CHAPTER FOUR

Physiology

Normal Eustachian tube functions of pressure regulation, protection, and clearance, within its normal system, are necessary to maintain a healthy middle ear.

As described in Chapter 3, “Anatomy,” the Eustachian tube is not just a tube but an organ, which is part of a system of organs. In this chapter, I review our current understanding of the physiology (functions) of the Eustachian tube within its system, which includes the nasal cavities, palate, and nasopharynx at the proximal (pharyngeal) end of the Eustachian tube and the middle ear and mastoid gas cells at its distal end (see Figure 3–1). Thus, the functions of the Eustachian tube must be assessed within this system because the normal Eustachian tube functions most effectively when the system at either end is also normal. The Eustachian tube may function normally, but if any part of the rest of the system is abnormal, middle-ear disease can develop. For example, in the face of a normally functioning Eustachian tube, if the tympanic membrane is not intact or there is persistent nasal or nasopharyngeal obstruction, middle-ear disease can occur. Thus, to maintain a healthy middle ear, the entire Eustachian tube system should have normal function and structure. Knowledge of normal Eustachian tube function, within its system, is necessary to understand the pathophysiology of the system that can lead to middle-ear disease. This is described in Chapter 5, “Pathophysiology.”

Physiology of the Eustachian Tube within Its System

There are three physiologic functions attributed to the Eustachian tube:

- Pressure regulation (ventilation) of the middle ear that equilibrates gas pressure in the middle ear with atmospheric pressure
- Protection of the middle ear from nasopharyngeal sound pressure and secretions
- Clearance (drainage) of secretions produced within the middle ear into the nasopharynx (Figure 4–1)

Figure 4–1. Functions of the Eustachian tube (ET)—middle ear (ME)—mastoid (Mast) gas cell system. Pressure regulation function is related to active dilation of the tube by contraction of the tensor veli palatini muscle (TVP) (upper figure). Protective function is dependent, in part, on an intact middle ear and mastoid gas cells to maintain a gas cushion (middle figure). Clearance function is enhanced by mucociliary activity and muscular activity during tubal closing (lower figure). EC = external canal; NP = nasopharynx; TM = tympanic membrane.
Table 4–1. Classification of Physiology of Eustachian Tube System

<table>
<thead>
<tr>
<th>Function</th>
<th>Subcategories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure regulation</td>
<td>Ventilatory function, Anatomic factors, Immunologic and mucociliary defense</td>
</tr>
<tr>
<td>Protection</td>
<td></td>
</tr>
<tr>
<td>Clearance</td>
<td>Mucociliary clearance, Muscular clearance (“pumping action”)</td>
</tr>
<tr>
<td>Surface tension factors</td>
<td></td>
</tr>
</tbody>
</table>

Table 4–1 presents a classification of the physiology of the Eustachian tube system.

**Pressure Regulation**

Of the three physiologic functions of the Eustachian tube, the most important is regulation of pressure (ventilation) within the middle ear because hearing is optimal when middle-ear gas pressure is relatively the same as air pressure in the external auditory canal; that is, tympanic membrane and middle ear compliance is optimal.

**Eustachian Tube Mechanics of Opening and Closing**

Normally, the Eustachian tube is passively closed. Intermittent active opening of the Eustachian tube, which happens when the tensor veli palatini muscle contracts during swallowing, maintains nearly ambient pressures in the middle ear (see Chapter 3).1–4 Key experiments from our laboratory, employing the monkey, confirmed that active opening of the Eustachian tube is related to the contraction of the tensor veli palatini muscle: when the tensor veli palatini was expunged or transected at the hamulus, contraction occurred; when botulinum was injected into the tensor through the palate, no tubal opening occurred; and when the mandibular nerve was electrically stimulated at the base of the skull, the Eustachian tube dilated (Figure 4–2).5 The role of the levator palatini muscle in opening the Eustachian tube remains unclear, but we excised the palatal portion of the levator in the monkey and found no demonstrable change in normal Eustachian tube opening during manometric tubal function tests (Figure 4–3).6 We concluded that the levator palatini muscle does not dilate the Eustachian tube; others have come to the same conclusion.7 Figure 4–4 shows the Eustachian tube opening during active muscular dilation of the tubal lumen owing to the contraction of the tensor veli palatini muscle, which allows gas to pass in either direction depending on the pressures at either end of the tube.

As postulated by Sando and colleagues, the lateral lamina of the cartilage of the Eustachian tube in the superior portion of the lumen most likely dilates the greatest during tensor veli palatini contraction, and the inferior portion of the tubal lumen is related more to the protective function with it mucosal folds, glands, and goblet cells.8,9 Figure 4–5 is an illustration of these hypotheses, which have been postulated following assessments of normal human temporal bone histopathologic specimens.

The sequence of tubal dilation has been assessed by radiography in the human and the animal.10–12 As shown in Figure 4–6, the normal Eustachian tube is closed at rest and opens first in its proximal cartilaginous portion on swallowing owing to contraction of the tensor veli palatini muscle, which is then followed by distal tubal dilation. Following active dilation, the tube passively collapses to return to its resting position starting from the distal end and then to the proximal end, which is important for the muscular clearance function of the tube (see Clearance). Figure 4–6 shows a suggested spring-like action of Eustachian tube active muscular opening and then passive closing owing to elastic recoil.

Recently in our laboratory, Ghadiali and colleagues developed a modified forced-response test of Eustachian tube function that correlates experimental pressure-flow rate measurements with a standard engineering model of flow in a collapsible tube.13 Correlation between model and experimental data yielded quantitative measurements of Eustachian tube compliance and hysteresis in the monkey. Using this engineering model.

![Figure 4–2. The distribution of the various branches of the mandibular division of the trigeminal nerve in the rhesus monkey. These branches are (1) the nerve to the tensor veli palatini muscle, (2) the nerve to the internal pterygoid muscle, (3) the external pterygoid nerve, (4) the masseteric nerve, (5) the deep temporal nerve, (6) the auriculotemporal nerve, and (7) the condylar nerve. The letters A to E correspond to various electrode positions on the nerve. Reproduced with permission from Cantekin EI et al.2](attachment:image.png)
Figure 4–3. Artist’s drawing of a cross section of the palate in the monkey in which the palatal portion of the levator palatini muscle was excised, which had no effect on Eustachian tube opening during manometric function testing. This experiment failed to show any effect of the levator palatini on tubal opening. Reproduced with permission from Cantekin EI et al.6

Figure 4–4. Illustration showing Eustachian tube (ET) dilation (opening) owing to the contraction of the tensor veli palatini muscle (TVP) during swallowing, which allows equilibration of gas pressures within the middle ear (ME) with that of the nasopharynx (NP). EC = external auditory canal; Mast = mastoid gas cells.

Figure 4–5. Illustration depicting the probable superior portion of the Eustachian tube lumen opening during active dilation (DL) by the tensor veli palatini muscle (TVPM/TVP), which is attached to the lateral lamina (LL) of the cartilage. Sando and colleagues suggested that the superior portion (R) is related to pressure regulation during active dilation and the inferior portion (F) of the tubal lumen is related to protection with its folds, glands (G), and goblet cells (GL). Elastin in the hinge portion (ie, junction between the medial and lateral laminae) aids in returning the medial lamina to the resting position. GL = glands in the folds of the inferior portion of the tubal lumen; ML = medial lamina of Eustachian tube cartilage; OF = Ostmann’s fatty tissue (ie, fat pad); R = superior portion of lumen at rest. Reproduced with permission from Sando I et al.8
of the Eustachian tube, Ghadiali and colleagues considered a collapsible tube with global parameters of hysteresis and tubal elastance, which they considered to be dependent on interfacial and tissue mechanical properties (Figure 4–7). Various physical components, such as the mucosal surface condition and muscle tension, were evaluated in tubal mechanics. The investigators concluded that the engineering-based measure of compliance is more accurate than current summary parameters (ie, tubal compliance index) and that knowledge of how specific physical components alter Eustachian tube function may lead to improved treatments that target the underlying mechanical properties. Indeed, this team evaluated the effect of surfactant on tubal mechanics (see Clearance).

It has been estimated that the normal Eustachian tube opening time is approximately 400 milliseconds, and humans swallow while awake approximately once per minute. During sleep, swallowing occurs about once in 5 minutes.

Table 4–2. Gas Composition and Pressure in the Nasopharynx, Middle Ear, and Microcirculation of the Middle-Ear Mucosa Compared with Air (mm Hg)

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Nasopharynx (Mixed Expiratory Air)</th>
<th>Middle-Ear Cavity</th>
<th>Microcirculation of Middle-Ear Mucosa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{N_2}$</td>
<td>596</td>
<td>Lower (566)</td>
<td>Higher (621)</td>
<td>Lower (573)</td>
</tr>
<tr>
<td>$P_{O_2}$</td>
<td>158</td>
<td>Low (120)</td>
<td>Lower (46)</td>
<td>Lowest (40)</td>
</tr>
<tr>
<td>$P_{CO_2}$</td>
<td>0.3</td>
<td>High (27)</td>
<td>Higher (46)</td>
<td>Higher (46)</td>
</tr>
<tr>
<td>$P_{H_2O}$</td>
<td>5.7</td>
<td>Higher (47)</td>
<td>Higher (47)</td>
<td>Higher (47)</td>
</tr>
</tbody>
</table>

Adapted from Felding JU et al and Ostfeld EJ and Silberberg A.

$P_{CO_2}$ = carbon dioxide partial pressure; $P_{H_2O}$ = water partial pressure; $P_{N_2}$ = nitrogen partial pressure; $P_{O_2}$ = oxygen partial pressure.
oxygen. However, later research into the gas composition of the middle ear indicates that the middle ear and the microcirculation of the mucosa are similar with respect to oxygen and carbon dioxide.\textsuperscript{22} Ostfeld and Silberberg found that oxygen in the middle ear is slightly higher than in the microcirculation, in contrast to middle-ear carbon dioxide, which is in equilibrium.\textsuperscript{23} The diffusion gradient is created by differences in the partial pressures of nitrogen and relatively inert gas with low solubility and permeability in an aqueous environment.\textsuperscript{24} The hydrops ex vacuo theory predicts that as the equilibrium condition is approached, transudation of liquid will occur, thereby decreasing the volume of the middle ear and consequently the pressure (see Chapter 6, “Pathogenesis”).

In early experiments in our laboratories, gas absorption was studied in the rhesus monkey using politzerization of air or oxygen gas, which showed that when the middle-ear gas composition is changed, middle ear negative pressures rapidly occur.\textsuperscript{9} Serial tympanograms were obtained 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\textsubscript{2}O 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 \(\mu\)L) entering into the middle ear. However, an abnormally functioning Eustachian tube may alter this mechanism.

In a later study in the monkey, the rate of constants for the middle-ear cavity to middle-ear mucosa exchange of oxygen and carbon dioxide is constant with a diffusion-limited process but not for N\textsubscript{2}, which indicated a much slower rate of N\textsubscript{2} exchange than predicted. These studies showed that for relatively short time periods, middle-ear pressure is controlled by experimentally established oxygen and carbon dioxide gradients.\textsuperscript{19} In this animal model, the effects of varying oxygen and carbon dioxide tensions in the middle ear influenced the functions of Eustachian tube ventilation of the middle ear, probably through receptors in the middle ear, implying a possible feedback loop.\textsuperscript{25} In the monkey, rates of exchange of gases across the tympanic membrane were assessed. Reports are that there is a measurable rate, but primarily for nitrogen, and then probably not physiologically under normal circumstances of breathing.\textsuperscript{25} Using a mathematical model, Doyle showed that mucosal surface area determines the middle-ear pressure response following sniff-induced middle-ear negative pressure, which did not support the previous hypothesis of a pressure regulation function of the mastoid gas cell mucosa.\textsuperscript{27}

The Eustachian tube provides a potential communication between the nasopharynx and the middle ear. When the tube opens owing to contraction of the tensor veli palatini muscle or other maneuvers, pressure differences between the ambient environment and the middle ear are equilibrated by the inflow and outflow of gases. Inflow of gas from the nasopharynx into the middle ear is end-expiratory gas. Thus, the pressure regulatory function of the Eustachian tube maintains near equilibrium between external and internal pressures, thereby maintaining nearly optimal transducer function of the middle ear and preventing the pathologic consequences that result from unabated middle ear to mucosa gas exchange.

Even though some investigators have postulated that gases can pass to and from the middle ear through the tympanic membrane, Doyle and colleagues conducted experiments that showed there is no oxygen and carbon dioxide transtympanic membrane exchange from the external ear canal into the middle ear.\textsuperscript{26} There is an exchange of N\textsubscript{2}, although not at physiologic rates.

**Eustachian Tube Function in Normal Adults**

Normal Eustachian tube function has been assessed by investigators in Malmö, Sweden. Using the microflow technique inside a pressure chamber, Elner and colleagues, in a classic study, evaluated 102 adults with intact tympanic membranes and no apparent history of otologic disorders (Table 4–3).\textsuperscript{28} Patients were divided into four groups according to their abilities to equilibrate static relative positive and negative pressures of 100 mm H\textsubscript{2}O in the middle ear. Patients in group 1 were able to completely equilibrate pressure differences across the tympanic membrane. Those in group 2 equilibrated positive pressure, but a small residual negative pressure remained in the middle ear. Subjects in group 3 equilibrated only relative positive pressure with a small residual remaining but no negative pressure. Those in group 4 were incapable of equilibrating any pressure. These data probably indicate decreased stiffness (increased compliance) of the Eustachian tube in the subjects in groups 2, 3, and 4 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. In an earlier study at the same laboratory, all 36 “healthy” ears could equilibrate over- and underpressures applied to the ears of adults.\textsuperscript{29}

This important study showed that all adults with a negative history of ear disease and a healthy-appearing tympanic membrane can completely equilibrate applied pressure, especially when the pressure is negative. This finding helps explain why some individuals, despite a lack of recurrent or chronic middle-ear disease, have difficulty with equilibration of cabin pressures during descent in an airplane; the middle-ear pressure is negative while in air flight and must be actively equilibrated.
by swallowing (or other maneuvers, such as Valsalva’s maneuver or jaw movements) when descending. It should be kept in mind that the pressure chamber investigation described above is not physiologic, but it does help in assessing the function of the Eustachian tube. Similar to the unphysiologic nature of the testing, flying in an airplane or scuba diving is also not physiologic. We humans did not evolve with the capacity to equilibrate negative pressure developed during these endeavors. In addition, as every pilot and scuba diver knows, the more rapid the descent, the more difficult it is to equilibrate the middle-ear negative pressure, and if extreme, the Eustachian tube can even “lock.”

Also, the study in adults has bearing on clinical trials that have been conducted in the past. In studies conducted in our department, apparently healthy adult volunteers were recruited for nasal challenge studies that involved virus and allergic antigens. Despite a lack of a history of middle-ear disease and normal tympanic membranes, some of the volunteers could not completely equilibrate applied pressures during the prechallenge Eustachian tube function testing in both ears. The subjects in these studies who could not perform all of the testing completely influenced the design and outcome of some of the early clinical trials, but this finding was taken into account for later ones.30–34

In an effort to determine normal Eustachian tube function in adults, we conducted two studies in the past. In the first study, we tested six subjects (average age 29 years) who had a negative otologic history and previously normal tympanic membranes until they sustained a traumatic perforation of the tympanic membrane. All were tested using the inflation-deflation test of function, which was considered normal function, and were compared with patients with otitis media (see Chapter 8, “Diagnosis and Tests of Function”).2 In a more recent study, we recruited nine normal adult volunteers who had no history of middle-ear disease and normal tympanic membranes and who agreed to sign an informed consent form to allow me to perform a myringotomy, using topical anesthesia and a myringotomy knife under the otomicroscope. Of the nine subjects, one did not open the Eustachian tube during sonometric testing and was excluded from further testing. The remaining eight subjects successfully opened the tube during swallowing when tested by sonometry, equilibrated positive and negative pressure during the inflation-deflation testing, and had normal values for the forced-response testing.33 Table 4–4 shows

### Table 4–3. Eustachian Tube Function Test Results of 102 Otologically Normal Adults with Intact Tympanic Membranes

<table>
<thead>
<tr>
<th>Tubal Function</th>
<th>Number of Subjects (%)</th>
<th>Equilibration when Middle-Ear Pressure Is +100 mm H₂O</th>
<th>−100 mm H₂O</th>
<th>Toynbee Phenomenon</th>
<th>Valsalva’s Maneuver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Positive/Number Tested (%)</td>
<td>Positive/Number Tested (%)</td>
</tr>
<tr>
<td>1</td>
<td>74 (72)</td>
<td>Yes</td>
<td>Yes</td>
<td>67/69 (97)</td>
<td>63/73 (86)</td>
</tr>
<tr>
<td>2</td>
<td>21 (21)</td>
<td>Yes</td>
<td>Residual</td>
<td>7/18 (39)</td>
<td>16/21 (76)</td>
</tr>
<tr>
<td>3</td>
<td>2 (2)</td>
<td>Residual</td>
<td>No</td>
<td>0/2 (0)</td>
<td>2/2 (100)</td>
</tr>
<tr>
<td>4</td>
<td>5 (5)</td>
<td>No</td>
<td>No</td>
<td>0/5 (0)</td>
<td>5/5 (85)</td>
</tr>
<tr>
<td>Total</td>
<td>74/94 (79)</td>
<td>86/101 (85)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adapted from Elner A et al.28

### Table 4–4. Results of Forced-Response Eustachian Tube Function Test of Eight Normal Subjects Who Had a Myringotomy

<table>
<thead>
<tr>
<th>Forced-Response Parameter</th>
<th>mm H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Po</td>
<td>405 ± 50</td>
</tr>
<tr>
<td>Pc</td>
<td>133 ± 77</td>
</tr>
<tr>
<td>Rₑ = Pₑ/Qₑ</td>
<td>11.9 ± 7</td>
</tr>
<tr>
<td>Qₐ</td>
<td>115 ± 70</td>
</tr>
<tr>
<td>Rₐ = Pₐ/Qₐ</td>
<td>2.3 ± 1.1</td>
</tr>
</tbody>
</table>

Adapted from S. J. Swarts, unpublished data.
Pc = closing pressure; Po = opening pressure; Qₐ = equilibrium flow; Rₑ = Pₑ/Qₑ = active resistance; Rₐ = Pₐ/Qₐ = equilibrium resistance.
ferences in the ability to open the Eustachian tube during swallowing activity to equilibrate pressure differences between the middle ear and the nasopharynx (see Chapter 3).

Another explanation for finding 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. However, this mechanism is uncommon in children.

High middle-ear pressures have been identified, by otoscopy and tympanometry, in many children with no apparent middle-ear disease. An inefficient active opening of the tube in children probably explains this frequent finding. Brooks studied the parameters of middle-ear pressure using tympanometry and determined that the resting middle-ear pressure in a large group of apparently normal children was between 0 and −175 mm H₂O. However, pressures outside this range have been reported as normal for large populations of apparently asymptomatic children. High negative middle-ear pressure does not necessarily indicate disease. It may indicate only physiologic obstruction of the Eustachian tube. 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 of middle-ear problems until more is learned about the normal and abnormal physiology of the Eustachian tube. In normal adults, Alberti and Kristensen obtained resting middle-ear pressures between 50 and −50 mm H₂O. Again, a pressure outside this range does not necessarily mean that the patient has ear disease.

Because infants have an inefficient active opening mechanism, they most likely compensate in some way to regulate pressure within the middle ear. One possible compensatory mechanism is crying, and high positive pressure is apparent when some infants with no middle-ear effusion cry during otoscopy and tympanometry. This mechanism could also explain why infants cry when they are descending in an airplane; they are most likely insufflating air into their middle ears (Figure 4–8).

Posture and Seasonal Variation
Posture has been demonstrated to affect Eustachian tube function. The mean volume of air passing through the Eustachian tube was found to be reduced by one-third when the body was elevated 20° to the horizontal and by two-thirds when in the horizontal position. This reduced function with change in body position was found to be the result of venous engorgement of the Eustachian tube. Venous blood flow is increased in the head and neck in the supine position because, as opposed to the veins in the extremities, there are no valves.

Studies of nasal conductance (using anterior and posterior rhinomanometry) and Eustachian tube function (using sonotubometry) in healthy humans showed that, physiologically, these functions are influenced by body position. The conclusion from this study is that the mucosa of the Eustachian tube experiences autonomically modulated cyclic fluctuations, similar to the nasal mucosal cycle.

Beery and colleagues showed a seasonal variation in Eustachian tube function in children. Children who 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. The explanation for this observation remains unclear, but it could be explained by the relative lack of upper respiratory tract viral infection affecting the Eustachian tube during the respiratory seasons of the year. It has been shown, from adult volunteer nasal virus challenge studies, that virus can be recovered from the nose in the absence of the signs and symptoms of a cold.

<table>
<thead>
<tr>
<th>Tubal Function Group</th>
<th>Tubal Function Children</th>
<th>Tubal Function Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>24</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>34</td>
</tr>
<tr>
<td>Total</td>
<td>85</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4–5. Eustachian Tube Function Test Results in 85 Otologically Normal Children Compared with 92 Otologically Normal Adults with Intact Tympanic Membranes

Adapted from Bylander A et al.37

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**FIGURE 4–8.** Because the Eustachian tube is short and floppy in the infant, crying most likely insufflates nasopharyngeal gas into the middle ear to compensate for their inefficient tubal opening mechanism. But during periods of upper respiratory tract infection, nasopharyngeal secretions—and viruses and bacteria—may also be insufflated into the middle ear (see Chapter 5, “Pathophysiology”).
Role of the Mastoid Gas Cell System

The role of the mastoid gas cell system in relation to the normal middle ear is not fully understood and remains controversial. Current thinking is that it either acts as a surge tank of gas (air) available to the relatively smaller middle-ear cavity, that the mucosa lining the mastoid gas cells is the primary area for the transfer of gases between the middle ear and mastoid gas cells and the microcirculation, or that both functions coexist. During intervals of Eustachian tube dysfunction, compliance of the tympanic membrane and ossicular chain (which would affect hearing) would not be decreased owing to reduced middle-ear gas pressure because there is a reservoir of gas in the mastoid air cells. If this thinking is correct, then a small mastoid air cell system could be detrimental to the middle ear if the Eustachian tube is dysfunctional. Likewise, a small mastoid cellular system would allow for a less efficient gas exchange between the middle-ear cleft and the microcirculation of the mucosa. If this thinking is correct, then a small mastoid air cell system could be detrimental to the middle ear if the Eustachian tube is dysfunctional. Likewise, a small mastoid cellular system would allow for a less efficient gas exchange between the middle-ear cleft and the microcirculation of the mucosa.

Magnuson suggested that the mastoid cell system could be a pressure regulator. But, using a mathematical model, Doyle showed that mucosal surface area determines the middle-ear pressure response following sniff-induced middle-ear negative pressure, which did not support the previous hypothesis of a pressure regulation function of the mastoid gas cell mucosa. From experimental results, Doyle rejected the hypothesis that the mastoid gas cell system has a pressure regulation system; rather, it is a gas reserve. From studies in monkeys, Felding and colleagues concluded that the air-phase gas exchange between the middle ear and the mastoid is rapid and that partial pressure gradients across the middle ear will be dissipated quickly and are not an important contributor to regulation of pressures in the middle ear.

Protection

The protective function of the Eustachian tube system maintains a healthy middle ear by preventing unwanted secretions and other noxious agents from entering the middle ear. The Eustachian tube system helps protect the middle ear and mastoid gas cell system in two ways: through its functional anatomy and through the immunologic and mucociliary defense of its mucous membrane lining. Protection of the middle ear from abnormal nasopharyngeal sound pressures and secretions depends on the normal structure and function of the Eustachian tube and the ability of the middle ear and mastoid gas cell system to maintain a gas cushion. In addition, the proximal end of the system (nasal cavities, palate, and pharynx) should have normal anatomy and physiologic gas pressures. The middle ear—mastoid is also protected by the respiratory epithelium of the Eustachian tube lumen through its local immunologic defense and its mucociliary defense (clearance). An immunoreactive pulmonary surfactant protein that is thought to facilitate the clearance of microbial pathogens from the alveoli of the lung has been isolated from the middle ears of animals and humans and is hypothesized to have the same function in the ear.

Radiographic Studies

Using radiography, under fluoroscopic control, and using radiopaque contrast media, the protective function of the Eustachian tube has been evaluated. In these studies, radiopaque material was instilled into the nose and nasopharynx of children who had otitis media and then compared with those who were otologically healthy. In the physiologic state, radiopaque material entered the nasopharyngeal end of the Eustachian tube during swallowing activity but did not enter the middle ear. By contrast, the dye did reflux into the middle ear in some patients who had middle-ear disease, especially during closed-nose swallowing.

These radiographic studies in children revealed the following sequence of events. At rest, the normal Eustachian tube is collapsed and the tubal lumen is closed. This prevents liquid—and abnormal nasopharyngeal sound pressures—from entering the nasopharyngeal end of the tube. During swallowing, when the proximal end (the cartilaginous portion) opens, liquid can enter this part of the tube but does not go into the middle ear owing to the tube’s narrow midportion, the isthmus. Figure 4–9 shows a radiographic spot film during fluoroscopy of an 8-year-old male who had no history of otitis media and normal tympanic membranes. After instillation of the radiopaque contrast material into the nose, with the patient in the supine position, no contrast media were visualized in the Eustachian tube when the child was not swallowing (upper frame). But, as shown in Figure 4–10, during swallowing activity, the contrast material entered the proximal (pharyngeal) end of the Eustachian tube and stopped at the isthmus. No radiopaque material entered the middle ear. Because the middle ear was intact (neither a tympanic membrane perforation nor a tympanostomy tube was present), the normal structural anatomy of the tube and the middle ear gas cushion prevented the contrast from entering the middle ear. If the tympanic membrane had not been intact or the Eustachian tube was abnormal (patulous), dye could have refluxed into the middle ear during swallowing (see Chapter 5).

Flask Model

To better understand this anatomic concept, think of the entire Eustachian tube—middle-ear system as a flask with a long, narrow neck. The mouth of the flask represents the nasopharyngeal end; the narrow neck, the isthmus; and the bulbous portion, the middle ear and mastoid gas cell system (Figure 4–11). Fluid flow through the neck depends 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, the 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 (Figure 4–12).
This basic geometric design is considered critical for the protective function of the Eustachian tube–middle-ear system. Figure 4–13 shows that the fluid (gases and liquids) flow through the flask model would be dependent on the viscosity of fluid, the length and radius of the neck, and the pressure at either end of the flask (flask opening and bulbous portion). In this model, flow would be less likely as the neck becomes longer and more likely as the radius of the neck increases (to the fourth power). Naturally, thinner viscosity of liquids would flow more readily than thicker, and air (gas) would flow better than a liquid. Positive or negative pressure at either end of the neck (mouth and bulbous portions of the flask) would influence fluid flow in either direction. The model would approximate Poiseuille’s law. But in the body, the Eustachian tube has compliance (floppiness) or is a collapsible tube, just like other “tubes” such as veins and arteries; thus, the law does not completely apply because the radius is dynamic.

**Clearance**

Clearance (drainage) of normally produced secretions (and foreign material) from the middle ear is provided by two mechanisms: the mucociliary system of the Eustachian tube and some areas of the middle-ear mucous membrane and muscular clearance or the “pumping function” of the Eustachian tube when the tube closes. Before describing these two functions, the histology of the mucous membrane of the system needs to be reviewed.

**Mucosa of the Eustachian Tube–Middle Ear–Mastoid System Related to Clearance**

To better understand this function, the mucous membrane of the Eustachian tube system is reviewed (see also Chapter 3). The mucous membrane of the middle ear is continuous with that of the nasopharynx via the Eustachian tube and is characterized as respiratory epithelium. 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, cuboid cells at the posterior portion of the promontory, aditus ad antrum, and mastoid cells.

Structural differentiation of the mucosal lining of the lumen of the Eustachian tube is evident: mucous glands predominate at the nasopharyngeal orifice, and there is a graded...
Figure 4–11. Flask model of the Eustachian tube–middle ear–mastoid gas cell system in which the mouth of the flask represents the nasopharyngeal end of the Eustachian tube, the neck is the cartilaginous portion of the tube, and the bulbous portion represents the middle ear and mastoid air cells (see text). NP = nasopharynx; ET = Eustachian tube; ME = middle ear; Mast = mastoid.

Figure 4–12. Protective function of the Eustachian tube–middle ear–mastoid gas cell system can be visualized using the flask model. When liquid is instilled into the mouth of the flask (nasopharyngeal end of tube), the liquid stops in the narrow neck (isthmus of the cartilaginous portion of the tube) owing to the presence of positive (back) pressure built up in the bulbous portion and distal end of the narrow neck of the flask (middle-ear gas cushion). ET = Eustachian tube; Mast = mastoid gas cells; ME = middle ear.

Figure 4–13. Illustration of the factors related to fluid flow through the neck of the flask model. Flow would be dependent on the viscosity of the fluid, length and radius of the neck, and pressure at either end of the neck. Even though the neck of the flask is rigid, to make the analogy to the Eustachian tube, the neck should be compliant (floppy), which would influence flow.
change to a mixture of goblet, columnar, and ciliated cells near the tympanum. The products of these glands include active components. Matsune and colleagues found that the density of goblet cells was significantly lower in the roof of the Eustachian tube than in the floor of the tube and was highest in the midcartilaginous area. From the same laboratory, Sando and colleagues postulated from their extensive examination of temporal bone specimens that the superior portion of the tubal lumen is associated with pressure regulation of the middle ear and the inferior portion is responsible for clearance, whereas both parts are involved with protection of the middle ear. These investigators have also shown that the folds in the mucosa of the lumen of the tube are most pronounced in infants and children compared with adults. The folding affords greater surface area for the tubal lumen, which, in turn, provides greater abundance of ciliated cells, which should enhance clearance function. The mucociliary defense system within the tube begins in fetal life and is well established soon after birth.

**Mucociliary Clearance**

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

**Muscular Clearance**

In a series of elegant experiments employing cineradiography by Honjo and colleagues, the Eustachian tube was shown to “pump” liquid out of the middle ear in both animal models and humans. Figure 4–14 is a cartoon with the sequence of events during opening (dilation) and passive closing of the Eustachian tube illustrating the muscular pumping action of the tube on closure. These investigators also studied both the mucociliary and muscular clearance in the cat using various viscosities of colored liquid and showed that when the volume of middle-ear liquid was small, the fluid was cleared by the mucociliary system, whereas when the volume of liquid was large and of low viscosity, it was cleared by muscular activity. Highly viscous fluid was cleared by both ciliary and muscular clearance. Also, clearance time is affected by both the volume and viscosity of the liquid, and clearance was more effective in the tympanic cavity than in the mastoid.

**Clearance Rate and Time**

The clearance rates and times of materials instilled into the middle ear in both humans and animals have been evaluated; they varied depending on the viscosity of the liquid and other experimental factors. A study in humans by Takeuchi and colleagues tested clearance time in children following myringotomy when no effusion was present. Using technetium 99m, the clearance time was approximately 30 minutes (see Chapter 8).

**Surface Tension Factors**

Other factors may be involved in maintaining normal Eustachian tube function. One of these factors may involve the surface tension within the lumen of the Eustachian tube. In Malmö, Flisberg and colleagues were the first investigators to suggest the presence of a surface-lowering substance in the Eustachian tube. Birkin and Brookler isolated surface tension-lowering substances from the washings of Eustachian tubes of dogs. They postulated that these substances could enhance Eustachian tube functions, similar to surfactant in the lung. Rapport and colleagues described a similar substance and demonstrated the effect that washing out the Eustachian tube had on the opening pressure in the experimental animal. Others have also demonstrated a surfactant-like phospholipid in the middle ear and Eustachian tube of animals and humans. Franz and Anderson, in experiments in rodents, tested the effect of modulating parasympathetic innervation on the surface tension of the Eustachian tube and concluded that cholinergic nerve transmission from the parasympathetic division of the autonomic nervous system can influence tubal function, possibly owing to changes in surface tension. Assessment of surfactant has also been the focus of investigations into its role in otitis media. Miura and colleagues reported the administration of a surfactant-like substance to modify a function test. In a study in gerbils, Fornadley and Burns produced middle-ear effusions by injecting killed Streptococcus pneumoniae into the middle ear through the tympanic membrane to increase the opening pressure of the Eustachian tube. When the investigators introduced exogenous surfactant, the opening pressure dropped. Also, Ramet and colleagues reported a surfactant protein A gene locus associated with recurrent otitis media (see Chapter 5).

In our laboratory, Ghadiali and colleagues conducted experiments in the monkey model to determine the effect of surface tension and surfactant administration on the function of the Eustachian tube. They first developed an engineering model showing the Eustachian tube lumen to be slit-like with a fluid-mucosa interface; surface tension forces of the mucosa were directed toward collapse of the tube, in which the translu-
Eustachian Tube: Structure, Function, Role in Otitis Media

The pathobiology of the Eustachian tube can also be compared with that of the larynx (see Chapter 5). Both can be obstructed mechanically (anatomically) or functionally. Clearly, both structures can have intrinsic (owing 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), 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

- Aspiration pneumonia caused by an abnormally patent or incompetent glottis (eg, paralysis of the vocal cords in the lateral position)
- Reflux esophagitis, which can also cause aspiration pneumonia, resulting from incompetence of the esophagogastric junction
- Cricopharyngeal achalasia, resulting in a similar condition

The analogies in the middle-ear system include

- Reflux otitis media, caused by the reflux of nasopharyngeal secretions through an abnormally patent (patulous or semipatulous) Eustachian tube
- The aspiration through the Eustachian tube of secretions into a middle ear that has high negative pressure

Nasal obstruction can have an effect on both Eustachian tube (the 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 or 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 assess its function. The larynx and tracheobronchial-pulmonary system have been extensively studied through many different methods, some of which are simple. For instance, laryngeal function can be readily 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 and in the laboratory. Unfortunately, because 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. Despite these disadvantages, 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 and the methods of assessment of Eustachian tube function are described in detail in Chapter 8.

References


