Chapter 142: Anatomy and Physiology of the Eustachian Tube

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In 1960 Macbeth stated: "One would have thought that it would be reasonably easy to have learned all there is to know about such a small and fixed structure (the Eustachian Tube), but it does two odd things - it runs from within a soft-tissue viscus into a cavity of the skull; and it links the two major areas in our profession (Otolaryngology). On its brief but entertaining course, it has many important companions and neighbors ... and it seems unlikely that the last has been written about it".

During the approximate 2400 years since Alcmaeon of Sparta first described the tube, much has been written on its anatomy, function, and dysfunction. Alcmaeon thought that the tube that connected the nasal airway and the ear enabled goats to breathe through their ears as well as through their noses.

Bartholomeus Eustachius published the first detailed description of the auditory (Eustachian) tube in 1562 in his thesis *Epistola de auditus organis* (translated by Graves and Galante, 1944). Eustachius wrote:

From the cavity of the petrous bone, there in which the auditory passage called concha such a passage toward the nasal cavity is perforated ... Others would perhaps think that this passage about which this dissertation is being written, ends in that place; this is not so, however, for it is augmented by a substance of different nature and is carried on between two muscles of the pharynx ... and it ends in either cavity of the nose near the internal part of the root of the apophysis of the bone that is shaped like the wings of the bat, and is inserted in a thick revestment of the palate near the root of the uvula. Its substance, where it touches the extremity of the fissure which is common to the temporal and wedge-shaped bones, is cartilaginous, and quite thick; but the substance of the opposite part is not exactly cartilaginous, but is somewhat membranous and becomes thinner gradually; but the internal end of the passage facing the middle of the nasal cavity has a strong cartilage which is very thick and is covered by the mucous membranes of the nares, and is seen at the end of the same meatus as if it were a guardian. It is not round, but is somewhay depressed and makes two angles. It is as large as a writing cane, but is twice as large at the end as at the beginning, which is eaully invested by a mucous membrane, which is, however, thinner.

The eustachian tube is part of a system of contiguous organs, including the nose, nasopharynx, middle ear, and mastoid (Fig. 142-1). It is usually divided into an osseous intratemporal portion and a cartilaginous portion. Respiratory mucosa lines the entire system. Thus effects of infection or obstruction, such as inflammation, in one area are likely to be reflected in the other areas. A knowledge of the anatomy and physiology of the eustachian tube is a necessary prerequisite of the proper diagnosis of the symptoms of this region.

Descriptions of eustachian tube anatomy and knowledge of its function have evolved over many years. This chapter reviews our present understanding of the structure and function of the eustachian tube and middle ear system. As in the past, however, this knowledge will expand with continued study.

Anatomy

Development

Adult eustachian tube morphology is the culmination of 18 years of development and growth; thus its structure and function can best be appreciated in the context of these processes. Further, identification of abnormalities and their consequences depend on a knowledge of normal anatomy.

The eustachian tube lumen is the persistence of the first pharyngeal pouch. The structures associated with this lumen develop from the surrounding mesenchyme in a predictable sequence. Swarts et al (1986) studied tubal development in 20 human fetuses between 7 and 38 weeks post conception. Their results confirm and extend those of Wolff (1934) and Tos (1971). Figure 142-2 illustrates the differentiation and development of the tubal structures. Before 10 weeks post conception only the epithelial lining of the lumen has differentiated. Between 10 and 12 weeks after conception the levator veli palatini and tensor veli palatini muscles develop and become delineated from the surrounding mesenchyme (Fig. 142-2, A). The first evidence of the third muscle, the tensor tympani muscle, is apparent approximately 2 weeks later. At about the same time (14 weeks post conception) the initial differentiation of the cartilage begins (Fig. 142-2, B). This is indicated by a more darkly staining region just medial to the tubal lumen. Also at this time, the lumen begins to show folding of the epithelium into the rugae characteristic of the adult eustachian tube. Concomitant with these changes, glandular tissue appears in the pharyngeal wall, medial to the cartilage and between it and the more lateral lumen. By 20 weeks after conception the initial center of chondrification has increased in size and a perichondrium is clearly differentiated in the anteromedial portions of the tube (Fig. 142-2, C). An anteromedial to posterolateral gradient of development is apparent in the differentiation of the eustachian tube structures. By parturition these processes yield a eustachian tube structure very similar to that observed in the adult. The cartilage is clearly delimited by a perichondrium throughout its length and shows the classic J-shaped form. The muscles are well circumscribed and evidence positions, relative to the cartilage, reminiscent of those of th eadult (compare Fig. 142-2, D and 142-4, B). Glandular tissue has proliferated and now occupies the regions between the cartilage and nasopharynx, between the cartilage and the lumen, and between the lumen and the tensor veli palatini muscle.

As ontogeny proceeds, morphometric changes occur among the eustachian tube structures and also with respect to the rest of the head. The most pronounced change is the increase in tubal length from 1 mm at 10 weeks to 13 mm at birth. Most of this increase occurs in the cartilaginous portion of the tube. If the increase in tubal length is standardized to changes in body size, such as crown-rump length or nasion-sella length, allometric growth is apparent. That is, the cartilaginous portion of eustachian tube increases in length faster, between 16 and 28 weeks post conception, than either of these two measures of body size. The osseous portion of the eustachian tube displays isometric growth with respect to these measures of body size until 28 weeks, when its growth outpaces theirs. Changes also occur in lumen height. At about 10 weeks after conception the lumen is an anteriorly opening flask, with a very short neck. As development proceeds, the neck of the flask (the eustachian tube) elongates, but throughout gestation the diameter (height) grows isometrically with respect to body size. Thus the cylindrical configuration of the cartilaginous lumen persists until birth and for an undetermined period of time afterward. Finally, the angle between the tensor veli palatini and the cartilage becomes more acute throughout ontogeny. This change follows the same gradient established in the differentiation of eustachian tube structures.

Because the fetal cranial base is relatively flat, the tube deviates from the horizontal plane only about 10 degrees, a condition that persists into early adulthood. The cranial base angle increases during postnatal development, as do the vertical dimensions of the skull. The hard palate drops away from the skull base. As this occurs, the angle between the cartilaginous tube and the skull base increases. The eustachian tube lengthens rapidly durig early childhood, essentially reaching its adult size by 7 years of age (Sadler-Kimes et al, 1989). The effect of these changes on efficiency of eustachian tube function has yet to be determined, but age-related changes in eustachian tube function (Bylander et al, 1983; Bylander and Tjernstrom, 1983) suggest more efficient muscular activity and a system that is less likely to act as a passive conduit for nasal secretions.

The period between birth and adulthood is one of the great lacunae in our understanding of the ontogeny of this region. The importance of developmental changes to our understanding of middle ear disease during this interval should not be underestimated because there is a concurrent decrease in the prevalence of disease with increasing age.

Adult morphology

The otolaryngologic and general anatomic literature focuses on the active, anteroinferior two thirds of the adult eustachian tube. In adults the eustachian tube forms and angle of 45 degrees with respect to the horizontal plane (Frankfort horizontal plane), considerably larger than the 10-degree angle of infants (Proctor, 1967). It forms a 42 ± 9 degree angle with a parasagittal plane through the medial pterygoid plate. The tube is longer 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 (Speilberg, 1927) and as long as 40 mm (Bacher, 1912), but the usual range of length reported in the literature is 31 to 38 mm (Anson, 1967; Anson and Donaldson, 1967; Doyle, 1977; Goss, 1967; Macbeth, 1960; Proctor, 1967). 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 (Graves and Edwards, 1944; Proctor, 1967).

The adult eustachian tube begins in the middle ear and passes anteriorly and medially through the petrous temporal bone. Little is written about the intratemporal, protympanic, or osseous portion of the tube because it remains patent (Fig. 142-3). The aural orifice, an oval structure, lies above the floor of the middle ear space and measures about 5 by 2 mm (Graves and Edwards, 1944). The medial wall of the osseous portion of the eustachian tube lies close to the carotid canal and the labyrinth. Djerić and Savić (1985) found that in about two thirds of the specimens they examined the carotid canal noticeably impinged on the osseous eustachian tube. The mucosal lining of this portion of the eustachian tube is similar to that of the middle ear, including both mucus-producing and ciliated cells.

The eustachian tube does not take a straight course from the middle ear to the nasopharynx, but rather a slowly curving inverted S course. Speilberg (1927) found that in adults "the tube makes two curves as it leaves the tympanic cavity, arching downward and forward across the space between the anterior canal wall and the bony external auditory meatus in the condyle of the mandible. Before the pharyngeal orifice, it makes another slight curve downward and forward". Additional observations (Swarts et al, 1986) support Speilberg's observations, although variability is great.

The nasopharyngeal terminus of the eustachian tube lies about 20 mm above the plane of the hard palate (Graves and Edwards, 1944). The cartilage protrudes into the nasopharynx; this protrusion is known as the *torus tubarius* (see Fig. 142-1). A thick layer of epithelium continuous with the soft tissue lining of the nasopharynx covers it. An observer viewing the nasopharynx endoscopically cannot see the torus tubarius but can see the mucosa overlying the cartilage. Any inferences drawn from observing motion in this area must consider this point of the anatomy.

Cartilage

The contribution of the cartilage to the efficient functioning of the eustachian tube depends on its structure, composition, and attachment to the cranial base and paratubal muscles. The cartilage of the eustachian tube is shaped like an inverted J in cross section (Fig. 142-4). Extrusion of this form yields its gross structure (Fig. 142-5). The cartilage has been described as being composed of a short lateral lamina and an elongated medial lamina (Fig. 142-5). It is misleading to speak of two laminae: the cartilage is actually a dome-shaped structure, with arms of different lengths. The lateral arm has a constant height. The medial arm, however, starts as a short structure, which increases rapidly in height to 13 mm just posterior and lateral to the attachment of the cartilage to the medial pterygoid plate (Fig. 142-4, A, 142-5). This attachment is visible as a slight protuberance of the posterior edge of this plate (Fig. 142-6). Posteriorly, the cartilage height decreases to 9 mm, a height it retains until it enters the petrous temporal bone. In the midsection of the cartilaginous tube, a lateroinferior extension of the medial arm interposes itself between the lumen and the levator veli palatini muscle in most of the specimens examined (Swarts and Rood, 1990). The cartilage persists into the petrous temporal bone as a dome-shaped structure itself between the lumen and the superiorly placed tensor tympani muscle (Fig. 142-4, D). Thus the suggestion in the literature that the cartilaginous tube ends where the osseous tube begins is incorrect. Eustachius (Graves and Galante, 1944), von Troltsch (Terracol et al, 1949), and others report that the eustachian tube cartilage is a single piece of cartilage. Graves and Edwards (1944), Terracol et al (1949), Simkins (1943), and Rood and Doyle (1978) reported finding one to several pieces of accessory cartilages and a single large principal cartilage. This latter configuration seems to be the most frequent finding (Fig. 142-4, C).

A second factor influencing cartilage function is its attachment to the cranial base. Two viewpoints exist with respect to this characteristic: first, that the cartilage is tightly bound to the cranial base in the sphenoid sulcus (sulcus tubae auditivae) throughout its length (Bryant, 1907; Graves and Edwards, 1944; Rood and Doyle, 1978; Sief and Dellon, 1978), or, second, that it is attached more loosely to the cranial base (Proctor, 1973; Swarts and Rood, 1990). As indicated by histologic examination of the Eustachian tube, the nasopharyngeal end of the cartilage is tightly fixed to the medial pterygoid plate by a broad attachment (Fig. 142-4, A). Posteriorly, this attachment to the cranial base is reduced to a small insertion superior and slightly lateral to Rosenmüller's fossa (Fig. 142-4, B). The connective tissue of this attachment arises from the medial pharyngeal surface of the cartilage's medial arm before it coalesces into a ligamentous structure that inserts on the cranial base. This insertion is seen on the skull base as a bony ridge forming the medial margin of the sulcus tubarius (Fig. 142-7). In this region the superior surface of the cartilage is about 2 mm from the cranial base (Figs. 142-4, A, B and C, 142-5). Just before its entrance into the petrous temporal bone the medial arm of the cartilage is again broadly anchored to the cranial base.

The tubal cartilage is similar in composition and elasticity to those found in the pinna and the nose. Several authors have reported dispersed elastic fibers within the tubal cartilage. Reiner (1969) found elastic fibers that ran longitudinally and that spiraled laterally in the dog. The highest density of these fibers was just deep to the perichondrium of the inferior surface of the cartilage's hook in an "almost cap-like arrangement" Guild (1955) found much the same distribution in human eustachian tubes. The radial organization of elastic fibers around the dome of the cartilage suggests that motion of the lateral arm relative to the medial arm of the cartilage is possible.

Lumen

The structure of the adult eustachian tube lumen resembles two truncated cones attached at their narrow ends, their broadest ends representing the nasopharyngeal and tympanic orifices. The nasal orifice is 8.5 mm in height. This dimension decreases steadily to a minimum, 3.5 mm, after the eustachian tube enters the petrous temporal bone. A 20-degree angle exists between the roof of the lumen and its floor. The sum of this angle with that formed by the cranial base and roof of the lumen accounts for the 45-degree descent the eustachian tube makes in its course from the middle ear to the nasopharynx. The narrowed intratemporal region is known as the isthmus of the eustachian tube. Because of its reduced caliber it is often implicated as the critical component in the development of otitis media. However, Sadé et al (1989) found no difference in the calibers of the isthmus in a comparison of children with otitis media and those without.

The eustachian tube is lined with pseudostratified, columnar epithelium of the ciliated type, which sweeps material from the middle ear to the nasopharynx. The mucosa is continuous with the lining of the tympanic cavity at its upper end, as it is with the nasopharynx at its lower end. Associated with these ciliated epithelial cells are goblet cells that comprise about 20% of the cell population (Lim, 1984). This density of goblet cells reflects a reduction from their abundance in children (Tos and Bak-Pederson, 1976). In adults, the highest densities of these cells occur near the nasopharyngeal orifice. The submucosa of the anterior one half of the cartilaginous eustachian tube also contains numerous mucoserous glands (Tomoda et al, 1981). As with the goblet cell populations, the proportion of mucus-producing cells in the submucosa decreases with increasing age. Thus Tomoda and his colleagues postulated that the viscosity of the secretions from these cells also decreases with age. The products of these glands include mucopolysaccharides, lysozyme, secretory immunoglobulins, and surface active compounds (Hills, 1984a and b; Lim, 1984; Rapport et al, 1975; Svane-Knudsen et al, 1988). Clearly, the activity of the eustachian tube is affected by the concentrations and distributions of these compounds.

Lateral membranous wall

Closely associated with the lumen of the eustachian tube is the lateral membranous wall. This structure, although not clearly delineated, is invoked in many descriptions of eustachian tube function. It is most clearly defined in the middle portion of the cartilaginous eustachian tube (Fig. 142-4, C). Its medial boundary is the submucosa of the lumen. Laterally, a robust connective tissue layer serves as the insertion of the tensor veli palatini muscle. This fibrous lateral membrane is anchored superiorly to inferior curvature of the lateral arm of the eustachian tube cartilage. The region between these two boundaries is occupied by glandular tissue anteriorly and adipose tissue posteriorly. There is little evidence of connective tissue bridges spanning the space between these two components. Thus, it would appear that forces developed by the tensor veli palatini muscle would be passed to the lateralarm of the cartilage rather than to the lateral submucosa of the lumen.

Paratubal musculature

Traditionally four muscles are commonly cited as being associated with the eustachian tube: 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; Van Dishoeck, 1947).

Usually the eustachian tube is closed; it opens during such actions as swallowing, yawning, or sneezing, thereby permitting the equalization of middle ear and atmospheric pressures. Although the mechanism of tubal dilation remains controversial, most anatomic and physiologic evidence supports active dilation induced either solely by the tensor veli palatini muscle (Cantekin et al, 1979; Honjo et al, 1979; Rick, 1920) or with assistance from the levator veli palatini (Proctor, 1973; Swarts and Rood, 1990). Closure of the tube has been attributed to passive reapproximation of tubal walls by extrinsic forces exerted by the surrounding deformed tissues, by the recoil of elastic fibers within the tubal wall and cartilage, or by both mechanisms. More recent experimental and clinical data suggest that, at least for certain abnormal populations, the closely applied internal pterygoid muscle may assist tubal closure by an increase in its mass within the pterygoid fossa; this increase applies medial pressure to the tensor veli palatini muscle and consequently to the lateral membranous wall of the eustachian tube (Cantekin et al, 1979; Doyle et al, 1980; Ross, 1971).

The tensor veli palatini is composed of two fairly distinct bundles of muscle fibers divided by a layer of fibroelastic tissue. The bundles lie mediolateral to the tube. This muscle is composed predominantly (60%) of the white (fast) fiber type (Tomoda et al, 1984). The more lateral bundle (the tensor veli palatini proper) is of an inverted triangular design, taking its origin from the scaphoid fossa and from the greater wing of the sphenoid bone superior to the eustachian tube cartilage (Figs. 142-4, A to C, and 142-5). The force this muscle exerts on this origin creates the lateral osseous ridge of the sulcus tubarius (Fig. 142-7). The muscle descends anteriorly, laterally, and inferiorly to converge in a tendon that rounds the hamular process of the medial pterygoid lamina about an interposed bursa (Fig. 142-8). 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 (Fig. 142-9). The more posterosuperior muscle fibers, lacking an osseous origin, extend instead into the semicanal of the tensor tympani muscle. Here they receive a second muscle slip, which originates from the tubal cartilages and sphenoid bone. These muscle fibers 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 (Lupin, 1969; Rood and Doyle, 1978). The tensor tympani does not appear to be involved in the function of the eustachian tube (Honjo et al, 1983).

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 tube* muscle (Goss, 1967; Rood and Doyle, 1978). It has its superior origin in the posterior one half of the fibrous lateral membranous wall of the cartilaginous eustachian tube (Figs. 142-4, C, 142-5). The fibers descend sharply to enter and blend with the fibers of the lateral bundle of the tensor veli palatini muscle. This inner bundle is primarily responsible for active dilation of the tube.

The levator veli palatini muscle arises from the inferior aspect of the petrous apex of the temporal bone. The fibers pass inferomedially, paralleling and lying beneath the tubal cartilage and luminal floor (see Fig. 142-5). In most instances the interaction of the levator veli palatini with the posterior one half of the cartilaginous eustachian tube lumen is precluded by an extension of the medial arm of the cartilage. Near the nasopharyngeal end of the eustachian tube, when the cartilage is at its maximum height, the levator veli palatini lies lateral to its medial arm (Figs. 142-4, B, 142-5). The fibers of this muscle insert by fanning out and blending with the dorsal surface of the soft palate (Bryant, 1907; Graves and Edwards, 1944; Rood, 1973). Most investigators deny a tubal origin for this muscle and believe that it is related to the tube only by loose connective tissue (McMyn, 1940; Simkins, 1943). This muscle is composed of equal numbers of red (slow) and white (fast) fiber types (Tomoda et al, 1984). The levator is not the primary dilator of the tube (Cantekin et al, 1983) but probably contributes by elevating the medial arm of the cartilage at the nasopharyngeal end of the eustachian tube (Swarts and Rood, 1990).

The salpingopharyngeal muscle arises from the medial and inferior borders of the tubal cartilage via slips of muscular and tendinous fibers (see Fig. 142-3, A). The muscle then courses inferoposteriorly to blend with the mass of the palatopharyngeal muscle (Graves and Edwards, 1944; McMyn, 1944). Rosen (1970) examined 10 hemisected human heads and identified the muscle in 9 specimens. However, in all cases the muscle fibers were few in number and appeared to lack any ability to perform physiologically.

Innervation

The pharyngeal orifice of the eustachian tube is innervated by a branch from the otic ganglion, the sphenopalatine nerve, and the pharyngeal plexus. The remainder of the tube receives its sensory innervation from the tympanic plexus and the pharyngeal plexus. The glossopharyngeal nerve probably plays the predominant role in tubal innervation. Sympathetic innervation of the tube depends on the sphenopalatine ganglion, the otic ganglion, paired glossopharyngeal nerves, the petrosal nerves, and the caroticotympanic nerve (Proctor, 1967). Mitchell (1954) suggested that the parasympathetic nerve supply is derived from the tympanic branch of the glossopharyngeal nerve. Nathanson and Jackson (1976) provided experimental evidence for secondary parasympathetic innervation via the Vidian nerve from the sphenopalatine ganglion. Innervation of the tensor veli palatini is from the ventromedial part of the ipsilateral trigeminal motor nucleus through the trigeminal nerve (mandibular division), and the levator veli palatini muscle receives its innervation from the nucleus ambiguus through the vagus nerve (Eden and Gannon, 1987; Ito et al, 1987).

Function

The eustachian tube has at least three physiologic functions with respect to the middle ear (Fig. 142-10): (1) ventilation of the middle ear to equilibrate air pressure in the middle ear with atmospheric pressure; (2) drainage and clearance into the nasopharynx of secretions produced within the middle ear; and (3) protection from nasopharyngeal sound pressure and secretions. Even though the ventilatory function is the most important of these functions, the protection, drainage, and clearance functions are reviewed so that the reader will be better able to visualize and understand the ventilatory function; in the following discussion fluid flow through the tube includes gas (airflow) and liquid flow.

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, caused only by contraction of the tensor veli palatini muscle during swallowing, maintains nearly ambient pressures in the middle ear (Cantekin et al, 1979; Honjo et al, 1979; Rich, 1920). Assessment of these functions has been helpful to the understanding of the physiology and pathophysiology of eustachian tube function, as well as to the diagnosis and management of middle ear disease in children.

Ventilatory function

The transducer function of the middle ear is optimal with the tympanic membrane in the neutral position, a condition realized when ambient and middle ear pressures are equivalent. This equivalence is processually disrupted by asynchronous fluctuations in the ambient and middle ear pressures. Opening of the eustachian tube allows exchange of gases and equalization of pressures between the environment and middle ear, thus establishing a dynamic equilibrium centered about a negligible pressure differential.

Under conditions normally experienced by most mammals, the fluctuations in ambient pressure are bidirectional, relatively small in magnitude, and not readily appreciated. They reflect the rise and fall in barometric pressures associated with changing weather conditions or elevation, or both. In contrast, the changes in middle ear pressure show a mass directionality, can achieve appreciable magnitudes, and, in the limit, may have pathologic consequences. This can be understood by recognizing that the middle ear is a relatively rigid (noncollapsible) gas pocket surrounded by a vascular mucosa. Gases are exchanged between the middle ear space and the mucosa; partial pressures of gases in the mucosa approximate that of the microcirculation in the middle ear mucosa. Differential pressure exceeds 54 mm Hg between the middle ear space at atmospheric pressure and the microcirculation in the middle ear mucosa (Ostfeld and Silberberg, 1991). This represents a diffusion-driven gradient from the middle ear to the mucosa that would produce middle ear underpressure (relative to ambient) of more than 600 mm H_2O during equilibration. Whereas more traditional views ascribed the middle ear mucosal gas gradient to differences in the partial pressure of O_2, recent studies of middle ear gas composition suggest that the middle ear and the microcirculation of the middle ear mucosa are similar with respect to O_2 and CO_2 (Felding et al, 1987); Ostfeld and Silberberg (1991) reported that middle ear O_2 is slightly higher than in the microcirculation, whereas CO_2 is in equilibrium. The diffusion gradient is created by differences in N_2 partial pressures and relatively inert gas with low solubility and permeability in an aqueous environment (Ranade et al, 1980). The hydrops ex vacuo theory predicts that on approaching the equilibrium condition, fluid transudation from mucosa to middle ear will occur, thereby decreasing middle ear volume and consequently its pressure. Table 142-1 compares the gas composition in the nasopharynx and middle ear cavity and the microcirculation of the middle ear mucosa with that of air.

The eustachian tube is a potential communication between the nasopharynx and middle ear. When it is opened by activity of the paratubal musculature associated with deglutition and other maneuvers, pressure differences between the ambient environment and middle ear are equalized by the inflow or outflow of gases. Thus, the ventilatory function maintains near-equilibrium between the external and internal pressures, thereby maintaining near-optimal transducer function of the middle ear and preventing the pathologic consequences that result from unabated middle ear to mucosa gas exchange.

From studies in children the function of the eustachian tube has been postulated (Bluestone and Beery, 1976). 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 dilatation (opening) of the tube maintains near-ambient pressures in the middle ear. It is suspected that when active function is inefficient in opening the eustachian tube, functional collapse of the tube persists, causing negative pressure in the middle ear. When tubal opening does occur, a large bolus of air could enter the middle ear, potentially ultimately producing 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 et al (1971; p 356) studied 102 adults with intact tympanic membranes and no apparent history of otologic disorder. The patients were divided into four groups according to their ability to equlibrate static relative positive and negative pressures of 100 mm H_2O in the middle ear (Table 142-2). 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; those in group 4 were incapable 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% of normal adults could equilibrate an applied positive pressure and that 93% could equilibrate applied negative pressure to some extent by active swallowing. However, 28% 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 were apparently otologically healthy. Employing a pressure chamber, Bylander reported that 35.8% of the children could not equilibrate applied negative intratympanic pressure (- 100 mm H_2O) by swallowing, whereas only 5% of the adults were unable to perform this function. Children between 3 and 6 years of age had worse function than those of ages 7 to 12 years. 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 in a manner similar to that recommended by Elner et al in 1971 (Table 142-3).

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; this condition would contribute to the higher incidence of middle ear disease in children.

Many children who have no apparent middle ear disease have high negative ear pressure. However, in children eustachian tube function does improve with advancing age; this improvement is consistent with the decreasing incidence of otitis media from infancy to adolescence (Bylander and Tjernstrom, 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 underpressure within the middle ear by this act (Falk and Magnuson, 1984). However, this mechanism is uncommon in children.

In studying the measurement 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, 1967b; Riu et al, 1966). However, because 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 (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 mm H_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 because 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 milliliters) entering into the middle ear. However, an abnormally functioning eustachian tube may alter this mechanism.

The relation of the physiologic role of the *mastoid air cell system* 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 smaller 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 as a result of reduced middle ear gas pressure because 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 eustachian tube function is abnormal.

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, 1967a). This reduction in function with change in body position was found to be the result of venous engorgement of the eustachian tube (Johnson and Rundcrantz, 1969).

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

Protection, drainage, and clearance function

The clearance and drainage functions of the eustachian tube have been assessed by a variety of methods. By means of radiographic techniques, the flow of contrast medium from the middle ear (tympanic membrane not intact) into the nasopharynx has been assessed by Welin (1947), Aschan (1952, 1955), Compere (1960, 1970), Parisier and Khilnani (1970), Bluestone (1971), Bluestone et al (1972a, 1972b), Ferber and Holmquist (1973), and Honjo et al (1981). Rogers et al (1962) instilled a solution of fluorescein into the middle ear and assessed the clearance function by subsequently examining the pharynx with an ultraviolet light. LaFaye et al (1974) used a radioisotope technique to monitor the flow of saline solution down the eustachian tube. Bauer (1975) assessed clearance by observing methylene blue in the pharynx after it had been instilled into the middle ear. Elbrønd and Larsen (1976) assessed middle ear - eustachian tube mucociliary flow by determining the time that elapsed after saccharin had been placed on the mucous membrane of the middle ear until the subject reported tasting it. Unfortunately, all of these methods are qualitative and actually test eustachian tube patency rather than measure the clearance function of the tube quantitatively.

Abnormalities of the protection function are directly related to the pathogenesis of otitis media. The function has been assessed only by radiographic techniques (Bluestone, 1971; Bluestone et al, 1972a, 1972b) by a test that was a modification of a tubal patency test described by Wittenborg and Neuhauser (1963).

Model of protection and drainage functions

Understanding of these radiographic studies can be best shown by a model of the system (Bluestone and Beery, 1976). The eustachian tube, middle ear, and mastoid air cells system can be likened to a flask with a long, narrow neck (Fig. 142-11). 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 depend on the pressure at either end, the radius and length of the neck, and the 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 as a result of capillarity within the neck and the relative positive air pressure that develops in the chamber of the flask. This basic geometric design is considered critical to 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 are 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". Fig. 142-12 shows that a flask with a short neck would be less protective than a flask with a long neck (Bluestone, 1985). Because infants have a shorter eustachian tube than adults, reflux is more likely to occur in babies. 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 of developing reflux otitis media because they are frequently supine.

Reflux of a liquid into the vessel can also occur if a hole is made in the bulbous portion of the flask (Fig. 142-13) because 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, after 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 (Fig. 142-13). In the clinical situation represented by the model, high negative middle ear air pressure could lead to 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 (Fig. 142-13). Nose blowing, crying, closed-nose swallowing, diving, or descent in an airplane could create high positive nasopharyngeal pressure and produce a similar condition in the human system.

One of the major differences between a flask with a rigid neck and a biologic structure 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 Fig. 142-14; 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 the compliance in such a system appear to be factors critical to the results obtained. Clinically, aspiration of gas into the middle ear is possible, because 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 the descent in an airplane, in a descent after 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 flow from the middle ear into the nasopharynx can be demonstrated by inverting the flask of the model (Fig. 142-15). 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 may also relieve the pressure; this action may explain the occasional success of the Politzer method and Valsalva maneuver in clearing a middle ear effusion.

The examoples of fluid flow through a flask present some of the mechanical aspects of the physiology of the human middle ear system. Other factors that can affect flow of liquid and air through the middle ear include (1) the mucociliary transport system of the eustachian tube and middle ear (ie, clearance) (Sadé and Afula, 1967; Sadé and Eliezer, 1970); (2) active tubal opening and closing, acting to pump liquid out of the middle ear (Honjo, 1981); and (3) surface tension characteristics.

The clearance function has been studied by insertion of foreign material into the middle ear of animal models (Albiin et al, 1983; Stenfors et al, 1985). Such material flows toward the middle ear portion of the eustachian tube. This movement is related to ciliary activity that occurs in the eustachian tube and parts of the middle ear; these ciliated cells in the middle ear are increasingly more active as their location becomes more distal to the opening of the eustachian tube (Ohashi et al, 1985, 1986). In a series of experiments by Honjo (1981, 1985), the eustachian tube was shown to "pump" liquid out of the middle ear in both animal models and humans. However, when negative pressure was present within the middle ear, this function was impaired (Nozoe et al, 1984).

Several investigators have determined certain surface tension factors that could be involved with normal eustachian tube function. Brikin and Brookler (1972) isolated surface-tension-lowering substances from washings of eustachian tubes of dogs. They postulated that these substances could act to enhance eustachian tube functions, similarly to surfactant in the lung. Rapport et al (1975) described a similar substance and demonstrated the effect of washing out the eustachian tube on the opening pressure in the experimental animal; others also have demonstrated a surfactantlike phospholipid in the middle ear and eustachian tube of animals and humans (Grace et al, 1987; Hagen, 1977; Hills, 1984a, b).

From these studies, it is apparent that the drainage and clearance functions of the eustachian tube - middle ear system are important in maintaining a healthy middle ear. Because otitis media is very common in humans, efficient removal of middle ear effusions must depend, to a large extent, on these functions.

Summary

The medical and anatomic literature is replete with reports on the anatomy, physiology, and pathophysiology of the eustachian tube. Many important questions, however, remain unanswered or only partly answered. Much work remains to be done in describing the postnatal anatomic changes of the tube and its surrounding structures. Nothing is known about the changes in tubal structure and position from approximately ages 3 to 6 or 7 years. This information would help to explain the improved function of the tube and the corresponding decrease in frequency in middle ear disease. Little is known about postnatal and adult normal anatomic variation. In addition, no precise description of the tube's physiology in both children and adults has yet been published.