Endoscopic Anatomy of the Pediatric Middle Ear

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Endoscopic Anatomy of the Pediatric Middle Ear

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Abstract

Traditionally, otologists have aimed to produce a clean, dry, safe ear with the best possible hearing result. More recently, "less invasively" has been added to this list of goals. The development of small-diameter, high-quality rigid endoscopes and high-definition video systems has made totally endoscopic, transcanal surgery a reality in adult otology and a possibility in pediatric otology. This article reviews the anatomy of the pediatric middle ear and its surrounding airspaces and structures based on the work of dozens of researchers over the past 50 years. It will focus on the developmental changes in ear anatomy from birth through the first decade, when structure and function change most rapidly. Understanding the limits and possibilities afforded by new endoscopic technologies, the pediatric otologist can strive for results matching or exceeding those achieved by more invasive surgical approaches.

Keywords

anatomy, cholesteatoma, chronic otitis media, development, endoscopy, middle ear surgery, minimally invasive surgery, pediatric otology, temporal bone histology

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Endoscopically assisted pediatric ear surgery was described 2 decades ago.[1,2] Endoscopes, used in combination binocular operating microscopes, improve visualization of middle ear recesses not well seen in the 0-degree microscopic view (**Figure 1**). Recent improvements in the quality of small rigid rod endoscopes and high-definition video cameras[3] have expanded the potential for endoscopic surgery of the middle ear.[4] Transcanal, totally endoscopic surgeries are gaining popularity in adult otology and are possible in the pediatric age group as well.[5] There are important differences in the dimensions, structure, and histologic makeup of a child's ear. This article highlights the anatomic similarities and differences between the middle ears of small children and adults, focusing on those features most important to endoscopic approaches.

The External Auditory Canal

While not a part of the middle ear, some discussion of the postnatal development of the external auditory canal (EAC) is necessary as it forms the primary surgical path to the middle ear and changes rapidly during the first decade of life.[6] The EAC of the adult is usually described as one third cartilaginous and two thirds osseous with a length of approximately 25 mm on the posterosuperior wall and 31 mm on its anteroinferior wall due to the obliquity of the tympanic membrane. The tympanic bone forms the anterior and inferior walls of the bony EAC while the mastoid portion forms the posterior wall and the squamosa the roof.[7] The EAC of the young child is quite different (**Figure 2**).

At birth, the cartilaginous canal sits directly against the tympanic ring. Thus, the tympanic membrane comes immediately into view on entering the cartilaginous canal with an endoscope. In the first 5 years of life, ossification and growth of the lateral portion of the tympanic ring form the anterior and posteromedial portions of the bony canal. As these 2 processes approach one another, the tympanic foramen (of Huschke) forms and is gradually obliterated. In 4% to 20% of adults, the foramen persists, creating a pathway from the EAC to the temporomandibular joint and infratemporal fossa.[8] The osseous EAC doubles in length between 5 and 18 years of age. Similarly, the width and height of the osseous canal increase from age 5 years to adulthood (mid-canal width, 4.5-5.4 mm; mid-canal height, 6.5-7.1 mm).[9] Thus, the EAC is entirely soft tissue in the infant, with the bony portion forming and lengthening through the first 2 decades.[10] Most children older than 5 years have adequate EAC to admit a 4-mm telescope for photodocumentation. Newer high-resolution 3-mm telescopes allow both visualization and limited transcanal surgical instrument access.

The Tympanic Membrane

The tympanic membrane is the membranous partition between the external auditory canal and the tympanic cavity.

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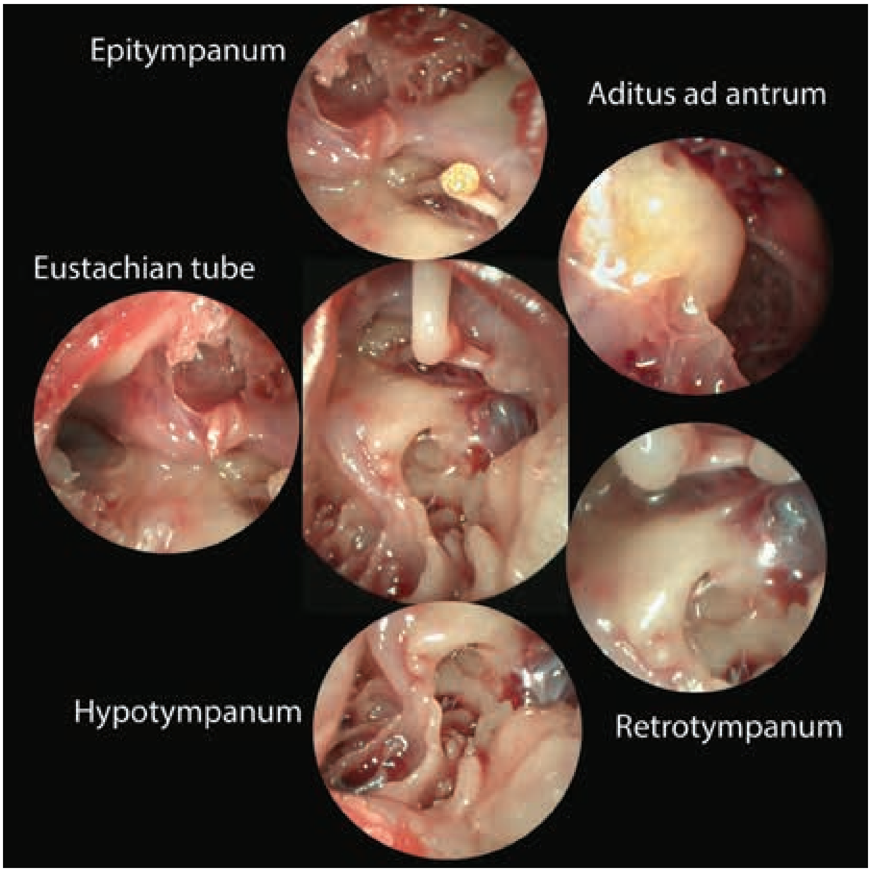

Figure 1. Comparison of 0-, 30-, and 70-degree endoscopic views of the middle ear. The eustachian tube, epitympanum, aditus ad antrum, retrotympanum, and hypotympanum are all visible with angled telescopes (adult middle ear, 0-, 30-, and 70-degree telescopes).

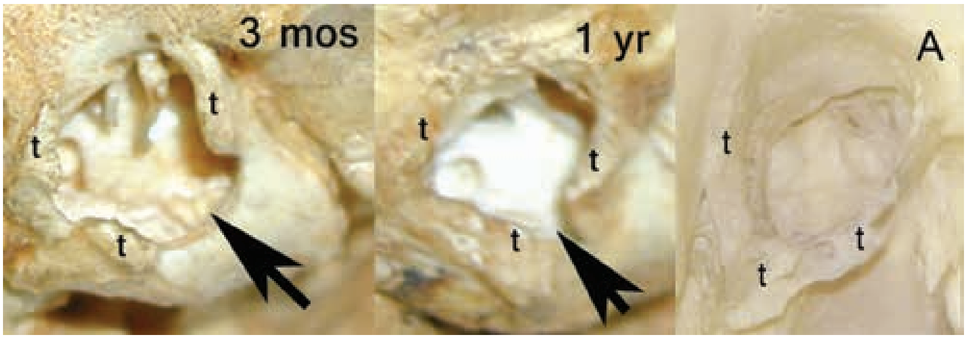

Figure 2. The tympanic annual at 3 months, 1 year, and adulthood (A). t, tympanic bone (arrow points to the foramen of Huschke).

It is semitransparent and elliptical in shape. While there is growth during the fetal period,[11] the newborn tympanic membrane is full adult size—measuring 9 to 10 mm vertically and 8 to 9 mm horizontally. It slopes medially from posterosuperior to anteroinferior.[12] It is curved in shape—deepest at the periphery and at the attachment of the manubrium of the malleus. Its anteroinferior quadrant is perpendicular to incident light, producing a light reflex in that region on endoscopy. The average thickness value of the pars tensa is 89.2 $\pm$ 3.8 μm. Its thickness rapidly increases near the umbo of the malleus and the tympanic annulus, approaching 120 to 140 μm.[13] The normal tympanic membrane is composed of 4 laminae (**Figure 3**). The most superficial layer is stratified squamous epithelium contiguous with the skin of the external auditory canal. Next are radiate then circumferential fibrous layers and finally a mucous layer of cuboidal epithelium contiguous with the lining of the middle ear space. The position of the tympanic membrane (and thus the light reflex) changes with variations in middle ear barometric pressure.[14] The plane of the tympanic annulus changes from a nearly horizontal orientation (34 degrees from the horizontal plane) in neonates to a more vertical orientation (63 degrees from the horizontal plane) in adults.[15] This change in angulation is due to

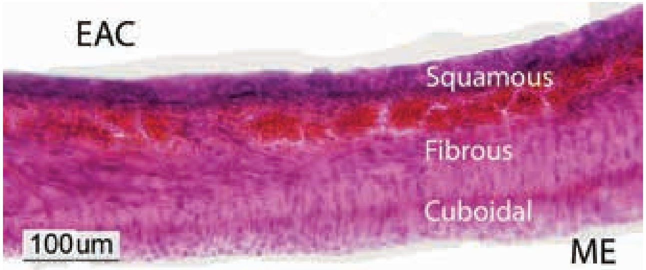

Figure 3. Transverse section of tympanic membrane of a 3-month-old child. EAC, external auditory canal; ME, middle ear.

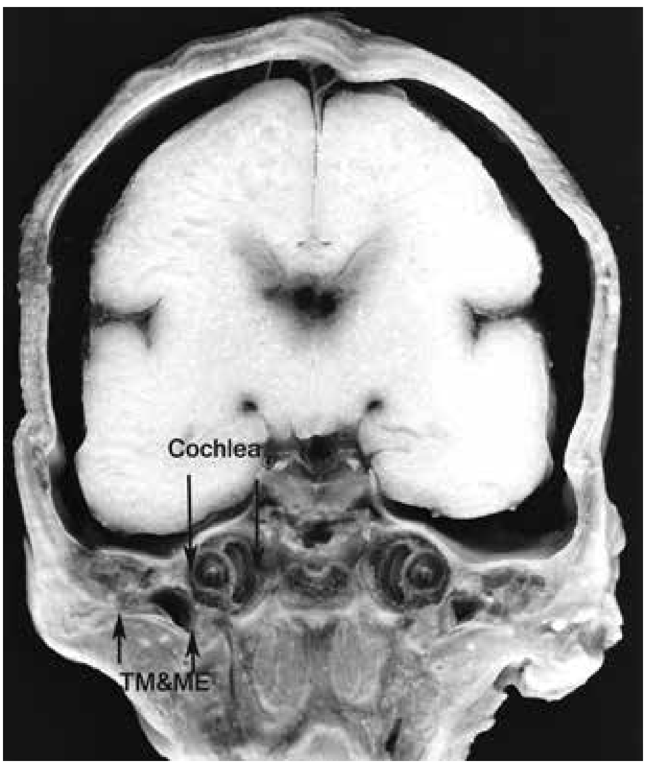

Figure 4. Coronal anatomic section of a 24-week fetal head. ME, middle ear; TM, tympanic membrane.

growth of the skull base and temporal lobe of the brain rather than a change in the dimensions of the tympanic cavity (**Figures 4** and **5**).

Of the ossicles, only the malleus is normally in direct contact with the tympanic membrane. The umbo and lateral process are tightly attached. The remainder of the manubrium is more loosely adherent to the drum (**Figure 6**). The anterior and posterior mallear folds stretch toward their respective edges of the tympanic sulcus, forming a triangular area designated as the pars flaccida. The remaining, larger part of the tympanic membrane is designated the pars tensa. Its thickened border (limbus) is attached by a fibrocartilaginous ring called the annulus. The annulus is deficient in the area of the tympanic sulcus (notch of Rivinus).[16]

The Ossicles

The 3 middle ear bones—the malleus, incus, and stapes—arise in condensations of mesenchyme derived from the first and second branchial arches (**Figure 7**). They begin as cartilage models and undergo refinement during the fetal period. The stapes evolves from an annular shape to an arch, while the malleus and incus retain their cartilaginous forms and gradually accumulate bulk. Following initial ossification around the fourth month after conception, the ossicles develop marrow cavities. Marrow is present at birth and gradually involutes into cancellous bone with vascular channels during the first decade (see malleus in **Figure 6**). The articular surfaces of the incudomalleal and incudostapedial joints remain as cartilage throughout life.

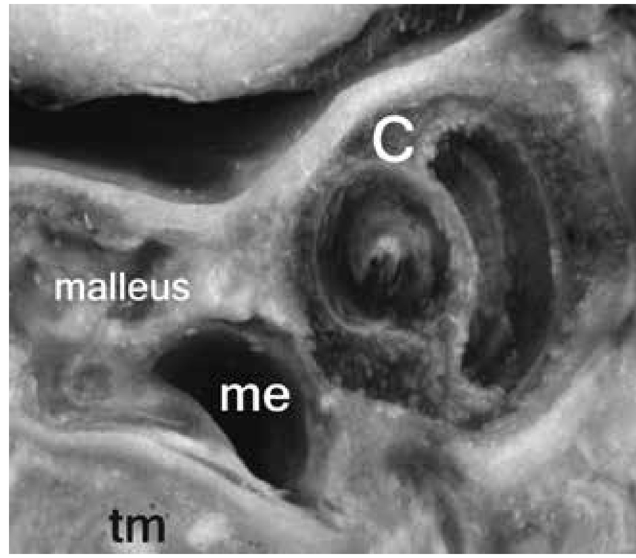

Figure 5. Coronal anatomic section of a 24-week fetal head. Close-up view of ear structures. C, cochlea; me, middle ear; tm, tympanic membrane.

The anterior process of the malleus is a remnant of Meckel's cartilage.[17] It extends anteriorly from the neck toward the tympanosquamous fissure, where it gives rise to the anterior ligament of the malleus. The malleus is suspended from the tympanic wall by this anterior ligament as well as more delicate superior and lateral mallear ligaments (**Figure 8**). The superior ligament extends to the epitympanic roof. The broad, short lateral ligament joins the neck of the malleus to the margin of the tympanic sulcus. The tendon of the tensor tympani also stabilizes the malleus (**Figure 9**).

The anterior body of the incus fits against the posterior head of the malleus in the epitympanum, forming the true diarthrodial incudomalleal joint.[18] The incus body is suspended by a sturdy posterior ligament extending from the short process and a superior ligament running from the incus body to the roof of the epitympanum (**Figure 8**). The slender long process of the incus terminates in a knob-like lenticular process. A diarthrodial incudostapedial joint connects the lenticular process to the stapes head.

From its articulation with incus, the stapes extends to the oval window. The two are united by an annular ligament that allows movement. The vestibular surface of the stapes footplate remains as cartilage from the embryonic period.

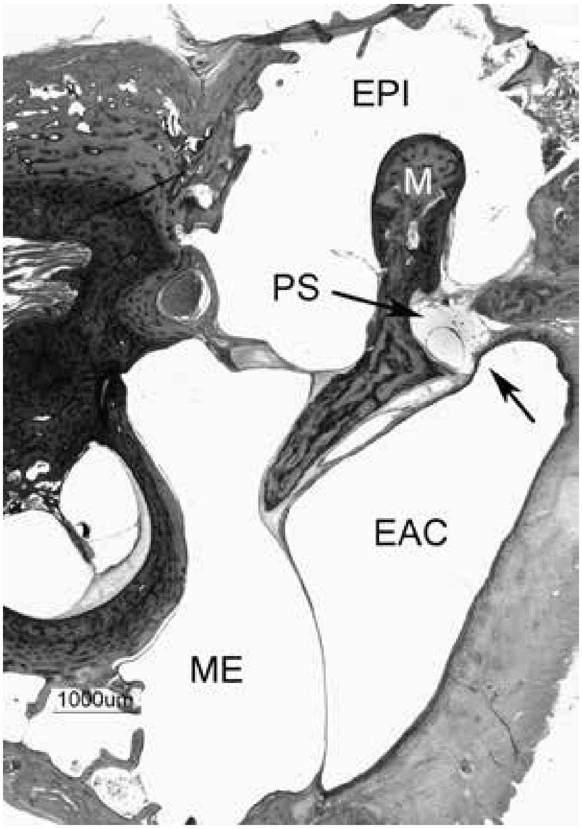

Figure 6. Coronal histologic section of a 3-month-old child's ear. Sando collection. EAC, external auditory canal; EPI, epitympanic space; M, malleus; ME, middle ear; PS, Prussak's space; unlabeled arrow, pars flaccida.

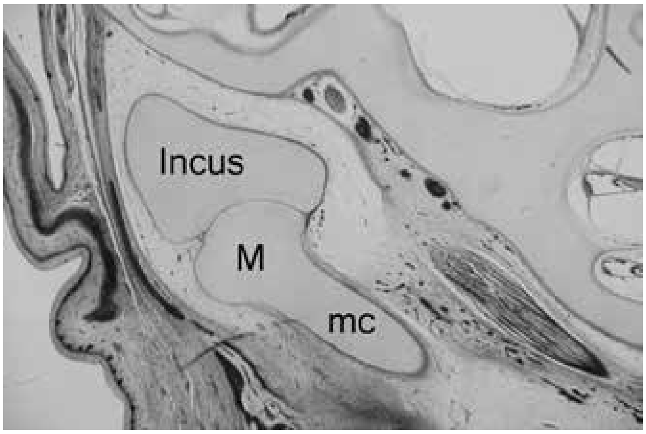

Figure 7. Horizontal section of the epitympanum of a 14-week fetus. Sando collection. Mesenchyme fills the epitympanic cleft. M, malleus head; mc, Meckel's cartilage.

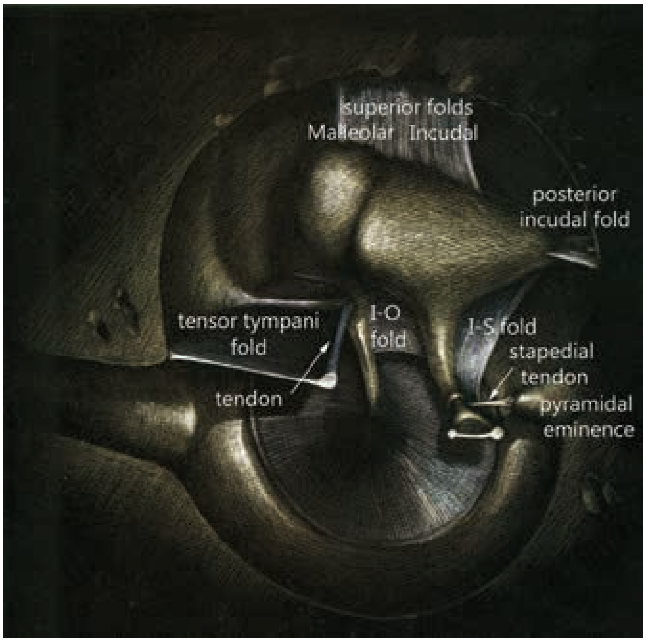

Figure 8. Artist rendering of the middle ear viewed from its medial wall. I-O fold, interossicular fold; I-S fold, incudostapedial fold. Modified after Proctor[22] by permission.

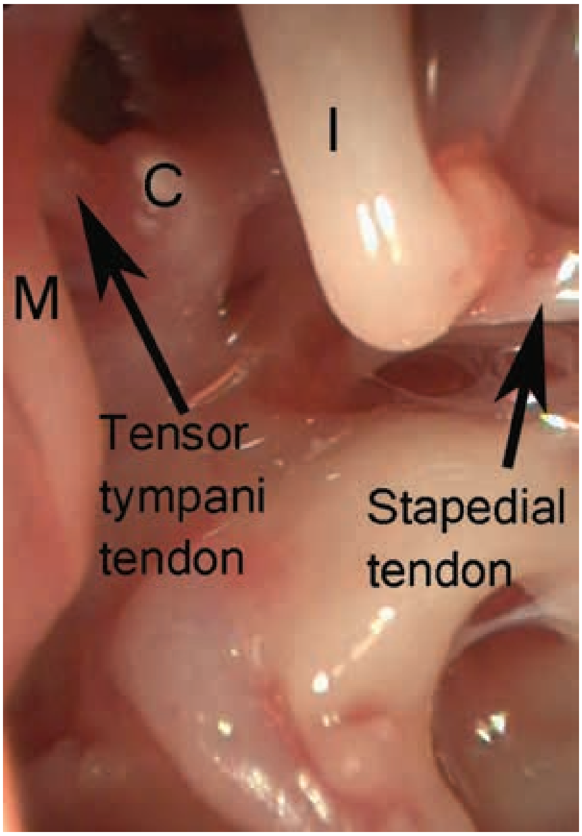

Figure 9. Endoscopic view of posterior mesotympanum (adult); 30-degree, 3-mm telescope. C, cochleariform process; I, incus long process; M, malleus manubrium.

The stapes is further supported by the stapedius muscle. The stapedius muscle fibers merge into the stapedial tendon, which emerges through an opening at the apex of the pyramidal eminence to attach to the posterior aspect of the stapes head and upper portion of its posterior crus (**Figure 9**).

The ossicles have achieved their full adult size and configuration at birth. They increase in density during the first years of life, replacing marrow cavities with endosteal bone, fine trabeculae, and channels contiguous with submucosal vascular.

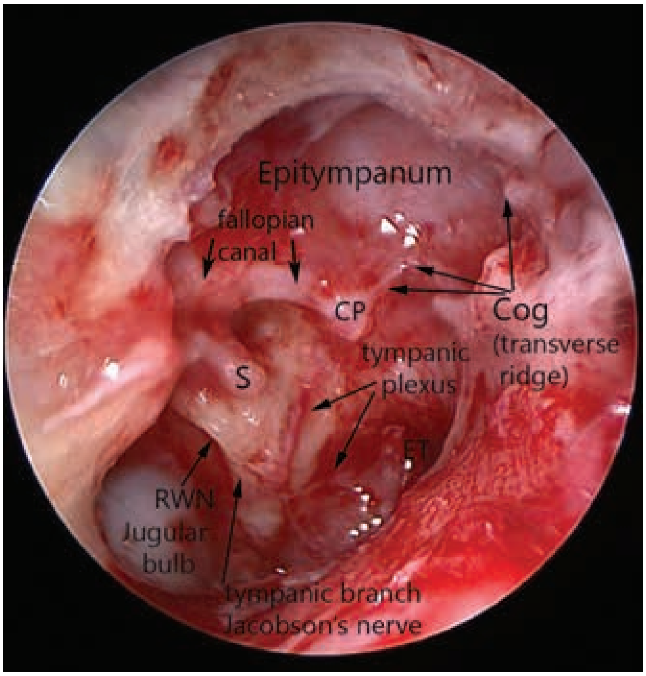

Figure 10. Endoscopic view of right middle ear after completion of an atticotomy and excision of cholesteatoma in a 7-year-old; 0-degree, 3-mm telescope. CP, cochleariform process; ET, eustachian tube; RWN, round window niche; S, stapes.

The axis of the ossicles shifts with growth of the middle cranial fossa in parallel to that of the tympanic membrane.

The Middle Ear Cleft

The tympanic cavity has 6 walls. The roof is a thin plate of bone abutting the middle cranial fossa. The floor is related to the fossa of the internal jugular vein, tympanic air cells, and styloid process. Posteriorly, the mastoid wall contains additional tympanic air cells and the projection of the pyramidal eminence. Lateral to this is the posterior foramen of the chorda tympani. Between the pyramidal eminence, the facial canal, and the chorda tympani is the facial recess. Cephalad to the facial recess resides the fossa incudis. The epitympanic recess occupies the most superior portion of the posterior wall. It communicates with the mastoid antrum.[19]

The anterior wall is narrow inferiorly. The thin bony wall guarding the carotid canal is covered by tympanic air cells and pierced by the caroticotympanic nerves. The eustachian tube opens in the central portion of the anterior wall. Just above it lies the semicanal of the tensor tympani muscle, terminating at the cochleariform process (**Figure 10**).

The medial boundary of the middle ear provides connection to the inner ear labyrinth. Inferiorly, the promontory covers the basal turn and hook region of the cochlea. An inferior depression in the promontory is designated the round window niche. Posterior to the promontory is a supporting projection of bone, the subiculum promontorii, which forms the inferior border of the sinus tympani. The superior border is defined by a small bridge of bone designated the ponticulus. Superior lies the oval window niche containing the stapes footplate and oval window to the inner ear. Further cephalad, the canal of the horizontal portion of the facial nerve traverses the medial wall as it approaches its second genu. The medial epitympanic wall covers the geniculate ganglion anterior and superior to the horizontal facial nerve and the cochleariform process (**Figure 10**).

The lateral wall of the middle ear is mainly composed of the tympanic membrane and its bony tympanic ring. The lateral epitympanic wall is a wedge of squamous bone called the scutum.

There is little postnatal growth of the mesotympanum. The otic capsule of the inner ear comprises much of the medial wall of the middle ear and has reached it full adult size in the 22-week fetus (**Figures 4** and **5**). The average volume of the tympanic cavity in adults (640 $\pm$ 69 mm^3) is about 1.5 times larger than the volume of the infant cavity (452 $\pm$ 68 mm^3).[20] The hypotympanum and epitympanum account for most of the increase, so the postnatal increase in the height of the tympanic cavity is greater than change in width or depth.[21]

Middle Ear Pneumatization and Partitioning

In the early fetal period, the future middle ear cleft is filled with loose mesenchyme, surrounding the cartilaginous condensations of the developing ossicles. This mesenchyme is gradually resorbed during the fetal period but may persist in middle ear recesses beyond the first year of extrauterine life. During the process of resorption, fetal middle ear mesenchyme is invaded by 4 endothelial outpouchings arising from the first branchial pouch—the future lining of the eustachian tube[22] (**Figure 11**). Hammar[23] named these 4 pouches the saccus anticus, saccus medius, saccus superior, and saccus posticus. Where these pouches expand and contact each other, mucosal folds are formed containing mesodermal remnants, including blood vessels. Anatomically, these folds invest the ossicles much as the peritoneum and mesentery invest the abdominal viscera. The saccus anticus is the smallest pouch, extending upward anterior to the tensor tympani tendon to form the anterior pouch of von Troeltsch.

The saccus medius forms the bulk of the attic airspace. It extends superiorly from the eustachian tube through the same anterior gap as the succus anticus. It then extends medially, wrapping around the incus body and malleus head. The saccus medius sends an offshoot forward between the lateral malleolar and lateral incudal folds to form Prussak's space. A posterior division of the saccus medius extends posteriorly to the anterior crus of the stapes, then medial to the long process of the incus and finally posterior to pneumatize the mastoid antrum and air cells of the petrous portion of the temporal bone.

The saccus superior extends posteriorly and laterally in the interval between the malleus handle and the tip of the long process of the incus. It forms the posterior pouch of von Troeltsch and the inferior incudal space. Posteriorly, the succus superior passes over the pyramidal eminence into the antrum. It pneumatizes the mastoid air cells derived from the squamous portion of the temporal bone. The saccus

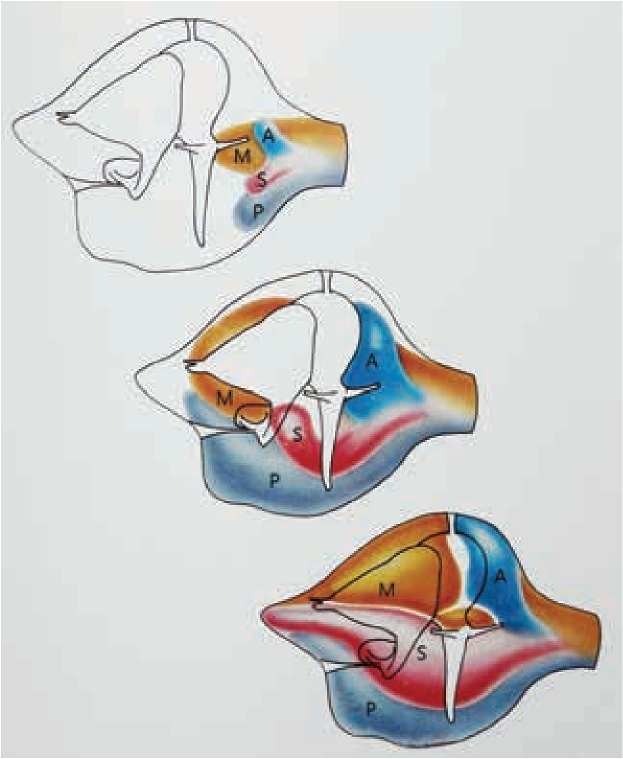

Figure 11. Progressive pneumatization of the middle ear cleft. A, saccus anticus; M, saccus medius; P, saccus posticus; S, saccus superior. Modified after Proctor[22] by permission.

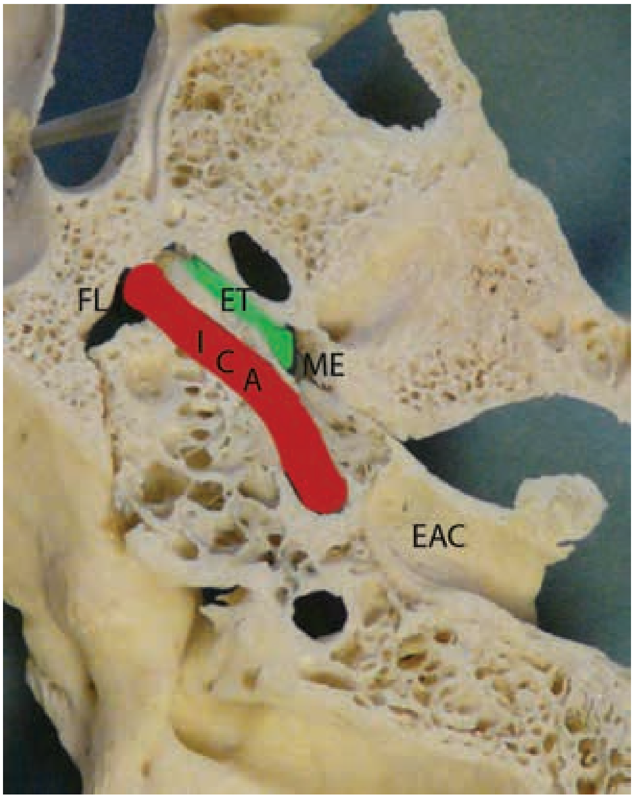

Figure 12. Transverse section of the skull base (adult) showing the relationship of the petrous internal carotid artery (ICA) to the eustachian tube (ET). EAC, external auditory canal; FL, foramen lacerum; ME, middle ear.

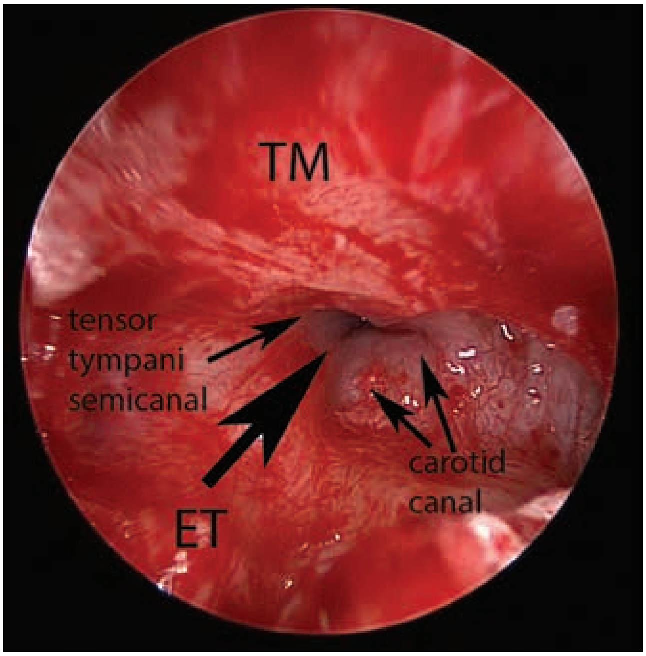

Figure 13. Endoscopic view of eustachian tube (ET) orifice of a 5-year-old at surgery; 30-degree, 3-mm telescope. TM, tympanic membrane.

posterior extends along the hypotympanum to form the round window niche. It may extend beneath the stapedial tendon to pneumatize the sinus tympani.

The Eustachian Tube Orifice and Anterior Wall Anatomy

The eustachian tube extends from the anterior wall of the mesotympanum medially and inferiorly to reach the nasopharynx along a length of 31 to 37mm.[24] The osseous medial third of the tube is contained in a bony semicanal. Superiorly, it is separated from the tensor tympani muscle by a thin septum. Its medial wall approximates the internal carotid canal.[25] The carotid canal wall measures 4.5 mm from the tympanic annulus. It averages 1.5 mm in thickness but may be dehiscent[26] (**Figure 12**). Viewed endoscopically from the middle ear, the bony canal is triangular in shape, narrowing at its junction with the cartilaginous canal. The semicanal of the tensor tympani is visible above and the bulge of the carotid canal wall below (**Figure 13**).

The medial two-thirds of the eustachian tube further narrows at its central isthmus. Its walls are principally supported by the tubal cartilage, which is curved like a shepherd's crook in the mid-portion of the eustachian tube. It has a broad medial plate and a smaller lateral lamina. The tensor veli palatini inserts onto this lateral lamina—its contraction dilates the auditory tube to allow the influx of nasopharyngeal air.[27]

The Retrotympanic Spaces

The nomenclature describing the recesses surrounding the mesotympanum is inconsistent, as are the dimensions and details of these air cells. Marchioni et al[28] have expanded

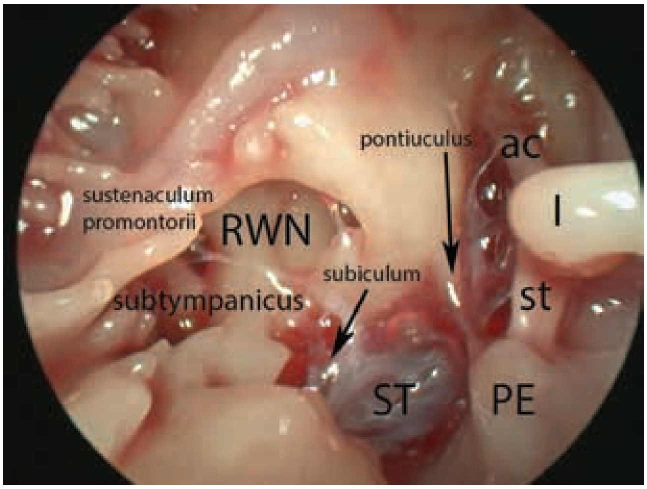

Figure 14. Endoscopic view of the sinus tympani (ST); adult, 30-degree, 3-mm telescope. ac, anterior crus of stapes; I, incus; PE, pyramidal eminence; RWN, round window niche; st, stapedial tendon.

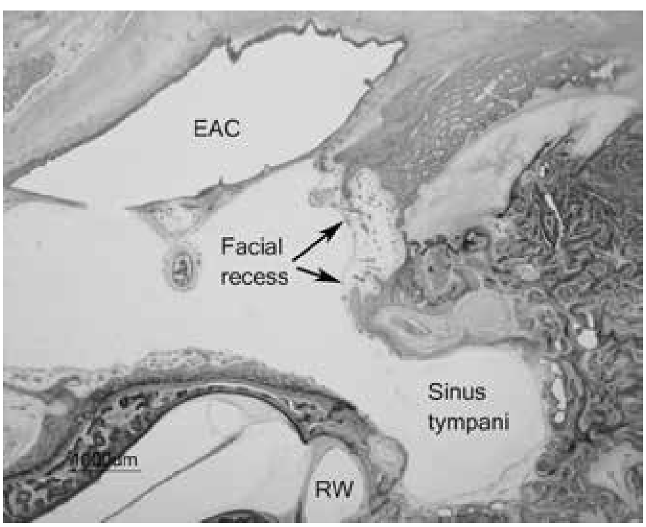

Figure 15. Histologic section of middle ear of term infant. Sando collection. Note residual submucosal mesenchyme in facial recess and sinus tympani. EAC, external auditory canal; RW, round window niche.

on the work of Proctor[29] and others in describing the retrotympanum. They divide the region into superior and inferior retrotympana, separated by the subiculum. The sinus tympani are the largest of the superior recesses. They lie medial to the pyramidal eminence, stapedius muscle, and facial nerve and lateral to the posterior semicircular canal and vestibule. The superior limit of this space is defined by the ponticulus and the inferior extent by the subiculum, extending posteriorly from the rim of the round window niche (**Figures 14-16**). Marchioni et al presented a series of 40 adult endoscopic cholesteatoma surgeries. They describe 4 different sinus tympani configurations and discuss the limits these place on dissection. Most are fully accessible with 30- and 45-degree, 3-mm telescopes.[30]

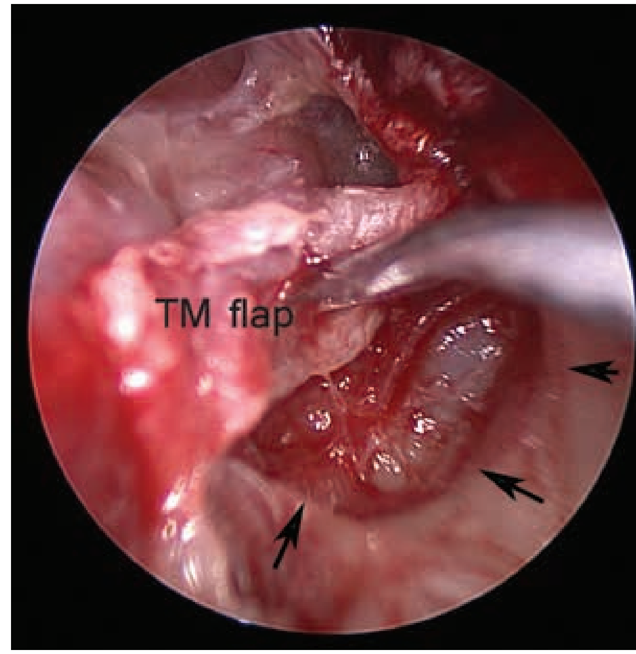

Figure 16. Endoscopic view of sinus tympani (arrows) during cholesteatoma surgery in a 7-year-old; 30-degree, 3-mm telescope. TM, tympanic membrane.

The sinus tympani and facial recess are well formed and near adult proportions in the newborn.[31] Residual mesenchyme is commonly seen in temporal bone specimens from infants (**Figure 15**). Residual mesenchyme lies between the mucosa and the underlying bone. If appreciable, it could decrease the apparent depth of the posterior tympanic recesses on endoscopy in the first years of life.[32]

The inferior retrotympanum is the posterior space that houses the sinus subtympanicus, delimited posteriorly by the styloid complex and the third portion of the seventh cranial nerve, anteriorly by the round window with its pillars and the inferior and posterior portions of the promontory, superiorly by the subiculum, and inferiorly by the sustenaculum promontorii[33] (**Figure 14**).

The Hypotympanum

The hypotympanum represents the inferior compartment of the tympanic cavity and is located anteriorly and inferiorly to the retrotympanum (**Figure 17**). Its upper limit is a virtual plane passing through the styloid eminence and continuing to the inferior margin of the external auditory canal. Its inferior limit is formed by the floor of the tympanic cavity and jugular bulb.[34,35] The hypotympanic floor has an irregular surface due to the presence of osseous trabeculae and small irregular tympanic cells.[36] These trabeculae can interfere with tympanostomy tube insertion and can trap fingers of the cholesteatoma matrix. A "high" or dehiscent jugular bulb may present in the hypotympanum[37] (**Figure 10**).

The Epitympanum

Patterns of epitympanic aeration have received considerable attention to help explain the origin and spread of acquired

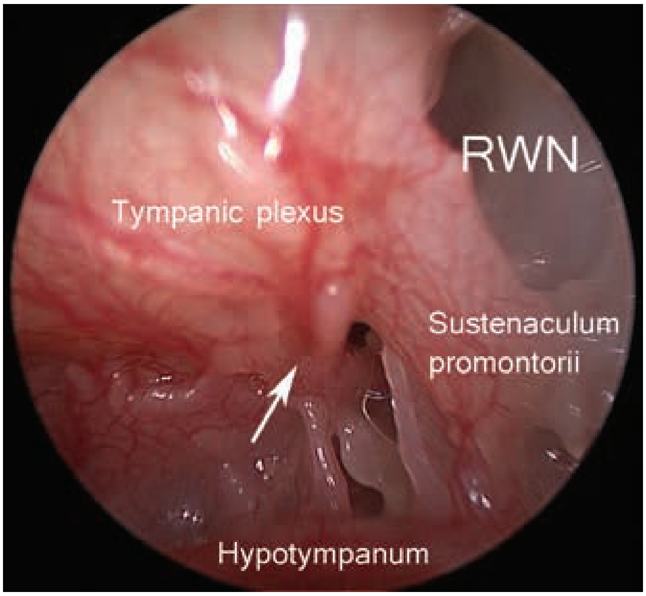

Figure 17. Endoscopic view of the hypotympanum in a 5-year-old; 30-degree, 3-mm telescope. RWN, round window niche; arrow, tympanic canaliculus.

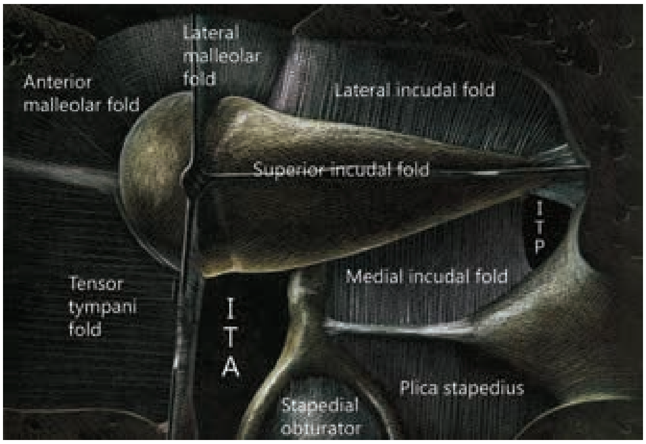

Figure 18. Artist rendering of the epitympanum viewed from its roof. ITA, isthmus tympani anticus; ITP, isthmus tympani posticus. Modified after Proctor[22] by permission.

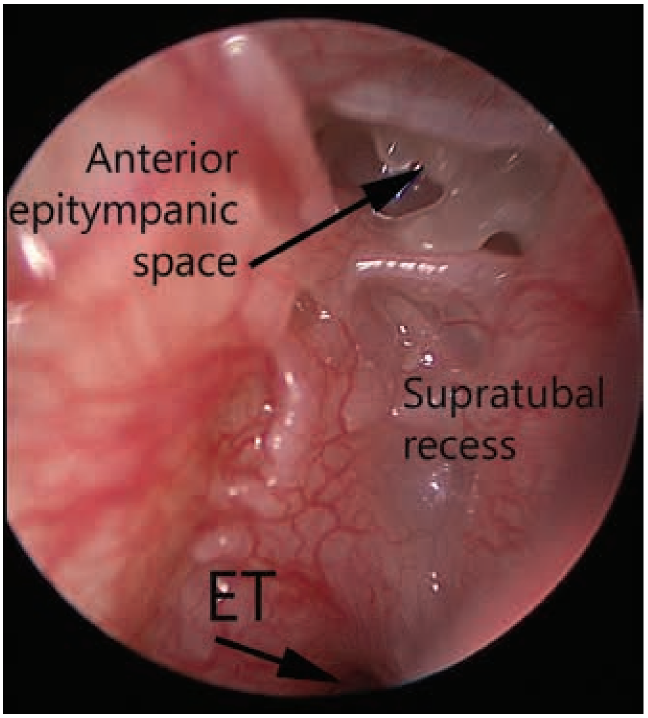

Figure 19. Endoscopic view of the supratubal recess and anterior epitympanic space in a 5-year-old; 30-degree, 3-mm telescope. ET, eustachian tube.

cholesteatomas.[38] Microdissections by Palva and Ramsay[39] confirm the existence of an epitympanic diaphragm composed of various ligaments and membranous folds, which, together with the malleus and incus, form the floor of the epitympanum.[40] Proctor[22] described 2 main ventilation pathways from the eustachian tube to the epitympanum. These openings in the tympanic diaphragm include a large anterior (isthmus tympani anticus) and a small posterior (isthmus tympani posticus) dehiscence (**Figure 18**). The anterior epitympanum is ventilated by a separate route recapitulating the pathway of the fetal saccus anticus, anterior to the malleus head and into the supratubal recess and anterior epitympanic space (**Figure 19**).

Prussak's space is located between the pars flaccida and the neck of the malleus. The connections between Prussak's space and the rest of the epitympanum are variable and often quite narrow. Obstruction of these connections occurs easily during middle ear inflammation, making the pars flaccida particularly vulnerable to cholesteatoma formation in the adult.[41] Mesenchyme fills Prussak's space at birth. It is gradually absorbed by age 4 years in normal toddlers but may persist until age 9 years in children with persistent middle ear effusions.[42] This persistence of mesenchyme during the first years of life may account for the rarity of acquired pars flaccida cholesteatomas in young children[43] (**Figure 6**).

Failed epitympanic ventilation results in retraction pockets that follow any of 3 pathways (**Figure 20**). Anterior epitympanic acquired cholesteatomas tend to extend anterior superiorly to fill the anterior epitympanic space before wrapping around and deep to the malleus head and incus body.[44] Pars flaccida cholesteatomas erode the scutum and fill the epitympanum from lateral to medial following a superior course before wrapping around the ossicular heads.[45] Posterior acquired cholesteatomas can follow several routes but often wrap around the incus long process and stapes superstructure on their way to the attic (medial to incus body and malleus head) and the mastoid antrum.[46]

Conclusions

The availability of high-resolution video cameras and small-diameter endoscopes has opened the recesses of the middle ear to detailed examination and new less traumatic interventions. An understanding of the detailed anatomy of the

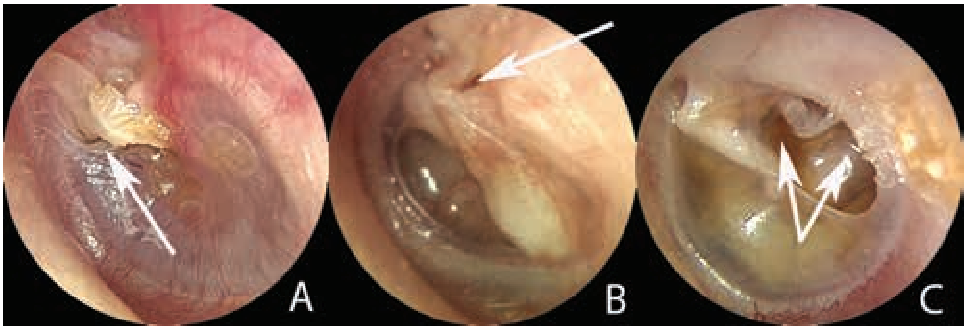

Figure 20. Endoscopic view of 3 tympanic membranes with retractions. (A) Anterior retraction toward the anterior epitympanic space. (B) Pars flaccida cholesteatoma eroding scutum and wrapping around the ossicular head to present in the mesotympanum. (C) Posterosuperior retraction anterior and posterior to the incus long process and stapes and toward the sinus tympani.

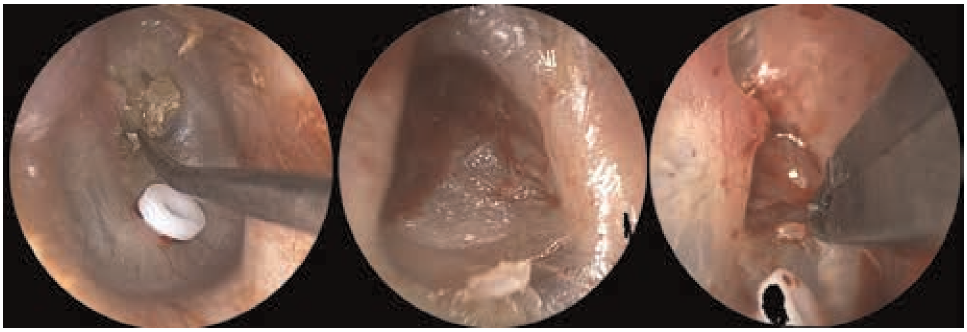

Figure 21. Endoscopic management of an anterior attic cholesteatoma (saccus anticus). (A) Middle ear ventilation and removal of cholesteatoma debris. (B) Assessment of cholesteatoma extent with 30-degree telescope (limited to supratubal recess). (C) Attempted reduction of retraction pocket with endoscopic guidance.

middle ear, its contiguous air spaces, and surrounding vital structures lays the groundwork for future endoscopic operative interventions (**Figure 21**). A fuller understanding of the variable anatomy of these structures, between individuals and over time in a growing child, should expand our capabilities and lead to better surgical outcomes.

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Glenn Isaacson, conception, data collection, preparation of illustrations, preparation of manuscript.

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