Paparella: Volume I: Basic Sciences and Related Principles

Section 2: Physiology

Part 1: Ear

Chapter 6: Physiology of the Middle Ear and Eustachian Tube

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The middle ear is part of a functional system composed of the nasopharynx and eustachian tube (anteriorly) and the mastoid air cells (posteriorly) (Fig. 1). Knowledge of the anatomy and physiology of this system is necessary before the clinician can fully understand the pathophysiology of this area and the pathogenesis of diseases that affect it; the reader is also referred to Volume II, Chapter 26, "Diseases and Disorders of the Eustachian Tube - Middle Ear".

Anatomy of the Middle-Ear System

A description of the anatomy of the middle ear and its related structures follows as related to the physiology of the system; however, the reader is referred also to Chapter 2 in this volume.

Nasopharynx

The nasopharynx lies behind the nasal cavities and above the soft palate. Unlike the oral cavity, it is continually patent, and communication with the oral cavity is by means of the velopharyngeal port, which may be closed by elevation of the soft palate (its inferior boundary) and inward movement of the constrictor muscles of the oropharynx. On the lateral wall is a prominence, the torus tubarius, which protrudes into the nasopharynx. This prominence is formed by the abundant soft tissue overlying the cartilage of the eustachian tube. Anterior to the torus tubarius is the triangularly shaped nasopharyngeal orifice of the tube. From the torus, a raised ridge of mucous membrane, the salpingopharyngeal fold, descends vertically. On the posterior wall lie the adenoids, or pharyngeal tonsil, composed of abundant lymphoid tissue. Above the tonsil is a variable depression within the mucous membrane called the pharyngeal bursa. Behind the torus lies a deep pocket, extending the nasopharynx posteriorly along the medial border of the eustachian tube. This pocket, the fossa of Rosenmüller, varies in height from 8 to 10 mm and in depth from 3 to 10 mm (Proctor, 1967). Adenoid tissue usually extends into this pocket, giving soft tissue support to the tube.

Eustachian Tube

In adults, the tube lies at an angle of 45 degrees in relation to the horizontal plane, whereas in infants this inclination is only 10 degrees. The tube is loner in the adult than in the infant and young child, and its length varies with race; it has been reported to be as short as 30 mm and as long as 40 mm, but the usual range of length is 31 to 38 mm. It is generally accepted that the posterior third (11 to 14 mm) of the adult tube is osseous and the anterior two-thirds (20 to 25 mm) is composed of membrane and cartilage.

The morphology of the eustachian tube and its relation to other structures are presented in Figure 3. The osseous eustachian tube (protympanum) lies completely within the petrous portion of the temporal bone and is directly continuous with the anterior wall of the superior portion of the middle ear. The juncture of the osseous tube and epitympanum lies 4 mm above the floor of the tympanic cavity. The course of the osseous tube is linear anteromedially, following the petrous apex and deviating little from the horizontal plane. The lumen is roughly triangular, measuring 2 to 3 mm vertically and 3 to 4 mm along the horizontal base. The healthy osseous portion is open at all times, in contrast to the fibrocartilaginous portion, which is closed at rest and opens during swallowing or when forced open, such as during the Valsalva maneuver. The osseous and cartilaginous portions of the eustachian tube meet at an irregular bony surface and form an angle of about 160 degrees with each other.

The cartilaginous tube then courses anteromedially and inferiorly, angled in most cases 30 to 40 degrees to the transverse plane and 45 degrees to the sagittal plane (Graves and Edwards, 1944). The tube is closely applied to the basal aspect of the skull and is fitted to a sulcus tubae between the greater wing of the sphenoid bone and the petrous portion of the temporal bone. The cartilaginous tube is firmly attached at its posterior end to the osseous portion of the tube. At its inferomedial end it is attached to a tubercle on the posterior edge of the medial pterygoid lamina (Anson and Donaldson, 1967; Bryant, 1907; Doyle, 1977; Graves and Edwards, 1944; Proctor, 1967; and Rood and Doyle, 1982).

The cartilaginous tube has a crook-shaped mediolateral superior wall (see Fig. 3). It is completed laterally and inferiorly by a veiled membrane (Terracol et al, 1949; Anson, 1967; and Proctor, 1967), which serves as the site for the attachment of the fibers of the dilator tubae, or tensor veli palatini muscle (Bryant, 1907; and Rood and Doyle, 1978). The tubal lumen is shaped like two cones joined at their apices. The juncture of the cones is the narrowest point of the lumen and has been called the "isthmus", and its position is usually described as at or near the juncture of the osseous and cartilaginous portions of the tube. The lumen at this point is approximately 2 mm high and 1 mm wide (Proctor, 1967). From the isthmus, the lumen expands to approximately 8 to 10 mm in height and 1 to 2 mm in diameter at the pharyngeal orifice (Rees-Jones and McGibbon, 1941). Tubal cartilage increases in mass from birth to puberty, and this development has physiologic implications. The cartilaginous eustachian tube does not follow a straight course in the adult but extends along a curve from the junction of the osseous and cartilaginous portions to the medial pterygoid plate, approximating the cranial base for the greater part of its course. The eustachian tube crosses the superior border of the superior constrictor muscle immediately posterior to its terminus within the nasopharynx. The thickened anterior fibrous investment of the medial cartilage of the tube presses against the pharyngeal wall to form a prominent fold, the torus tubarius, which measures 10 to 15 mm in thickness (Proctor, 1967). The torus is the site of origin of the salpingopalatine muscle (Simkines, 1943) and is the point of origin of the salpingopharyngeal muscle, which lies within the inferoposteriorly directed salpingopharyngeal fold (Rosen, 1970).

Muscles Associated with the Eustachian Tube

Traditionally, there are four muscles that are commonly cited as being associated with the eustachian tube: the tensor veli palatini, levator veli palatini, salpingopharyngeus, and tensor tympani. Each has at one time or another been directly or indirectly implicated in tubal function (Anson, 1967; Brash, 1951; Bryant, 1907; Goss, 1967; Rood, 1973; Thomsen, 1957; and Van Dishoeck, 1947).

Usually, the eustachian tube is closed; it opens during such actions as swallowing, yawning, or sneezing and thereby permits the equalization of middle-ear and atmospheric pressures. Active dilation is induced solely by the tensor veli palatini muscle. Closure of the tube has been attributed to passive reapproximation of tubal walls by extrinsic forces exerted either by the surrounding deformed tissues, by the recoil of elastic fibers within the tubal wall, or by both mechanisms.

The tensor veli palatini muscle is composed of two fairly distinct bundles of muscle fibers divided by a layer of fibroelastic tissue. The bundles lie mediolateral to the tube. The more lateral bundle (the tensor veli palatini proper) is of an inverted triangular design, taking the origin from the scaphoid fossa and entire lateral osseous ridge of the sulcus tubae for the course of the eustachian tube. The bundles descend anteriorly, laterally, and inferiorly to converge in a tendon that rounds the hamular process of the medial pterygoid lamina about an interposed bursa. This fiber group then inserts into the posterior border of the horizontal process of the palatine bone and into the palatine aponeurosis of the anterior portion of the velum. The more posteroinferior muscle fibers lack an osseous origin, extending instead into the semicanal of the tensor tympani muscle. Here, the latter group of muscle fibers receive a second muscle slip, which originates from the tubal cartilages and sphenoid bone. These muscle masses converge to a tendon that rounds the cochleariform process and inserts into the manubrium of the malleus. This arrangement imposes a bipennate form to the tensor tympani muscle. The tensor tympani muscle does not appear to be involved in the function of the eustachian tube.

The medial bundle of the tensor veli palatini muscle lies immediately adjacent to the lateral membranous wall of the eustachian tube and is called the dilator tubae muscle. It takes its superior origin from the posterior third of the lateral membranous wall of the eustachian tube. The fibers descend sharply to enter and blend with the fibers of the lateral bundle of the tensor veli palatini muscle. It is this inner bundle that is responsible for active dilation of the tube by inferolateral displacement of the membranous wall.

The levator veli palatini muscle arises from the inferior aspect of the petrous apex and from the lower border of the medial lamina of the tubal cartilage. The fibers pass inferomedially, paralleling the tubal cartilage and lying within the vault of the tubal floor. They fan out and blend with the dorsal surface of the soft palate. Most investigators deny a tubal origin for this muscle and believe that in fact it is related to the tube only by loose connective tissue. The levator is not an active opener of the tube but probably adds support.

The salpingopharyngeal muscle arises from the medial and inferior borders of the tubal cartilage via slips of muscular and tendinous fibers. The muscle then courses inferoposteriorly to blend with the mass of the palatopharyngeal muscle.

Infant Eustachian Tube

The eustachian tube in the infant is about half as long as that in the adult; it averages about 18 mm. The cartilaginous tube represents somewhat less than two-thirds of this distance, whereas the osseous portion is relatively longer and wider in diameter than it is in the adult. The height of the pharyngeal orifice of the infant eustachian tube is about one-half that of the adult, but the width is similar. The ostium of the tube is more exposed in the infant than it is in the adult, since it lies lower in the shallower nasopharyngeal vault. The direction of the tube varies, from horizontal to an angle of about 10 degrees to the horizontal, and the tube is not angulated at the isthmus but merely narrows. In infants the medial cartilaginous lamina is relatively shorter since there is less tubal mass and stiffness in the infant tube than there is in that of the older child and adult. The tensor veli palatini muscle is less efficient in the infant.

Middle Ear

The middle ear is an irregular, laterally compressed air-filled space lying within the petrous portion of the temporal bone between the external auditory canal and the inner ear. This cavity can be considered to be divided into three parts superoinferiorly in relation to the tympanic membrane. The epitympanum, or attic, refers to that space lying above the superior border of the tympanic membrane. The mesotympanum lies opposite the membrane, and the hypotympanum lies below the membrane. At birth, the cavity and associated structures are of adult size. The vertical and anteroposterior diameters measure about 15 mm, whereas the transverse diameter measures 4 mm at the epitympanum, 2 mm at the mesotympanum, and 6 mm at the hypotympanum.

Walls of the Middle Ear and the Contiguous Structures

Superiorly, the cavity is bounded by a thin plate of bone, the tegmen tympani, which extends forward to cover the semicanal of the tensor tympani muscle and posteriorly to cover the attic, thereby isolating the middle ear from the middle cranial fossa. The floor of the cavity consists of a bony plate that separates the cavity anteriorly from the jugular fossa and the posterior wall of the ascending portion of the carotid canal. Dehiscences are common in these bony structures occupying the floor of the middle ear.

Anteriorly, the floor of the middle ear cavity is raised to become continuous with that of the bony portion of the eustachian tube. Superiorly and beneath the tegmen tympani lies the cylindrical semicanal for the tensor tympani muscle, which is separated from the eustachian tube by an upwardly concave thin bony septum, the cochleariform process. This process enters the middle ear along its superomedial margin to end just above the oval window, at which point it flares laterally. This termination of the cochleariform process serves as a pulley about which the tendon of the tensor tympani muscle makes a right-angled turn to proceed laterally to its insertion on the muscular process of the malleus.

The middle ear is bounded medially by the lateral surface of the bone covering the labyrinth of the inner ear. The bone is twice interrupted by areas of middle ear-inner ear communication - the oval window and the round window. The oval window is an opening leading from the middle ear into the vestibule of the inner ear. It is located at about the level of the superior border of the tympanic membrane. The raised prominence demarcating the position of the bony canal of the facial nerve is immediately superior to the oval window and curves vertically downward along its posterior border. The footplate of the stapes occupies the window and is tightly tied to the margin by an annular ligament. The round window is situated within a funneled depression, the round window niche. The window is closed by the secondary tympanic membrane, which consists of a lateral mucosal layer derived from the lining of the cochlea and an intermediate fibrous layer. The membrane is drawn into the cochlea, giving it a concave appearance from the middle ear. A bulbous, hollowed prominence formed by the outward projection of the basal turn of the cochlea occupies the position between the oval and round windows. This structure, the promontory, is cross-hatched by the various branches of the tympanic plexus of nerves.

The lateral wall is formed by the tympanic membrane, the tympanic ring, and a portion of the squamous temporal bone called the septum. The tympanic ring is superiorly incomplete, thereby forming the notch of Rivinus.

The posterior border of the middle ear is demarcated by the anterior wall of the mastoid cavity, pyramidal prominence, and mastoid antrum. The pyramidal prominence is a hollow, forward-projecting bony pyramid located behind the round window and anterior to the vertical portion of the facial nerve. It contains the stapedius muscle, whose tendons exits through a small hole in the apex of the pyramid. A small branch of the facial nerve pierces the pyramid to innervate the stapedius muscle. In the posterior part of the epitympanum is a small depression that lodges the short process of the incus.

Mucosa

The mucous membrane of the middle ear and mastoid is continuous with that of the nasopharynx via the eustachian tube. This membrane covers all structures within the middle ear, including the ossicles, vessels, and nerves. Examination of cells of the mucous membrane within the tympanic cavity reveals a gradual change from tall, columnar cells with interspersed goblet cells to shorter cuboidal cells at the posterior portion of the promontory and aditus ad antrum.

Innervation

The tympanic cavity and contained structures are innervated by branches of the tympanic plexus of nerves. Jacobson's nerve, a branch of the glossopharyngeal nerve, enters the cavity through its floor, divides, and ramifies about the promontory to contribute to the plexus. Sympathetic innervation to the plexus is provided by the superior and inferior caroticotympanic nerves and parasympathetic fibers by the smaller superior petrosal nerve. These fibers may be involved in controlling middle-ear aeration.

Also contained within the middle-ear cavity is the chorda tympani nerve, which arises from the sensory part of the descending facial nerve. It enters the cavity through the iter chordae posterior, traverses the cavity by crossing the manubrium of the malleus and the long process of the incus, and exits via the iter chordae anterius.

Tympanic Membrane

The eardrum is a thin, semitransparent membrane that separates the middle ear from the external ear canal. It measures about 8 to 10 mm in diameter and is positioned downward and inward. The outer margin is thickened and forms a fibrocartilaginous ring, the tympanic annulus, which is fitted into a sulcus in the bony tympanic ring. Superiorly, where the ring is deficient, the eardrum is lax and thin. This triangular region of the eardrum is called the pars flaccida, or flaccid part, and communication between the external ear and the middle ear may occur in this area. The remaining eight-ninths of the eardrum is called the pars tensa. The most depressed part of this concavity is called the umbo. The tympanic membrane has three layers. The most lateral layer is derived from the skin of the external ear canal. The medial layer is derived from the mucous membrane of the middle ear. The intermediate fibrous layer consists of two sublayers: a radial layer with fibers diverging out from the manubrium like the spokes on a bicycle tire, and a circumferential layer with abundant fibers near the circumference and few fibers near the center.

The Ossicles

Tiny bones, or ossicles, bridge the middle-ear cavity and provide a mechanical transmission of vibrations from the eardrum to the oval window and inner ear. The most lateral of these is the malleus. The malleus has a superior rounded head containing a posteriorly facing facet for articulation with the incus, a neck from which various processes are extended, and a manubrium, or handle, which is connected to the tympanic membrane on its internal surface. These ligaments attach to the processes arising from the neck, and they support the malleus within the cavity. The tendon of the tensor tympani muscle is inserted on a posteriorly directed muscular process. The middle ossicle is called the incus and has a body and two crura, or legs, which project at right angles to each other. The body is compressed transversely and presents a concavoconvex facet on its anterior surface for articulation with the head of the malleus. The short crus projects backward and gives rise to a ligament that connects the incus to the fossa incudis of the epitympanic recess. The long crus descends vertically and bends medially to end in a small lens-shaped structure, the lenticular process, which provides an articulating surface for the stapes. The most medial ossicle is the stapes, which has a head, a neck, two crura, and a footplate. The small head presents a concavity at its termination for articulation with the lenticular process of the incus. Below the head, the stapes narrows to its neck, which provides insertion for the stapedius muscle tendon. From the neck, the two crura diverge and are connected at their end to the flattened oval footplate. The footplate fills the oval window, to which it is affixed by an annular ligament.

Mastoid Air Cells

Directly posterior to the epitympanum is a large air space called the mastoid antrum. The antrum serves as a patent communication between the middle ear and the mastoid air cells. The mastoid refers to that portion of the petrous temporal bone that lies posterior to the middle-ear cavity. In the adult, the mastoid is extended exteriorly and interiorly to form a process to which the MSCM is attached superficially. The mastoid cavity is partitioned by numerous air cells of variable size that intercommunicate n varying ways.

In the young infant, the mastoid process is small and the degree of pneumatization low. By between 5 and 10 years of age, the process of pneumatization is for the most part complete. Incomplete development of the air cell system has been associated with frequent bouts of otitis media in infancy and childhood. The mastoid antrum and air cells are a reservoir of gas for the middle ear.

Physiology of the Eustachian Tube

The eustachian tube has at least three physiologic functions with respect to the middle ear: (1) protection from nasopharyngeal sound pressure and secretions; (2) drainage into the nasopharynx of secretions produced within the middle ear, and (3) ventilation of the middle ear to equilibrate air pressure in the middle ear with atmospheric pressure and to replenish oxygen that has been absorbed. Clearance of secretions from the middle ear is provided by the mucociliary system of the eustachian tube and some of the middle-ear mucous membrane. In ideal tubal function, intermittent active opening of the eustachian tube, due only to contraction of the tensor veli palatini muscle during swallowing, maintains nearly ambient pressures in the middle ear. Assessment of these functions has been helpful in understanding the physiology and pathophysiology of the eustachian tube, as well as the diagnosis and management of children with middle-ear disease.

Protective and Drainage Functions

The protective and drainage functions of the eustachian tube and middle ear have been studied in children by using radiographic techniques (Bluestone, 1971; Bluestone et al, 1972; and Honjo et al 1981). Understanding of these radiographic studies can be shown by a model of the system (Bluestone and Beer, 1976). The eustachian tube, middle ear, and mastoid air cell system can be likened to a flask with a long, narrow neck (Fig. 11). The mouth of the flask represents the nasopharyngeal end; the narrow neck, the isthmus of the eustachian tube; and the bulbous portion, the middle ear and mastoid air chamber. Fluid flow through the neck would be dependent upon the pressure at either end, the radius and length of the neck, and viscosity of the liquid. When a small amount of liquid is instilled into the mouth of the flask, liquid flow stops somewhere in the narrow neck owing to capillarity within the neck and the relative positive air pressure that develops in the chamber of the flask. This basic geometric design is considered to be critical for the protective function of the eustachian tube - middle-ear system. Reflux of liquid into the body of the flask occurs if the neck is excessively wide. This is analogous to an abnormally patent human eustachian tube in which there is not only free flow of air from the nasopharynx into the middle ear but also free flow of nasopharyngeal secretions, which can result in "reflux otitis media". Figure 12 shows that a flask with a short neck would not be as protective as a flask with a long neck. Since infants have a shorter eustachian tube than adults, reflux is more likely in the baby. The position of the flask in relation to the liquid is another important factor. In humans, the supine position enhances flow of liquid into the middle ear; thus, infants might be at particular risk for developing reflux otitis media because they are frequently supine.

Figure 13 shows that reflux of a liquid into the vessel can also occur if a hole is made in the bulbous portion of the flask, since this prevents the creation of the slight positive pressure in the bottom of the flask that deters reflux; that is, in this situation, the middle ear and mastoid physiologic cushion of air is lost. This hole is analogous to a perforation of the tympanic membrane or the presence of a tympanostomy tube that could allow reflux of nasopharyngeal secretions as a result of the loss of the middle ear-mastoid air cushion. Similarly, following a radical mastoidectomy, a patent eustachian tube could cause troublesome otorrhea (Bluestone et al, 1978).

If negative pressure is applied to the bottom of the flask, the liquid is aspirated into the vessel. In the clinical situation represented by the model, high negative middle-ear air pressure could lead to the aspiration of nasopharyngeal secretions into the middle ear. If positive pressure is applied to the mouth of the flask, the liquid is insufflated into the vessel. Nose blowing, crying, closed-nose swallowing, diving, or ascent in an airplane could create high positive nasopharyngeal pressure and result in a similar condition in the human system.

One of the major differences between a flask with a rigid neck and a biologic tube such as the eustachian tube is that the isthmus (neck) of the human tube is compliant. Application of positive pressure at the mouth of a flask with a compliant neck distends the neck, enhancing fluid flow into the vessel. Thus, less positive pressure is required to insufflate liquid into the vessel. In humans, insufflation of nasopharyngeal secretions into the middle ear occurs more readily if the eustachian tube is abnormally distensible (has increased compliance). The effect of applied negative pressure in a flask with a compliant neck is shown in Figure 14; liquid flow through the neck does not occur until a negative pressure is slowly applied to the bottom of the flask. In this case, fluid flow occurs even if the neck is collapsed. If the negative pressure is applied suddenly, however, temporary locking of the compliant neck prevents flow of the liquid. Therefore, the speed with which the negative pressure is applied and also the compliance in such a system appear to be critical factors in the results obtained. Clinically, aspiration of gas into the middle ear is possible, since negative middle-ear pressure develops slowly as gas is absorbed by the middle-ear mucous membrane. On the other hand, sudden application of negative middle-ear pressure such as occurs with rapid alterations in atmospheric pressure (as in descent in an airplane, in descent during diving, or during an attempt to test the ventilatory function of the eustachian tube) could lock the tube, thus preventing the flow of air.

Certain aspects of fluid from the middle ear into the nasopharynx can be demonstrated by inverting the flask of the model (Fig. 15). In this case the liquid trapped in the bulbous portion of the flask does not flow out of the vessel because of the relative negative pressure that develops inside the chamber. However, if a hole is made in the vessel, the liquid drains out of the flask because the suction is broken. Clinically, these conditions occur in cases of middle-ear effusion; pressure is relieved by spontaneous rupture of the tympanic membrane or by myringotomy. Inflation of air into the flask could also relieve the pressure, which may explain the frequent success of the Politzer and Valsalva methods in clearing a middle-ear effusion.

The example of fluid flow through a flask presents some of the mechanical aspects of the physiology of the human middle-ear system. Other factors that probably affect fluid flow (liquid and air) through the middle ear include: (1) the mucociliary transport system of the eustachian tube and middle ear (ie clearance); (2) active tubal opening and closing, acting to pump liquid out of the middle ear (Honjo et al, 1985); and (3) surface tension factors.

Ventilatory Function

The normal eustachian tube is functionally obstructed or collapsed at rest; there is probably a slight negative pressure in the middle ear. When the eustachian tube functions ideally, intermittent active dilation (opening) of the tube maintains near-ambient pressures in the middle ear (Fig. 16). It is suspected that when active function is inefficient in opening the eustachian tube, functional collapse of the tube persists, which results in negative pressure in the middle ear. When tubal opening does occur, a large bolus of air could enter the middle ear, which could eventually result in even higher negative pressure (Cantekin et al, 1980). This type of ventilation appears to be quite common in children, as moderate to high negative middle-ear pressures have been identified by tympanometry in many children who have no apparent ear disease (Beery et al, 1975).

In an effort to describe normal eustachian tube function by using the microflow technique inside a pressure chamber, Elner and co-workers (1971) studied 102 adults with intact tympanic membranes and apparently no history of otologic disorder (Table 1). The patients were divided into four groups according to their abilities to equilibrate static relative positive and negative pressures of 100 H_2O in the middle ear. The patients in group 1 were able to equilibrate pressure differences across the tympanic membrane completely. Those in group 2 equilibrated positive pressure, but a small residual negative pressure remained in the middle ear. The subjects in group 3 were capable of equilibrating only relative positive pressure with a small residual remaining, but not negative pressure, and those in group 4 were not capable of equilibrating any pressure. These data probably indicate decreased stiffness of the eustachian tube in the subjects in groups

2 to 4 when compared with those in group 1. This study also showed that 95 per cent of normal adults could equilibrate an applied positive pressure and that 93 per cent could equilibrate applied negative pressure to some extent by active swallowing. However, 28 per cent of the subjects could not completely equilibrate either applied positive or negative pressure or both.

Children have less efficient eustachian tube ventilatory function than adults. Bylander (1980) compared the eustachian tube function of 53 children with that of 55 adults, all of whom had intact tympanic membranes and who were apparently otologically healthy. Employing a pressure chamber, Bylander reported that 35.8 per cent of the children could not equilibrate applied negative intratympanic pressure (-100 mmH_2O) by swallowing, whereas only 5 per cent of the adults were unable to perform this function. Children between 3 and 6 years of age had worse function than those aged 7 to 12. In this study and a subsequent one conducted by the same research group (Bylander et al, 1983), children who had tympanometric evidence of negative pressure within the middle ear had poor eustachian tube function; children were grouped similarly to that recommended by Elner and associates, 1971 (Table 2).

From these two studies, it can be concluded that even in apparently otologically normal children, eustachian tube function is not as good as in adults, which would contribute to the higher incidence of middle-ear disease in children.

Many children without apparent middle-ear disease have high negative ear pressure. However, in children, eustachian tube function does improve with advancing age, which is consistent with the decreasing incidence of otitis media from infancy to adolescence (Bylander and Thernstrom, 1983).

Another explanation for the finding of high negative middle-ear pressure in children is the possibility that some individuals who are habitual "sniffers" actually create under pressure within the middle ear by this act (Falk and Magnuson, 1984). However, this mechanism is uncommon in children.

In studying the parameters of middle-ear pressure, Brooks (1969) determined by tympanometry that the resting middle-ear pressure in a large group of apparently normal children was between 0 and -175 mm H_2O. However, pressures outside this range have been reported as normal for large populations of apparently asymptomatic children who were measured for middle-ear pressure by screening (Jerger, 1970). High negative middle-ear pressure does not necessarily indicate disease; it may indicate only physiologic tubal obstruction. Ventilation occurs, but only after the nasopharynx-middle-ear pressure gradient reaches an opening pressure. It has been suggested that these children probably should be considered at risk for middle-ear problems until more is learned about the normal and abnormal physiology of the eustachian tube (Bluestone et al, 1973). In normal adults, Alberti and Kristensen (1970) obtained resting middle-ear pressures of between 50 and -50 mm H_2O. Again, a pressure outside this range does not necessarily mean the patient has ear disease.

The *rate of gas absorption* from the middle ear has been reported by several investigators to be approximately 1 mL in a 24-hour period (Elner, 1972, 1977; Ingelstedt et al, 1967; and Riu et al, 1966). However, since values taken over a short-period were extrapolated to arrive at this figure, the true rate of gas absorption over 24 hours has yet to be determined in humans.

In a study by Cantekin and co-workers (1980), serial tympanograms were obtained in rhesus monkeys to determine the gas absorption process. During a 4-hour observation period, the middle ear pressure was approximately normal in alert animals, whereas when the animals were anesthetized and swallowing was absent, the middle ear pressure dropped to -60 mmH_2O and remained at that level. The experiment indicated that, normally, middle-ear gases are nearly in equilibrium with the mucosal blood-tissue gases or inner-ear gas pressures. Under these circumstances, the gas absorption rate is small since the partial pressure gradients are not great. In the normally functioning eustachian tube, the frequent openings of the tube readily equilibrate the pressure differences between the middle ear and the nasopharynx with a small volume of air (1 to 5 mL) entering into the middle ear. However, an abnormal functioning eustachian tube may alter this mechanism.

Eden has postulated that normal middle-ear aeration may be controlled to some extent by middle-ear receptors, which could influence eustachian tube function (Eden, 1981; 1987).

The physiologic role of the mastoid air cell system in relation to the middle ear is not fully understood, but the current concept is that it acts as a surge tank of gas (air) available to the relatively small middle-ear cavity. During intervals of eustachian tube dysfunction, the compliance of the tympanic membrane and ossicular chain (which would affect hearing) would not be decreased owing to reduced middle-ear gas pressure since there is a reservoir of gas in the mastoid air cells. If this concept is correct, then a small mastoid air cell system could be detrimental to the middle ear if abnormal eustachian tube function is present.

Posture appears to have an effect on the function of the eustachian tube. The mean volume of air passing through the eustachian tube was found to be reduced by one-third when the body was elevated 20 degrees to the horizontal, and by two-thirds when in the horizontal position (Ingelstedt et al, 1967). This reduction in function with change in body position was found to be the result of venous engorgement of the eustachian tube (Jonson and Rundcrantz, 1969).

A seasonal variation in eustachian tube function occurs in children (Beery et al, 1979). Children who had had tympanostomy tubes inserted for recurrent or chronic otitis media with effusion and were evaluated using serial inflation-deflation studies had better eustachian tube function in the summer and fall than in the winter and spring.

Comparison of the Functions of the Eustachian Tube and Larynx

The physiologic functions of the eustachian tube cannot be isolated from the other components of the middle ear system: the nose, nasopharynx, and palate at the proximal end, and the middle ear and mastoid air cells at the distal end. Likewise, the larynx is within a system made up of the pharynx at the proximal end, and the tracheobronchial-pulmonary system distally (Fig. 17). Within these respective systems, the eustachian tube and the larynx play critical roles in the functions of the middle ear and lungs, respectively, in their connections to the aerodigestive tract (Bluestone et al, 1981). The tympanic membrane and malleus (which may be compared to a rib) and tensor tympani muscle (which may play a role similar to that of the intercostal muscles) could even be compared to the rib cage and diaphragm of the pulmonary system. The mastoid air cell system, in its role as a reservoir for gas for the middle ear, can also be compared to the reserve volumes of the lungs. Physiologically, both the eustachian tube and the larynx have ventilatory, protective, and drainage functions. The eustachian tube *ventilates* the middle ear to regulate middle ear pressure, which maintains optimum *hearing.* The larynx ventilates the lungs to provide respiration which, in humans, has also evolved phylogenetically into *phonation.* In order to perform these critical physiologic functions, the eustachian tube and larynx must *protect* the middle ear-mastoid and the tracheobronchial-pulmonary systems from unwanted secretions. In the absence of swallowing, the middle ear and mastoid are protected (also from nasopharyngeal sound pressures) by the functional collapse of the normal eustachian tube; however, during swallowing, the normal eustachian tube actively opens due to contraction of one muscle, the tensor veli palatini (Rich, 1920; Cantekin et al, 1979; and Honjo et al, 1979), and the palate seals off the nasopharynx from the contents of, and extreme pressure developed in, the oropharyngeal cavity. The larynx, on the other hand, is open (by the activity of one paired muscle) when swallowing is not occurring but closed during swallowing activity. The epiglottis, although less important in humans, protects the glottis during swallowing much like palatal closure protects the nasopharyngeal end of the eustachian tube.

Both systems have *clearance* (or drainage) functions primarily provided by the mucociliary activity of their mucosal linings, but the larynx is integrally involved in coughing, acting to clear (and therefore to protect) the lungs. Likewise, the eustachian tube is now thought to have a pump-like activity that actually "milks" secretions out of the middle ear and mastoid (Honjo et al, 1981).

The pathophysiology of the eustachian tube can also be compared with that of the larynx. Both can be obstructed mechanically (anatomically) or functionally. Clearly, both structures have intrinsic (due to inflammation) or extrinsic (as from a tumor) mechanical obstructions. However, *functional* obstruction of the eustachian tube is much less easy to visualize conceptually than this type of obstruction of the larynx and tracheobronchial tree. Functional obstruction of the larynx caused by bilateral vocal cord paralysis (in the median or paramedian position), or laryngomalacia, or, more distally, tracheobronchial malacia, is well known and understood. However, an abnormally compliant (floppy) eustachian tube or an abnormal tubal opening mechanism, even though it may have similarities to the pathophysiology of laryngeal dysfunction, is not as easily understood. This is because the larynx, trachea, and bronchi are more readily available for examination and have been studied much more than the eustachian tube. Other instances in which laryngeal abnormalities lead to disease include: (1) *aspiration* pneumonia caused by an abnormally patent or incompetent glottis (eg paralysis of the vocal cords in the lateral position); (2) reflux esophagitis, which can also cause aspiration pneumonia, resulting from incompetence of the esophagogastric junction; and (3) cricopharyngeal achalasia, resulting in a similar condition. The analogies in the middle ear system include: (1) "reflux otitis media", caused by the reflux of nasopharyngeal secretions through an abnormally patent (patulous or semipatulous) eustachian tube; and (2) the *aspiration* through the eustachian tube of secretions into a middle ear that has high negative pressure. Nasal obstruction may have an effect on both eustachian tube (Toynbee phenomenon) and pulmonary function.

Some of the pathologic conditions found at the distal ends of the two systems are also comparable. Atelectasis of the tympanic membrane, which is analogous to pulmonary atelectasis, is the result of hypoaeration of the middle ear. A retraction pocket of the posterosuperior or pars flaccida areas of the tympanic membrane could be likened to segmental pulmonary atelectasis, for instance, atelectasis of the right middle lobe; both of these conditions may result from the unique anatomies of the parts involved. A middle-ear effusion that is sterile may develop in a way similar to that in which pulmonary edema develops, and suppurative otitis media could be compared with bacterial pneumonia in its pathogenesis.

In conclusion, then, the larynx plays a well-recognized and critical role in the functioning of the pulmonary system; however, although the eustachian tube plays a similar role in the middle-ear system, this role is poorly understood. This is due to the obscure location of the eustachian tube and the limited methods available to access its function. The larynx and tracheobronchial-pulmonary system have been extensively studied through many different methods, some of which are quite simple. For instance, laryngeal function can readily be assessed by indirect laryngoscopy, one of the simplest assessment techniques, although more sophisticated laryngeal and pulmonary function tests are available and are used frequently in clinical practice as well as in the laboratory. Unfortunately, since the eustachian tube is not as accessible to the clinician or investigator and therefore has not been studied as extensively as its counterpart, it is thus not as well understood. However, in spite of these advantages, it is as important to assess the function of the eustachian tube of a patient with tympanic membrane-middle ear-mastoid disease as it is to assess the function of the larynx of a patient who has tracheobronchial or pulmonary disease. The various instruments available to the clinician and investigator, as well as the methods of assessment of eustachian tube function, have been described in detail elsewhere (Bluestone and Cantekin, 1980). In the following discussion only the instruments and assessment techniques available to the clinician will be reviewed.

Tests of Eustachian Tube Function

The roentgenographic tests developed to assess the protective and clearance system of the eustachian tube-middle-ear system have been helpful in understanding these functions but are not feasible in the usual clinical setting. However, methods to assess the ventilatory function of the system are readily available to the clinician and should be performed when indicated (these tests are described later). The ventilatory function is the most important of the three functions, since adequate hearing depends upon the maintenance of equal air pressure on both sides of the tympanic membrane. In addition, impairment of the ventilatory function can result not only in hearing loss but also in otitis media.

Prior to the examination of the patient, the presence of certain signs and symptoms may be helpful in determining whether or not eustachian tube dysfunction is present. Conductive hearing loss, otalgia, otorrhea, tinnitus, or vertigo may be present with this disorder.

Otoscopy

Visual inspection of the tympanic membrane is one of the simplest (and oldest) ways to assess the functioning of the eustachian tube. The appearance of a middle-ear effusion or the presence of high negative middle-ear pressure, or both, as determined by the pneumatic otoscope (Bluestone and Shurin, 1974), is presumptive evidence of eustachian tube dysfunction, but the type of impairment, such as functional or mechanical obstruction, as well as the degree of abnormality, cannot be determined by this method. Moreover, a normal-appearing tympanic membrane cannot be considered to be evidence of normal functioning of the eustachian tube. For instance, a patulous or semipatulous eustachian tube may be present when the tympanic membrane appears to be normal. In addition, the presence of one or more of the complications or sequelae of otitis media (such as a perforation or atelectasis, as observed through the otoscope) may not correlate with dysfunction of the eustachian tube at the time of the examination, since eustachian tube function may improve with growth and development.

Nasopharyngoscopy

Indirect mirror examination of the nasopharyngeal end of the eustachian tube is also an old but still important part of the clinical assessment of a patient with middle-ear disease. For instance, a neoplasm in the fossa of Rosenmüller may be diagnosed by this simple technique. The development of endoscopic instruments has greatly improved the accuracy of this type of examination, but the function of the eustachian tube cannot be determined with the aid of currently available instruments.

Tympanometry

The use of an electroacoustic impedance 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 the assessment of eustachian tube function (Bluestone, 1980). The presence of a middle-ear effusion or high negative middle-ear pressure as determined by this method usually indicates impaired eustachian tube function; however, unlike the otoscopic evaluation, the tympanogram is an objective way of determining the degree of negative pressure present in the middle ear. 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, whereas in others, symptoms such as hearing loss, otalgia, vertigo, and tinnitus may be associated with modest degree of negative pressure or even with normal middle-ear pressures. The middle-ear air pressure may depend upon 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 pressure within the middle ear while he or she has the cold but may be otherwise otologically normal (Casselbrant et al, 1985). The decision as to whether high negative pressure is abnormal or is only a physiologic variation should be made by taking into consideration the presence or absence of signs and symptoms of middle-ear disease. If severe atelectasis or adhesive otitis 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.

Therefore, 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.

Manometry

The pump-manometer system of the electroacoustic impedance bridge is usually adequate to assess eustachian tube function clinically when the tympanic membrane is not intact. However, due to the limitations of the manometric systems of all of the commercially available instruments, a controlled syringe and manometer (a water manometer will suffice) should be available when these limitations are exceeded (eg pressure required to open the eustachian tube is in excess of + 400 to + 600 mm H_2O.

Classical Tests of Tubal Patency

Valsalva and Politzer have developed methods to assess patency of the eustachian tube. When the tympanic membrane is intact and the middle ear inflates following one of these tests, then the tube is not totally mechanically obstructed. Likewise, if the tympanic membrane is not intact, passage of air into the middle ear would indicate patency of the tube. The assessment is more objective with a tympanogram obtained when the tympanic membrane is intact, and with a manometric observation on the impedance instrument when the tympanic membrane is not intact. However, inflation of the eustachian tube and middle ear from the end of the system containing the nasopharynx by one of these classical methods assesses only tubal patency, not function, and failure to inflate the middle ear does not necessarily indicate a lack of patency of the eustachian tube. Elner and co-workers (1971) reported that 86 per cent of 100 otologically normal adults could perform the Valsalva test. In young children, the Valsalva test is usually more difficult to perform than the Politzer test. However, in a recent study by Bluestone and co-workers (1981), six of seven children who had a traumatic perforation but who were otherwise otologically "normal" could perform the Valsalva test, but only 11 of 28 children who had a retraction pocket or a cholesteatoma could do so. The Valsalva and Politzer maneuvers are more beneficial as management options in selected patients than they are as methods to assess tubal function.

Toynbee Test

One of the oldest and still one of the best tests of eustachian tube function is the Toynbee test (Fig. 18). Tests results are usually considered positive when an alteration in middle-ear pressure results. More specifically, if negative pressure (even when it is transitory in the absence of a patulous tube) develops in the middle ear during closed-nose swallowing, eustachian tube function can be considered most likely to be normal. When the tympanic membrane is intact, the presence of negative middle-ear pressure must be determined by pneumatic otoscopy or, more accurately, by obtaining a tympanogram before and immediately following the test (Fig. 19). When the tympanic membrane is not intact, the manometer of the impedance bridge can be observed to determine middle-ear pressure. In the study by Elner and co-workers (1971), results of the Toynbee test were positive in 79 per cent of normal adults. Catekin and colleagues (1976) reported that only seven of 106 ears (6.6 per cent) 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 to 200 mm H_2O). Likewise, in a series of patients, most of whom were older children and adults with chronic perforations of the tympanic membrane, only three of 21 (14.3 per cent) passed the test. However, in children with a traumatic perforation of the tympanic membrane but who otherwise had a negative otologic history, three of 10 (30 per cent) could pass the test. In the study by Bluestone and co-workers (1981) 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. 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, eustachian tube function is most likely normal, since the eustachian tube actively opens and is sufficiently stiff to withstand nasopharyngeal negative pressure (ie it does not "lock"). If positive pressure is noted or no change in pressure occurs, the function of the eustachian tube still may be normal and other tests of eustachian tube function should be performed.

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 (Bluestone, 1980). One tympanogram is obtained while the patient is breathing normally, and a second is obtained while the patient holds his or her breath. Fluctuation of the tympanometric trace that coincides with breathing confirms the diagnosis of a patulous tube (Fig. 20). 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, since it causes the patulous eustachian tube to close.

Nine-Step Inflation-Deflation Tympanometric Test

Another method of assessing the function of the eustachian tube when the tympanic membrane is intact, developed by Bluestone (1975), is called the nine-step inflation-deflation tympanometric test, although the supplied middle-ear pressures are very limited in magnitude. The middle ear must be free of effusion. The nine-step tympanometry procedure may be summarized as follows (Fig. 21):

1. The tympanogram records resting middle-ear pressure.

2. Ear canal pressure is increased to +200 mm H_2O, 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 membranes moves outward). The tympanogram documents the established underpressure in the middle ear.

4. The subject swallows in an attempt to equilibrate negative middle-ear pressure. If equilibration is successful, airflow is from nasopharynx to middle ear.

5. The tympanogram records the extent of equilibration

6. Ear canal pressure is decreased to -200 mm H_2O, 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 membranes moves medially. The tympanogram records the overpressure established.

8. The subject swallows to reduce the 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 part of this test, but even normal children have difficulty in performing it. However, if a child can pass some or all of the steps, eustachian tube function is considered good.

Modified Inflation-Deflation Test (Nonintact Tympanic Membrane)

When the tympanic membrane is not intact, the pump-manometer system of the electroacoustic impedance bridge can be used to perform the modified inflation-deflation eustachian tube function test (Fig. 22), which assesses passive as well as active functioning of the eustachian tube (Cantekin et al, 1976; Ingelstedt and Ortegren, 1963). The middle ear should be free of any drainage to obtain an accurate assessment of eustachian tube function using this test. The middle ear is inflated (ie positive pressure is applied) until the eustachian tube spontaneously opens (Fig. 23). At this time, the pump is manually stopped and air is discharged through the eustachian tube until the tube closes passively. The pressure at which the eustachian tube is passively forced to open is called the opening pressure, and the pressure at which it closes passively is called the closing pressure. The patient is then instructed to equilibrate the middle-ear pressure actively by swallowing. The residual pressure remaining in the middle ear after swallowing is recorded. The active function is also recorded by applying overpressure and underpressure to the middle ear, which the patient then attempts to equilibrate by swallowing. The residual negative pressure that remains in the middle ear after the attempt to equilibrate applied negative pressure of -200 mm H_2O is also noted (Fig. 24). This procedure is not performed in patients who cannot equilibrate applied overpressure. If the eustachian tube does not open following application of positive pressure using the electroacoustic impedance bridge and if no reduction in positive pressure occurs during swallowing, then the eustachian tube must be assessed using a manometric system other than that available with the electroacoustic impedance bridge. The opening pressure may be higher than 400 to 600 mm H_2O pressure or not present at all (severe mechanical obstruction). Example A in Figure 25 shows that, following passive opening and closing of the eustachian tube during the inflation phase of the study, the patient was able to equilibrate completely the remaining positive pressure. Active swallowing also completely equilibrated applied negative pressure (deflation). This is considered to be characteristic of normal eustachian tube function. Example B shows the eustachian tube passively opened and closed following inflation, but subsequent swallowing failed to equilibrate the residual positive pressure. In the deflation phase of the study the patient was unable to equilibrate negative pressure. Inflation to a pressure below the opening pressure but above the closing pressure could not be equilibrated by active swallowing. This type of result is considered to be abnormal but may be found in a few subjects who do not have any obvious otologic disease.

Failure to equilibrate the applied negative pressure may indicate 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 a tube with perfect function. The tensor veli palatini muscle is unable to open (dilate) the tube.

Even though the inflation-deflation test of eustachian tube function does not strictly duplicate physiologic functions of the tube, the results are helpful in differentiating normal from abnormal function. The mean opening pressure for apparently normal subjects with a traumatic perforation and negative otologic history reported by Cantekin and co-workers ()1976) was 330 mm H_2O (70 mm H_2O). If the test results reveal passive opening and closing with the normal range, if residual positive pressure can be equilibrated by swallowing, and if applied negative pressure can also be equilibrated completely, then the eustachian tube can be considered to have normal function. However, if the tube does not open to a pressure of 100 mm H_2O, 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 (eg greater than 500 to 600 mm H_2O) may indicate partial obstruction, whereas a very low opening pressure (eg less than 100 mm H_2O) 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 (ie one that is open at rest). Complete equilibration of applied negative pressure by swallowing 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, since even a normal eustachian tube locks when negative pressure is rapidly applied. Therefore, inability to equilibrate applied negative pressure may not indicate poor eustachian tube function, especially when it is the only abnormal result of testing.

Other Methods Available for Laboratory Use

There are other available methods to test the functioning of the eustachian tube, but they are currently limited to use in the laboratory for investigational purposes. When the tympanic membrane is intact, the microflow technique (Ingelstedt et al, 1967) or an impedance method (Bylander, 1980), both of which require a pressure chamber, or sonometry (Murti et al, 1980; and Virtanen, 1987) may be used. When the tympanic membrane is not intact, the forced-response test shows great promise for future use in the clinical setting.

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 (such as otalgia, snapping or popping in the ear, fluctuating hearing loss, tinnitus, or vertigo). An example of of such a case would be a child or adolescent who has a complaint 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 could be due to an inner-ear disorder. A tympanogram that reveals high negative pressure (-50 mm H_2O or less) is presumptive evidence of tubal 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 Toynbee's test or can perform all or some of the functions in the 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 inability to pass the nine-step test does not necessarily indicate poor eustachian tube function, since many children who are otologically normal cannot actively open their tubes during these tests. Tympanometry not only is of value in determining whether or not eustachian tube obstruction is present but can also identify an 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 (ie children with known sensorineural hearing losses, developmentally delayed and mentally impaired children, children with cleft palates or other craniofacial anomalies, American Indian and Eskimo children, and children with Down's syndrome) appears to be helpful in identifying those individuals who may need to be monitored closely for the occurrence of otitis media (Harford et al, 1978).

Tympanometry appears to be a reliable method for detecting the presence of high negative pressure as well as otitis media with effusion in children (Beery et al, 1975; and Brooks, 1968). The identification of high negative pressure without effusion in children is indicative of some degree of eustachian tube obstruction. These children as well as those with middle ear effusions, should have follow-up serial tympanograms, since 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 nine-step test, when the eardrum is intact, or, when it is not intact, the inflation-deflation test. A perforation of the tympanic membrane or a tympanostomy tube must be present in order to perform the latter test. The test uses the simple apparatus described earlier, with or without the electroacoustic impedance bridge pump-manometer system. This test aids in determining the presence or absence of a dysfunction as well as the type of dysfunction (obstruction versus 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, computed tomography of the nasopharynx-eustachian tube-middle ear region can be performed to determine the site and cause of the blockage, such as cholesteatoma or tumor. In most cases in which mechanical 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 or middle-ear surgery, or both. Serial inflation-deflation studies should show resolution of the mechanical obstruction. However, if no cause originating from the middle ear is obvious, other studies should be performed to rule out the possibility of neoplasms in the nasopharynx.

Management

Ideally, patients with recurrent acute otitis media or chronic otitis media with effusion, or both, should have eustachian tube function studies performed as part of their otolaryngologic workup, but for most children, one can assume that eustachian tube function is poor. However, 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 aid the clinician in determining the proper time to remove the tubes. Cleft palate repair (Bluestone et al, 1972; and Paradise and Bluestone, 1974) adenoidectomy (Bluestone et al, 1972; 1975), elimination of nasal and nasopharyngeal inflammation (Bluestone et al, 1977), treatment of a nasopharyngeal tumor, or growth and development of a child (Holborow, 1970) may be associated with improvement in eustachian tube function.

Studies of the eustachian tube function in the patient with a chronic perforation of the tympanic membrane may be helpful in determining preoperatively the potential results of tympanoplastic surgery. Holmquist (1968) 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 (ie 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 (Miller and Bilodeau, 1967; and Siedentop, 1972), but other investigators (Cohn et al, 1979; Ekvall, 1970; Lee and Schuknecht, 1971; and Virtanen et al, 1980) found no correlation between the results of the inflation-deflation tests and the 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 co-workers (1979) assessed children prior to tympanoplasty and found that of 51 ears of 45 children, eight ears could equilibrate an applied negative pressure (-200 mm H_2O) to some degree; in seven of these ears, the graft was accepted, no middle-ear effusion occurred, and no recurrence of the perforation developed during a follow-up period of between 1 and 2 years. 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 does not help the clinician in deciding not to operate. However, the value of testing a patient's ability to equilibrate negative pressure lies in the possibility of determining from the test results whether or not a young child is a candidate for tympanoplasty when one might decide on the basis of other findings alone to withhold surgery until the child is older.

In children who have unilateral perforation of the tympanic membrane or a tympanostomy tube in place and the contralateral tympanic membrane is intact, the status of the intact side, observed for at least 1 year, can aid in determining whether tympanoplasty should be performed or a tube should be removed. Repair of the eardrum or removal of the tube is usually successful if the contralateral intact side has remained normal (ie no middle-ear effusion or negative pressure). Conversely, if the opposite ear has developed middle-ear disease during the previous year, tympanoplasty should be postponed, or, if a tympanostomy tube is in place, it should be removed.

Physiology of the Middle Ear

In vertebrates it has been shown that fishes can hear or perceive vibration of surrounding water by means of the lateral line organ. Sensory hair cells soaked in sea water in the lateral line canal are stimulated directly by the movement of the surrounding water. Highly developed vertebrates that live temporarily or permanently on land have to hear air-conducted sound; consequently, they must have developed receptors to profit by the vibration of air, because it is necessary that air vibrations be introduced from outside the body to the inner-ear fluid. We call such receptors, which contribute to the matching of impedance between air and fluid, the middle ear.

Tympanic Membrane

Properties of the Tympanic Membrane

The cross-section of the tympanic membrane vary in shape according to classes of animals. In amphibians and reptiles the tympanic membrane is flat. In birds it is convex, whereas in mammals it is concave. The degree of the deflection is smaller in birds than in mammals, and the tympanic membrane in birds is almost flat. Let us take the diaphragm of a loudspeaker as an example. The tympanic membrane in amphibians, reptiles, and birds corresponds to a flat cone type of diaphragm. The cross-section of this type is a cone with a straight line (Fig. 26). The tympanic membrane in mammals, on the other hand, corresponds to a curved cone type, whose cross-section is a cone with a curved line. As a diaphragm, a curved cone affords less distortion and broader frequency characteristics than a flat cone. This, in analogy, adds to the fact that the tympanic membrane in mammals is superior to those of other classes in its function.

Physiologic Functions of the Tympanic Membrane

The most important function of the tympanic membrane is transmission of vibration to the window, but it also has important protective functions related to the middle ear and the eustachian tube.

Vibration of the Tympanic Membrane

Vibration Mode at Lower Frequencies. Many workers have studied the dynamics of the tympanic membrane. There are many methods for observing the movements of the membrane resulting from a change of pressure in the meatus. Classic experiments were done by optical methods using minute pieces of gold foil attached to the surface of the tympanic membrane (Mach and Kessel, 1874; and Wada, 1924). Stroboscopic or cinematographic observations have also been done (Kobrak, 1941, 1953; Perlmand, 1945). Others used the electronic condenser method that consists of evaluating the minute displacement of the tympanic membrane by a capacitative probe (Wilska, 1935; Békésy, 1941). Holographic technique using laser ray has been applied for studying the pattern of displacement of the tympanic membrane (Tonndorf and Khanna, 1968; Khanna and Tonndorf, 1972; and Lokberg et al, 1980).

The vibration mode of the human tympanic membrane differs at three zones: central, intermediate, and peripheral. The central or conic zone is situated around the umbo and is 1.2 to 1.5 mm in radius. The peripheral zone is surrounded by the annulus tympanicus and is 2.0 to 3.0 mm in width. The intermediate is the zone between the central and peripheral and is 0.7 to 2.0 mm in width.

During vibration, the central zone moves back and forth like a piston and its conic shape is retained. The peripheral zone makes a hingelike movement, and the angular deflection takes place at its junction with the annulus tympanicus. The intermediate zone moves in greater amplitude than the other two and its mode of vibration corresponds to that of the membrane with freely mobile boundaries. Figure 27 summarizes the results of various measurements of the human tympanic membrane; the membrane does not show a strictly concentric arrangement of zones, and the width of a zone differs in various tympanic portions.

The mode of vibration of the tympanic membrane should be analyzed not only by cross-sections (Figs. 27 and 28) but also be areal observations. Békésy (1941) used a very sensitive electrical probe to measure the linear displacement of the membrane. Figure 26 shows the areas of equal excursion during acoustic stimulation by a tone of 2000 Hz. The largest excursion is seen along the line extended from the handle of malleus and is near the bottom. According to our observation, this portion corresponds to the intermediate zone. Figures 27 and 28 show different ways of explaining the same situation, and the results are in accordance with each other.

There is a close relationship between the arrangements of fibers and the movement of the membrane. The fact that radial and circular fibers cross each other and that the membrane is thick around the umbo makes the membrane ready to vibrate as a stiff cone. During vibration the surface of the membrane rotates around the axis at the edge near the tympanic sulcus. The parabolic fibers that originate from the portion near the short process of the malleus are mainly suitable to strengthen the periphery of the membrane (Fig. 26).

Vibration Mode at Higher Frequencies. The mode of membrane vibration, as proved in general physics, becomes segmental as the frequency becomes higher. This is true also in the tympanic membrane. Figures 28 and 29 show that the membrane moves back and forth like a piston and this movement involves the whole area as long as the frequency of vibration is low or medium. Békésy (1941) observed by using his capacitative probe that above 2400 Hz the tympanic membrane starts to vibrate in segments and loses its stiffness. Later, Tonndorf and Khanna (1972) recorded displacement patterns at higher frequency than Békésy by means of the holographic technique. They observed that the tympanic membrane started breaking up into sectional vibrations above 3000 Hz and their complexity increased with further increases in frequency (Fig. 29).

These studies by Tonndorf and Khanna (Tonndorf and Khanna, 1972; and Khanna and Tonndorf, 1972) showed that the tympanic membrane does not vibrate like a stiff plate as observed by Békésy in human cadavers but rather as a curved membrane as proposed by Helmholz. At all frequencies, the tympanic membrane vibrates maximally in the posterosuperior quadrant and less in the anterior and inferior ones. Clinically, the posterosuperior quadrant can be seen to move to the greatest degree when performing pneumatic otoscopy and is the area of the pars tensa in which a retraction pocket can develop secondary to persistent negative middle ear pressure (see Vol. II, Chap. 26).

Effect of Ear Canal and Middle-Ear Pressures on Vibration. Vibration of the tympanic membrane is greater when the air pressure within the middle ear is the same as the external canal. When the pressure in the external canal was either increased or decreased by 10 cm H_2O, Békésy (1929) found subjective loudness reduced low tones up to 1.5 kHz. In more recent studies employing self-recording Békésy audiometry in patients with normal ears, a relative overpressure in the ear canal produced threshold losses for the frequency range from 0.5 to 1 kHz (Arnold and Schindler, 1963; and Truswell et al, 1979). When a relative negative pressure was introduced in the middle ear, Erlandsson and co-workers (1980) reported threshold losses at 0.5, 1, and 4 kHz and threshold gains at 2 and 6 kHz, in which the losses and gains increased as the middle ear pressure was decreased from 5, 10 to 15 cm H_2O (Table 3). From a clinical standpoint, relative negative middle-ear pressure is frequently identified in patients, especially in children, by tympanometry. Some have conductive hearing loss that is asymptomatic, despite the lack of middle-ear effusion or other obvious middle ear disease, whereas other individuals may have high negative pressure within the middle ear documented without measurable conductive hearing loss. Further research into the effect of static middle-ear pressures on hearing is needed to more fully understand this relationship, because eustachian tube dysfunction with high negative middle-ear pressures is such a common clinical problem.

Protective Functions of the Tympanic Membrane

The tympanic membrane has two major protective functions: one relates to sound protection and the other to protection of the middle ear and mastoid from foreign material. The intact tympanic membrane intercepts sound waves from reaching the round window directly so as to prevent the cancelling effect on inner fluid vibration, which has been called the "curtain action" of the tympanic membrane (see Role of the Round Window later in this chapter).

As described earlier in this chapter, the intact tympanic membrane also protects the middle ear from contamination from the external auditory canal and maintains the middle ear-mastoid air cushion that prevents reflux or insufflation of unwanted secretions from the nasopharynx through the eustachian tube (see section on Physiology of the Eustachian Tube).

Physiology of the Ossicular Chain

The function of the ossicles is to transmit the vibration of the tympanic membrane to the cochlea. If simple transmission alone were the function, all that would be needed would be a single intermediate structure between the membrane and the cochlea. This is true in the evolution of the hearing organ, and the ossicle up to the avian level is, in fact, a single structure called the columella, which corresponds to the stapes of mammals. The three ossicles, the malleus, incus, and stapes, were first seen in mammals. The middle ear of the mammals reached the highest stage of development with increasing complexity in structure and function. Helmholz in 1868 first studied in detail the function of the ossicles as a sound transmitter. Subsequent periods saw many important works in this field done by such notable persons as Dahmann (1930), Stuhlman (1943), and Fumagalli (1949).

Structure and Function of the Ossicles

The dynamic structure of the ossicles was learned from study of the thickness of the bony cortex and the arrangement of the bony fibers or split lines. These studies explain to a certain degree the mode of the working forces. Another approach is a photoelastic experiment using three-dimensional models of ossicles made from a plastic material called diallyl phthalate.

When force or pressure is applied, photoelastic fringe patterns are visualized. Let us take the stapes as an example. The cortex is thick at the head and at the lateral aspects of the neck. The bony fibers or split lines run from the neck, diverging into the two crura, down to the footplate. Photoelastic experiments showed that boundary stress is great where the cortex is thick. The structure of the stapes is in accordance with the dynamics of the force that is first applied to the head, passes the neck and, hence, is divided symmetrically into the two crura (Fig. 30). Similar experiments that were performed on the malleus and incus also show that the structure is in accordance with the dynamics of the force applied to the ossicles.

Mode of Vibration of the Ossicular Chain

This is best explained from the sphere of kinetics. The ossicular chain is taken as a mechanical transformer of sound energy. Let us take, as an example, the relationship between the center of gravity and the axis of rotation. If by the ossicular chain the center of gravity falls on the axis of rotation, the inertial moment of the system would be naught. As the principles of kinetics show, this system becomes a very effective transformer.

Center of Mass and Axis of Rotation of the Ossicles. The classic teaching has been that the axis of rotation of the ossicles matches the line drawn between the extremity of the long process of the malleus and the short process of the incus (Helmholz, 1868; Dahmann, 1930; Bárány, 1938) (Fig. 31). It is ascertained that the axis of rotation of the ossicular chain coincides with the center of mass of the whole sound-conducting system. This mechanical system is very effective with the minimal inertial moment.

Incudomallear Articulation. Helmholtz (1868) interpreted the joint as a kind of tooth-edged wheel or cog mechanism that makes an articulatory movement in only one direction. Bárány (1938) held, on the other hand, that the joint does not make an articulatory movement. Recent studies are favor of the latter view. The incudomalleal joint is rigidly rocked under the intensity of ordinary sounds. Only when the intensity exceeds a certain level does the joint make an articulatory movement, the amplitude of vibration of the incus being held within a certain limit. This is interpreted as a protective mechanism of the ear.

Motion of the Stapes. Vibratory motion of the stapes varies in two ways, according to the intensity of the sounds. Békésy (1936, 1939) showed that in sounds of moderate intensity the anterior end of the footplate oscillates with an amplitude greater than that of the posterior end (Fig. 32). In other words, a rocking motion occurs at the transverse axis near the posterior end.

According to our observation, the footplate also shows a piston-like back-and-forth movement and, in this case, the rocking motion is accompanied by a piston-like component (Fig. 33). The actual movement of the stapes is quite complex, as shown in Figure 33. This is because the annular ligament around the footplate is unequally distributed. The footplate is more rigidly fixed posteriorly than it is anteriorly, and the stapes rocks around the axis near the posterior edge.

With high sound levels, the mode of action changes and a side-to-side rocking movement is seen around the axis running longitudinally through the length of the footplate (Fig. 32). As a result, the cochlear fluid flows only from one edge of the footplate to the other, with much less fluid displacement than when the mode of vibration is through a vertical axis and the footplate is acting like a piston. This rotational shift of the axis is protective mechanism for the inner ear.

Ossicular Chain as a Transformer

The outer end of the ossicular chain faces the air by the tympanic membrane and the inner end is connected to the inner ear by the oval window. The ossicular chain in the intermediate structure connects two different kinds of substances, namely, air and fluid. According to the well-known principle in acoustics, sound waves traveling in a medium of some given elasticity and density do not pass readily into a medium with a different elasticity and density but, rather, most of the sound will be reflected away. Thus, only 0.01 per cent of the sound in the air will pass into water, while the remaining 99.9 per cent is reflected back. Figure 34 shows the results obtained from experiments on cats (Wever et al, 1948). The average transmission loss calculated is around 20 to 35 dB. In other words, the total mechanical advantage afforded by the middle ear is 20 to 35 dB. This value is comparable to the theoretical figure for the human ear, as calculated from the transformation ratio of 22:1. (The product of the areal and lever ratios is discussed in the following sections.

Ossicular Chain Lever. Helmholz (1868) measured the amplitudes of displacement of the stapes and the manubrium of the malleus. He reported that the movement of the stapes is two-thirds that of the manubrium and that their lever ratio is 1.5:1. He concluded that the force exerted upon the manubrium was increased by 1.5 and the amplitude reduced correspondingly. Dahmann's (1929) optical method revealed that the lever ratio as calculated from the length of the arms is 1.31:1. Stuhlman's (1943) model study showed the ratio to be 1.27:1. Wever's (1954) experiments on cats using cochlear microphonics showed that the lever ratio of the manubrium and the long process of the incus is 3:1 to 1:1. These comparable results show that the ossicular chain lever ratio is near 1 and its functional significance is not so great.

Areal Ratio of the Tympanic Membrane and the Oval Window. The difference in areas of the tympanic membrane and the stapes footplate results in a transformer action by hydraulic principle. Helmholz (1868) measured the areas and he gave 64.3 sq mm for the tympanic membrane and 3.2 sq mm for the footplate. The areal ratio is 20:1. Subsequent studies of the ratio give slightly different values: 18.2:1, 19.1:1 (Wever et al, 1948), 21:1 (Fumagalli, 1949), and 26.6:1 (Békésy, 1951). The average of these five values is about 21:1 (Fig. 35). This is the anatomic ratio.

As we have seen, the tympanic membrane does not vibrate as a whole because it is fixed all around the periphery. Wever and Lawrence (1954) deduced that the effective area for the tympanic membrane lies between 60 and 72 per cent of the anatomic area in the cat. Thus, the effective areal ratio will be 14:1. If we accept Dahmann's figure of 1.31 for the ossicular chain lever ratio, we obtain the overall ratio for the middle ear as the product, 14x1.31=18.3.

By means of the transformer action of the middle ear, the amplitude is greatly reduced at the oval window as compared with the amplitude at the tympanic membrane, and the force (pressure) at the oval window is increased in the same proportion, or 18.3 times.

Disturbance of the Ossicular Chain. When the ossicular chain is disrupted by causes such as head trauma and infection, a hearing loss of about 50 to 60 dB is seen even if the tympanic membrane is left intact. This hearing loss is caused by loss of the ossicular chain (28 dB) and by the existence of the tympanic membrane, which interferes with the sound conduction to the inner ear (Fig. 36). On the other hand, even if the ossicular lever is lost by type III tympanoplasty, the hydraulic principle is restored because the head of the stapes is in contact with the tympanic membrane, as in the columella of birds. Loss of hearing in this case would be 20 dB or less (Fig. 37).

Role of the Round Window

The area of the round window is 2 sq mm. The window seals off the scala tympani and is situated at a right angle to the oval window. The round window is a relief opening to the labyrinth that permits the contained fluid to move under the influence of the stapes. As an entrance route for sounds this is a very poor path, and the sound traveling by this route would be seriously attenuated because the tympanic membrane is in the way. The phase of sounds entering this window differs from that of the oval window because the two windows are not situated in the same plane.

This normal condition changes if the middle-ear transformer is lost. The oval window is no longer superior to the round window and the sound wave strikes the two windows simultaneously. The sound waves in the labyrinth, however, travel from both ends and cancer each other. The loss of energy is about 12 dB, and this is called the cancel effect (Fig. 38).

When we protect the round window with a small piece of wet cotton or tissue, the sound does not strike the window directly. This results in the improvement of hearing by 20 dB over low and middle frequencies. This is called the sound protection of the round window (Fig. 38). A similar effect is expected when we close the perforated membrane or make a small tympanum (curtain action of the tympanic membrane).

Function of the Intrinsic Muscles of the Middle Ear

The middle ear structure includes two muscles, the tensor tympani and the stapedius, which are the smallest muscles in the body. The tensor tympani is the larger of the two.

Both are pennate muscles consisting of many short striated and nonstriated muscle fibers. They make involuntary contractions during acoustic stimulation. The reflex contraction starts first in the striated muscles, and the contraction is kept tense by nonstriated muscles.

Acoustic Reflex Contraction of the Intratympanic Muscles

Acoustic reflex contraction of the intratympanic muscles can be evoked bilaterally by unilateral stimulation. The reflex arc is considered to consist of the input pathway starting from the cochlear hair cells and reaching either the facial (stapedial reflex) or trigeminal (tensor tympani reflex) motor nucleus via the ventral cochlear nucleus, the superior olivary complex, and the medial longitudinal fascicles, and the output pathway originating from the motor nuclei and descending to the peripheral intratympanic muscles. It is also found that there exists a bilateral connection in the central pathways of the reflex arc.

This reflex contraction depends upon the frequency and intensity of stimulating sounds. Results obtained by experimenting with rabbits are shown in Figure 39 (Lorente de Nó, 1933). The threshold for the reflex contraction in a rabbit is about 40 to 100 dB. When the sounds are of frequencies less than 1500 Hz, the threshold of the stapedius reflex is lower than that of the tensor tympani muscle; above the frequencies of 4000 Hz, similar thresholds are seen in both muscles.

Because of technical limitations, separate observation of thresholds for the two muscles is hardly possible in humans. Two muscles are grouped together, and the threshold of this group in humans is 70 to 90 dB above the thresholds of hearing in frequencies ranging from 250 to 4000 Hz. The threshold is somewhat lower for noise than for pure tones.

Electromyographic study of cats showed that the latency time for the burst of action current of the muscle is 6 to 8 sec in the case of the tensor and always shorter in the case of the stapedius. In addition, effective muscle contraction takes place after 2 to 3 msec, and maximal tension is obtained after a few more milliseconds (Kirikae, 1960) (Fig. 40). In humans, the values of 35 msec and 25 msec were obtained as the latency period to the onset of an impedance change for the highest intensity sounds by Metz (1951) and Borg (1968), respectively. Near the reflex threshold, the latency period can be as long as 150 msec. These values are longer than those obtained in animals.

Effects of the Intratympanic Muscle Contraction

According to the experiments made on cats, the contraction of the tensor by sound stimuli produces inward displacement of the tympanic membrane accompanied by decrease in the amplitude of vibration (Fig. 40). Contraction of the stapedius exerts a force on the head of the stapes and draws it posteriorly. This displacement is not accompanied by a long process of the incus followed by a shift seen between the head of the stapes and the long process of the incus. Contraction of the stapedius alone does not cause any displacement of the tympanic membrane.

The effect of the reflex contraction on the cochlear microphonics was studied in cats. A great decrease of amplitude was seen in the contraction of the stapedius and the tensor (Møller, 1964) (Fig. 41). According to a detailed study made by Wever and co-workers (1955), the effect of the strong contraction of the tensor or the stapedius is a reduction in transmission. Being frequency selective in lower tones, this attenuation was only 5 to 10 dB.

To summarize, both muscles exert a force at right angles in the direction of ossicular movement and act as a damping mechanism that suppresses the degree of ossicular movement.

Tympanic Muscle Reflex in Humans

Kawat (1958) measured the inward displacement of the manubrium mallei caused by reflex contraction of the muscles. Kobrak (1948) made direct measurement of the tilting of the footplate caused by reflex contraction of stapedius in a patient with a radical mastoid cavity. An experiment was done by Kobrak (1948), who made an optical perforation; ie the superior portion of the tympanic membrane was made transparent but not perforated. Maximal contraction was seen at maximal sensitivity of the human ear in frequencies ranging from 2500 to 3000 Hz. Møller (1964) observed in humans the change in the acoustic impedance caused by tympanic muscle contraction. The change was measured in the external auditory canal. Figure 42 shows the results obtained from measurements of the impedance change of contralateral stimulation at various intensities. Sensitivity of muscle contraction is defined as the sound intensity required to give a certain percentage of maximal impedance change.

Attenuation of reflex contraction in humans is said to be about 10 dB at low frequencies (Wever et al, 1954), or 5 to 10 dB (Békésy, 1951). Nakamura and Okamoto (1956) reported the value to be less than 5 dB in humans, which coincided with the value of Metz's (1946) human experiments using the measurement of the impedance, which show that the reduction of sound absorption of 5 dB can be demonstrated at the maximal.

Physiologic Role of the Tympanic Muscle Reflex

The stapedius and tensor tympani muscles exert force in directions opposite to each other (anatomic antagonists) but perpendicular to the primary rotational axis of the ossicular chain (functional synergists). Several functions have been attributed to the tympanic muscle reflex.

Protective Intensity Control Theory. The effect of the muscle reflex on the performance of the ear, as stated previously, is reduction of transmission, which is frequency selective in lower tones. This reflex mechanism serves to protect the cochlea from excessive stimulation caused by loud noises. In humans, however, actual attenuation afforded by this mechanism is small, or its intensity control is not great.

Accommodation or Frequency Selection Theory. This is a theory that supposes that in certain frequencies muscle contraction selectively increases hearing sensitivity. But evidence is lacking to actually show the degree of augmentation afforded by reflex contraction.

Fixation Theory. The tympanic muscles have a simple and obvious function to provide stability of suspension for the ossicular chain.

Role of the Tensor Tympani Muscle

Some would argue that the tensor tympani has no demonstrable function in the physiologic function of the human middle ear (Howell, 1984). Honjo and associates (1983) have shown that tensor tympani is not involved in eustachian tube function even though it is part of a bipennate muscle with the tensor veli palatini. In addition, electromyographic studies have failed to elicit significant electrical activity in the tensor tympani muscle in response to contralaterally presented sound (Djupesland, 1965). However, loud sounds do occasionally elicit tensor tympani activity; this activity is usually associated with a generalized startle reaction. More recently, Stach and co-workers (1984) recorded an acoustic tensor tympani reflex in one patient with facial paresis. Even though this finding may be an isolated occurrence, it shows that further research is required to determine the role of tensor tympani in middle ear physiology.

Acoustic Impedance of the Middle Ear

The main function of the middle ear is to facilitate the transmission of sound waves from air to the cochlear fluids (Fig. 43). If sound waves act directly on the cochlear fluids, there will be a significant transmission loss of about 30 dB. This is because the values of acoustic resistance (or impedance), which are determined by elasticity and density, are widely different between two media such as air and the inner-ear fluid. In an example given previously, we speak of impedance mismatching, in which most of the sound energy is reflected. When the impedances are similar, or approximated by an intervening mechanical device, sound energy is transmitted effectively from one medium to the other, and this is called impedance matching. Thus, the middle ear acts as a transformer that "matches" the low impedance of air to the high impedance of the cochlear fluids.

The middle ear is a vibrating mechanical system whose acoustic impedance is determined by three factors: mass, stiffness (elasticity), and frictional resistance. We might draw our analogy from the principles of electronics, which state that the flow in an electrical circuit is determined by three factors: resistance, inductance, and capacitance. The relation between the acoustic impedance (Za) and the mechanical impedance (Zm) is expressed by the following formula:

$$\mathbf{Za = Zm / A^2}$$

in which A is the area of the piston.

If the acoustic system shown in Figure 44 is compared with the middle ear, the piston represents the tympanic membrane; M, the mass; S, the stiffness; and Rm, the friction of the middle-ear mechanism. M represents the total weight of the tympanic membrane, the ossicular chain, and the inner-ear fluids. The effective M would be less than the actual M since the center of mass of the ossicular chain falls on the axis of rotation. S consists of the ligaments of the middle ear, the incudostapedial joint, the tension of the tympanic membrane, the tension of the tympanic muscles, and the air in the tympanic cavity.

The concept of acoustic impedance facilitates an understanding of various kinds of hearing loss seen in pathologic conditions of the middle ear.

Pathophysiology of the Middle Ear

According to Johansen (1948), the acoustic impedance of a vibrating system having mass, stiffness, and frictional resistance is calculated from the formula:

$$I^2 = r^2 + (mf - s/f)^2$$

where I is the impedance; r, the frictional resistance; m, the mass; s, the stiffness, and f, the frequency.

From the formula, calculated threshold value curves are obtained as shown in Figure 45. The natural resonance point of the middle ear is said to be about 800 Hz, although Békésy (1936) obtain a value of 1000 Hz and Perlman (1947), 750 Hz. High values of f will exaggerate the effect of changes in mass.

When the mass is increased, the transmission of higher frequencies is impaired and the resonance point is shifted toward low tones. Low frequency values emphasize the effect of changes in stiffness. When the stiffness is increased, transmission of lower frequencies is impaired and the resonance point is shifted toward higher tones. These give rise to "mass curve" and "stiffness curve". When the mass is increased by loading the tympanic membrane with water and mercury, the thresholds for higher tones are elevated (Fig. 46). Similar audiograms are seen with accumulation of fluids in ears with otitis media. The stiffness is increased by such causes as negative pressure in the tympanic cavity, eustachian tube obstruction, ossicular chain adhesion, and otosclerosis (Fig. 47).

Acoustic Properties of the Air Spaces of the Middle Ear

The middle ear cavity consists of the tympanic cavity, tympanic antrum and mastoid cells, and the eustachian tube. The tympanic cavity communicates with the tympanic antrum and mastoid cells by the tympanic aditus posterosuperiorly, and with the eustachian tube anteroinferiorly.

These communicating air spaces are regarded as an entity in the sound-conducting system. This closed air cavity has the physical effect of acting as a damping body. At low frequencies, the air cavity of the middle ear affects vibration of the tympanic membrane, but at high frequencies only the tympanic cavity operates as an acoustic impedance. The larger the volume of the air space, the smaller the acoustic impedance or the less effect on the vibration of the tympanic membrane. The air spaces of tympanic antrum and mastoid cells add to the enlargement of the middle-ear cavity, which corresponds to about 2 ml of air in acoustic impedance. The middle-ear cavity has resonance at 1800 Hz and antiresonance at 2600 Hz.