# Chapter 1
# Anatomy of the Inner Ear

**Tatsunori Sakamoto and Harukazu Hiraumi**

**Abstract** The inner ear of mammals consists of the cochlea, the vestibule, and three semicircular canals. The macro anatomy of each component and the microstructure of each sensory region, especially all the components of the organ of Corti, are explained. The clinically available surgical approaches to the inner ear are also explained.

**Keywords** Cochlea • Crista • Hair cell • Macula • Saccule • Semicircular canals • The organ of Corti • Utricle

## 1.1 Morphology of the Inner Ear

The inner ear of mammals consists of the cochlea, the vestibule, and three semicircular canals. Because of its complex anatomy, the inner ear is referred to as a labyrinth. The inner ear is a double-walled structure. The outer wall is bony one, named otic capsule. The lumen of the otic capsule is called bony labyrinth. The inner membranous wall is known as a membranous labyrinth. The space between the bony and membranous labyrinth is called perilymphatic space and is filled with perilymph. Inside the membranous labyrinth is called endolymphatic space and is filled with endolymph. The perilymph is sodium rich and its component is similar to that of cerebrospinal fluid. The endolymph is potassium rich and very different from other fluids in the body.

The inner ear is accompanied by many vital structures. The inner ear is connected to the brain stem with the auditory nerve through the internal auditory canal. The facial nerve courses superiorly (labyrinthine and tympanic portion) and posteriorly (mastoid portion) to the cochlea and laterally (a junction between the

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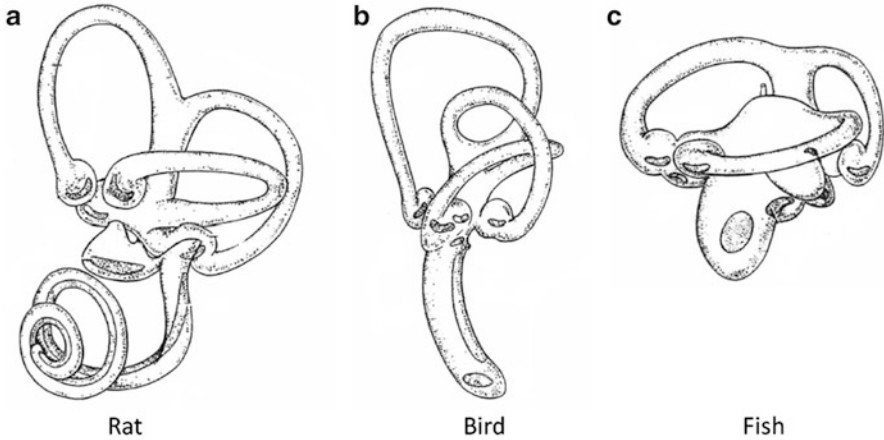e-mail: sakamoto@ent.kuhp.kyoto-u.ac.jp

**Fig. 1.1** Membranous labyrinth of vertebrates. Membranous labyrinths of a rat (**a**), a bird (**b**), and a fish (**c**) were shown. (Modified from "The Vertebrate body" by Romer et al. [1])

tympanic portion and the mastoid portion of the facial nerve) to the vestibule. Ventral to the cochlea, the internal carotid artery forms a knee. The jugular bulb of the jugular vein is positioned inferior to the cochlea.

### 1.1.1 The Cochlea

The cochlea is a hearing organ. The mammalian cochlea has a characteristic coiling morphology, where it has 2.75 turns in humans, 2 turns in mice, 4.25 turns in guinea pigs, and 2.75 turns in monkey [1, 2] (Fig. 1.1). The sensory epithelium of the cochlea is the organ of Corti, in which sensory hair cells stay in array (Figs. 1.3 and 1.4). In birds, the cochlea does not coil, and the sensory epithelium looks differently as basilar papilla [3] (Figs. 1.1 and 1.5). Fish and frogs do not have a hearing-specific organ; however, the sense of sound vibration is received by the saccule and the lagena (Fig. 1.1). The lagena is responsible also for linear acceleration and the magnetoreception [4].

The axis of the cochlea is known as the modiolus, in which cochlear nerve runs (Fig. 1.2). The cross section of the membranous labyrinth in the cochlea forms triangular shape bordered by the basilar membrane, the stria vascularis, and the Reissner's membrane (Fig. 1.3). The endolymphatic space inside the cochlea is called scala media or cochlear duct. The perilymphatic space facing the Reissner's membrane is called scala vestibuli, and the space facing the basilar membrane is called scala tympani. The scala tympani and scala vestibuli are connected through a small hole of the basilar membrane at the apex of the cochlea, called a helicotrema. Therefore, perilymphatic space is divided into two spaces by the cochlear duct. The basal portion of the scala tympani ends with a blind sac. The basal end of the scala
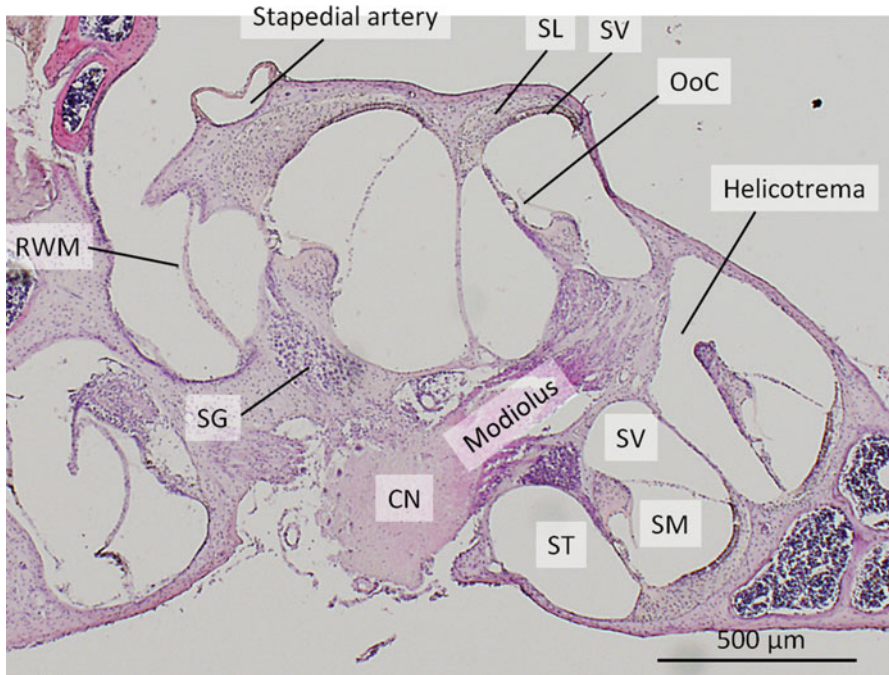
**Fig. 1.2** Cochlea. Mid-modiolar section of an adult mouse cochlea, stained with hematoxylin and eosin. The cochlear nerve (CN) runs in the modiolus. Cell bodies of CN exist as spiral ganglions (SG) in Rosenthal's canal. The cochlear duct is seen as scala media (SM). Scala tympani (ST) and scala vestibuli (SV) are connected in the apical turn of the cochlea as helicotrema. Stapedial artery runs on the surface of the basal turn of the cochlea. Round window membrane (RWM), the organ of Corti (OoC), stria vascularis (SV), the spiral ligament (SL)
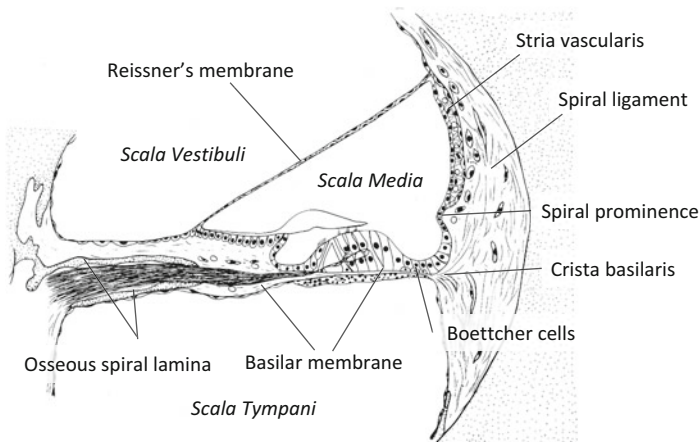


**Fig. 1.3** The cochlear duct. (Modified from "Atlas of Otology" by Nomura et al. [5])
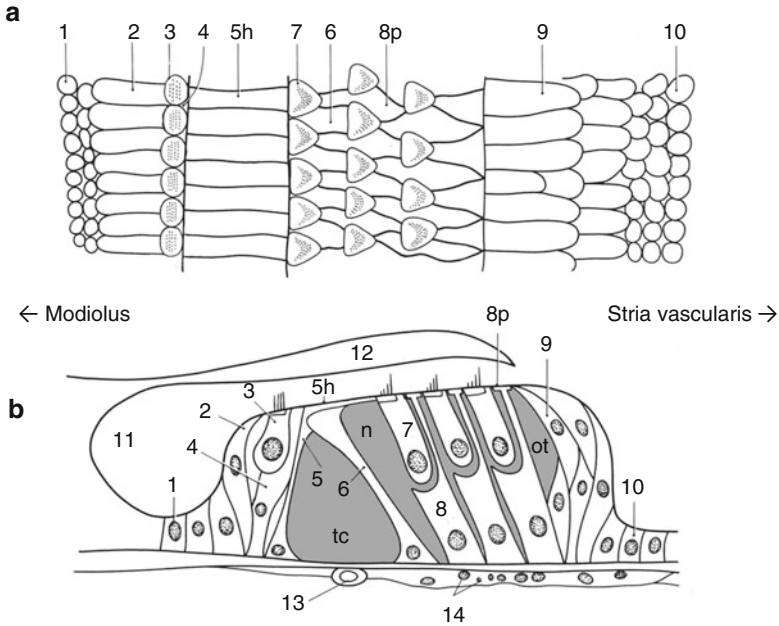
**Fig. 1.4** The organ of Corti, surface view (**a**) and cross sectional view (**b**). The tunnel of Corti (**tc**), Nuel's space (**n**), and the outer tunnel (**ot**) are filled with cortilymph. *1* Inner sulcus cell, *2* border cell, *3* inner hair cell, *4* inner phalangeal cell, *5* inner pillar cell, *5h* the head of inner pillar cell, *6* outer pillar cell, *7* outer hair cell, *8* Deiters' cell, *8p* phalanx of Deiters' cell, *9* Hensen's cell, *10* Claudius' cell, *11* inner spiral sulcus, *12* tectorial membrane, *13* vessel of the basilar membrane, *14* tympanic border cell. (Modified from "Atlas of Otology" by Nomura et al. [5])

vestibuli is connected to the saccule via ductus reuniens. The basilar membrane is a resonant structure spreading between osseous spiral lamina and the crista basilaris. The basilar membrane in the basal turn is narrower and stiffer, leading to higher natural resonance frequency, than that in the apical turn. The organ of Corti is positioned on the scala media side of the basilar membrane.

The organ of Corti (Figs. 1.2, 1.3, and 1.4) is composed of hair cells and several types of supporting cells. When the sound vibration displaces the basilar membrane, the shearing force between the basilar and the tectorial membranes deflects the hair bundle at the apical surface of the inner hair cells and then is conveyed as the release of the neurotransmitter. Approximately 3,500 inner hair cells exist in one human cochlea [5]. The inner hair cells are innervated by type I afferent neurons with myelinated axons. The inner phalangeal cells are the direct supporting cells for inner hair cells. Border cells and inner sulcus cells are located next to the inner phalangeal cells. The outer hair cells appear as three rows, and 12,000 outer hair cells exist in one human cochlea [5]. These cells change their length through the function of the motor protein, prestin, in response to the sound stimuli [6, 7]. The outer hair cells are innervated by type II afferent neurons

**Fig. 1.5** The basilar papilla of a chicken. *T* tall hair cell, *S* short hair cell, *inf* inferior margin of the cochlea, *sup* superior margin of the cochlea, *BM* basilar membrane, *TM* tectorial membrane. (From Tilney and Saunders [3])
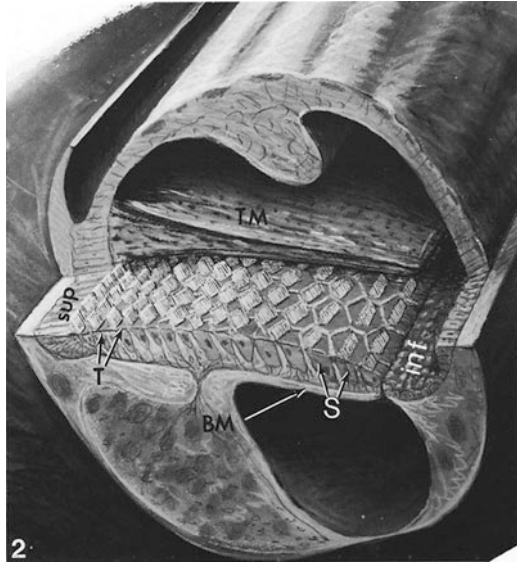
with unmyelinated axons. Deiters' cells support the outer hair cells. Deiters' cells have two parts: The cell body directly attaches to the basilar membrane and supports the basal side of the outer hair cell. The phalangeal process extends from the cell body to the apical surface of the sensory epithelium between outer hair cells and forms a part of reticular lamina. Inner and outer pillar cells exist between inner hair cells and the first row of outer hair cells and form a fluid-filled space called the tunnel of Corti. The space between outer pillar cells and the first row of outer hair cell/Deiters' cell is called Nuel's space. Hensen's cells are located next to the third row of the Deiters' cells and form several layers. Claudius' cells exist between Deiters' cells and the spiral prominence, forming outer sulcus. Boettcher cells are located beneath the Claudius' cells in the lower turns of the cochlea (Fig. 1.3). Tympanic border cells are cells lining the scala tympani side of the basilar membrane.

The loose connective tissue on the outer wall of the cochlear duct is the spiral ligament (Fig. 1.3). The stria vascularis is a vascular-rich structure on the spiral ligament spreading from the attachment of Reissner's membrane to the spiral prominence. The stria vascularis functions to maintain the high potassium concentration and positive potential of the endolymph (endocochlear potential (EP)) via Na/K-ATPase.

The basilar papilla is a sensory epithelium in the cochlear duct of birds, amphibians, and lizards, which functions like the organ of Corti (Fig. 1.5) [3]. Hair cells and supporting cells are compactly arranged on the basilar membrane. The tall hair cells exist near the superior margin of the basilar membrane, while the short hair cells exist near the inferior margin.
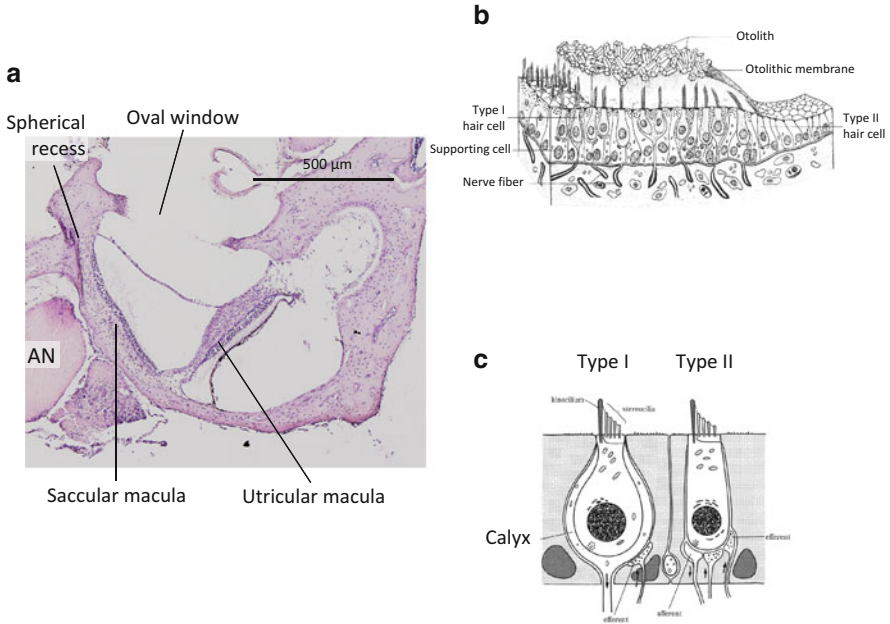
**a**

Spherical recess

Oval window

500 μm

AN

Saccular macula          Utricular macula

**b**

Otolith

Otolithic membrane

Type I hair cell

Type II hair cell

Supporting cell

Nerve fiber

**c**          Type I          Type II

kinocilium          stereocilia

Calyx

efferent

efferent          afferent          efferent

**Fig. 1.6** The vestibule. (**a**) A section of adult mouse inner ear, stained with hematoxylin and eosin. The stapes was removed from the oval window. *AN* auditory nerve. (**b**) Macula. (Modified from "Modern Oto-rhino-laryngology" by Kirikae and Nomura [12]) (**c**) Type I and II vestibular hair cells. (Modified from "Atlas of Otology" by Nomura et al. [5])

## 1.1.2    The Vestibule

The vestibule (the utricle and saccule) is positioned superior to the cochlea and functions to sense linear acceleration (Fig. 1.6). In the vestibule, the membranous labyrinth forms two sacs which are connected each other. The sac near the semi-circular canals is called the utricle, while the other located near the cochlea is called the saccule. The saccule is connected to the cochlea by a small channel called the ductus reuniens. The sensory epithelium of the vestibule is located in the macula of the utricle and saccule. The utricular macula is located horizontally with a free margin. It resembles a visor of a cap separating the utricle and perilymphatic space of the vestibule. The saccular macula is attached to the medial wall of the saccule. The bony labyrinth forms a shallow bowl called spherical recess at the attachment site of saccular macula. Each macula is overlaid by the otolithic membrane, which is a rigid layer composed of gelatinous extracellular matrix and otolith. The space between the otolithic membrane and the apical surface of the sensory epithelium is secured by the columnar filament layer [8]. Each macula is divided into two regions by the striola. In the utricle, hair cells are arranged in such a manner that the tall cilia face the striola. In the saccule, the tall cilia face the peripheral side instead of

the striola. Hair cells in the maculae are classified into type I and II hair cells [5, 9]. Type I hair cells have a bulbous shape and its basal part is surrounded by large socket-like afferent nerve endings called the calyx. Type II hair cells have a cylindrical shape and display simpler button-like afferent nerve contacts. Both type I and II hair cells receive efferent nerve contacts. Type I hair cells exist near the striola, and type II in the peripheral region. Type I and II hair cells are morphologically distinguishable, but the functional difference is not fully understood. Dark cells are responsible for the maintenance of endolymph through ion and water transport [10]. Dark cells exist around the edge of the utricular macula, but not the saccular macula [11].

### 1.1.3  Three Semicircular Canals

The three semicircular canals (lateral, superior, and posterior) are located postero-superior to the vestibule and cochlea. They form three perpendicular planes and work as detectors for angular acceleration. To be precise, the angle formed by two semicircular canals is not right angled and each canal is twisted; however the relative special arrangement of three semicircular canals contributes to the stimulus perception of three-dimensional head rotation. The superior and posterior semicircular canals share one canal at the insertion to the vestibule or the common crus. The semicircular canals are postero-superior to the facial nerve. The lateral semicircular canal is placed lateral to the vestibule adjacent to the facial nerve. The lateral semicircular canal forms an eminence in the middle ear, which is called the prominence of the lateral semicircular canal and is a very important landmark in ear surgery. The superior semicircular canal sometimes protrudes into the middle cranial fossa. The posterior semicircular canal is positioned between the posterior fossa dura and the mastoid portion of the facial nerve.

In each semicircular canal, the membranous labyrinth presents as a tubelike structure. At one end of each semicircular canal, the tube is dilated to form a spindle-like structure, which is known as the ampulla (Fig. 1.7). A crescent-shaped structure (crista) is located inside the ampulla. The crista is attached to the outer wall of the ampulla, and the hair cells of the semicircular canals are located in the sensory epithelium of the crista. In the crista, type I hair cells preferably exist at the central part, while type II hair cells are found in the peripheral part of the crista, which are equivalent to the vestibular maculae. The hair cells are surrounded and separated by supporting cells. The site next to the sensory epithelium is the transitional area and the dark cell area. The cupula is a gelatinous substance, which extends from the crista and stretches across the ampulla to the roof. Tips of the cilia of hair cells are embedded in the base of the cupula. When the rotating movement is applied to a semicircular canal, the relative movement of the liquid displaces the crista; thus the cilia will be bent.
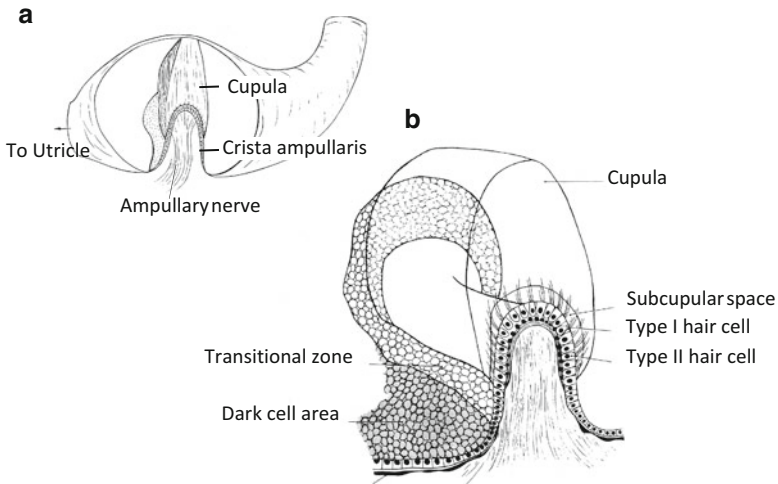
**Fig. 1.7** Ampulla of the semicircular canal. (**a**) Membranous labyrinth of the semicircular canal. (**b**) Cupula and crista ampullaris. (Modified from "Atlas of Otology" by Nomura et al. [5])

### 1.1.4 Round and Oval Windows

The bony labyrinth has two windows facing the middle ear, i.e., the oval window and round window. The oval window is an opening in the vestibule, and the footplate of the stapes is attached to this window. The round window, which is an opening in the scala tympani of the cochlea, is closed with the round window membrane. The round window membrane is lodged deep in a pit called the round window niche, which is often closed at the opening by a membranous structure, called the pseudomembrane. The oval window faces laterally, and the round window faces inferiorly.

### 1.1.5 Endolymphatic Sac

The endolymphatic sac is a protrusion of the membranous labyrinth out of the bony capsule of the inner ear. The endolymphatic sac is positioned between the posterior semicircular canal and the posterior fossa dura and is connected to the utricle and saccule via the endolymphatic duct. In the other portion of the endolymphatic sac, the endolymphatic space is surrounded by the perilymphatic space. The endolymphatic sac is the only endolymphatic space that is accessible without violating the perilymphatic space.

## 1.2 Auditory and Vestibular Nerves

The medial side of the inner ear is connected to the auditory nerve, which comprises the cochlear, superior vestibular, and inferior vestibular nerves. The bone between the inner ear and the nerve forms a plate with small fenestrations, i.e., the cribriform plate. The superior vestibular nerve innervates the crista of the superior and lateral semicircular canals and utricle. The inferior vestibular nerve innervates the posterior semicircular canal and saccule. The nerve innervates the inferior semicircular canal branches to form he inferior vestibular nerve, which is called the singular nerve.

## 1.3 Blood Supply

The arterial blood supply to the membranous labyrinth is from the labyrinthine artery [13]. The labyrinthine artery is usually a branch of the anterior-inferior cerebellar artery. The labyrinthine artery branches to form the common cochlear artery and anterior vestibular artery. The common cochlear artery subdivides to form the main cochlear and vestibulocochlear arteries. The main cochlear artery supplies apical three-fourths of the cochlea. The main cochlear artery enters the modiolus and branches to form the external and internal radiating arterioles. The external radiating arterioles course over the scala vestibuli and ramify a capillary network of the stria vascularis and other structures in the outer wall of the cochlea. Internal radiating arterioles furnish blood supply to the spiral ganglion and structures above the basilar membrane. The vestibulocochlear artery supplies blood to the basal one-fourth of the cochlea and modiolus (cochlear ramus artery), the macula of the saccule, and crista of the posterior semicircular canal (posterior vestibular artery). The anterior vestibular artery provides blood circulation to the macula of the utricle and crista of the superior and lateral semicircular canal.

## 1.4 Surgical Approaches to the Inner Ear

The inner ear has a hard bony shell of the otic capsule, at sites of the two windows and endolymphatic sac. Therefore, a surgical approach to the inner ear needs drilling of the otic capsule or opening these two windows or the sac. There are three approaches to the inner ear: (i) transcanal, (ii) transmastoid, and (iii) extra-temporal bone.

Since the cochlea is positioned just behind the eardrum, the transcanal approach (i) is the most simple with minimal invasive method. By elevating the eardrum and removing some portion of the external auditory canal bone, the oval window and the round window niche can be well manipulated. This approach is used in the

surgery for otosclerosis and perilymphatic fistula. Recent advance in endoscopy enables access to the two windows via myringotomy. The endoscope provides excellent visualization of the round window membrane, since it is perpendicular to the eardrum and lodged deep in the round window niche. Drilling of the promontorium provides access to the cochlea. This approach is sometimes used in the cochlear implantation surgery.

The transmastoid approach (ii) is the most popular method in a clinical setting. This approach can be subdivided into two prongs: facial recess and retrofacial approach. The facial recess approach is widely utilized in the cochlear implantation surgery, where a bony portion between the facial nerve and chorda tympani is drilled to provide access to the oval window and the round window niche. By removing the lip of the round window niche, the round window membrane is accessible. Cochleostomy is also available for accessing the cochlea. The retrofacial approach is commonly used in the mastoid-endolymphatic shunt surgery. Using this approach, the endolymphatic sac is accessible with minimal damage to the inner ear. By incising the dura matter ventral to the sigmoid sinus, cisternal portion of the auditory nerve is visible (retrolabyrinthine approach). The otic capsules of the three semicircular canals are accessible with the transmastoid approach. By gently removing the otic capsule, the lumen of semicircular canal can be opened without causing sensorineural hearing loss.

The extra-temporal bone approach (iii) is extensively used in the surgery for vestibular schwannoma. In the middle fossa approach, the temporal lobe and dura matter are elevated from the temporal bone. By removing the bone above the internal auditory canal, it is possible to access the auditory nerve without violating the inner ear. This approach also provides good access to the superior semicircular canal and is used for surgery of the superior canal dehiscence syndrome. The retrosigmoid approach is another extra-temporal bone approach. By incising the dura matter behind the sigmoid sinus and depressing the cerebellum, a cisternal portion of the auditory nerve can be secured. Further removal of the bone dorsal to the internal auditory canal provides access to the whole part of the auditory nerve.

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