3 Middle Ear Contents

Contents

Traditionally, the ossicular chain is considered as the essential content of the middle ear. It is suspended inside the cavity by ligaments and muscles, which will be addressed in their embryological development and their anatomical details in this chapter.

Nowadays, it is admitted in middle ear mechanics that the most important content of the middle ear to assure a normal sound transmission, in addition to the ossicular chain, is gas (air).

The tympanic cavity contains an average of 2 cc of air. The minimal volume of air necessary for a normal function of the middle ear is at least 0.5 cc. Air transmits the sound wave from outside to the tympanic membrane and inside the middle ear, air serves as an insulator. When air of the middle ear is replaced by an effusion, hearing loss will result due to the reduction of pressure difference of the sound wave in between the oval window and the round window with an escape of sound energy to the surrounding bony structures.

Furthermore, the middle ear cavity contains several mucosal folds that divide the middle ear cavity in different compartments and spaces. The folds and their openings define middle ear aeration pathways and play an important role in the evolution of some middle ear pathologies, such as inflammation or cholesteatoma.

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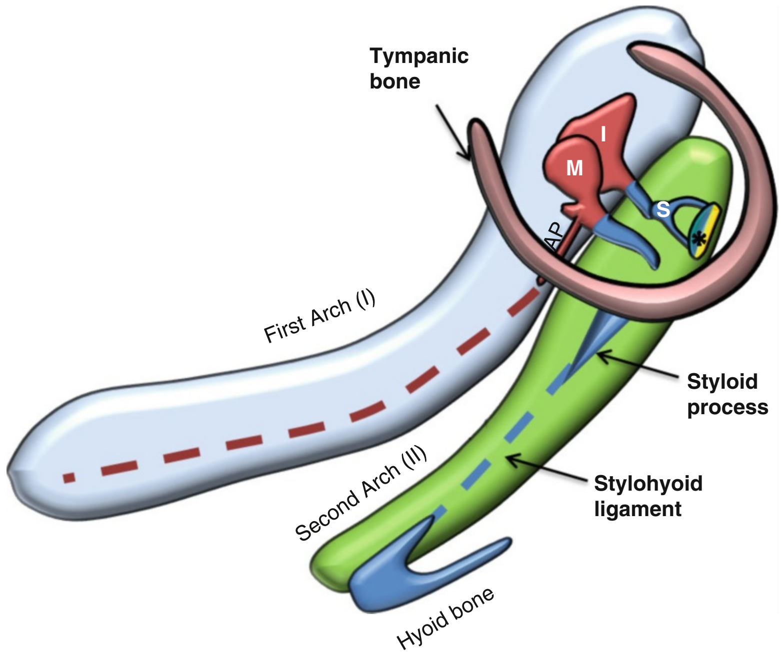

Fig. 3.1 Destination of the first and the second branchial arches. *M* malleus, *I* incus, *S* stapes, *AP* anterior malleal process, (*) double origin of the footplate

3.1 The Auditory Ossicles

The auditory ossicles are the *malleus*, *incus*, and *stapes*; they are named after the objects they resemble (hammer, anvil, and stirrup). The ossicles are suspended in the middle ear cavity by numerous *suspensory ligaments,* and they are covered by the mucous membrane of the middle ear cavity. The auditory ossicles form the ossicular chain which is responsible for transmission of sound-induced vibrations of the tympanic membrane to the oval window. This system is the cornerstone of middle ear mechanics.

3.1.1 Embryology of the Auditory Ossicles

The ossicles, muscles, and tendons of the middle ear are formed from the mesenchyme of the middle ear and are covered by the epithelial lining of the first pharyngeal pouch [1].

The mesenchyme forming the ossicles is derived from neural crest cells present in the first and second branchial arches. These cells migrate to the branchial arch from the dorsal part of the developing neural tube during the fourth week of gestation [2].

There is controversy about the contribution of each arch to ossicular formation; there are two main theories regarding this subject:

- *The classical theory:* postulates that the incus and the malleus are derived from Meckel's cartilage of the first branchial arch; the stapes is derived from Reichert's cartilage of the second branchial arch [3–7].
- *The alternative theory*: proposes that the head of the malleus and the body of the incus originate from the first arch, while the handle of the malleus, the long process of the incus, and most of the stapes originate from the second arch (Fig. 3.1) [8–13].

In both theories, the labyrinthine side of the footplate was considered to originate from the mesenchyme of the otic capsule. However, some normal and teratologic observations in the literature support the idea that the stapes could entirely derive from the Reichert's cartilage without any contribution of the otic capsule [14–16].

Ossicular development in the human embryo starts at the fourth week of gestation as an interbranchial mesenchymal bridge connecting

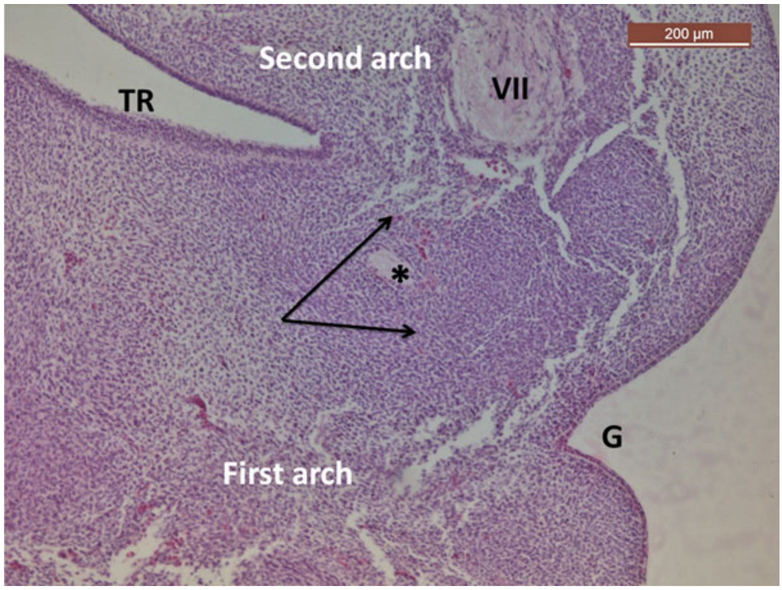

Fig. 3.2 13-mm human embryo. The common blastema of the handle of the malleus and the long crus of the incus (the *two arrows*) crossed by the chorda tympani (*). *TR* tubotympanic recess of the first branchial pouch, *G* first ectodermal groove, *VII* facial nerve in the second branchial arch. Hematoxylin-eosin staining

the mesenchyme of the upper part of the first branchial arch and the central part of the second branchial arch. This condensed mesenchyme gives rise to the primordial malleus and incus [12, 17, 18]. This mesenchymal mass is crossed by the chorda tympani that divides it in two parts: the malleal primordium laterally and the incudal primordium medially (Fig. 3.2). This common rudiment keeps connection with the Reichert's cartilage, supporting the "alternative" theory in that all of the stapes blastema derives from the second arch mesenchyme.

During the sixth week, a precartilage forms in the future ossicles. A rapid transformation into true cartilage occurs during the seventh week. By the end of the eighth week, the cartilaginous malleus resembles adult ones. Thereafter, progressive and extensive ossicular growth occurs and, by the 20th week, the ossicles reach adult size and have begun to ossify.

Ossification of the incus takes place slightly earlier than that of the malleus. In the 25th to 26th week, both the incus and malleus are fully ossified with the exception of the distal extremity of the malleus handle. Meanwhile, the pneumatization process of the tympanic cavity extends into the epitympanum and antrum, making the ossicles free only tethered to the tympanic cavity in a mesentery-like fashion.

Clinical Application
Before birth, the ossicles have achieved adult size and shape. The endochondral bone of the ossicles, similar to that of the otic capsule, undergoes only little changes over lifetime of the individual and demonstrates poor reparative capacity in response to fractures.

3.1.1.1 Stapes Development

The stapes, the first ossicle to appear, develops from an independent anlage derived from the cranial end of the cartilage of the second branchial arch (Fig. 3.1). The stapedial anlage connects to the remaining Reichert's cartilage by a formation called the interhyale; the internal part of the interhyale gives rise to the tendon of the stapedial muscle.

The stapedial anlage will be crossed by the stapedial artery during embryonic period, giving the stapes its characteristic ring shape (Fig. 3.3).

Footplate Development

There are two theories regarding the origin of stapedial footplate. Despite the fact that there are several differences between both theories, it is accorded that footplate development is characterized by a progressive replacement of

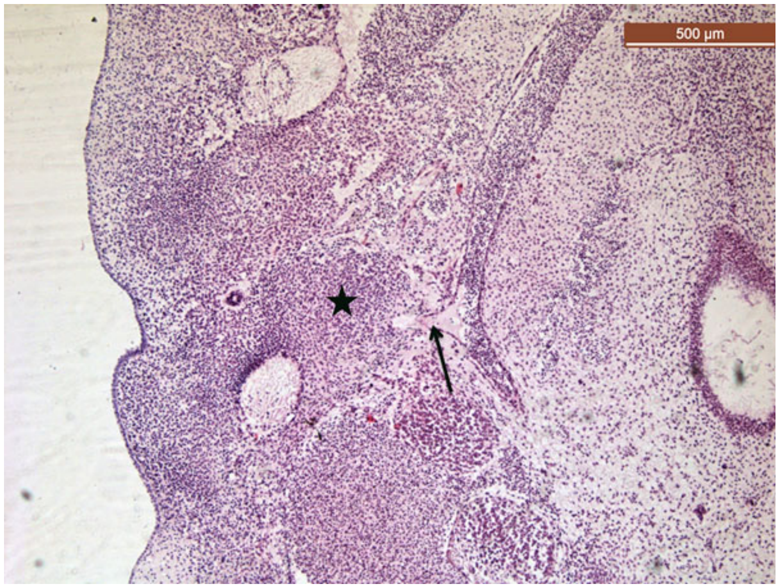

Fig. 3.3 13-mm human embryo section showing the stapedial (*) rudiment crossed by the stapedial artery (*arrow*). Hematoxylin-eosin staining

undifferentiated mesenchyme by chondroblasts, and differentiation of the peripheral mesenchyme into the annular ligament around the presumptive footplate, as demonstrated by Jacksoll in the chick embryo [19] (Fig. 3.4).

- *Classical theory of footplate origin*
  The classical theory presumes that the footplate has two origins: the tympanic side derived from the stapedial ring and the vestibular side derived from the lamina stapedialis of the otic capsule [16]. The medial border of the stapedial ring comes in contact with a facing depression in the lateral wall of the otic capsule. This depression, called the *lamina stapedialis*, is the future oval window. The medial border of the stapedial ring fuses with the lamina stapedialis to form the stapedial footplate (Fig. 3.5).
- *Alternative theory of footplate origin*
  According to this theory, the otic capsule is not involved in the formation of the base of the stapes and the entire stapes derives from the stapedial anlage of the Reichert's cartilage [14, 15, 19, 20] (Fig. 3.6).

Annular Ligament

At the beginning, the footplate is attached to the otic capsule by a band of mesenchyme that later transforms into the annular ligament, once the footplate reaches adult size [19, 20]. The stapediovestibular joint, stapes and the inner ear being decoupled, shows its definitive characteristics at 12th week (Figs. 3.4 and 3.5).

Stapes Ossification

Stapes endochondral ossification starts at the end of the fourth month from a single ossification center present at the center of the footplate. The ossification extends to the two branches and then to the head of the stapes [21].

> ***Clinical Application***
> Congenital stapes anomalies are sometimes related to an aberrant facial nerve development. During the crucial time period of sixth week, anterior displacement of the second genu region of the facial nerve hinders the normal fusion of the stapedial ring with the lamina stapedialis, resulting in a malformed stapes in conjunction with anomalous facial nerve trajectory.

3.1.1.2 Incus Development

The incus is the second ossicle to appear, but the first to be ossified. The body of the incus derives from the cranial part of the Meckel's

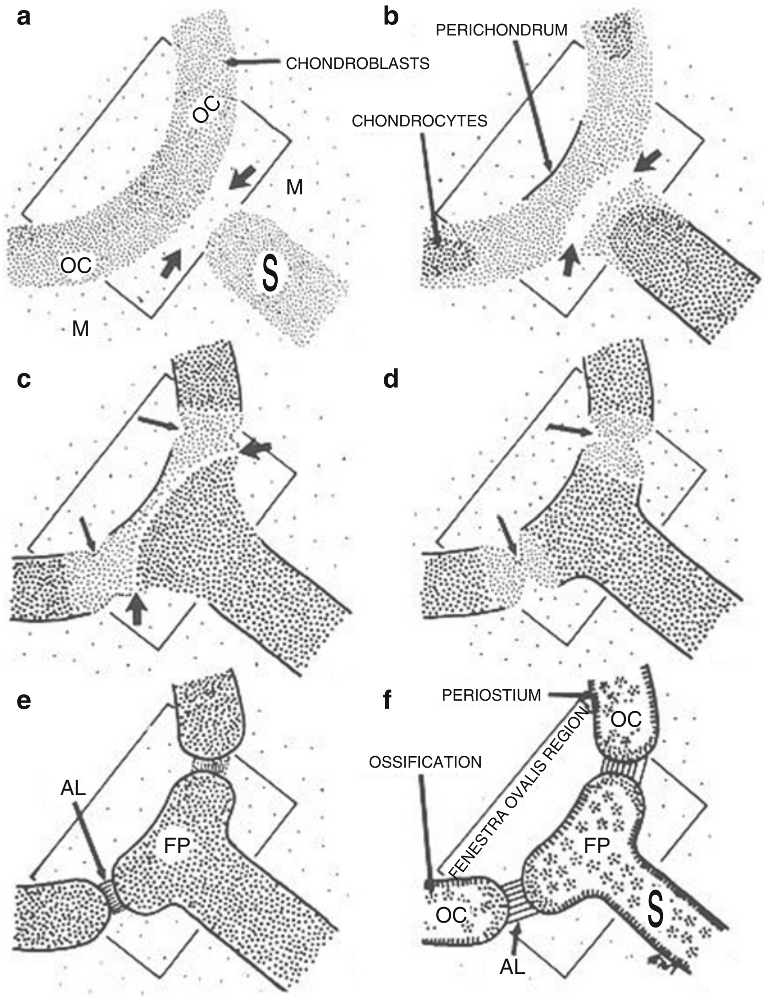

Fig. 3.4 Footplate development in the bird (According to Jaskoll 1980 [19]. (**a**)–(**f**): Successive stages of development of the footplate and related structures. This material is reproduced with permission of John Wiley & Sons, Inc.). Chondroblasts of the otic capsule and stapes are initially separated by undifferentiated mesenchyme. This mesenchyme progressively disappears and becomes present in the "isthmus" (*arrows*) in which will develop the annular ligament. *FP* footplate, *AL* annular ligament, *OC* otic capsule

cartilage. The long process of the incus derives from Reichert's cartilage (Figs. 3.1 and 3.7). Endochondral ossification starts at the beginning of the fourth gestational month from the anterior face of the long process and ends at the sixth month reaching adult size.

> ***Clinical Application***
> Congenital absence of the long process of the incus results in a near-maximal conductive hearing loss [22, 23].

3.1.1.3 Malleus Development

The head of the malleus (Figs. 3.1, 3.7, and 3.8) appears as a mass connected to the cranial end of the Meckel's cartilage. This connection disappears later to be replaced by the anterior process of the malleus and anterior malleal ligament. The anterior process, which can be up to 10 mm in neonates, remains in the adult malleus only as a small prominence. A lack of bony involution can keep the malleus fixed at the petrotympanic fissure [24].

The handle of the malleus has close relationships with the long process of the incus in a blastema originally connected to the Reichert's cartilage.

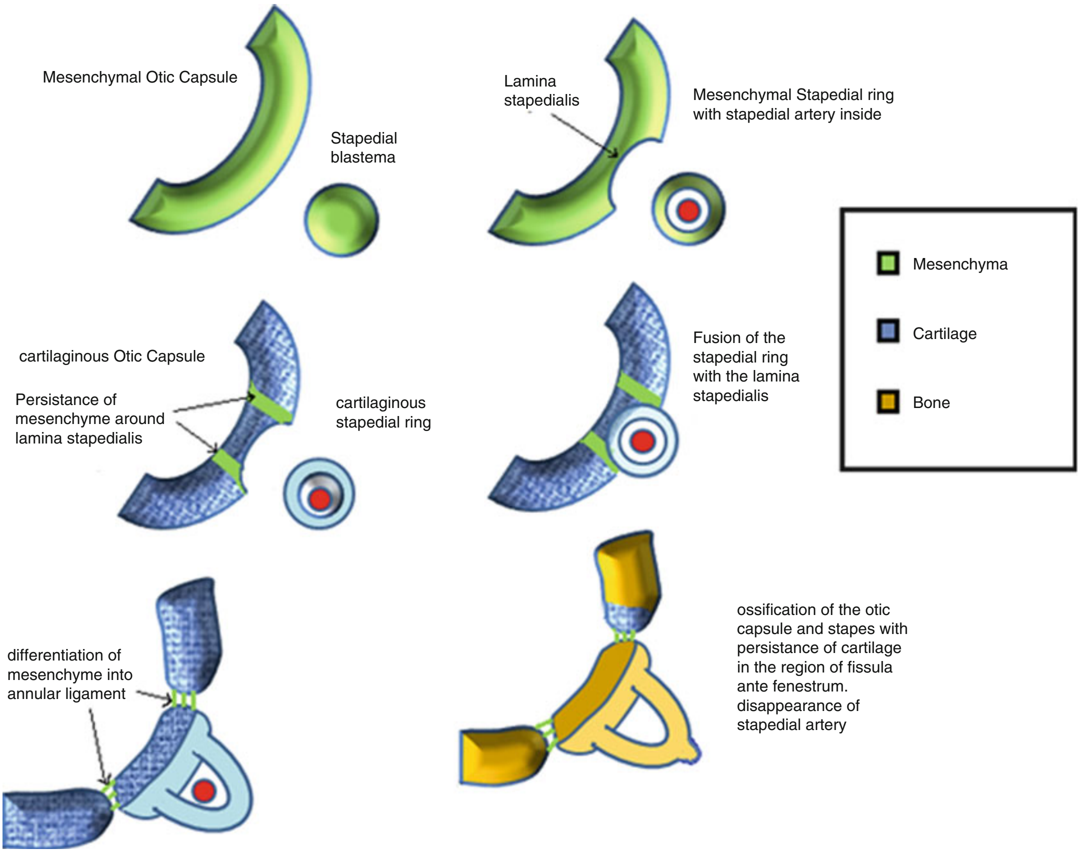

Fig. 3.5 Stapes development according to the classical theory

Failure of resorption of this connection with Reichert's cartilage leads to formation of malleus handle bony bar (see Sect. 3.1.1.4). Later, the handle of malleus becomes inserted in the tympanic membrane rudiment.

This different origin of the head and of the handle of the malleus explains why in aural atresia the head of the malleus is present while the handle is missing. Malleus ossification ends by the sixth month [25].

Congenital Ossicular Malformations

Congenital ossicular malformations could be associated with aural atresia and microtia, or it could be isolated without external ear anomaly as in minor ear atresia. Ossicular anomalies in minor atresia are subdivided into incudomalleal fixation, stapes fixation, and incudostapedial disconnection [26]. Incudomalleal fixations are the least common, where the malleus head and incus body are usually fused or fixed to the epitympanic walls [27]. Triple ossicular malformations are rare and could be associated with inner ear anomalies [28].

Malleus Congenital Anomalies

The incidence of malleus anomalies is lower than anomalies of the incus or stapes. Hypoplasia or aplasia of the malleus results from a failure of embryogenesis between 7th and 25th week. Given the common pharyngeal arch origin, hypoplasia of the malleus is often associated with hypoplasia of the incus [22].

Epitympanic fixation of the head of malleus is by far the most congenital anomaly of the malleus. This anomaly is related to an incomplete pneumatization of the epitympanum during malleus head ossification. Temporal bone exploration in these patients reveals bony bridges between the head of the malleus and the lateral epitympanum in the majority of cases [24, 27] (Fig. 3.9).

Malleus bar is a persistent bony bridge that connects the malleus handle to the posterior tympanic wall [29, 30].

Incus Congenital Anomalies

Hypoplasia or aplasia of the incus typically occurs in conjunction with hypoplasia of the malleus but may occur in isolation. The incus is also susceptible to fixation to the epitympanum (Fig. 3.9). Congenital absence of the long process of the incus might be associated with aplasia of the stapes and of the handle of malleus, supporting the hypothesis of their common origin [22, 23] (Fig. 3.10).

Stapes Congenital Anomalies

Congenital stapes footplate fixation is the most common isolated ossicular anomaly, approximately 40 % of all congenital ossicular malformations. It is thought to result from ossification of the peripheral mesenchyme of the footplate instead of differentiating into the annular ligament [31].

Although aplasia of the stapes is rare, multiple forms of hypoplasia that include small or absent crura and blob-like stapes have been described. In contrast, isolated hyperplasia of the stapes is often an incidental finding that does not require therapy; this anomaly is thought to result from a failure of the resorption and remodeling that occurs during the final stages of stapes development. Several crural anomalies have been described, including thin, absent, fused, and angled crura. The crura may also be replaced with a columella-like structure. Congenital stapes disorders are often related to aberrant facial nerve development [10, 22, 32].

Fig. 3.6 E16 mouse embryo whose mother received a teratogen molecule (methyl triazene) disturbing ossicles formation. A complete stapes develops independently from the otic capsule (*arrow*). In front of the stapes, we observe a narrowing of the otic capsule cartilage. Toluidine blue staining at pH2

3.1.2 Anatomy of the Auditory Ossicles

3.1.2.1 The Malleus

The malleus is shaped like a hammer and is the largest of the three middle ear ossicles. It is 8–9 mm in length and weighs about 20–25 mg. It consists of a head, neck, handle, and two processes arising from below the neck (Fig. 3.11).

The Malleus Head

The malleus head lies in the attic region of the middle ear and is 2.5 by 2 mm in size. On its posteromedial surface, there is an elongated saddle-shaped facet to articulate with the incus. This facet is covered by an articular cartilage.

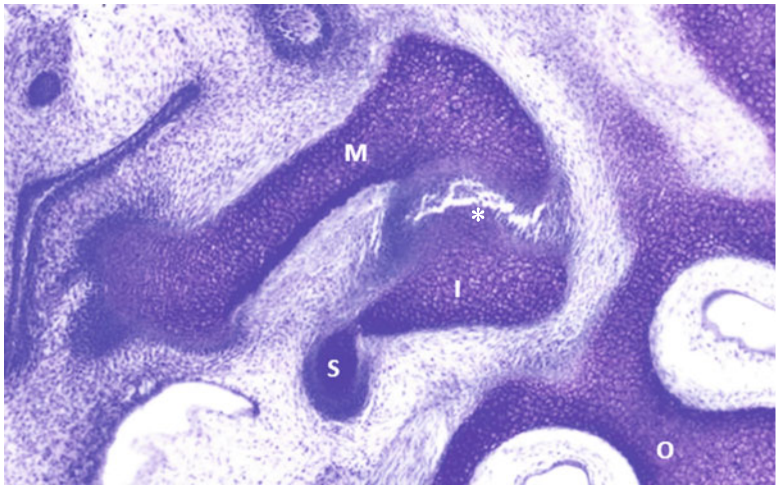

Fig. 3.7 Sagittal section of E17 mouse embryo displaying the cartilaginous malleus (*M*), incus (*I*), and stapes (*S*) in close relationship with the otic capsule (*O*). The incudomallear joint is just forming (*). Toluidine blue staining at pH4

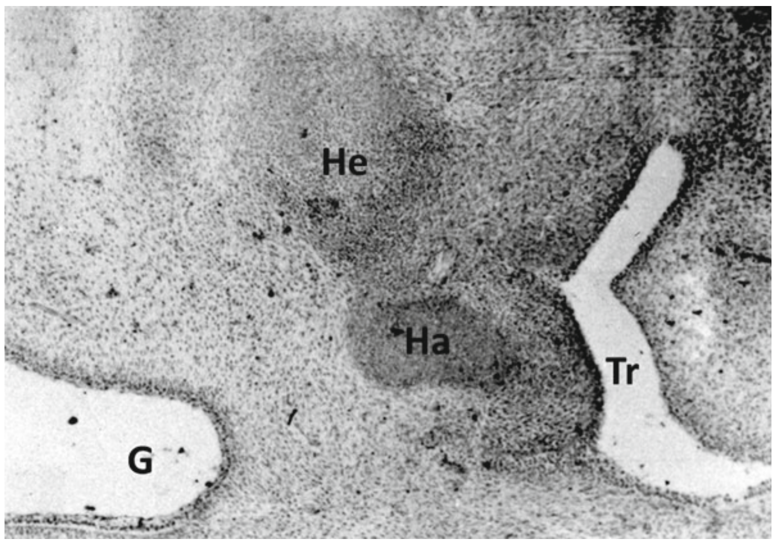

Fig. 3.8 Coronal section of a 19-mm human embryo revealing the coalescence of the handle of malleus (*Ha*) and the head of malleus (*He*). The handle projects between the first ectodermal groove (*G*) and the first endodermal pouch (*TR*). At this stage, the ossicles are cartilaginous. Hematoxylin-eosin staining

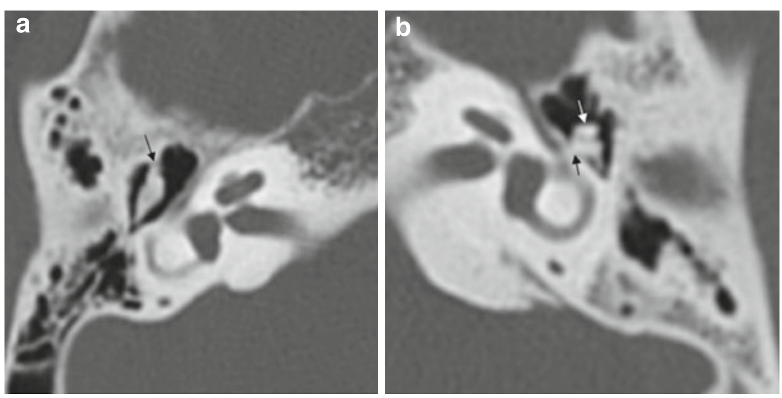

Fig. 3.9 (**a**) Transversal computed tomography of a right ear: bony bridge (*arrow*) between the malleus head and the tegmen. (**b**) Transversal computed tomography of a left ear with fixation of the incus on the medial attic wall (*black arrow*), malleus head (*white arrow*)

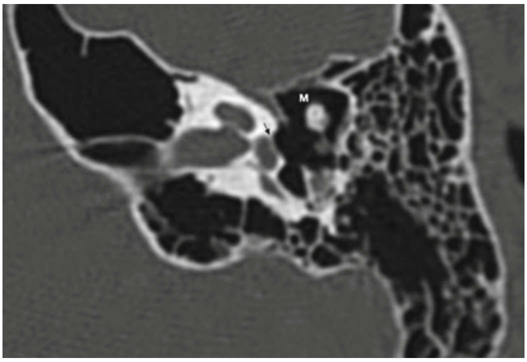

Fig. 3.10 Computed tomography of a left ear with aplasia of stapes suprastructure and the long process of the incus. *M* malleus; stapes footplate (*arrow*)

> *Malleus Head Fixation*: Malleus head fixation is not an uncommon pathology. It may be a congenital anomaly (Fig. 3.9) or acquired anomaly as in tympanosclerosis (Fig. 3.12). Clinically it manifests as a 15–25-dB conductive hearing loss [33].

The Neck

The neck is a narrow and flattened portion. The tendon of the tensor tympani muscle inserts on its medial surface, and the chorda tympani crosses its medial surface above the insertion of this tendon. Its lateral surface forms the medial wall of the Prussak's space.

The Manubrium (The Handle)

The handle forms with the malleus head a superoposteriorly open angle of 135–140°. It runs downwards, medially, and slightly backwards between the mucous and fibrous layers of the tympanic membrane. The inferior end of the handle is flattened and firmly attached to the tympanic membrane as the pars propria splits to envelop it forming the *umbo*.

In surgical procedures, the tympanic membrane can be readily separated from the malleus except at the umbo. At the level of the umbo, the periosteum of the handle continues directly with the fibrous layer. Midway between the lateral process and the umbo, the handle has a gentle medial curvature. At this level the handle is not embedded in the tympanic

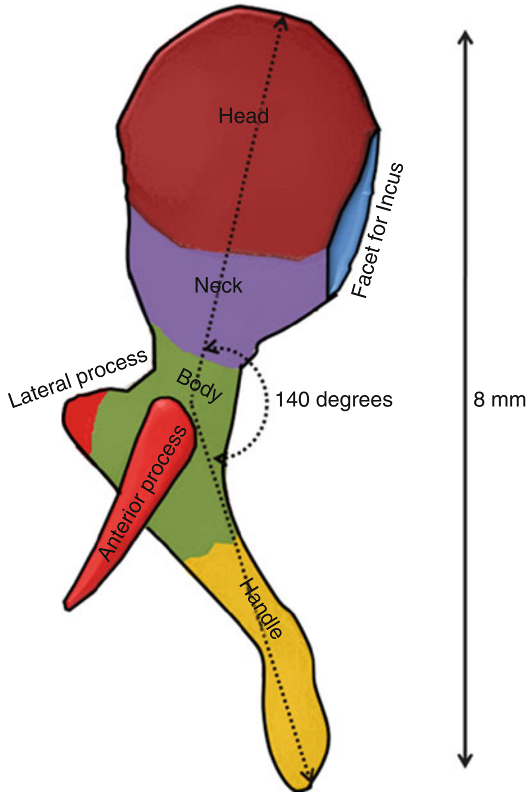

Fig. 3.11 Schematic drawing of the malleus

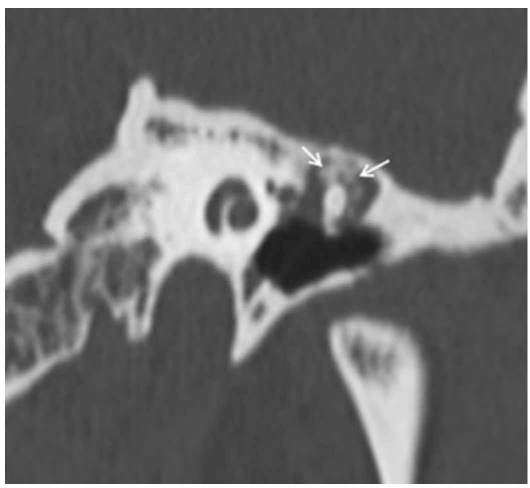

Fig. 3.12 Attical tympanosclerosis of a left ear, computed tomographic coronal reconstruction showing calcifications (tympanosclerosis, *arrows*), surrounding and fixing the malleus to the tegmen

membrane, rather it is linked to the tympanic membrane by a mucosal fold, the *plica mallearis*. A prosthesis clamped to the manubrium in this area may have little or no contact with the pars propria of the normal tympanic membrane and therefore present a very low risk of extrusion (Fig. 3.13).

> ***Clinical Application***
> Usually the handle lies midway between the anterior and posterior borders of the tympanic membrane, but may occupy a more anterior position. Surgical procedures on the tympanic membrane are especially difficult when an anteriorly located malleus is associated with bulging of the anterior canal wall. Rarely, the malleus handle is fixed to the posterior tympanic wall by a bony bar, a *malleus bar* [29, 30, 32].

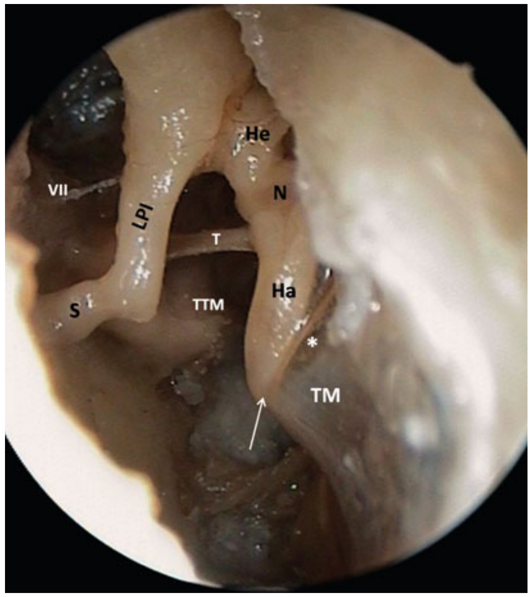

Fig. 3.13 Posterior view of a right middle ear cavity. The inferior end of the handle (*Ha*) is firmly attached to the tympanic membrane (*TM*) forming the umbo (*white arrow*). Relation of the middle part of the handle and the lamina propria of the tympanic membrane (*black arrow*). P*lica mallearis* (*). *LPI* long process of the incus, *S* stapes, *N* neck of the malleus, *He* head of the malleus, *VII* facial nerve, *TTM* tensor tympani muscle, *T* tensor tympani tendon

Malleus Processes

The malleus has two processes located at the union of the neck and the malleus handle.

- *The lateral process*
  The lateral process is a small conical eminence of 1 mm. It protrudes laterally to the side of the tympanic membrane and gives attachment to the anterior and posterior tympano-malleal ligaments.
- The anterior process (*processus gracilis*)
  The anterior process is a 3–5-mm long thin bony spine which extends from the neck of the malleus into the petrotympanic Glaserian fissure. On its medial aspect runs the chorda tympani nerve to enter anteriorly the petrotympanic fissure. It gives origin to the anterior malleal ligament, which also traverses the petrotympanic fissure to reach the angular spine of the sphenoid bone. An extremely long anterior process extending into the petrotympanic fissure may hinder the free movement of the malleus, with little impact on hearing, about 5-dB hearing loss.

Malleus Ligaments (Fig. 3.14)

The malleus is stabilized in place by five ligaments, one articulation, one tendon, and the tympanic membrane. Three of the five ligaments are outside the axis of rotation: they offer only a suspensory function. They are:

- *The anterior suspensory ligament* (*ASL*) lies superior to the anterior malleal ligament and attaches the head of the malleus to the anterior wall of the epitympanum.
- *The lateral suspensory ligament* (*LSL*) attaches the neck of the malleus to the bony margins of the tympanic notch (the notch of Rivinus) and forms the superior wall of the Prussak's space.
- *The superior suspensory ligament* (*SSL*) bridges the gap between the head of the malleus and the tegmen of the epitympanum and carries the superior tympanic artery branch of the middle meningeal artery.
  These three ligaments apparently do not interfere with sound transmission because of the small movements of the ossicles at their points of attachment. The suspensory ligaments do not play a role in middle ear mechanics.
- *The anterior malleal ligament* (*AML*) together with the posterior incudal ligament serves to establish the axis of rotation of the ossicles. The anterior malleal ligament must not be

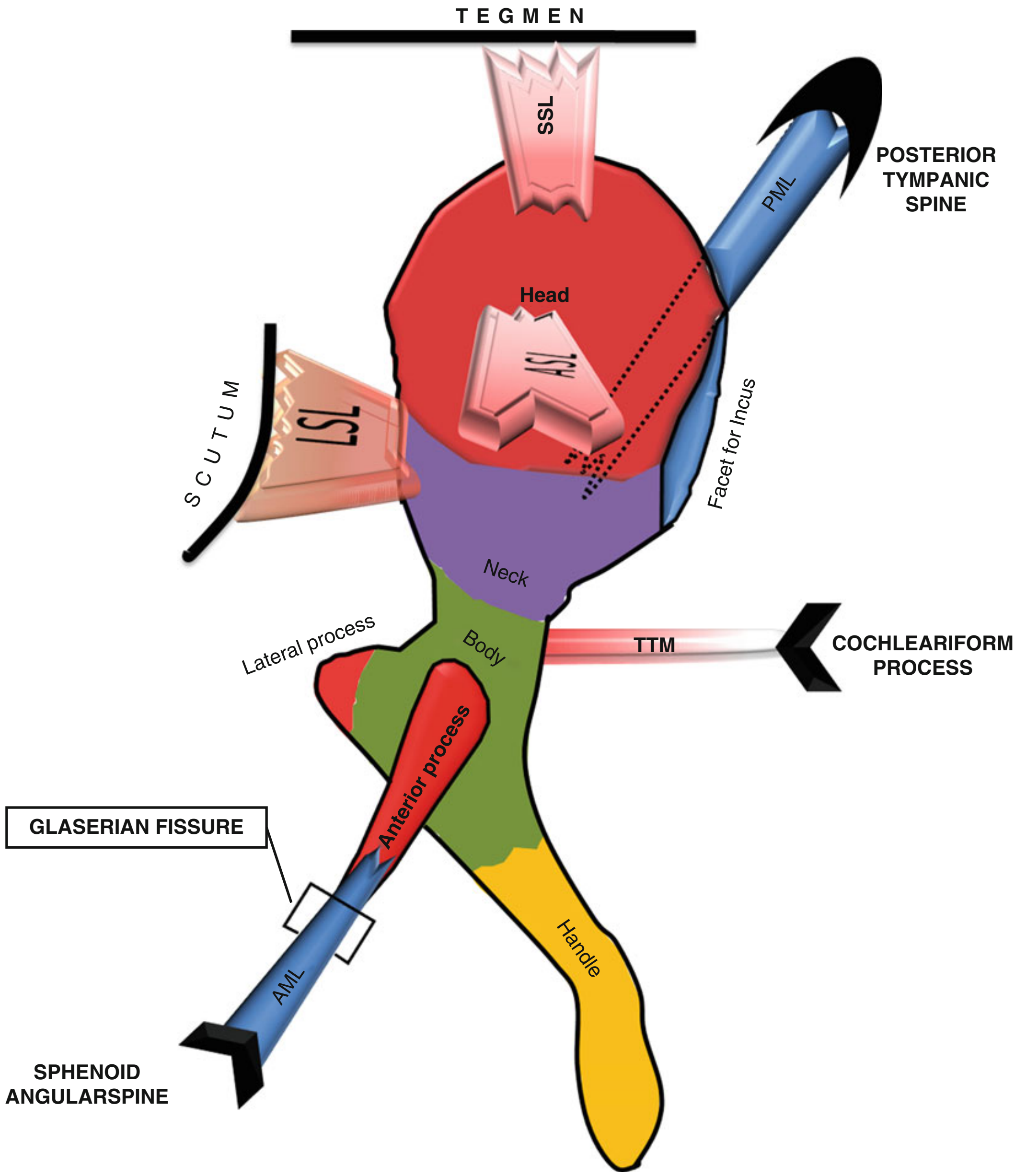

Fig. 3.14 Schema showing malleal ligaments and tensor tympani muscle tendon (*TTM*). *SSL* superior suspensory ligament, *ASL* anterior suspensory ligament, *LSL* lateral suspensory ligament, *AML* anterior malleal ligament, *PML* posterior malleal ligament. The AML and PML in *blue color* represent the axis of rotation of the malleus

confused with the anterior suspensory ligament of the malleus. The anterior malleal ligament extends from the angular spine of the sphenoid bone, passes through the petrotympanic fissure, accompanied by the anterior tympanic artery, and inserts on the neck of the malleus at the base of the anterior process of the malleus.

- *The posterior malleal ligament* (*PML*) extends from the neck of the malleus to the posterior tympanic spine.

3.1.2.2 The Incus (Fig. 3.15)

The incus measures about 5 by 7 mm and weighs about 30 mg. It has a trapezoidal body, short process, long process, and a rounded *lenticular process*.

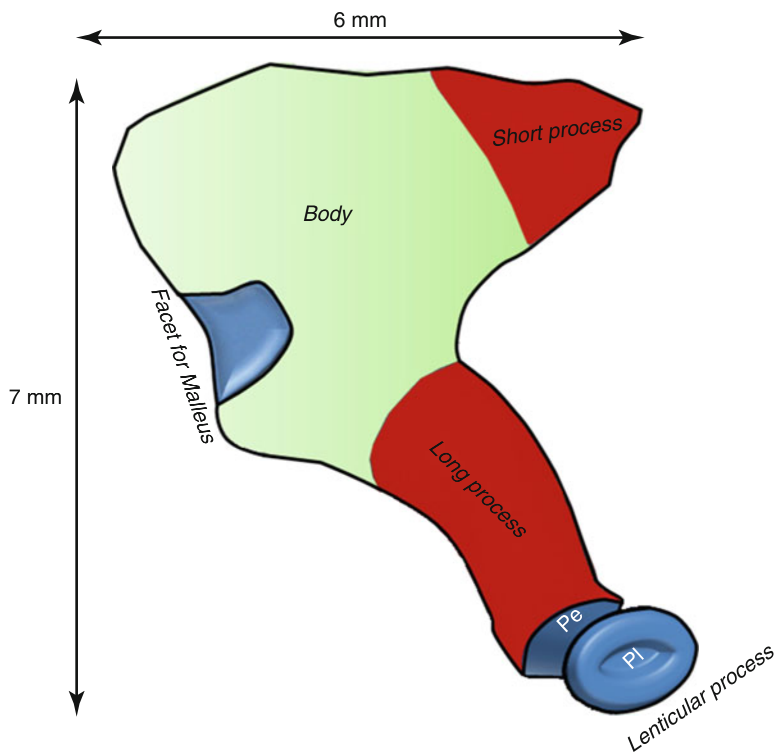

Fig. 3.15 Schematic drawing of the incus. *Pe* lenticular process pedicle, *Pl* lenticular process plate

Body of the Incus

The body of the incus is flat. Its anterior surface houses an elliptical articular surface to receive the head of the malleus. Both body of the incus and the head of the malleus are situated in the attic. Two spines arise from the lower posterior part of the body, the long and short processes. These two processes diverge from each other in a right angle:

Short Process of the Incus

The short process of the incus extends posteriorly from the body as a thick and triangular process; its major axis is horizontal. Its dorsal end lies on the incudal fossa situated in the floor of the aditus ad antrum.

Long Process of the Incus

The long process or vertical process of the incus follows a direction similar to the handle of the malleus but in a more posterior and medial plane. Its caudal end forms a hook at a right angle to end up with the lenticular process. The horizontal, cross-sectional configuration of the long process of the incus is circular, in contrary to the ovoid shape of the manubrium of the malleus. The mean diameter of the distal extremity of the long process is 0.63 mm [34].

Because of its terminal and poor vascularization, the long process of the incus is highly susceptible to osteitic resorption secondary to several conditions such adhesive otitis media or extremely tightened stapes prosthesis.

Lenticular Process

The lenticular process connects the long process of the incus to the head of the stapes. The lenticular process consists of a narrow *bony pedicle* and a flattened *distal plate.*

The bony pedicle is surrounded by a joint capsule of thick fibers. The mean diameter of the bony pedicle (0.26 mm) is less than half of the mean diameter of the distal long process (0.63 mm) and less than half of the mean diameter of the distal plate (0.71 mm) [34]. The bony pedicle is flexible and plays a role in the piston-like transmission of the incus movement to the stapes, lateral to medial, by the rotation movement of the incus. All other movements are reduced by the bending of this pedicle before reaching the stapes [35].

Clinical Application

Chronic otitis media (COM) is the most common cause of ossicular chain necrosis and concerns most frequently the long process of the incus (Fig. 3.16). It is the most vulnerable part of the ossicles because of its poor blood supply [36–38]. The malleus and the footplate are more resistant to necrosis [37, 38]. The blood supply of the long process of the incus is provided by end vessels, which descend down along the long process of the incus. Persistent or repeated infection in some cases of COM, or pressure from a severely retracted eardrum in chronic adhesive otitis media, or over-crimped stapes prosthesis, combined with the lack of collateral blood supply, is thought to be the cause of aseptic necrosis [36].

Occasionally dissolution is complete with total incudostapedial separation, but more frequently slow dissolution leads to replacement of the bone by a fibrous tissue [37, 38].

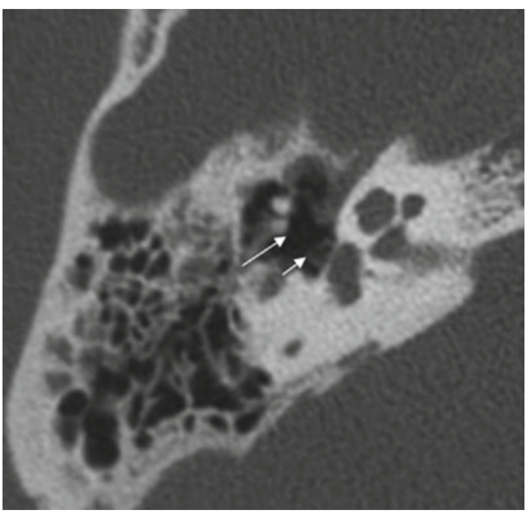

Fig. 3.16 Axial computed tomographic view of a right ear showing a necrosis of the long process secondary to chronic otits media: empty space between the intact stapes (*short arrow*) and the rest of the incus (*long arrow*)

Ligaments of the Incus (Fig. 3.17)

The incus has the least number of ligaments and is therefore more susceptible to traumatic dislocation compared to other ossicles. Two ligaments stabilize the incus in place:

- *The posterior incudal ligament* (*PIL*) secures the short process in the incudal fossa.
- *The superior incudal ligament* (*SIL*) descends from the tegmen to the incus body. It could be reduced to a single mucosal fold only.

3.1.2.3 The Stapes (Fig. 3.18)

The stapes is the smallest bone of the human body; it is 3.25 mm high and 1.4 mm wide with a weight of 3–4 mg [39]. It is situated in an almost horizontal plane between the lenticular process and the oval window and below the facial nerve canal. The stapes consists of a round head, a short neck, anterior and posterior crura, and an oval footplate.

The Head

The head is the most lateral part of the stapes. It is cylindrical or discoid in shape and bears laterally a glenoid cavity, the fovea, which corresponds to the articular surface of the lenticular process. Its medial end is constricted, forming the neck. Its anterior edge is smooth. Its posterior edge presents a small rough surface for the insertion of the stapedial muscle tendon.

Surgical Implication

Partial ossicular replacement requires implants (PORP) which fit onto the head of the stapes alone, thus necessitating the knowledge of the dimensions of the stapedial head. The width of the stapes head is about 1–1.5 mm [39].

The Crura

The stapes presents two unequal crura: the posterior and the anterior crura; the posterior crus is longer, thicker, and more curved than the anterior one. The relative thickness, the curvature, and the excavation of the crura vary among individuals. The area delimited by the concave arches of the crura is the *obturator foramen*, sometimes bridged by a veil of mucous membrane. The two crura could be very close to the walls of the niche of the oval window.

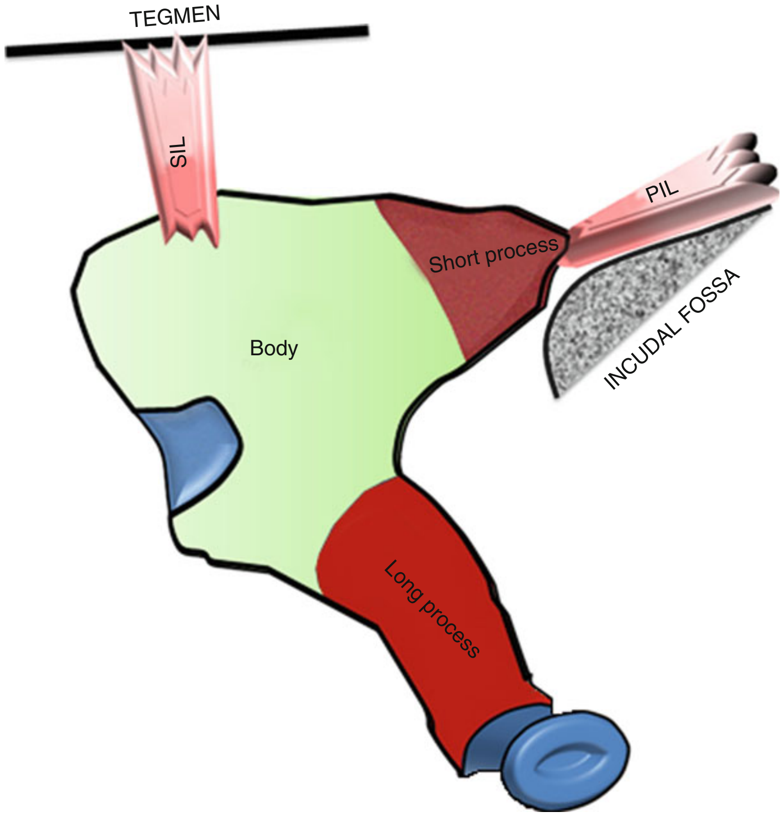

Fig. 3.17 Schematic drawing of incudal ligaments. *SIL* superior incudal ligament, *PIL* posterior incudal ligament

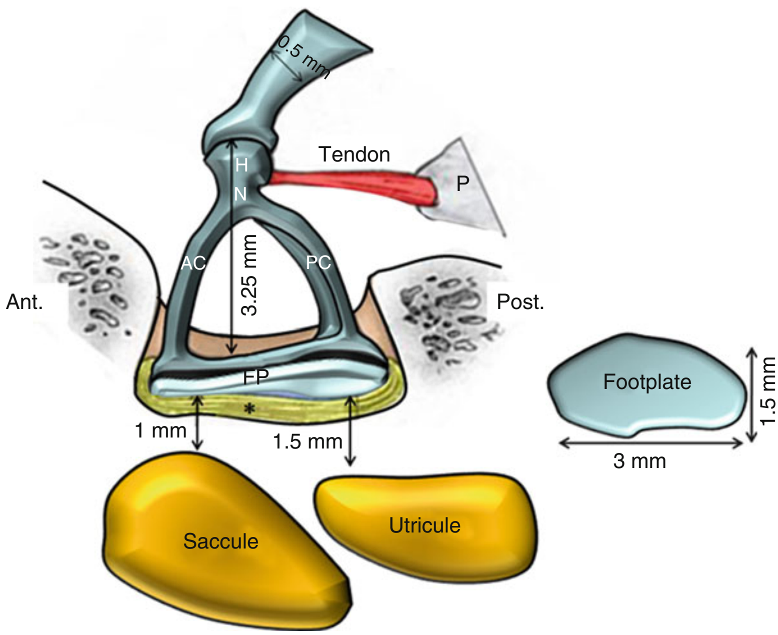

Fig. 3.18 Schematic drawing of stapes in the oval window niche and its relationship with the underlying saccule and utricle. Stapedial tendon in red. (*) annular ligament, *P* pyramidal eminence, *H* head, *N* neck, *AC* anterior crus, *PC* posterior crus, *FP* footplate

Surgical Implication

During stapedectomy, it is safer to cut the posterior crus of the stapes rather than to fracture it because the later carries a risk of footplate luxation. This is not the case of the anterior crus which is thinner and can be safely fractured.

The Footplate

The footplate is a thin and oval lamella of bone. Its length is about 3 mm; its width is about 1.5 mm; its thickness is about 0.25 mm [40].

The lateral or tympanic surface of the footplate is covered by mucoperiosteum of the middle ear; it is slightly twisted around its polar axis so that the anterior half looks to the floor of the vestibule and the posterior part looks up to the tegmen. The distance from the long process of the incus to the tympanic surface of the footplate is about 4 mm.

The medial or vestibular surface of the footplate is flat; it is lined by the endosteum of the otic capsule and is in close relation with the saccule and utricle. The saccule is 1 mm deep from the anterior part of the vestibular surface of the footplate, and the utricle is at 1.5 mm deep from its posterior part (Fig. 3.18).

Surgical Implication

The stapedial footplate forms a link between the middle and the inner ear. During reconstructive ear surgery, total ossicular replacement prostheses (TORP) may be used to bridge the gap between the tympanic membrane or the malleus and the stapes footplate. The positioning of the TORP shaft on the footplate has a significant bearing on the eventual outcome of the surgery. From an anatomic point of view, anterior footplate location is preferable because the annular ligament is thinner and wider and thus the footplate is more mobile [41].

Annular Ligament

The annular ligament of the stapes is a ring of elastic fibers that attaches the cartilaginous margin of the footplate to the border of the oval window. The fibers of the annular ligament fuse with the periosteum and endosteum all around the oval window borders. The ligament is thinner anteriorly than posteriorly and more mobile anteriorly [41]. Because of the differential thickness between its anterior and posterior aspects, the annular ligament works as a hinge-like attachment of the stapes into the oval window. This type of attachment allows a rocking oscillation of the footplate in the oval window, which is the essential movement for the transmission of high-frequency sounds. Low-frequency sound transmission depends on piston-like movements of the stapes that necessitates elasticity of the whole annular ligament.

Clinical Application

Otosclerotic involvement of the anterior aspect of the annular ligament hinders the piston-like movement of the stapes rather than the rocking movement. This explains why in early stages of otosclerosis, there is only a low-frequency conductive hearing loss. In addition, the posterior part of the annular ligament conserves its insulator capacity; this explains the on/off stapedial reflex phenomena found in early otosclerosis.

3.2 Middle Ear Articulations

3.2.1 Embryology of Middle Ear Articulations

3.2.1.1 The Incudostapedial Joint

At the seventh to eighth week of gestation, the outlines of the lenticular process and of the stapes head are separated by a condensed mesenchyme interzone. After the 12th week of gestation, cavitation phenomena begin in this interzone. The different cavitations consolidate then to form the incudostapedial joint at the 16th week of gestation.

The primordium of the capsular ligament develops from the surface of the interzone by a condensation of the surrounding mesenchyme which forms a layer that is continued with the perichondrium of the ossicles [42].

3.2.1.2 The Incudomalleal Joint

The incus and malleus, previously one collection of mesenchyme, separate with formation of the incudomalleal joint at eighth to ninth week by the same mechanism as the incudostapedial joint (Fig. 3.7). Failure of this step results in a fused malleus-incus mass that is commonly found in patients with aural atresia.

3.2.2 Anatomy of Middle Ear Articulations

Middle ear articulation surfaces are lined by cartilage. Each articulation has a true capsule originating from the periosteum of the linked bones and lined by a synovial membrane.

3.2.2.1 The Incudomalleal Articulation

The head of the malleus articulates with the body of the incus in a diarthrodial joint in the attic (Fig. 3.19). The joint cavity is incompletely divided into two compartments by a wedge-shaped articular disk or meniscus. The capsule is trilaminar with (1) the synovial membrane lining the cavity, (2) the mucous membrane of the middle ear, and (3) an intervening fibrous layer.

Partial subluxation of the incudomalleal joint, happening during middle ear surgery, usually heals without sequela. Complete luxation will not heal and ossicular reconstruction is recommended.

3.2.2.2 The Incudostapedial Articulation (Figs. 3.19 and 3.20)

The incudostapedial articulation is a synovial diarthrodial articulation; it joins the convex

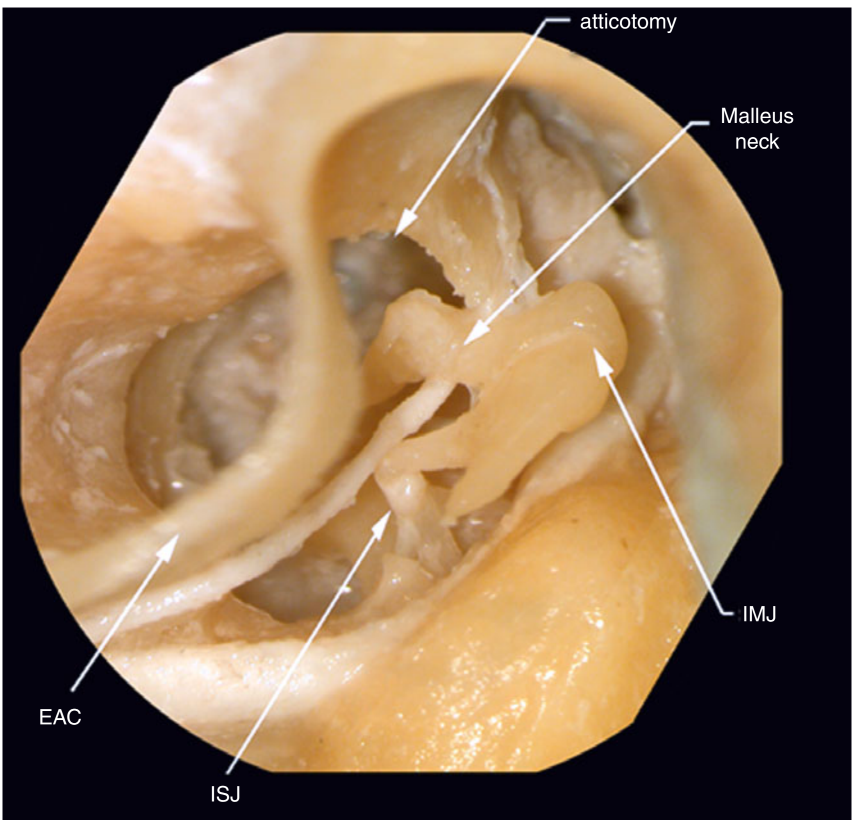

Fig. 3.19 Left middle ear after large mastoidectomy and anterior and posterior tympanotomies, showing both incudomalleal joint (*IMJ*) and incudostapedial joint (*ISJ*). *EAC* external auditory canal

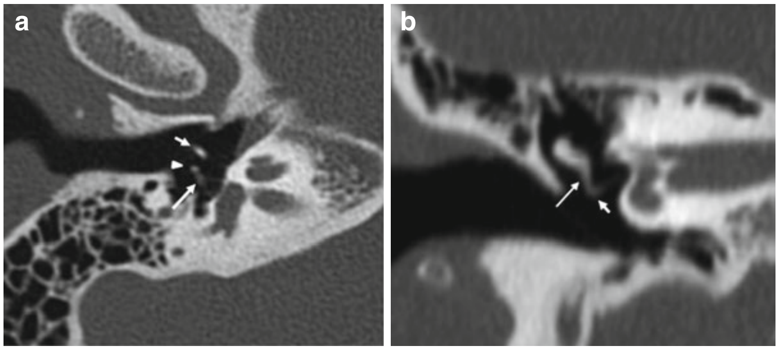

Fig. 3.20 Computed tomography of the normal appearance of the incudomalleal joint. (**a**) In the transversal view: continuity between the long process of the incus (*arrowhead*) and the head of the stapes (*long arrow*). malleus handle (*short arrow*). (**b**) Coronal reconstruction: continuity between the long process of the incus (*long arrow*) and the head of the stapes (*short arrow*)

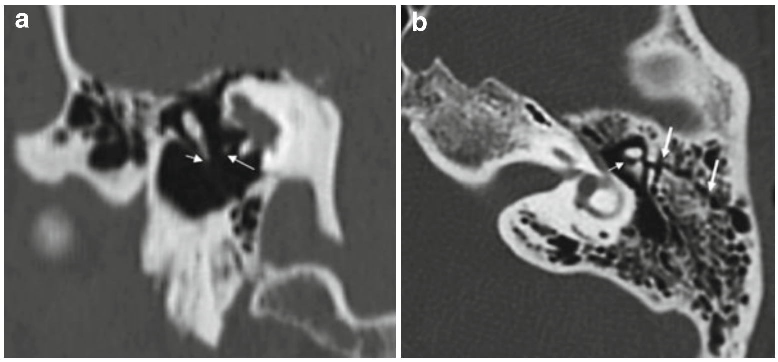

Fig. 3.21 Traumatic lesions of the ossicular chain. (**a**) The long process of the incus (*long arrow*) is displaced anteriorly to the stapes suprastructure (*short arrow*) secondary to traumatic incudostapedial luxation. (**b**) Horizontal temporal bone fracture (*long arrows*) with incudomalleal joint interruption (*short arrow*) and luxation of malleus head anteriorly

lenticular process of the incus and the concave surface of the head of the stapes. An interarticular cartilage is not usually present. This joint is fragile.

> ***Clinical Implication***
> **Ossicular Chain Trauma** (Fig. 3.21)
> - Incudostapedial joint separation is the most common ossicular injury in temporal bone trauma.
> - Incudomalleal dislocation is the second most common ossicular injury in temporal bone trauma.
> - Fracture of the stapes superstructure is the third most frequent ossicular injury in temporal bone trauma.
> - Fracture of the malleus is the least common

3.3 Middle Ear Muscles

3.3.1 Embryology of Middle Ear Muscles

The embryological origin of middle ear muscles follows the same patterns as the other muscles in the craniofacial area [43]. They develop from the paraxial mesoderm (mesenchyme) that migrates into the branchial arches.

3.3.1.1 Tensor Tympani Muscle

The tensor tympani muscle develops from the mesoderm of the first branchial arch. It is innervated by a branch from the trigeminal nerve, the nerve of the first branchial arch.

3.3.1.2 Stapedial Muscle

The stapedial muscle starts to develop, at the ninth week, as a condensation of blastema cells in the mesenchyme of the interhyale (which connects the stapedial anlage to the second branchial arch) close to the facial nerve. The internal segment of the interhyale gives rise to the tendon of the stapedial muscle. Moreover, the interhyale contributes to the development of the facial nerve canal, as well as the pyramidal eminence [44] (see Fig. 2.14). The bone of the pyramidal eminence housing the muscle derives from the precartilaginous cells of the second branchial arch [45].

3.3.2 Anatomy of the Middle Ear Muscles

3.3.2.1 The Tensor Tympani Muscle (TTM)

The TTM is fusiform in shape and is around 20 mm in length. The intratympanic portion of this muscle is 2.5 mm long. It arises from the cartilage of the Eustachian tube, from the walls of its enveloping bony semicanal, and from the adjacent portion of the greater wing of the sphenoid bone (Fig. 3.22). The fibers converge to form a central fibrous core which, proceeding posteriorly, forms the tendon of the muscle. The most medial fibers of the tendon attach to the cochleariform process, at which point the main body of the tendon turns laterally into the cavity to attach to the medial surface of the junction of the neck and the manubrium of the malleus (Fig. 3.23). It is innervated by the trigeminal nerve, via the nerve to the medial pterygoid muscle.

The function of the TTM is to draw the manubrium medially, thus tensing the tympanic membrane and damping the movements of the ossicular chain [46, 47].

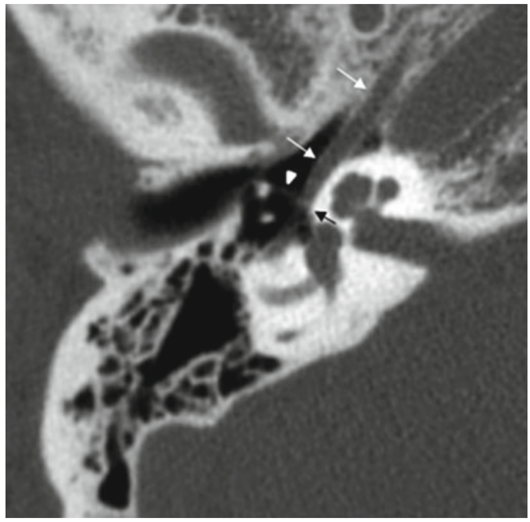

Fig. 3.22 Transversal computed tomography of a right ear, showing the tensor tympani muscle in its bony semicanal (*white arrows*), reaching the cochleariform process (*black arrow*), where its tendon (*white arrowhead*) turns laterally to insert on the neck of the malleus

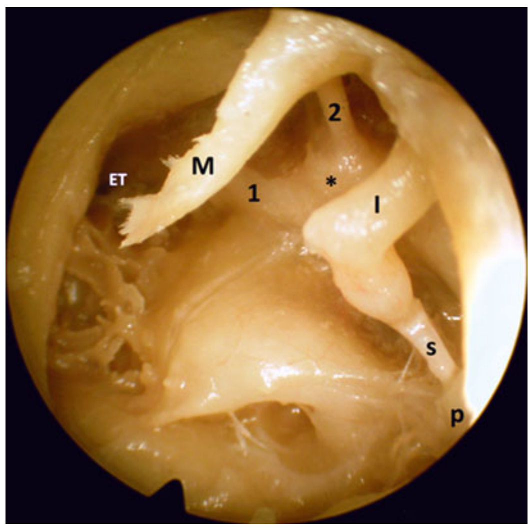

Fig. 3.23 Endoscopic view of a left middle ear showing the stapedial tendon (*s*) rising from the pyramidal process (*p*), the tensor tympani muscle (*1*) turning around the cochleariform process (*) to give the tensor tympani tendon (*2*) that inserts on the neck of malleus (*M*); *I* incus, *ET* Eustachian tube

> In normal conditions, the pull of the TTM is opposed by the elasticity of the pars tensa of the tympanic membrane. In a long-standing large perforation of the tympanic membrane, the unopposed pull of the TTM causes a medial displacement of the inferior end of the manubrium (malleus handle medialization).

3.3.2.2 Stapedial Muscle

The stapedial muscle is the smallest skeletal muscle in the body measuring only 1 mm. It lies in a bony cavity in the posterior wall of the tympanic cavity to emerge from the pyramidal eminence. The fibers of this muscle converge into a tendon which variably attaches to the head and/or posterior crus of the stapes (Fig. 3.23) [46, 47].

The stapedial muscle is innervated by the stapedial branch of the facial nerve. Its contraction provokes a tilting of the stapes by moving the anterior border of the footplate laterally and the posterior border medially. This tilting of the stapes stretches the annular ligament, thus fixing the footplate and damping its movements. It protects the inner ear from damage caused by loud noise. Lack of action of this muscle from nerve section or facial nerve palsy induces hyperacusis [46, 47].

Surgical Application
During microsurgical dissection around the stapes, for instance, a removal of the cholesteatoma matrix from the stapes, it is advisable to work parallel to the plane of the stapedial tendon, from posterior to anterior, so that the tendon prevents luxation of the stapes.

3.4 Middle Ear Nerves

The middle ear receives and transmits branches from the facial nerve, the glossopharyngeal nerve, and the sympathetic carotid plexus. The branches of the glossopharyngeal nerve and sympathetic carotid plexus contribute to the formation of an important middle ear neural plexus, the tympanic plexus.

3.4.1 Facial Nerve Branches

One branch of the facial nerve, the chorda tympani, passes through the middle ear cavity in its route to the infratemporal fossa. This is a sensory and secretory-motor branch of the facial nerve. It enters the middle ear cavity through the *iter chordae posterior*. It runs across the medial surface of the tympanic membrane lateral to the long process of the incus and passes medial to the upper portion of the handle of the malleus above the tendon of the TTM. It leaves the middle ear through the canal of Huguier placed within the petrotympanic fissure. It joins the lingual branch of the mandibular nerve in the infratemporal fossa (see Sect. 6.2.3.7).

3.4.2 Tympanic Plexus

The tympanic plexus consists of a network of nerves lodged in small grooves on the cochlear promontory of the medial wall of the middle ear. It is formed by the tympanic nerve and two or three filaments from the carotid plexus.

The tympanic (Jacobson's) nerve, carrying parasympathetic fiber, originates from the inferior ganglion of the glossopharyngeal nerve. After entering the tympanic cavity through the medial hypotympanic fissure, it branches repeatedly within shallow bony channels overlying the promontory to form the tympanic plexus.

Two or three filaments, the caroticotympanic nerves, coming from the carotid plexus and carrying sympathetic fibers join the tympanic plexus on the promontory (Fig. 3.24).

The tympanic plexus gives off:

- The lesser petrosal nerve
- Branches to the tympanic cavity mucosa

3.4.2.1 The Lesser Superficial Petrosal Nerve

The lesser superficial petrosal nerve originates from the tympanic plexus at the level of the cochleariform process and leaves the middle ear through a small canal below the tensor tympani muscle (Fig. 3.24). It passes through the temporal bone to emerge on the floor of the middle cranial fossa lateral to the greater superficial petrosal nerve. It exits the middle cranial fossa through the foramen ovale together with the mandibular nerve to join the otic ganglion in the infratemporal fossa. From there, it passes in the auriculotemporal nerve to reach the parotid gland.

The lesser petrosal nerve carries preganglionic parasympathetic fibers of the glossopharyngeal

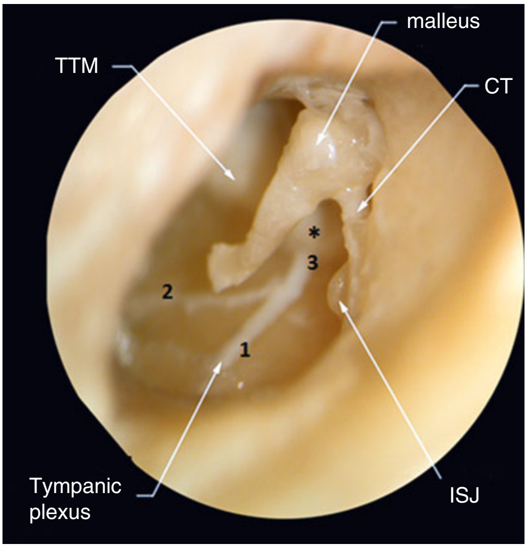

Fig. 3.24 Endoscopic view of a left middle ear showing the Jacobson nerve (*1*), the caroticotympanic nerve (*2*), and the lesser petrosal superficial nerve (*3*) passing outside the middle ear below the cochleariform process (*). *ISJ* incudostapedial joint, *CT* chorda tympani, *TTM* tensor tympani muscle

nerve (IX) to the parotid gland via the otic ganglion. After synapsing in the otic ganglion, postganglionic fibers supply secretory fibers to the parotid gland by the way of the auriculotemporal nerve.

Clinical Application
Tympanic paragangliomas are mostly small-sized tumors originating from the tympanic plexus of the middle ear.

Clinically, these tumors are symptomatic as pulsatile tinnitus and conductive hearing loss. Tympanic paragangliomas are diagnosed by careful otoscopic examination; they appear as a reddish retrotympanic mass behind a translucent tympanic membrane.

Frequently, it is impossible to visualize the entire tumor clinically; thus, computed tomography (CT) or magnetic resonance imaging (MRI) scans are diagnostic (Fig. 3.25).

3.5 Middle Ear Vessels

3.5.1 Embryology of Middle Ear Vessels (Fig. 3.26)

During the 4th week of gestation, the first and second aortic arches begin to involute and they leave behind the mandibular and hyoid arteries, respectively. At the same time the third arch artery becomes the internal carotid artery.

During the 4th to 5th week of gestation, the ventral pharyngeal artery arises from the aortic sac. This artery supplies the bulk of the first two branchial bars and subsequently is involved in the formation of the stapedial and external carotid arteries.

During the 6th week, the stapedial artery arises as a small offshoot of the hyoid artery near its origin from the internal carotid artery. It extends cranially and passes through the stapes blastema to enter the mandibular bar (Fig. 3.3). The stapedial artery divides into two arteries: the maxillomandibular artery and the supraorbital artery (which supplies the primitive orbit). The maxillomandibular division of the stapedial artery joins the distal part of the ventral pharyngeal artery, the future external carotid artery [48].

Over the 7th week, the two major divisions of the stapedial artery are annexed by the internal maxillary artery (from the external carotid artery) and the ophthalmic artery, respectively. The trunk of the maxillomandibular division becomes the stem of the middle meningeal artery. As the stapedial artery withers proximal to the stapes, its more distal stem becomes the superior tympanic branch of the adult middle meningeal artery. The hyoid artery, which gave rise to the stapedial artery, involutes to become a caroticotympanic branch of the internal carotid artery [48].

Persistent Stapedial Artery
Persistent stapedial artery is a rare vascular anomaly of the middle ear. The reported prevalence is of 0.5 % in cadaveric studies [49] and less than the 0.02–0.05 % in

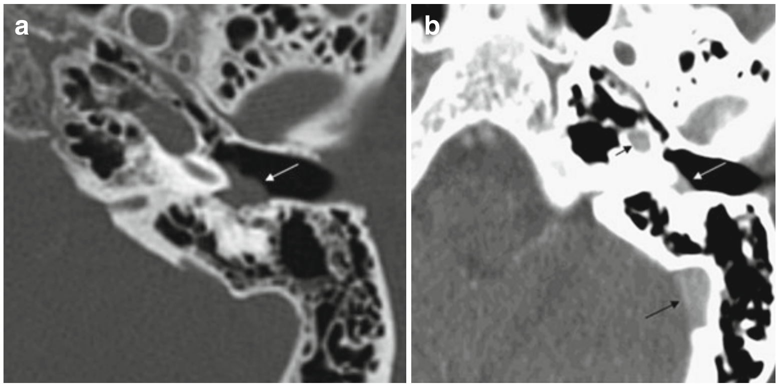

Fig. 3.25 (**a**) Transversal computed tomography with an image of condensation (*arrow*) filling the hypotympanum and covering the inferior half of the promontory. (**b**) After i.v. injection of iodine contrast, this lesion shows the same contrast uptake (*white arrow*) as the sigmoid sinus (*long black arrow*) and the internal carotid artery (*short black arrow*), confirming a hypervascular lesion

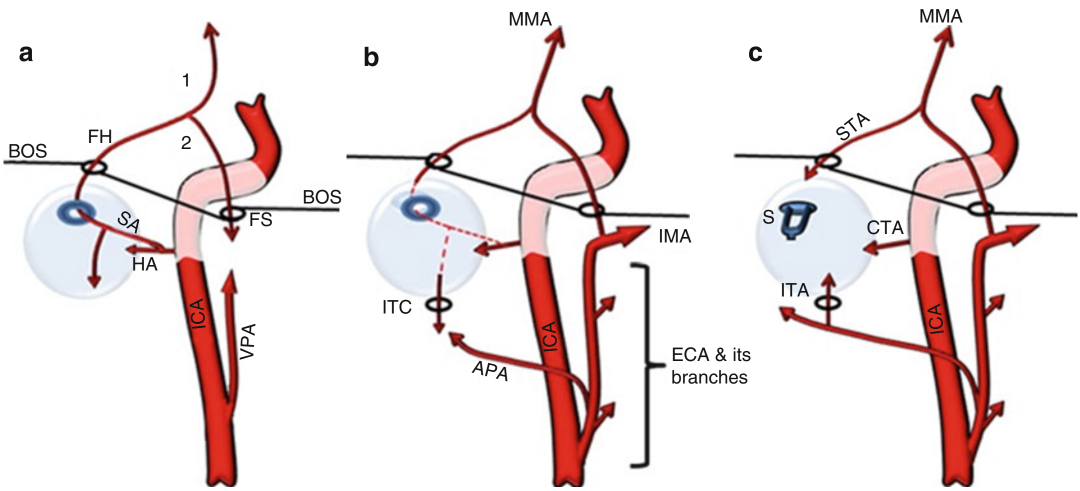

Fig. 3.26 Schema illustrating normal development of middle ear vessels. (**a**) Approximately 6 weeks. (**b**) Approximately 8 weeks. (**c**) Adult configuration. *BOS* base of skull, *FH* facial hiatus, *SA* stapedial artery; blue disk: otic capsule; *HA* hyoid artery, *ICA* internal carotid artery, *FS* foramen spinosum, *VPA* ventral pharyngeal artery, *1* supraorbital artery, *2* maxillomandibular artery, *APA* ascending pharyngeal artery, *ITC* inferior tympanic canaliculus, *MMA* middle meningeal artery, *IMA* internal maxillary artery, *ECA* external carotid artery, *ITA* inferior tympanic artery, *CTA* caroticotympanic artery, *STA* superior tympanic artery, *S* stapes

surgical series [50, 51]. Usually, it is asymptomatic; sometimes, it may cause pulsatile tinnitus and hearing loss [52].

Normally, the stapedial artery atrophies by 3 months of fetal development; however, in very rare cases it may persist as a 1.5- to 2.0-mm branch of the petrous internal carotid artery [52].

A persistent stapedial artery arises from the petrous part of the internal carotid artery, enters the hypotympanum through the medial hypotympanic fissure, crosses the cochlear promontory, and passes through the obturator foramen of the stapes. It enters the Fallopian canal behind the cochleariform process and travels anteriorly with the greater superficial petrosal nerve to enter the middle cranial fossa through the facial hiatus where it ends up as the middle meningeal artery. In case of persistent stapedial artery, the foramen spinosum will be absent [53] (Fig. 3.27).

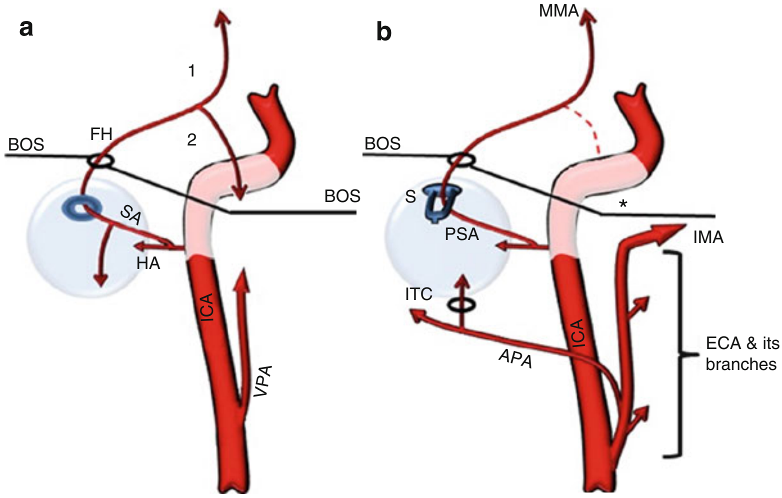

Fig. 3.27 Schema illustrating the development of persistent stapedial artery (PSA). (**a**) Embryonic phase: failure of development of foramen spinosum (*) and communication between maxillomandibular branch (*2*) of stapedial artery (*SA*) and ventral pharyngeal artery (*VPA*). (**b**) Adult configuration of persistent stapedial artery. *BOS* base of skull, *FH* facial hiatus, *SA* stapedial artery, *HA* hyoid artery, *ICA* internal carotid artery, *APA* ascending pharyngeal artery, *ITC* inferior tympanic canaliculus, *MMA* middle meningeal artery, *IMA* internal maxillary artery, *ECA* external carotid artery, *S* stapes

Aberrant Internal Carotid Artery

An aberrant internal carotid artery (ICA) is a variant of the ICA that passes through the middle ear; it appears as a white mass in the anteroinferior quadrant of the middle ear. Otologists should be aware of the possibility of an aberrant ICA when the patient presents with a retrotympanic mass. If mistaken for a tumor and biopsied, the results can be disastrous. Radiological investigation is required to make the differential diagnosis. A temporal bone CT scan in patients with carotid agenesis shows the complete absence of carotid bony canal (see Sect. 2.4.1.1).

The most accepted theory of the etiology of an aberrant internal carotid artery is the agenesis of the vertical internal carotid artery with compensatory vascular communication branches of the developing external carotid artery system. The ascending pharyngeal artery gives rise to the inferior tympanic artery, which is the aberrant internal carotid artery; it then enters the middle ear through the inferior tympanic canaliculus and after passing through the middle ear, it joins the horizontal petrous carotid artery anteriorly (Fig. 3.28).

The presenting signs and symptoms of an aberrant internal carotid artery include pulsatile tinnitus, otalgia, aural fullness, vertigo, and hearing loss [53, 54].

3.5.2 Anatomy of Middle Ear Vessels (Fig. 3.29)

The blood supply of the middle ear and mastoid cavity originates from the internal and external carotid arteries. We recognize the following important feeding arteries of the middle ear:

3.5.2.1 The Anterior Tympanic Artery

The anterior tympanic artery is a terminal branch of the internal maxillary artery. It gives rise to an important branch, the ossicular branch, which provides the main blood supply for the malleus

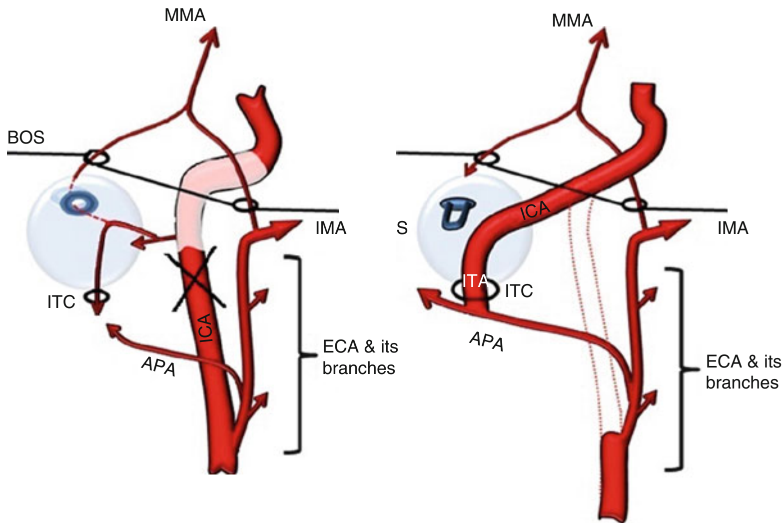

Fig. 3.28 Schema illustrating the development of aberrant internal carotid artery. (**a**) Embryonic phase, failure of development of vertical part of internal carotid artery (*ICA*). (**b**) Adult configuration of aberrant carotid artery. Notice the absence of development of the carotid canal. *BOS* base of skull, *ICA* internal carotid artery, *APA* ascending pharyngeal artery, *ITC* inferior tympanic canaliculus, *MMA* middle meningeal artery, *IMA* internal maxillary artery, *ECA* external carotid artery, *ITA* inferior tympanic artery

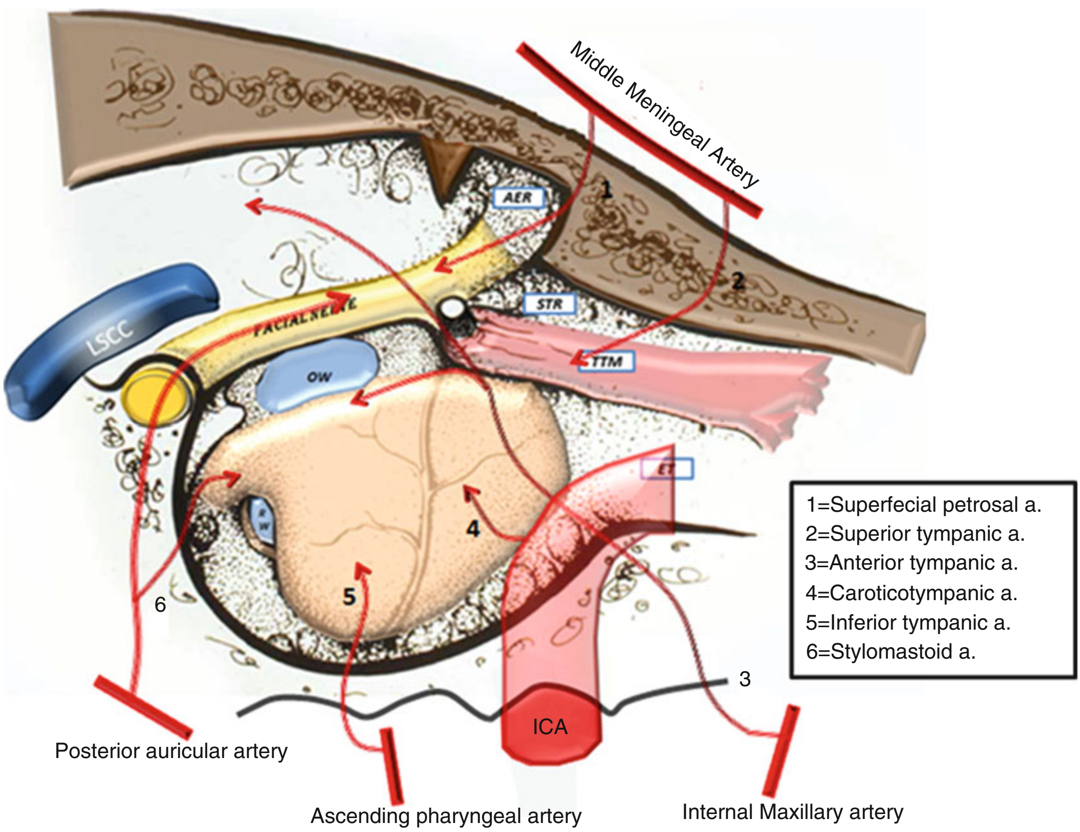

Fig. 3.29 Middle ear vessels. *ICA* internal carotid artery, *LSCC* lateral semicircular canal, *OW* oval window, *RW* round window, *AER* anterior epitympanic recess, *STR* supratubal recess, *TTM* tensor tympani muscle, *ET* Eustachian tube

and incus. The anterior tympanic artery also gives rise to branches that supply the bone and mucosa of the superior and lateral walls of the epitympanic cavity.

3.5.2.2 The Posterior Auricular Artery

The posterior auricular artery is another branch of the internal maxillary artery which provides two branches to the vascular ring of the tympanic membrane. A posterior branch supplies most of the tympanic membrane, whereas the anterior branch supplies a lesser portion of the anterior and inferior region.

3.5.2.3 Branches of the Middle Meningeal Artery

The Superficial Petrosal Artery

The superior petrosal artery enters the middle ear through the facial hiatus; it enters the Fallopian canal and provides blood supply to the geniculate ganglion and the tympanomastoid segment of the facial nerve. Also it provides vascularization of the incudostapedial joint and posterior part of stapes by giving rise to the superior and inferior arteries of the stapedial tendon and posterior crural artery.

The Superior Tympanic Artery

The superior tympanic artery enters the middle ear adjacent to the lesser petrosal nerve. The artery supplies the tensor tympani and a portion of the epitympanic space. It also forms an anastomotic plexus with the inferior tympanic artery, giving rise to the anterior stapedial artery and the anterior crural artery.

3.5.2.4 The Caroticotympanic Arteries

The caroticotympanic arteries are branches of the internal carotid artery that pass through the bony wall of the carotid canal to enter the middle ear cleft and eventually anastomose with branches of the inferior tympanic artery.

3.5.2.5 The Inferior Tympanic Artery

The inferior tympanic artery is a branch of the ascending pharyngeal artery; it enters the middle ear cleft with the tympanic (Jacobson's) nerve. This artery, along with the caroticotympanic arteries, provides the major blood supply to the mucosa of the promontory and the lower tympanic cavity (hypotympanum).

3.6 Middle Ear Mucosal Folds

In this section a detailed description of the mucosal folds of the middle ear will be presented in order to clarify their anatomical organization. A good understanding of the anatomy of these folds and their relationships inside the middle ear cavity is fundamental in the learning process of functional middle ear surgery. These folds delimit different compartments, spaces, and recesses, which will be described in detail in Chap. 4.

3.6.1 Mucosal Folds Development

Between the third and seventh fetal months, the mesenchymal tissue of the middle ear cleft is gradually absorbed. At the same time, the primitive tympanic cavity develops by a growth of an endothelium-lined fluid pouch extending from the Eustachian tube into the cleft. Four primary sacci bud out to define the different middle ear spaces. They are the saccus anticus, the saccus medius, the saccus superior, and the saccus posticus [55]. These sacci or pouches start to enlarge in the middle ear cleft to replace the preexisting mesenchyme. The walls of the pouches become the mucosal lining of middle ear cavity. At the plane of contact between two neighboring pouches, mucosal folds are formed. Between the mucosal layers of the folds, there are remnants of the mesenchyme that will transform into ligaments and blood vessels supplying the "viscera" of the tympanic cavity.

3.6.2 Mucosal Folds Anatomy

Middle ear mucosal folds pass from the walls of the middle ear to its contents and carry ligaments and blood vessels to the ossicles. Despite the fact that these folds may orient the progress of middle ear pathologies, they are not true barriers against their extension (Figs. 3.30, 3.31, and 3.32).

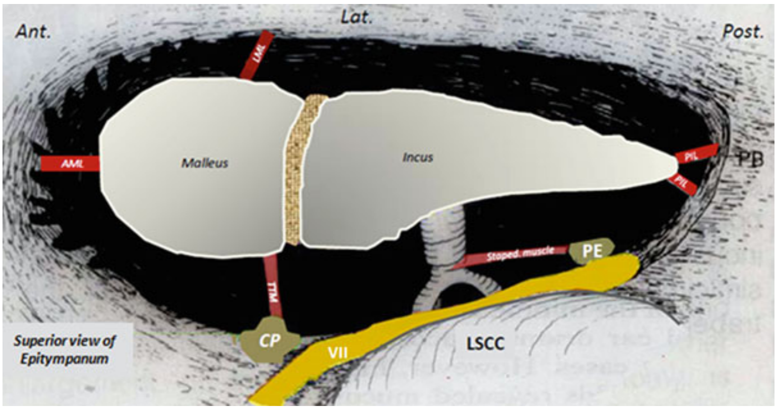

Fig. 3.30 Superior view of a right middle ear, showing middle ear ossicles and their ligaments after removal of all mucosal folds. *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone. (Reproduced from Tos [75, fig. 83].With permission from Thieme publishers)

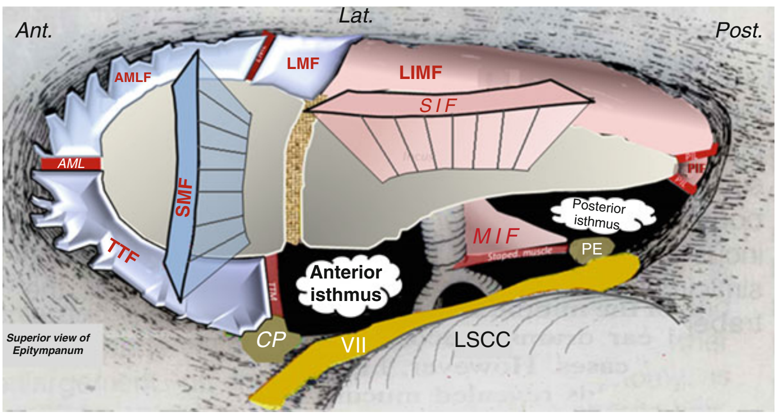

Fig. 3.31 Superior view of a right middle ear showing middle ear ossicles, ligaments, and mucosal folds. *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *TTF* tensor tympani fold, *AMLF* anterior malleal ligamental fold, *LMF* lateral malleal fold, *SMF* superior malleal fold, *MIF* medial incudal fold, *LIMF* lateral incudomalleal fold, *SIF* superior incudal fold, *PIF* posterior incudal fold

There are two different types of mucosal folds: composite folds and duplicate folds.

The composite folds, like the anterior malleal ligamental fold, the lateral malleal ligamental fold, and the posterior incudal fold, have an essential common feature: a combination of a ligament and lining mucosa, with a varying degree of mucosal extension over the ligamental limits and ending with free edges. They are formed when the expanding air sacs meet the preexisting ligament and cover it with mucosal membrane.

The duplicate folds, like the tensor tympani fold and lateral incudomalleal fold, are thin mucosal structures arising from the fusion of two expanding air sac walls in the absence of any interposing structure. Their positions change because the extent of the expansion of each air sac varies in different individuals [56, 57].

3.6.2.1 The Posterior Tympano-Malleal Fold

The posterior tympano-malleal fold, a ligamental fold, inserts on the posterior portion of the neck of the malleus. It involves the upper portion of the handle of the malleus and merges superiorly with the downturn of the anterior portion of the lateral

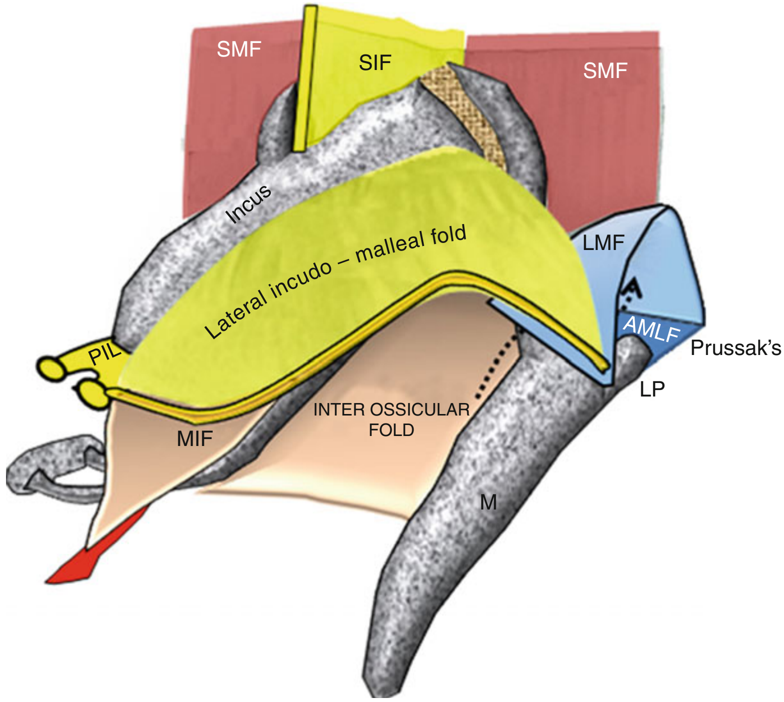

Fig. 3.32 Posterolateral view of a right middle ear showing middle ear ossicles and mucosal folds. *SMF* superior malleal fold, *SIF* superior incudal fold, *LMF* lateral malleal fold, *AMLF* anterior malleal ligamental fold, *MIF* medial incudal fold, *PIL* posterior incudal ligament, *M* malleus, *LP* lateral process of the malleus. The dotted arrow represents the ventilation tract of the Prussak's space

incudomalleal fold. It inserts posteriorly on the posterior tympanic spine and represents the medial wall of the posterior pouch of von Tröltsch. Its medial edge envelops the posterior portion of the chorda tympani [58] (Fig. 3.33).

3.6.2.2 The Anterior Tympano-Malleal Fold

The anterior tympano-malleal fold arises from the anterior portion of the neck of the malleus and inserts anteriorly on the anterior tympanic spine. It forms the medial wall of the anterior pouch of von Tröltsch [58] (Fig. 3.33).

3.6.2.3 The Anterior Malleal Ligamental Fold

The anterior malleal ligamental fold was described by von Tröltsch in 1856. It is part of the tympanic diaphragm. It originates from the neck of the malleus and extends to the anterior attic bony wall. It is reflected from the lateral wall of the middle ear over the anterior process and ligament of the malleus and the anterior part of the chorda tympani. Its low posterior part is broad and represents the anterior limit of Prussak's space [58] (Fig. 3.34).

3.6.2.4 The Lateral Malleal Ligament Fold

The lateral malleal ligament fold is a thick fold; it is first described by Helmholtz in 1868 [59]. This fold starts from the middle portion of the neck of the malleus to develop a fanlike spread before attaching to the attic outer wall; posteriorly, it is confluent with the anterior descending portion of the lateral incudomalleal fold (Fig. 3.35).

This fold is usually complete; it represents the roof of the Prussak's space and the floor of the lateral malleal space. It is considered to be strong to prevent progression of pars flaccida retraction pockets [60].

Defects in this fold, usually in its thin posterior membranous part, are observed in 7 %. In such cases, the defect provides a direct small communication between the upper and lower epitympanic units [56, 57] (see Sect. 4.5).

3.6.2.5 The Superior Malleal Fold

The superior malleal fold extends between the superior surface of the malleus head and the

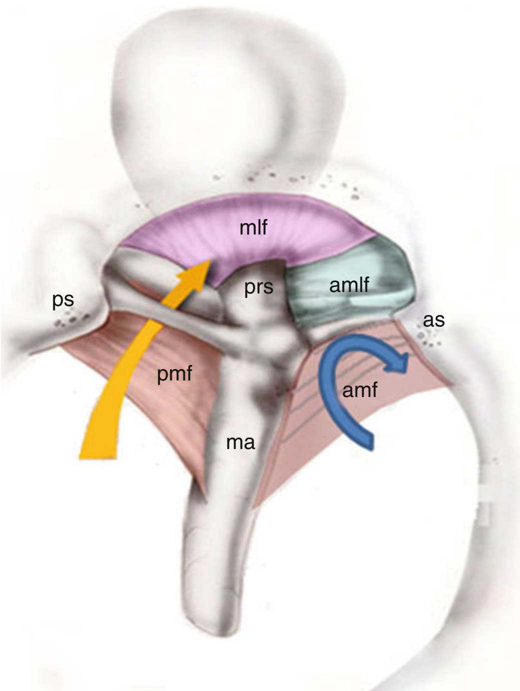

Fig. 3.33 Lateral view of a right middle ear after removal of the tympanic membrane, showing the anterior (*amf*) and the posterior (*pmf*) malleal folds. *as* anterior tympanic spine, *ps* posterior tympanic spine. The *yellow arrow* represents the route of ventilation of the Prussak's space (*prs*). *Blue arrow* represents the complete closure of the Prussak's space floor anteriorly, *mlf* lateral malleal fold, *amlf* anterior malleal ligamental fold, *ma* manubrium. (Reproduced with modification from Marchioni [76, figure 1]. With kind permission from Springer Science and Business Media, Springer and the original publisher)

tegmen in a transversal plane. It contains the superior malleal ligament and divides the attic into anterior and posterior parts (Figs. 3.31 and 3.32).

3.6.2.6 The Lateral Incudomalleal Fold

The lateral incudomalleal fold is a part of the tympanic diaphragm. It lies superiorly in relation to the lateral malleal ligamental fold and separates the upper lateral attic space from the lower lateral attic space. The level of this fold is about 1 mm higher than the roof of the Prussak's space [59]. This fold presents a defect in its anterior portion in about 20 % of cases [57].

The lateral incudomalleal fold has a posterior and a lateral extension: posteriorly, it presents a horizontal extension to insert medially onto the body of the incus and the incudomalleal joint. Laterally, it inserts onto the medial surface of the bony wall of the scutum.

The anterior portion of this fold bends inferiorly towards the neck of the malleus and merges with the posterior portion of the lateral malleal ligament fold, representing the posterior limit of the lateral malleal space (Figs. 3.32 and 3.36).

3.6.2.7 The Medial Incudal Fold

The medial incudal fold is located between the long process of the incus and the tendon of the stapedial muscle as far as the pyramidal eminence (Fig. 3.36).

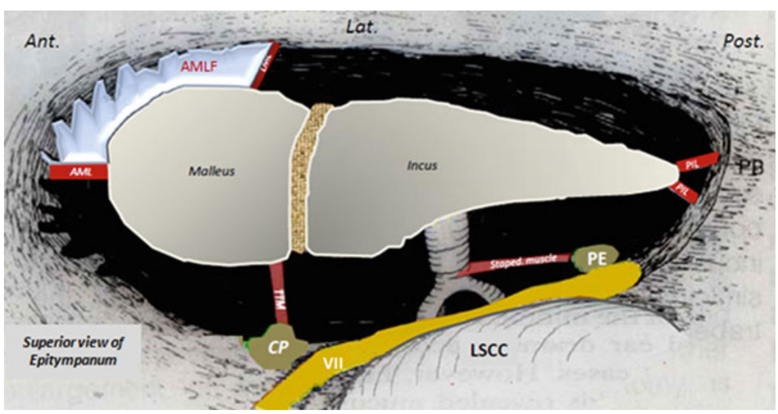

Fig. 3.34 Superior view of a right middle ear showing the anterior malleal ligamental fold (*AMLF*). *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone

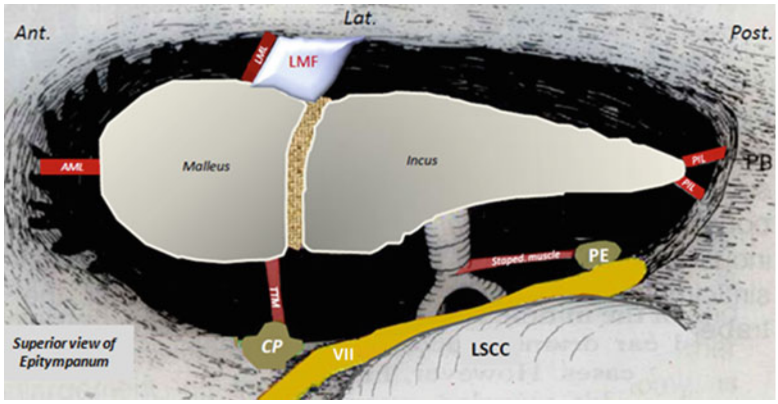

Fig. 3.35 Superior view of a right middle ear showing the lateral malleal fold (*LMF*). *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone

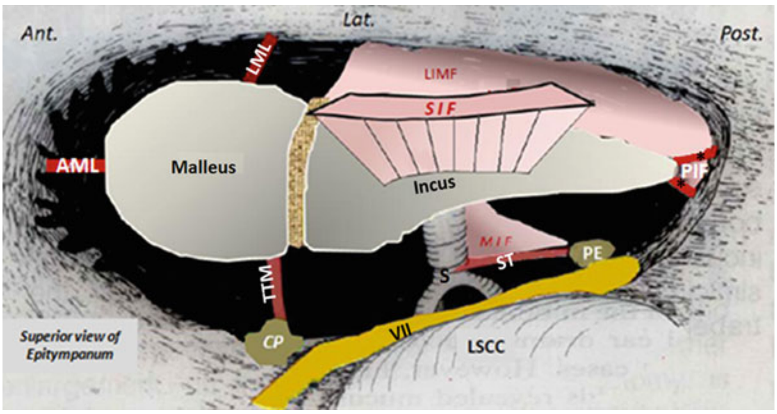

Fig. 3.36 Superior view of the right middle ear, showing the superior incudal fold (SIF), the medial incudal fold (*MIF*), the lateral incudomalleal fold (*LIMF*), and the posterior incudal fold (*PIF*). *TTM* tensor tympani muscle, *ST* stapedial tendon, *AML* anterior malleal ligament, *LML* lateral malleal ligament, *CP* cochleariform process, *VII* facial nerve, * posterior incudal ligament, *S* stapes, *PE* pyramidal eminence, *LSCC* lateral semicircular canal

3.6.2.8 The Superior Incudal Fold (SIF)

The superior incudal fold extends like the superior incudal ligament from the superior surface of the incudal body to the tegmen. It divides the posterior attic into lateral and medial attic (Fig. 3.36).

3.6.2.9 Posterior Incudal Fold

The posterior incudal fold is the fold that runs between the fibers of the posterior incudal ligament (Fig. 3.36).

3.6.2.10 The Tensor Tympani Fold (TTF)

The TTF is a part of the tympanic diaphragm. It arises posteriorly from the tensor tympani tendon, about 1.5 mm lower than the roof of Prussak's space [61]. It runs anteriorly towards the anterior wall of the attic inserting into a transverse crest: the supratubal ridge. Medially it inserts on the bony canal of the TTM and laterally it inserts on the anterior malleal ligament. The lateral part of the tensor fold keeps a close relationship with the most anterior portion of chorda tympani (Fig. 3.37). It separates the anterior epitympanic recess superiorly from the supratubal recess inferiorly.

Embryologically, the TTF results from the fusion of the saccus anticus and the anterior saccule of the saccus medius. The inclination angle of the TTF varies between 80° and 120° depending on the variable growth of each saccus [62, 63]. The size of the supratubal recess and the anterior epitympanic recess is dependent on the vertical orientation of the TTF. The more vertical the TTF is, the wider is the supratubal recess [61] (Fig. 3.38). A horizontal TTF results in a very small or even inexistent supratubal recess [62] (Fig. 3.38).

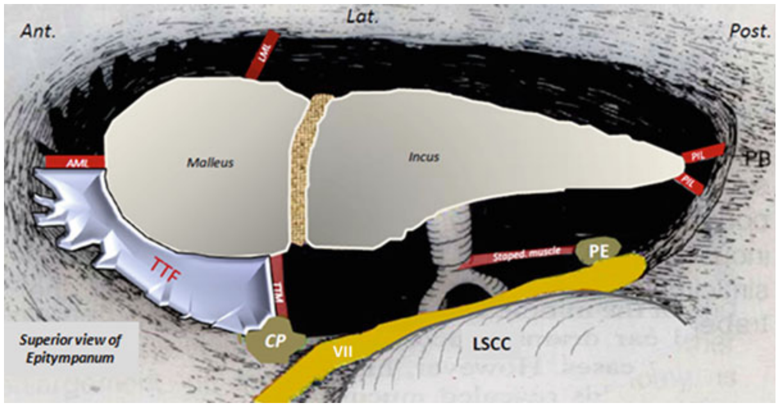

Fig. 3.37 Superior view of a right middle ear showing the tensor tympani fold (*TTF*) that inserts posteriorly on the tensor tympani muscle tendon (*TTM*), laterally on the anterior malleal ligament (*AML*), and anteriorly on the anterior attic wall. *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone

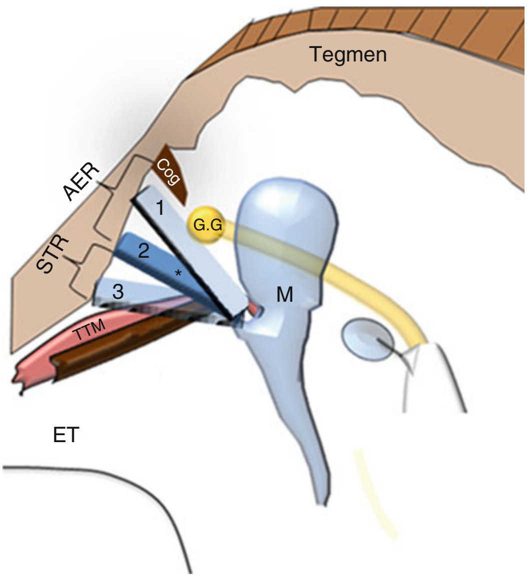

Fig. 3.38 Lateral view of a left ear showing the tensor tympani fold (*) with its variable anterior insertion (*1* high insertion, *2* intermediate insertion, *3* low insertion). The variable insertion of the TTF determines the volume of the anterior epitympanic recess (*AER*) which lies above the TTF and the supratubal recess (*STR*) which lies below the TTF. *TTM* tensor tympani muscle, *M* malleus, *GG* geniculate ganglion

The peripheral portion of the TTF is thick while the central portion is thin and transparent. In some ears, the fold is complete leading to a total separation between the anterior epitympanum and protympanum. In the majority of ears, the TTF is incomplete; this allows a direct communication from the Eustachian tube and supratubal recess to the anterior epitympanic recess and then to the posterior attic (Fig. 3.39). In such cases the direct aeration of the epitympanum prevents the development of attic dysventilation [63].

3.6.3 The Tympanic Diaphragm

Chatellier and Lemoine introduced the concept of the "epitympanic diaphragm" in 1946 [64], upon which the modern theories of tympanic ventilation have been developed. The authors described how the diaphragm was made up of various structures and membranous ligament that form together with the malleus and the incus the floor of the epitympanic compartment.

Palva et al. revised Chatellier's concept of the epitympanic diaphragm and added two other important folds: the TTF and the lateral incudomalleal fold [65, 66]. According to them, the complete tympanic diaphragm is made up of the three malleal ligamental folds (anterior, lateral, and posterior), the posterior incudal fold, the TTF, the lateral incudomalleal fold, and the incus and the malleus [61, 67] (Fig. 3.40).

The tympanic diaphragm is not fully horizontal because its components are on different levels. It separates the upper unit of the attic superiorly from the mesotympanum and the lower unit of the attic, the Prussak's space, inferiorly. The lateral malleal fold separates Prussak's space from the upper unit of the epitympanum; this is why we call the Prussak's space the lower unit of the attic [61] (see Sect. 4.5).

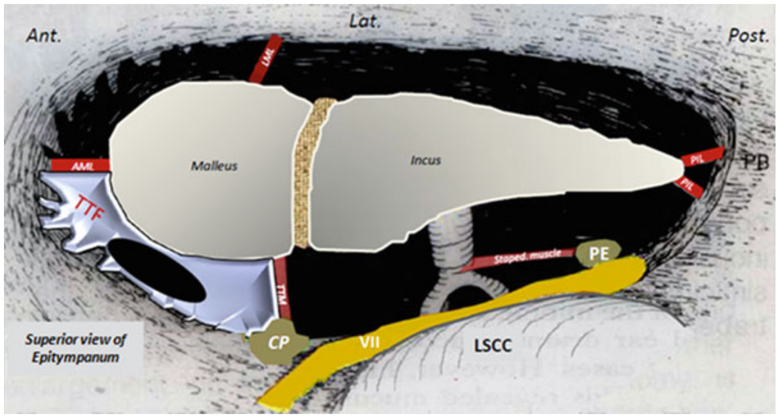

Fig. 3.39 Superior view of a right middle ear showing incomplete tensor tympani fold (*TTF*). *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone

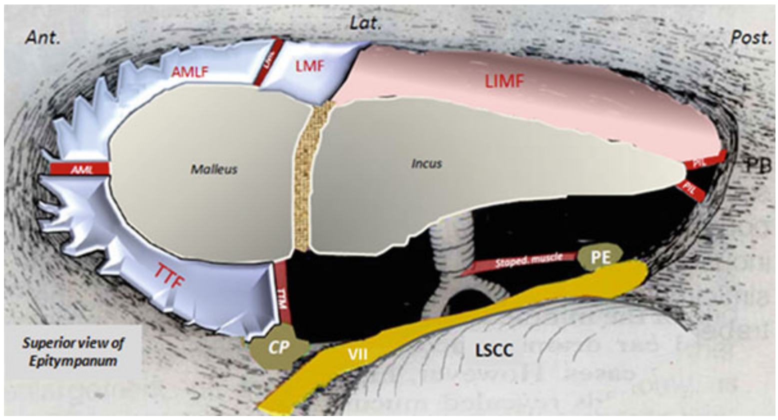

Fig. 3.40 Superior view of a right middle ear showing the tympanic diaphragm. *AMLF* anterior malleal ligamental fold, *TTF* tensor tympani fold, *LMF* lateral malleal fold, *LIMF* lateral incudomalleal fold, *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone

3.6.4 The Tympanic Isthmus

The mesotympanum connects with the Eustachian tube. However, the attic and the mastoid are isolated from the mesotympanum by the tympanic diaphragm. Attic aeration occurs through a 2.5-mm opening in the tympanic diaphragm called the tympanic isthmus (Fig. 3.41).

The entire attic is ventilated through the tympanic isthmus.

The Prussak's space is ventilated through the posterior pouch of von Tröltsch [65, 67].

The tympanic isthmus extends from the tensor tympani muscle anteriorly to the posterior incudal ligament posterosuperiorly and the pyramidal eminence posteroinferiorly. The distance from the TTM to the anterior edge of the posterior incudal ligament is around 6 mm [61]. The tympanic isthmus is limited medially by the attic bone and laterally by the body and short process of the incus and the head of the malleus.

The tympanic isthmus is divided by the medial incudal fold into two portions (Fig. 3.41).

3.6.4.1 The Anterior Tympanic Isthmus

The anterior tympanic isthmus, most important, is situated between the TTM anteriorly and the stapes posteroinferiorly. The diameter of this pathway is from 1 to 3 mm. It is a large open communication with the anterior epitympanum.

3.6.4.2 The Posterior Tympanic Isthmus

The posterior tympanic isthmus, less important, is situated between the short process of the incus and the stapedial muscle [65, 68].

Clinical Correlation

In long-standing chronic otitis media, granulation tissue and webs may block the tympanic isthmus and lead to failure of attic

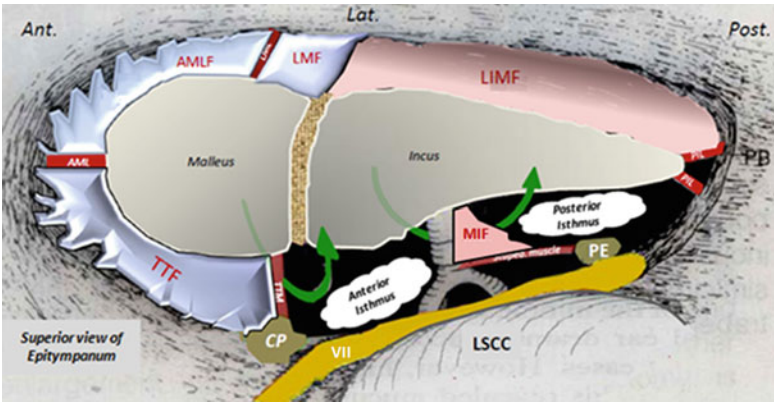

Fig. 3.41 Superior view of a right middle ear showing the tympanic diaphragm and the tympanic isthmus. The tympanic isthmus could be divided into anterior and posterior isthmus by the medial incudal fold (*MIF*). The *green arrows* represent the normal route of attic aeration from the mesotympanum. *AMLF* anterior malleal ligamental fold, *TTF* tensor tympani fold, *LMF* lateral malleal fold, *LIMF* lateral incudomalleal fold, *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone

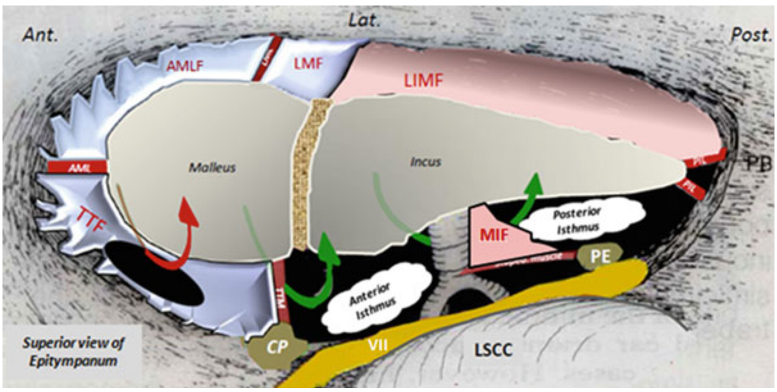

Fig. 3.42 Superior view of a right middle ear tympanic diaphragm showing a common variation of this structure. The tensor tympani fold (*TTF*) is incomplete and represents an accessory route of attic aeration (*red arrow*) from the protympanum. The *green arrows* represent the constant attic aeration through the tympanic isthmus. *AMLF* anterior malleal ligamental fold, *MIF* medial incudal fold, *LMF* lateral malleal fold, *LIMF* lateral incudomalleal fold, *AML* anterior malleal ligament, *LML* lateral malleal ligament, *PIL* posterior incudal ligament, *TTM* tensor tympani muscle tendon, *CP* cochleariform process, *PE* pyramidal eminence, *LSCC* lateral semicircular canal, *PB* petrous bone

ventilation even in the presence of a normally functioning Eustachian tube and well-aerated mesotympanum. This condition is called selective attic dysventilation and may result in chronic attical inflammation, attical retraction pockets, and attical cholesteatoma in the presence of a normal mesotympanum, and even in the presence of a tympanostomy tube (see Sect. 4.5.1.2 Clinical Applications).

Only a permanent large communication between the attic and the supratubal recess of the protympanum will guarantee the necessary aeration of the attic compartments to prevent attic dysventilation [69–71].

Incomplete TTF allows good ventilation from the protympanic space to the anterior attic and prevents attic dysventilation even in case of tympanic isthmus blockage. This confirms the importance of TTF removal during surgical treatment of middle ear disease to insure a good ventilation of the attic region [72–74] (Fig. 3.42).

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