

It would be ideal to assess Eustachian tube function in patients who have recurrent acute otitis media, chronic otitis media with effusion, or both as part of their otolaryngic workup, but we do not have a test when a middle-ear effusion is present. Even though Takahashi and colleagues devised a method to use a microtip catheter pressure transducer through the Eustachian tube to directly measure middle-ear pressures when an effusion was in the middle ear, the procedure is invasive and not a test of tubal function. (In the future, it might be possible to use MRI; see Chapter 11). Nevertheless, for most patients with these diseases, one can assume Eustachian tube function to be poor. Patients in whom tympanostomy tubes have been inserted may be associated with improvement in Eustachian tube function. (In the future, it might be possible to use MRI; see Chapter 11). Nevertheless, for most patients with these diseases, one can assume Eustachian tube function to be poor. Patients in whom tympanostomy tubes have been inserted may benefit from serial Eustachian tube function studies. Improvement in function as indicated by inflation-deflation tests might help the clinician determine the proper time to remove the tubes. Cleft palate repair, adenoidectomy, elimination of nasal and nasopharyngeal inflammation, treatment of a nasopharyngeal tumor, or growth and development of a child may be associated with improvement in Eustachian tube function. Function tests have been found to be helpful in the management of patients who have dysfunction of the tubal system.

**Table 8–1. Methods Used to Assess Mucociliary Clearance Function of the Middle Ear–Eustachian Tube System in Humans and Animals**

<table>
<thead>
<tr>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiographic</td>
<td>Welin, 1947(^{106}); Compere, 1960(^{105}); Wittenborg and Neuhauser, 1963(^{118})</td>
</tr>
<tr>
<td>Fluorescein</td>
<td>Rogers et al, 1962(^{214})</td>
</tr>
<tr>
<td>Fluoroscopic with contrast materials</td>
<td>Bluestone, 1971(^{20})</td>
</tr>
<tr>
<td>Methylen blue</td>
<td>Bauer, 1975(^{116})</td>
</tr>
<tr>
<td>Saccharin</td>
<td>Elbrod and Larsen, 1976(^{117})</td>
</tr>
<tr>
<td>Foreign bodies</td>
<td>Albini et al, 1983(^{119}); Sadé, 1987(^{120})</td>
</tr>
<tr>
<td>Radioisotopic</td>
<td>LaFaye et al, 1974(^{115}); Karja and Nuutinen, 1987(^{121}); Takeuchi et al, 1990(^{122})</td>
</tr>
<tr>
<td>Sequential computed tomography with contrast material</td>
<td>Niwa et al, 1990(^{17})</td>
</tr>
</tbody>
</table>

Studies of the Eustachian tube function of the patient with a chronic perforation of the tympanic membrane may be helpful preoperatively in determining the potential results of tympanoplastic surgery. Holmqquist studied Eustachian tube function in adults before and after tympanoplasty and reported that the operation had a high rate of success in patients with good Eustachian tube function (those who could equilibrate applied negative pressure), but that in patients without good tubal function, surgery frequently failed to close the perforation. These results were corroborated, but other investigators found no correlation between the results of the inflation-deflation tests and success or failure of tympanoplasty. Most of these studies failed to define the criteria for “success,” and the postoperative follow-up period was too short. Bluestone and colleagues assessed children before tympanoplasty and found that of 51 ears of 45 children, 8 ears could equilibrate an applied negative pressure (−200 mm H\(_2\)O) to some degree. In seven of these ears, the graft took, no middle-ear effusion occurred, and no recurrence of the perforation developed during a follow-up period of between 1 and 2 years. A subsequent study by Manning and colleagues had a similar outcome. However, as in the studies in adults, failure to equilibrate an applied negative pressure did not predict failure of the tympanoplasty.

The conclusion to be drawn from these studies is that if the patient is able to equilibrate an applied negative pressure, regardless of age, the success of tympanoplasty is likely, but failure to perform this difficult test will not help the clinician in deciding not to operate. Nevertheless, the value of testing a patient’s ability to equilibrate negative pressure lies in the possibility of determining from the test results whether a young child is a candidate for tympanoplasty. On the basis of other findings alone, one might decide to withhold surgery until the child is older (see Chapter 10, “Role in Certain Complications and Sequelae of Otitis Media”).

**References**

9. Poe DS, Pykkö I, Valtonen H, Silvola J. Analysis of Eustachian tube func-


137. Lee K, Schuknecht HF. Results of tympanoplasty and mastoidectomy at the Massachusetts Eye and Ear Infirmary. Laryngoscope 1971;81:529–43.


Pneumatic otoscope with piece of rubber tubing on tip of peculum when meatus is large for adequate seal.
Otoscope with diagnostic head and rubber bulb for pneumatic otoscopy.
Use of rubber bulb attached to pneumatic otoscope to determine compliance (i.e., mobility of eardrum to positive or negative pressure)

Positive

Negative

Adapted with permission from Bluestone CD, Klein JO. Otitis Media in Infants and Children. Philadelphia, PA: WB Saunders Co. 1988

Otoscopic appearance of normal right tympanic membrane

Schematic showing landmarks of normal right tympanic membrane

Adapted with permission from Bluestone CD, Klein JO. Otitis Media in Infants and Children. Philadelphia, PA: WB Saunders Co. 1988
Pneumatic-otoscopic findings in common middle-ear conditions

Normal

<table>
<thead>
<tr>
<th>Position</th>
<th>Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translucency</td>
<td>Translucent</td>
</tr>
<tr>
<td>Color</td>
<td>Normal</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moves briskly with slight positive and negative pressure</td>
</tr>
</tbody>
</table>

Pneumatic-otoscopic findings in common middle-ear conditions

Negative middle-ear pressure

<table>
<thead>
<tr>
<th>Position</th>
<th>Retracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translucency</td>
<td>Translucent</td>
</tr>
<tr>
<td>Color</td>
<td>Normal</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moves only with applied negative pressure</td>
</tr>
</tbody>
</table>

Pneumatic-otoscopic findings in common middle-ear conditions

Fluid level

<table>
<thead>
<tr>
<th>Position</th>
<th>Retracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translucency</td>
<td>Translucent</td>
</tr>
<tr>
<td>Color</td>
<td>Normal</td>
</tr>
<tr>
<td>Mobility</td>
<td>Moves only with applied negative pressure, fluid level bubbles change</td>
</tr>
</tbody>
</table>
Pneumatic-otoscopic findings in common middle-ear conditions

**Otitis media with effusion**

<table>
<thead>
<tr>
<th>Position</th>
<th>Usually retracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translucency</td>
<td>Opaque (may be translucent)</td>
</tr>
<tr>
<td>Color</td>
<td>White (or yellow or blue)</td>
</tr>
<tr>
<td>Mobility</td>
<td>Poor when both positive and negative pressures are applied</td>
</tr>
</tbody>
</table>


**Acute otitis media**

<table>
<thead>
<tr>
<th>Position</th>
<th>Full to bulging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translucency</td>
<td>Opaque</td>
</tr>
<tr>
<td>Color</td>
<td>Red (can be pink, white, or yellow)</td>
</tr>
<tr>
<td>Mobility</td>
<td>Poor when both positive and negative pressure are applied</td>
</tr>
</tbody>
</table>


**Perforation (or patent tympanostomy tube)**

<table>
<thead>
<tr>
<th>Position</th>
<th>Neutral or retracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translucency</td>
<td>Translucent or opaque</td>
</tr>
<tr>
<td>Color</td>
<td>White, pink, red, or normal</td>
</tr>
<tr>
<td>Mobility</td>
<td>None</td>
</tr>
</tbody>
</table>

CT scan showing congenital cholesteatomas (arrow) in base of skull obstructing the tube.

Continuous Middle-ear Pressure

Pressure developed during forced-response test until steady-state.