1 Ear

1.1 Applied Anatomy and Physiology

1.1.1 Embryology

Inner ear: The sensory organs for hearing and balance develop from ectoderm. The *membranous labyrinth* develops from the ectodermal otic placode. *Embryonic mesenchymal tissue* surrounding the *membranous labyrinth* is converted into cartilage and also, by a process of vacuolization, into a fine reticular network that forms the inner layer of the *perilymphatic space*. The outer layer of the cartilage forms the *labyrinthine capsule*.

Middle ear: The eustachian tube and the mucosa of the middle ear arise from a diverticulum of the first pharyngeal pouch (endoderm).

The malleus and incus develop from Meckel cartilage, which emerges from the first branchial arch and is supplied by the trigeminal nerve. The stapes develops from the second branchial arch and is supplied by the facial nerve.

Myxomatous embryonic connective tissue lies between the ectodermal and endodermal ingrowths and makes a preformed middle ear cavity. If this myxomatous tissue does not involute properly after birth, the epitympanic recess remains as a narrow cleft. This is easily occluded by inflammation and creates a predisposition for chronic ear disease to develop.

External ear: The external meatus and the tympanic membrane develop from an ectodermal diverticulum between the first and second branchial arches. Developmental disorders may therefore cause deformities of both the external and middle ears. Bilateral lesions causing severe conductive deafness or a psychologically unacceptable deformity should be corrected, for both esthetic and functional reasons (see p. 53 and p. 106) (▶ Fig. 1.1 and ▶ Fig. 1.2).

1.1.2 Basic Anatomy

The hearing and balance systems consist of the *peripheral receptor apparatus* (i.e., the ear in the strict sense), *neurological pathways*, and *centers in the central nervous system*. Two main subdivisions can therefore be distinguished:

Peripheral part:
- The external, middle, and inner ear.
- Vestibulocochlear nerve with its two parts, the cochlear and the vestibular divisions.

Central part:
- Central auditory pathways.
- Subcortical and cortical auditory centers.
- Central balance mechanism.

The *anatomic boundary* between the *peripheral* and *central* parts is the point of entry of the eighth cranial nerve into the brainstem (the cerebellopontine angle [CPA]), at which point the peripheral part of the vestibulocochlear nerve passes into the central part, interspersed with glial cells. In functional terms, however, the peripheral neurons end in the primary centers.

External Ear

The *auricle* consists of a framework of elastic cartilage covered by skin (▶ Fig. 1.3), located between the temporomandibular joint anteriorly and the mastoid process posteriorly. The skin adheres tightly to the perichondrium on the anterior surface, but is more loosely attached posteriorly. For this reason,

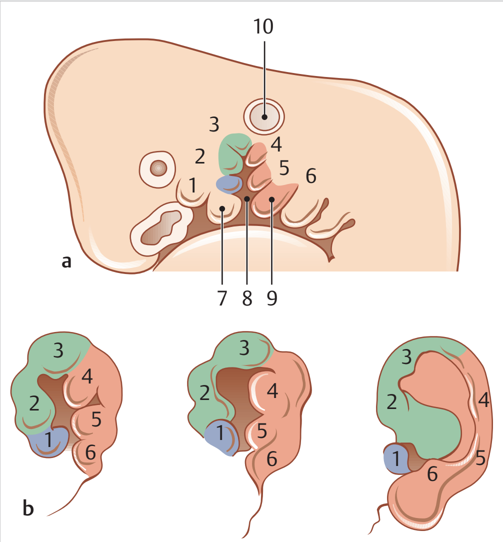

Fig. 1.1 Development of the external ear. **(a)** An 11-mm embryo, lateral view. **(b)** Development of the outer ear from six hillocks arising from the first and second branchial arches. **1**, Tragus; **2**, crus helicis; **3**, helix; **4**, crus anthelicis; **5**, antihelix; **6**, antitragus; **7**, first branchial arch; **8**, branchial cleft; **9**, second branchial arch; **10**, auricular plate.

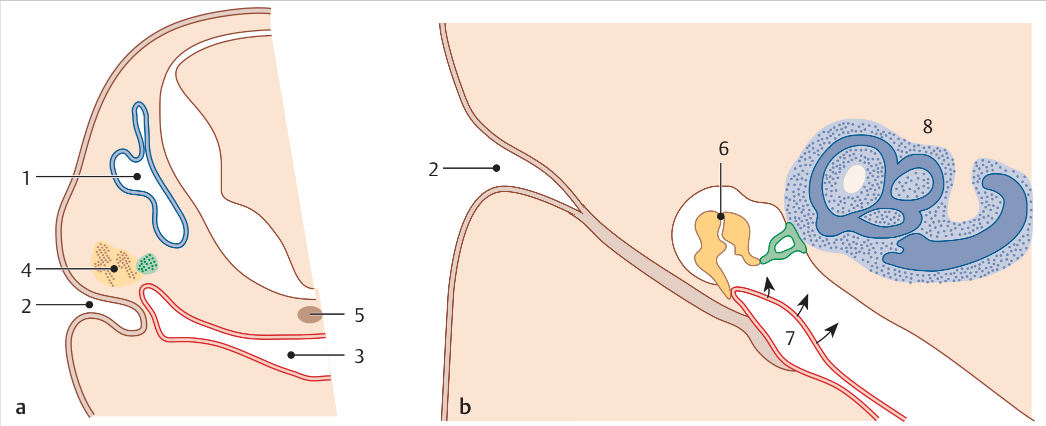

Fig. 1.2 Developmental stages of the external auditory canal, middle ear, and labyrinth. The epithelial auditory canal pouch with the tympanic plate opens through epithelial necrolysis (apoptosis) in the seventh month. The mesenchyme of the stapes develops from the second visceral arch; the remaining structures of the middle ear develop from the first visceral arch. **(a)** Approx. 8th week. **1**, Otic vesicle; **2**, primary auditory canal; **3**, tubotympanic recess; **4**, mesenchymal condensation; **5**, acousticofacial ganglion. **(b)** Approx. 7th month. **2**, Primary auditory canal; **6**, primordium of the auditory ossicles; **7**, tympanic cavity; **8**, primordium for the labyrinth.

Fig. 1.3 Topography of the external ear structures.
1, Helix; **2**, antihelix (**2a**: inferior crus, **2b**: superior crus); **3**, scaphoid fossa; **4**, cymba conchae; **5**, cavum conchae; **6**, tragus; **7**, antitragus; **8**, triangular fossa; **9**, earlobe.

contusions of the anterior surface often lead to detachment of the skin-perichondrial layer and to the formation of a hematoma (see p. 60).

The *external meatus* is ≈3 cm long, consisting of an outer cartilaginous part and an inner bony part. The cartilaginous meatus is curved and lies at an angle to the bony part. The tympanic membrane and the middle ear lying beyond it are thus protected from direct trauma.

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Note: For an otoscope to be introduced accurately, the curved cartilaginous mobile part of the external auditory meatus has to be drawn upward and posteriorly to bring it into the same axis as the bony part.

The cartilaginous part is attached firmly to the rim of the *bony meatus* by connective tissue. The bony canal is covered by a thin layer of skin that adheres to the periosteum. It contains no accessory structures, in contrast to the cartilaginous part of the meatus, which has numerous hair follicles and ceruminous glands that form wax (epidermis scale, sebaceous matter, pigment) (see p. 61).

The external meatus narrows medially. *Foreign bodies* may therefore become impacted at the junction of the cartilaginous and bony meatus. The meatal cartilage does not form a closed tube, but

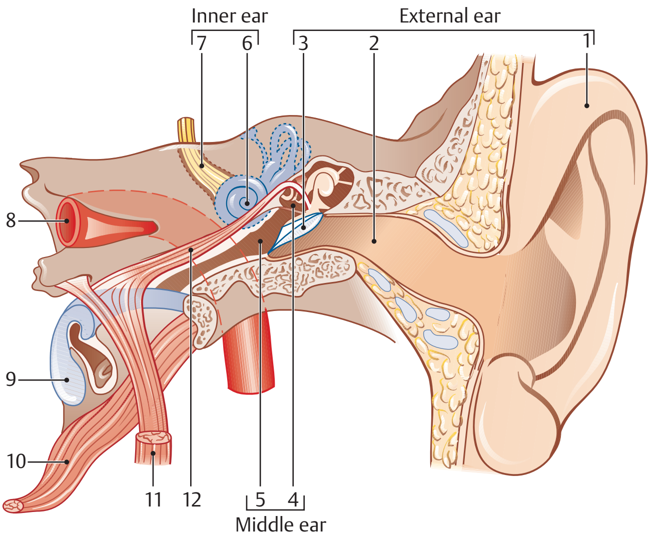

Fig. 1.4 Overview of the three sections of the ear. *External ear:* **1**, auricle; **2**, external ear canal; **3**, tympanic membrane. *Middle ear:* **4**, tympanic cavity; **5**, eustachian tube. *Inner ear:* **6** and **7**, labyrinth with inner ear canal and vestibulocochlear nerve; **8**, internal carotid artery; **9**, cartilage of eustachian tube; **10**, levator veli palatini muscle; **11**, tensor veli palatini muscle; **12**, tensor tympani muscle (Toynbee muscle).

rather a channel closed superiorly by fibrous tissue. The cartilage contains several fissures (Santorini fissures), which provide a pathway for the spread of severe bacterial infection to the parotid space, the infratemporal fossa, and the base of the skull.

The auricle and the cartilaginous meatus have very rich *lymphatic drainage* to an extensive regional lymphatic network consisting of parotid, retroauricular, infra-auricular, and superior deep cervical nodes. Infections of the external meatus with regional lymphadenitis can thus cause extensive swelling in these areas.

The *sensory innervation* is supplied by the trigeminal, great auricular, and vagus nerves and the sensory fibers of the facial nerve. Irritation of the posterior meatal wall stimulates the vagus and induces the cough reflex. Hypoesthesia of the posterosuperior meatal wall occurs with facial nerve impingement from a vestibular schwannoma (see the discussion of Hitselberger sign, p. 14 and p. 103).

Relations (▶ Fig. 1.4): The cartilaginous meatus abuts anteriorly on the parotid gland, allowing the spread of infection or malignant tumors.

The posterosuperior wall of the bony meatus forms part of the *lateral attic wall* (the partition between the external auditory meatus and the attic), the mastoid antrum, and the adjacent pneumatic system of the mastoid process. A middle ear infection can thus break through into the external auditory meatus, causing swelling of the posterosuperior wall or a fistula in acute mastoiditis. Destruction of the lateral attic wall by *cholesteatoma* may also lead to an open communication between the external auditory meatus and the attic or mastoid antrum. The anterior wall of the bony meatus forms part of the temporomandibular joint. There is therefore a risk of *fracture* resulting from a blow to the chin.

Middle Ear and Pneumatic System

The *middle ear cavity* consists of an extensive *pneumatic system* aerated by the eustachian tube. It has the following components:

- Eustachian tube.
- Tympanic cavity.
- Mastoid antrum.

The *eustachian tube* consists of a mobile, cartilaginous portion (two-thirds) suspended from the skull base, and a bony portion (one-third). The bony portion, together with the tensor tympani muscle, forms the musculotubal canal in the temporal bone.

This canal lies adjacent to the internal carotid artery. The funnel-shaped pharyngeal ostium of the cartilaginous part (the torus tubarius) lies in the nasopharynx. The bony end opens into the middle ear.

The junction between the two parts of the tube is very narrow. This *isthmus* is the site of predilection for inflammatory stenosis of the tube. The tube serves to equalize the pressure between the middle ear and the nasopharynx, and thus to equalize the pressure on each side of the tympanic membrane (see p. 7 and p. 37). An increase in pressure in the tympanic cavity is usually compensated for passively via the eustachian tube to the nasopharynx, whereas a decrease in pressure usually requires active ventilation from the nasopharynx along the tube to the middle ear cavity. The tube opens and closes in response to movements of the neighboring muscles and by differences of air pressure between the nasopharynx and the middle ear cavity that tend to equalize spontaneously. The principal closing mechanism is elastic recoil of the cartilage of the tube and the valvular action of the pharyngeal ostium of the tube. The tube opens by contraction of the tensor palati and levator palati muscles. The mechanism is partially under the control of voluntary muscle, but the reflex movements on yawning and swallowing and the muscle tone are under autonomic control. Tension opposing the opening muscles is provided by the elastic recoil of the tubal cartilage and the pressure of the peritubal tissues—i.e., the pterygoid muscles, Ostmann fatty bodies, the venous and lymphatic plexus of the tubal mucosa, and the pterygoid venous plexus.

The *middle ear cavity* is an air-containing space lying between the external ear and the inner ear. It is divided into three parts (▶ Fig. 1.5):

1. Epitympanic recess or attic.
2. Mesotympanum.
3. Hypotympanic recess.

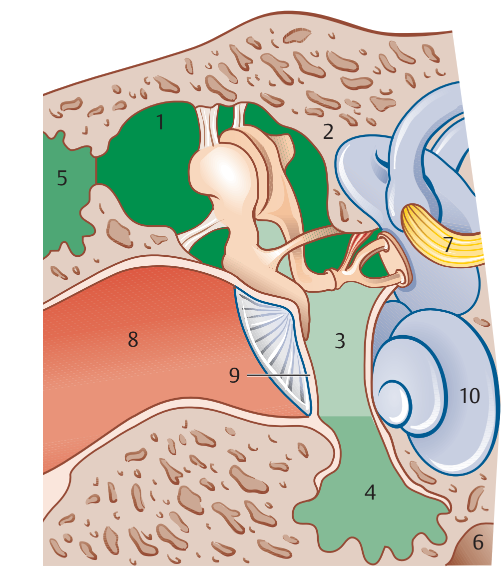

Fig. 1.5 Anatomy of the middle ear cavity. **1**, Epitympanum; **2**, zygoma; **3**, mesotympanum; **4**, hypotympanum; **5**, mastoid antrum; **6**, internal jugular vein. The lower part of the attic (**2**) is markedly narrowed by the facial nerve (**7**) and the horizontal semicircular canal. **8**, External meatus; **9**, tympanic membrane; **10**, cochlea.

There are two narrow zones within the middle ear cleft. First, there is an anatomic constriction between the epitympanum and mesotympanum that can lead to retention of secretions in inflammation and to deficient aeration of the attic. This is due to the considerable narrowing of this area caused by the head of the malleus, the body of the incus, numerous ligaments, nerves (the chorda tympani), and mucosal folds and pockets. This is one of the causes of chronic inflammation of the epitympanum (chronic epitympanitis), which is one of the causative factors for epitympanic cholesteatoma (see p. 76). A second narrow zone lies at the junction of the attic and the mastoid antrum (the aditus ad antrum). This may be blocked by granulation tissue in chronic inflammation, leading to deficient aeration or drainage of the mastoid cell system.

The hypotympanum is closely related to the bulb of the internal jugular vein.

Tympanic membrane: The lateral wall of the middle ear cavity is formed by the tympanic membrane. The tympanic membrane consists of the pars tensa and the pars flaccida. The *pars tensa* forms the stiff vibrating surface of the membrane and is attached to a fibrous ring (the *annulus fibrosus*), lying in the tympanic sulcus of the tympanic part of the temporal bone. The *pars flaccida* is the superior part of the membrane in the area of the tympanic notch (Rivinus notch) where the annulus fibrosus ends (▶ Fig. 1.6).

The microscopic cross-sectional appearance of the tympanic membrane is shown in ▶ Fig. 1.7. The epithelial or cuticular layer (the stratum corneum) is similar in structure to the skin of the external auditory meatus. Close to the tympanic annulus is the marginal zone of the tympanic membrane. This section shows extremely active proliferation due to papillary ingrowths into the stratum germinativum. This is another important factor in the genesis of cholesteatoma (see pp. 76–84).

The keratinizing squamous epithelium regenerates through migration of the epidermis from the center of the tympanic membrane to the periphery—in contrast to superficial desquamation, as occurs in normal skin. Migration of the outer epidermal layer forms an important part of the self-cleansing mechanism of the external meatus; this can be observed clinically in the movement of a blood clot from the tympanic membrane to the external meatus.

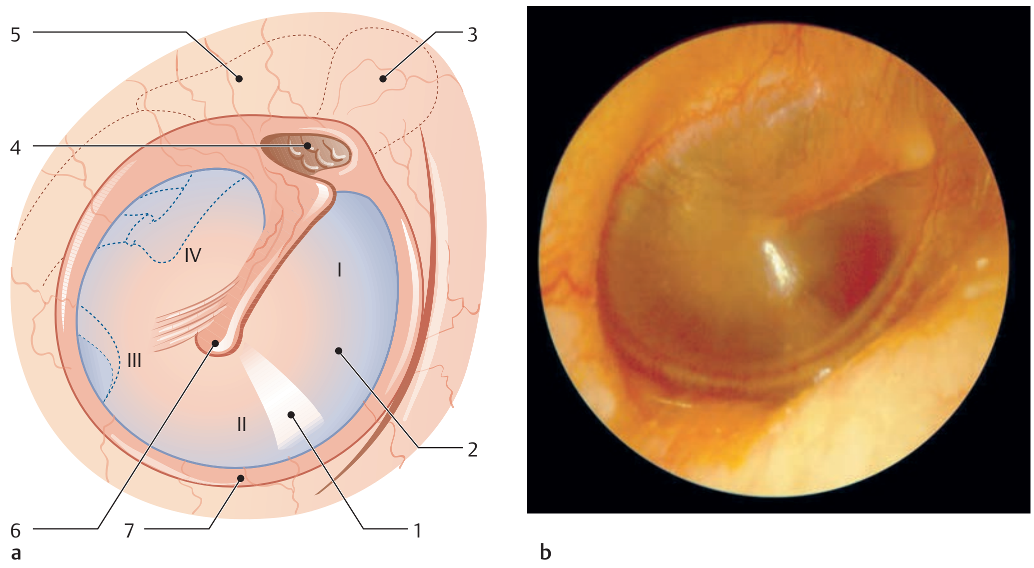

Fig. 1.6 (a) The macroscopic appearance of the right tympanic membrane. **1**, Light reflex; **2**, pars tensa; **3**, malleus head; **4**, pars flaccida; **5**, incus; **6**, umbo; **7**, annulus fibrosus. The visible part of the surface of the tympanic membrane is divided into four quadrants, in order of investigation: **I**, anterosuperior; **II**, anteroinferior; **III**, posteroinferior; and **IV**, posterosuperior. **(b)** The otoendoscopic appearance of a normal, transparent tympanic membrane. The tympanic ring, the handle of the malleus, and the short process of the malleus are visible. The light reflex is visible in the usual position —starting from the umbo across the anterior inferior quadrant.

The *lamina propria* has an external radial layer of fibers and an internal circular layer: this is evident during myringotomy. The annulus fibrosus forms a thickening of the edge of the tympanic membrane and is formed by both layers of fiber. A lamina propria can also be seen in the pars flaccida, but it lacks the characteristic radial and circular structure described above, which provides the normal pars tensa with the necessary functional tension.

The *middle ear*, or *tympanic cavity*, is empty except for air. Only the epitympanic recess contains solid structures—the ossicular chain and the chorda tympani. The ossicular chain consists of three separate bones connecting the lateral and medial wall of the middle ear. The medial wall of the middle ear also forms the lateral wall of the labyrinthine capsule. The malleus is the most lateral of the ossicles. Its inferior portion, or handle, is incorporated into the eardrum, while the superior portion, or head, is located in the anterior portion of the attic. The incus is connected to the head of the malleus by a genuine articulation surrounded by a joint capsule. The long process of the incus ends in the lenticular process, which bends medially to articulate with the head of the stapes. The lenticular process is covered by cartilage to form the incudostapedial joint (▶ Fig. 1.8 and ▶ Fig. 1.9).

The *mucosa* that lines the middle ear space consists of stratified cuboidal epithelium, which changes to pseudostratified ciliated epithelium around the mouth of the eustachian tube. A few goblet cells and submucosal glands are normally present. The submucosa is very thin, so that the mucosa lies directly on the periosteum, forming a tightly bound unit called the *mucoperiosteum*. In pathologic conditions such as tubal occlusion or chronic otitis media, the structure of the mucosa changes considerably to show hyperplasia of the glands, proliferation of the goblet cells, edema of the submucosa, vascular buds, and transformation of the flattened cuboidal epithelium to columnar epithelium.

The middle ear mucosa forms several pouches and folds (*Prussak space, Tröltsch pouch*), which narrow the junction between the attic and the rest of the middle ear and between the attic and the antrum. The epitympanic recess may remain as a narrow cleft with development, and if chronic hyperplastic inflammation follows an infection, the “mesenchyme” can completely obliterate the epitympanum. Ventilation and drainage of the

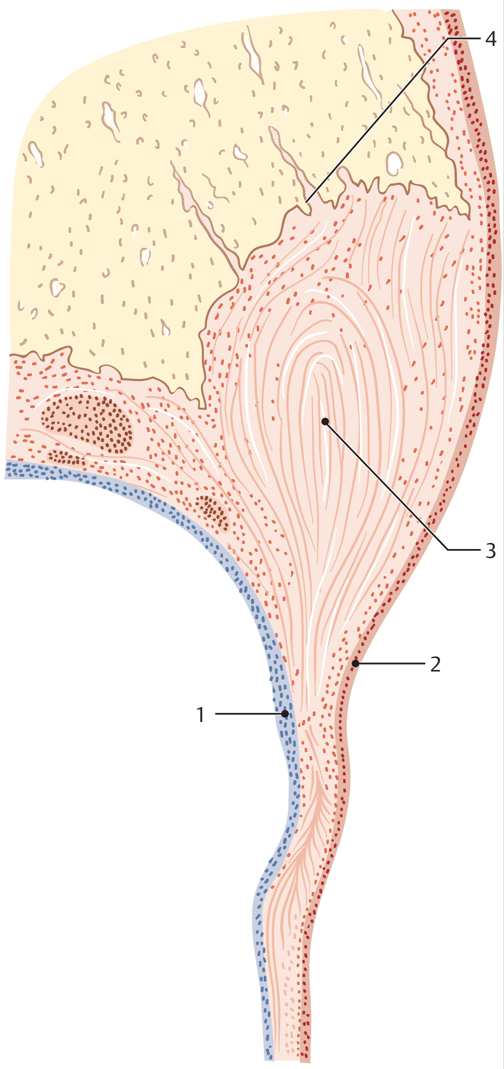

Fig. 1.7 The microscopic appearance of a sagittal section through the posterosuperior quadrant of the tympanic membrane. **1**, Epidermis layer, similar to the meatal skin bordering the tympanic membrane; **2**, middle ear mucosa; **3**, annulus fibrosus; **4**, bony sulcus of the fibrocartilaginous ring.

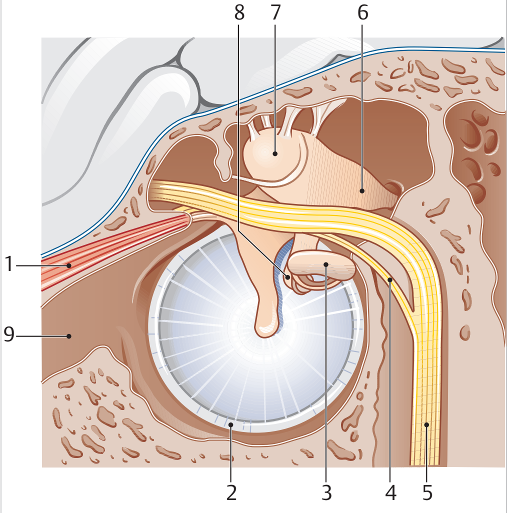

Fig. 1.8 Medial view of the middle ear, with the ossicular chain and facial nerve. **1**, Tensor tympani muscle. The pars tensa is anchored by the annulus fibrosus **(2)** in the bony niche of the tympanic ring. **3**, Stapes footplate. The handle and short process of the malleus lie lateral to the chorda tympani (**4**), as part of the facial nerve (**5**). The long process of the incus forms a joint (**8**) at its lenticular process with the head of the stapes. The body of the incus (**6**) forms the joint surface for the head of the malleus (**7**). The malleus and incus vibrate as one body in the middle part of the frequency range. The middle ear cavity is aerated via the eustachian tube (**9**).

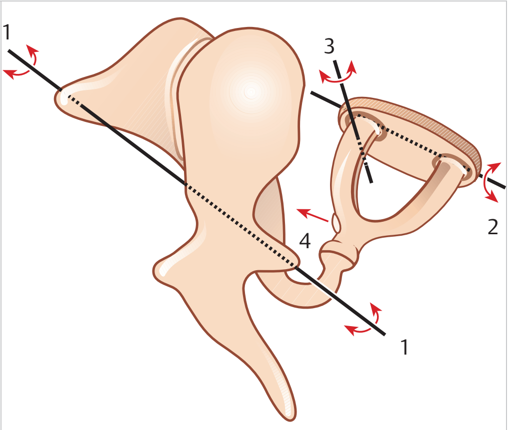

Fig. 1.9 The axis of ossicular chain movement. The malleoincudal joint can turn at a 90-degree angle according to the position of the footplate (**1**). The footplate itself can move from anterior to posterior (**2**) and in a lateral direction (**3**). The incudostapedial joint (**4**) moves only in a slight lateral bend.

attic is then impeded by thickened masses of inflammatory tissue, despite normal tubal function. Deficient aeration and drainage of this small space favors the development of chronic *epitympanitis* and plays a considerable role in the pathogenesis of *chronic otitis media* (see pp. 75–76), especially attic cholesteatoma.

The *arterial blood supply* originates from the basilar artery (the labyrinthine artery), the maxillary artery (the middle meningeal and tympanic arteries), and the stylomastoid artery. Venous drainage is via the middle meningeal veins, the venous plexus of the internal carotid artery and pharynx, and venous connections into the bulb of the internal jugular vein.

The *nerve supply* of the mucosa is provided from two sources: the tympanic branch of the glossopharyngeal nerve (cranial nerve IX) and the auriculotemporal branch of the trigeminal nerve (cranial nerve V).

Note: The shared sensory supply of the ear and upper respiratory tract explains why pain is referred to the ear in diseases of the teeth and the jaws, as well as of the larynx and pharynx.

Pneumatic System of the Temporal Bones

The air-containing cells of the mastoid process are continuous with the air in the middle ear. These multiple interconnecting spaces arise from the mastoid antrum, and the extent to which they are pneumatized is extremely variable. On the one hand, *pneumatization* may be well developed, extending to the temporal and occipital bones and the origin of the zygomatic arch. Acute infections of the mastoid may cause inflammatory swellings in these regions. At the other extreme, in a poorly pneumatized mastoid, the mastoid process may consist exclusively of compact bone, with the pneumatized cells lying in the immediate vicinity of the antrum.

The mastoid process begins to develop after birth as a small tuberosity, which is pneumatized synchronously with the growth of the mastoid antrum. In the first year of life it consists of cancellous bone, so that true mastoiditis cannot occur. Between the second and fifth years of life, as pneumatization proceeds, it consists of mixed cancellous and pneumatic bone. Pneumatization is complete between the sixth and twelfth years of life (▶ Fig. 1.10 and ▶ Fig. 1.11).

Principle of pneumatization (the concept of biological mucosal competence): Bone is destroyed by an enzymatic lacunar osteoclastic process. The resulting bony spaces are lined by continuous ingrowth of mucoperiosteum from the antrum. A system of

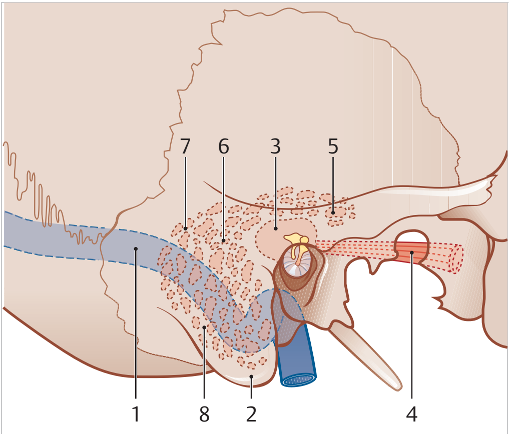

Fig. 1.10 The pneumatic system of the temporal bone. **1**, Transverse sinus; **2**, mastoid process with tip cells; **3**, mastoid antrum; **4**, eustachian tube; **5**, zygomatic cells; **6**, cells of the squamous part of the temporal bone; **7**, sinodural angle; **8**, retrosinus cells.

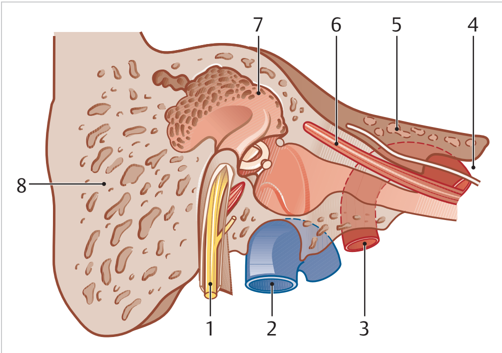

Fig. 1.11 Topographic relationships in the middle ear cavity. **1**, Facial nerve—inflammation and trauma often affect the mastoid segment; **2**, the bulb of the internal jugular vein, which is the site of predilection for extension of a glomus tumor into the middle ear cavity; **3**, the internal carotid artery—in petrositis, the inflammation can extend into the venous plexus around the carotid artery to create a cavernous sinus thrombosis; **4**, cavernous sinus; **5**, apical cells-purulent infection of the cells in petrositis (see pp. 88–89) causes Gradenigo syndrome; **6**, the tensor tympani muscle; **7**, the tegmen tympani, which is the site of predilection for mastoiditis to penetrate into the middle cranial fossa; **8**, the pneumatic system of the mastoid process—purulent infection of the cells causes subperiosteal abscess and sigmoid sinus thrombosis.

hollow cavities results, consisting of numerous spaces lined by mucosa and communicating with each other.

Normal tubal function is a prerequisite for biologically active, healthy middle ear mucosa, and thus for the normal process of pneumatization. The process of pneumatization can be related to the biological competence of the middle ear mucosa. The mucosa may be described as *biologically normal* or as *inferior*, depending on the degree of pneumatization. Good *pneumatization* indicates biologically competent middle ear mucosa, whereas *restricted pneumatization* indicates biological incompetence of the middle ear mucosa. Biologically incompetent middle ear mucosa may be due to two possible mechanisms—(1) a defective enzyme system that is impairing normal pneumatization, and/or (2) a deficient local immune system in the respiratory mucosa and middle ear mucoperiosteum that predisposes to chronic or recurrent otitis media.

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Note: Characteristically, pneumatization of the temporal bone is absent or restricted in chronic otitis media.

The better pneumatized the temporal bone is, the easier it is for infection to break through the thin cortical bone. When there is poor pneumatization (known as a *dangerous mastoid process*), the inflammatory process may be concealed in the depths and lead to unexpected complications.

Inner Ear

The inner ear, or labyrinth, is embedded in the temporal bone and is divided into two functionally separate receptor mechanisms:

1. The vestibule and semicircular canals (the vestibular end organ).
2. The cochlea (the acoustic end organ).

The labyrinth can also be divided morphologically into *bony* and *membranous* parts.

Bony labyrinth: This is formed by the *labyrinthine capsule*, which develops by periosteal and enchondral ossification. In systemic bone diseases (e.g., Paget disease and osteodystrophy) and in localized bone disease (e.g., otosclerosis), the bony labyrinth shows characteristic histopathological and chemical abnormalities. These conditions demonstrate continuous bone remodeling.

The oval and round windows form the bony and membranous openings to the labyrinth from the middle ear cavity, and are closed by the stapes footplate and round window membrane, respectively (see p. 4).

Membranous labyrinth and inner ear fluids (▶ Fig. 1.12)**:** The *membranous labyrinth* develops from the ectodermal otic placode. It encloses a hollow system filled with *endolymph*. This passes via the endolymphatic duct to end in a blind sac, the *endolymphatic sac*, in the posterior cranial fossa. The sac lies in the epidural space on the posterior surface of the petrous pyramid, close to the sigmoid sinus.

The *perilymphatic system* forms a hollow space consisting of the scala tympani and the scala vestibuli. The system communicates directly with the subarachnoid space in the jugular foramen via the cochlear aqueduct. Perilymph separates the membranous labyrinth from the internal layer of the labyrinthine capsule. Perilymph is the immediate substrate of the cochlear and vestibular sensory cells. The origin of perilymph is a matter of controversy; it may form from filtration of perilymphatic capillary blood and/or through diffusion of cerebrospinal fluid.

Endolymph is a filtrate of perilymph that has completely different concentrations of sodium and potassium, which are kept constant by the epithelium of the *stria vascularis* (see p. 12). The electrolyte composition of the endolymph regulates the volume of the fluid circulating in the endolymphatic system. The basis of the electrolyte exchange system, which maintains a constant ion concentration, is the cellular *potassium-sodium exchange pump* found in the stria vascularis, the utricle, and the saccule. There is also passive diffusion between the endolymphatic and perilymphatic spaces, with potassium-sodium ion exchange in the endolymphatic sac. Functional disturbances of this electrolyte regulation system lead to a disorder of the middle ear known as *Ménière disease* (see p. 109).

Vestibular-Semicircular Canal System

The anatomical fine structure of the balance mechanism system is shown in ▶ Fig. 1.13a, ▶ Fig. 1.14, and ▶ Fig. 1.15. It consists of the *utricle* and *saccule*

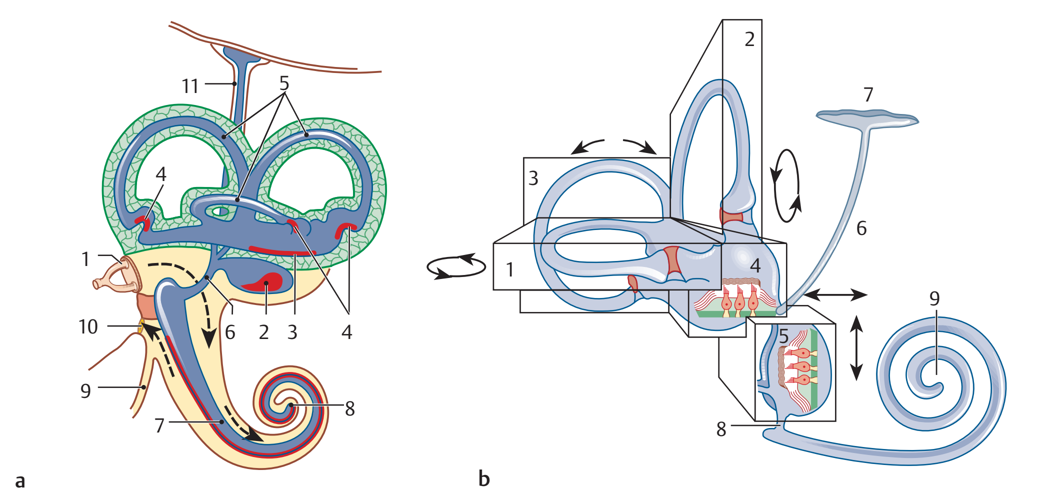

Fig. 1.12 (a) The inner ear. **1**, Oval window with stapes; **2**, saccule; **3**, utricle; **4**, ampulla of the semicircular canals, with cupula; **5**, membranous semicircular canals (horizontal, superior, and posterior); **6**, ductus reuniens; **7**, cochlear duct; **8**, helicotrema; **9**, the perilymphatic duct, which passes through the cochlear aqueduct; **10**, round window; **11**, endolymphatic sac on the posterior surface of the pyramid. **(b)** The vestibular apparatus. **1**, Lateral semicircular canal; **2**, vertical semicircular canal; **3**, posterior semicircular canal; **4**, utricle; **5**, saccule; **6**, endolymphatic duct; **7**, endolymphatic sac; **8**, ductus reuniens; **9**, cochlea. *Arrows* mark the direction of velocity forces.

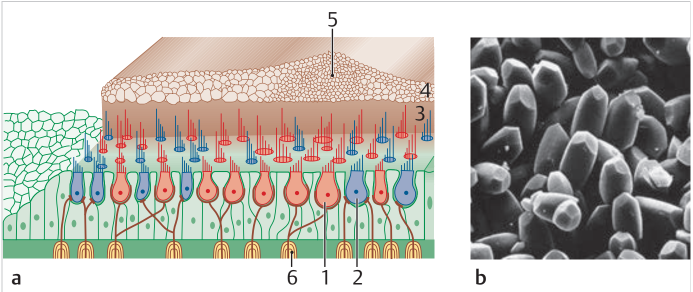

Fig. 1.13 (a) Static macula. A change in the polarity of the hair cells occurs below the striola. **1**, type I hair cell; **2**, type II hair cell; **3**, gelatinous layer; **4**, statolith membrane; **5**, statoliths, striola; **6**, afferent nerve fibers. **(b)** Scanning electron microscopic image of calcium carbonate crystals in the gelatinous layer of the utricle—otoliths.

enclosing the static *maculae* with the sensory end organs for the reception of linear acceleratory stimulation. These consist of *supporting cells* and *hair cells*, which have *cilia* embedded in a gelatinous mass consisting of sulfomucopolysaccharides. On their surface lie the *otoliths* (or statoconia), which consist of rhomboid calcium carbonate crystals (▶ Fig. 1.13b). Linear acceleration changes the otolith pressure, deflecting the sensory hairs. This stimulates the sensory cell by altering the *resting potential*.

The three semicircular canals arise from the utricle and have a pear-shaped expansion at one end called the *pars ampullaris*, enclosing the sensory cells, which are stimulated by angular acceleration (▶ Fig. 1.16). The sense organs consist of an *ampullary crest* (crista ampullaris), on which *sensory hair cells* are arranged in such a way that their cilia extend to the *cupula*, which reaches to the roof of the ampulla. The cupula acts as a mobile partition that closes off the pars ampullaris and is relatively impervious to endolymph (▶ Fig. 1.15).

Note: The hair cells of the maculae and ampullary crests have similar structural principles. They are mechanoreceptors that respond to tangential bending of their cilia.

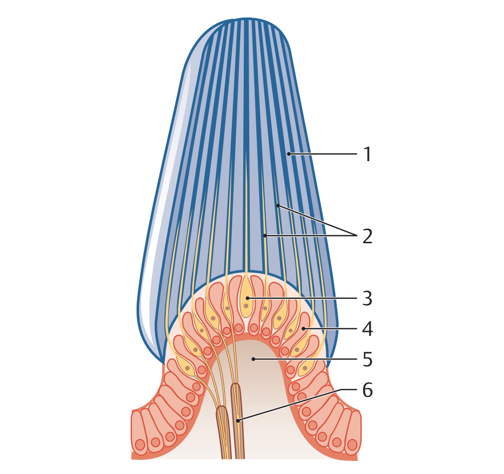

Fig. 1.14 A receptor in the semicircular canal. **1**, Cupula; **2**, cilia; **3**, sensory cells; **4**, supporting cells; **5**, crista ampullaris; **6**, afferent nerve fibers.

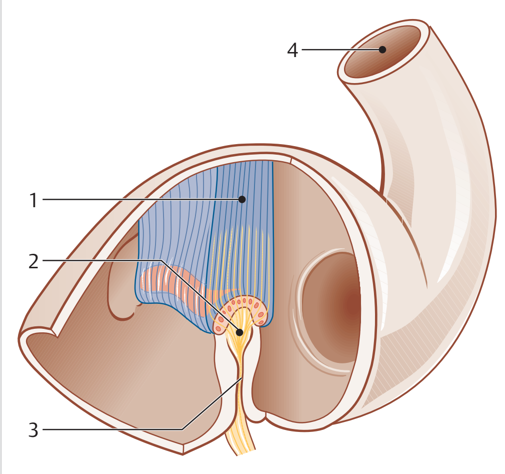

Fig. 1.15 The ampulla of a semicircular canal. **1**, Cupula; **2**, crista ampullaris; **3**, afferent nerve fibers; **4**, membranous semicircular canal.

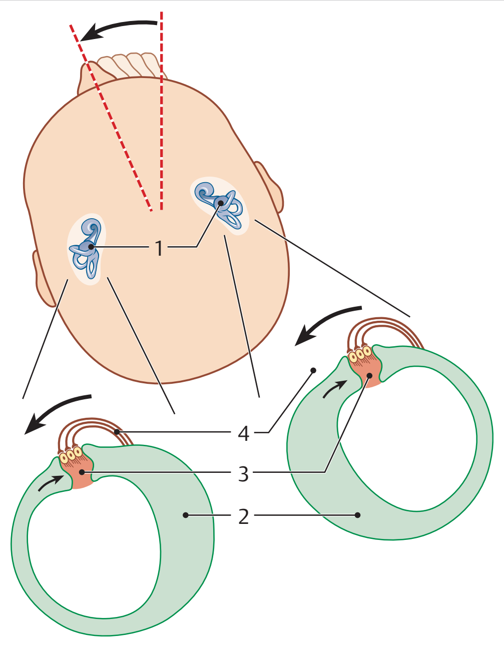

Fig. 1.16 Oscillation of the cupula. When the head is rotated (*long arrows*), the semicircular canals rotate as well. Owing to its viscosity, the endolymph initially remains motionless and directs the cupula in the opposite direction (*short arrows*). This causes the cilia to bend in the direction opposite to that of the head movement. **1**, Labyrinth; **2**, membranous canal of semicircular canal; **3**, cupula; **4**, vestibular nerve.

Cochlea (Acoustic End Organ)

The macroscopic and microscopic structure of the bony and membranous cochlea are shown in ▶ Fig. 1.17 and ▶ Fig. 1.18.

Functional structure of the organ of Corti: The basilar membrane supports the sensory apparatus of the organ of Corti. It stretches between the bony spiral lamina and the lateral cochlear wall and forms the border to the scala tympani. Surrounded by supporting cells, there are two types of receptor cells: one row of inner and three rows of outer hair cells, totaling ≈16,000 sensory cells. The hair cells have fine cilia on their free surfaces, with approximately 80 cilia per cell. So-called *tip links*, ≈10 µm thick, extend from the tips of the small cilia to the longer, very fine protein strings. There are ion channels where the tip links connect to the cilia, providing the basis for transduction of the sound stimulus to a receptor potential. Lying on top of the organ of Corti is the gelatinous tectorial membrane. The cilia of the outer hair cells lie below the tectorial membrane, while the cilia of the inner hair cells do not insert into the tectorial membrane. The hair cells are secondary sensory cells and have no nerve cell processes. They receive fibers from the spiral ganglion. Approximately 90% of the nerve fibers extend to the inner hair cells, and each inner hair cell is connected to many

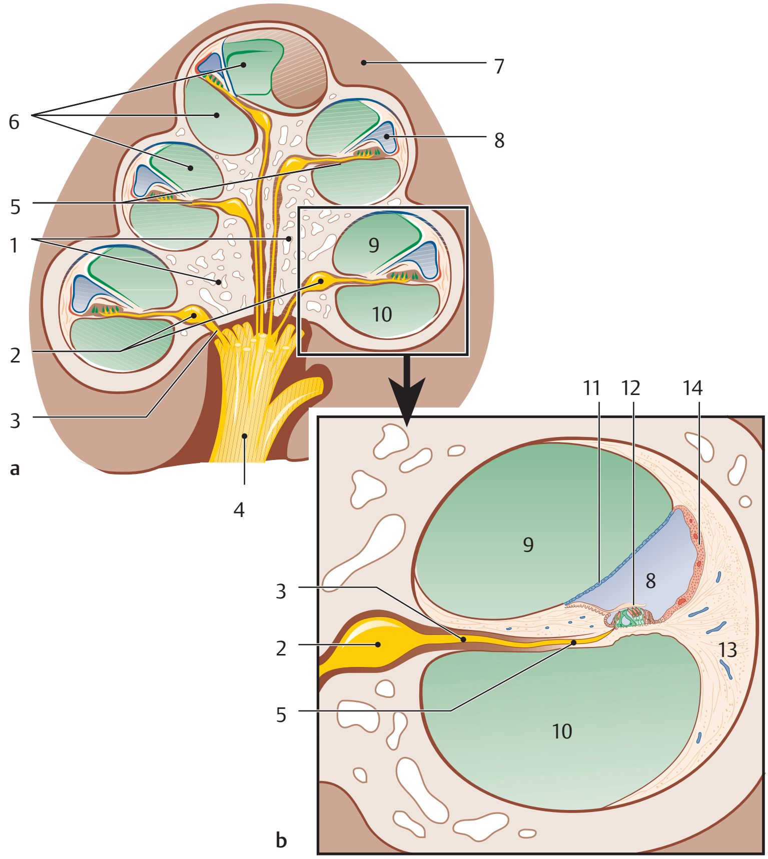

Fig. 1.17 Axial cross-section through the cochlea **(a)** and cochlear canal (spiral canal) **(b)**. The cochlea is arranged spirally (with two-and-a-half turns) around the central modiolus (**1**) lying horizontally. Its base lies against the lateral end of the internal acoustic meatus, and its apex is directed anterolaterally toward the medial wall of the middle ear. The spiral ganglion—i.e., the ganglion of the cochlear nerve (**2**)—is located within the modiolus, and its nerve fibers (**3**) join to form the stem of the cochlear nerve, the pars cochlearis of the vestibulocochlear nerve (**4**). The osseous spiral lamina or spiral plate (**5**) is a bony plate that runs spirally from the base to the apex (**7**). Nerve fibers pass through the channels of the spiral lamina to the spiral organ of Corti (**12**). The cochlear duct (scala media) (**b, 8**), filled with endolymph, lies between the scala vestibuli (**9**) above and the scala tympani (**10**) below, both of which contain perilymph (**6**). The osseous spiral lamina (**5**) and the basilar membrane form the separating wall between the scala tympani, on the one hand, and the scala vestibuli and cochlear duct on the other. The Reissner membrane (**11**) separates the scala vestibuli and the cochlear duct. The tectorial membrane (**12**) covers the sensory cells of the organ of Corti. The stria vascularis (**14**) forms the lateral wall of the cochlear duct and has numerous vessels. This layer of fibrous vascular tissue is the site of production of the endolymph. Laterally, it borders on the spiral ligament of the cochlea (**13**). The perilymphatic spaces of the cochlea, the scala tympani and scala vestibuli, communicate with each other at the apex of the cochlea (**a, 7**), at the helicotrema (see also ▶ Fig. 1.12**a**) and are also connected with the perilymphatic space of the membranous labyrinth of the vestibule, containing both the utricle and the saccule (see also ▶ Fig. 1.12**a, 2, 3**).