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Characteristic anatomical structures of rat temporal bone

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Abstract

As most gene sequences and functional structures of internal organs in rats have been well studied, rat models are widely used in experimental medical studies. A large number of descriptions and atlas of the rat temporal bone have been published, but some detailed anatomy of its surface and inside structures remains to be studied. By focusing on some unique characteristics of the rat temporal bone, the current paper aims to provide more accurate and detailed information on rat temporal bone anatomy in an attempt to complete missing or unclear areas in the existed knowledge. We also hope this paper can lay a solid foundation for experimental rat temporal bone surgeries, and promote information exchange among colleagues, as well as providing useful guidance for novice researchers in the field of hearing research involving rats.

Keywords: Rat; Temporal bone; Anatomy

1. Introduction

Through extensive experimental studies, functions and structures of most organs of the rat as well as its gene sequences have been well established, and rats are now widely used in various experimental medical studies. In the field of inner ear research, rats are used to study injuries to the inner ear by various agents including aminoglycoside antibiotics, platinum anti-cancer drugs, anti-malaria drugs, herbicides, insecticides, anti-inflammatories, loop diuretics, blast waves, noises, high-frequency electromagnetic radiation and heavy metals (Ding et al., 2012a, 2004, 2013a, 2009a; Ding and Salvi, 2005; Ding et al., 2009b, 2011a, 2011b, 2012b, 2013b, 2014a; Ding et al., 2014b; Fu et al., 2012; Liu et al., 2014, 2011; Nicotera et al., 2004; Qi et al., 2008; Wei et al., 2010a, 2010b; Wu et al., 2011; Kraus et al., 2011; Allman et al., 2011; Ewert et al., 2012; Mencher et al., 1995). A good understanding of the unique characteristics of rat temporal bone anatomy and exploration of surgical approaches for inner ear drug delivery and electrode insertion are essential for experimental research of the ear in rats. Temporal bone anatomy has been extensively described in humans and other mammals including the rat (Ding and Jiang, 1989; Ding et al., 2010, 2001; Gulya and Schuknecht, 1995; Schuknecht, 1974; Engstrom, 1951; Engstrom et al., 1972; Engstrom and Engstrom, 1971; Engstrom et al., 1979; Engstrom and Sjostrand, 1954; Hellstrom, 1982; Judkins and Li, 1997; Yang et al., 1985; Zhang et al., 2008; Huang et al., 2003; Wang et al., 2008), but still there lacks descriptions of some detailed yet important features in the rat temporal bone and some of the existed descriptions are not necessarily accurate. This paper intends to provide a detailed description of various parts of the rat temporal bone with diagrams to fill some of the blank spots in the knowledge of rat temporal bone anatomy. It also serves as a foundation of our next paper in a series of papers that introduces various surgical approaches for middle and inner ear surgeries in rats. We also hope that the

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information in this paper will help novice researchers in the field familiarize with the rat temporal bone anatomy.

2. Surface landmarks of rat temporal bone

The rat temporal bone shares similar structures with other mammals, including the squamosal, petrosal, tympanic and mastoid bones. The temporal bone is on the lateral side of the skull and contributes to the formation of the middle and posterior cranial fossas of the lateral skull base. It borders the parietal bone superiorly, sphenoid bone medially and inferiorly, zygomatic bone anteriorly and occipital bone posteriorly (Fig. 1A–F).

The lateral side of the temporal bone is comprised of the lateral side of the squamosal, tympanic and mastoid bones. The squamosal bone comprises the superior and anterior part of the temporal bone and borders the parietal, tympanic and mastoid bones. Anteriorly and inferiorly, its zygomatic process connects with the temporal process of maxilla bone to form the zygomatic arch. The posterior extension of the zygomatic process is called the temporal crista, where the temporalis muscle attaches. The tympanic bone forms the middle and lower part of the temporal bone, consisting of the tympanic bulla as well as the bony external auditory canal. It is connected to the squamosal and mastoid bones supero-anteriorly and posteriorly, respectively (Fig. 1A). The lateral wall of tympanic bulla forms part of the floor, roof and anterior wall of the bony auditory canal, while the supero-posterior wall of the canal is formed by the infero-posterior portion of the squamosal bone and anterior portion of the mastoid bone. Due to the more laterally protruding position of the bulla lateral wall as compared to the lower rim of the squamosal bone and the anterior rim of the mastoid bone in forming the ear canal, the opening of the bony canal is a ring of three quarters. Inferior and posterior to the ear canal, there is a bony prominence which is part of the lateral wall of the tympanic bone, but not part of the mastoid bone, different from the human temporal bone (Fig. 1B). The mastoid bone in rat connects with the squamosal bone supero-anteriorly, with the superior occipital bone infero-posteriorly, with the posterior portion of the tympanic bone infero-anteriorly and with the lateral occipital bone infero-posteriorly, with its lateral wall appearing as a diamond shaped plate surrounded by the aforementioned bones (Fig. 1B). Its rough surface indicates attachment of the sternomastoid muscle. Its lateral wall is thin and contains no air cells. On its inner side is the subarcuate fossa of the posterior fossa that houses the flocculonodular lobe of the cerebellum. There is no stylus process in rat temporal bone, but a paracondylar process behind the mastoid bone that originates from the occipital bone (Fig. 1A and C). Between the ear canal

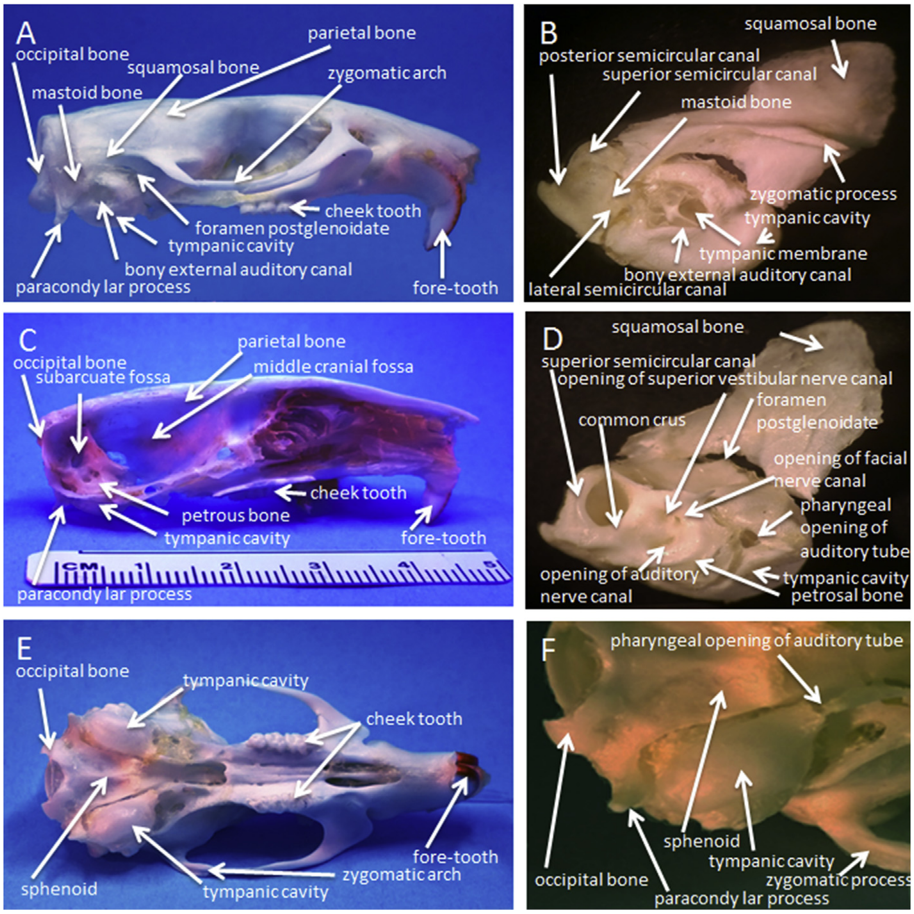

Fig. 1. Landmarks of rat temporal bone. A. Lateral view of rat cranium. B. Lateral view of rat temporal bone. C. Inside view of rat cranium. D. Medial side of rat temporal bone. E. Bottom of rat cranium. F. Bottom view of rat temporal bone.

posterior wall and the anterior side of the mastoid bone is an opening from which the facial nerve leaves the temporal bone and travels forward until branching into several branches to supple facial muscles. We call this opening the outer opening of the temporal segment of facial canal. Between the tympanic bulla and the lower border of the squamosal bone is the foramen postglenoidate (Fig. 1A–C), through which travels veins from the transverse sinus. It is difficult to control a bleeding if the veins was injured during surgeries because these veins are not covered by any bony structures.

The inner side of the temporal bone is the petrosal part of the lateral skull base, with its anterior section forming part of the posterior middle fossa, its medial side forming part of the lateral wall of the posterior fossa, and its bottom forming part of the skull base. The petrosal bone is connected with the occipital bone posteriorly (Fig. 1C and D). In the supero-posterior quarter of the medial aspect of the petrosal bone, there is a noticeable bony depression called the subarcuate fossa, which is separated by a bony wall from the vestibular cavity anteriorly, the ampulla of the superior semicircular canal medially, the superior semicircular canal posteriorly and the common crus of the superior and posterior semicircular canals inferiorly. Inside the subarcuate fossa is the flocculonodular lobe of the cerebellum (Fig. 1C and D). In contrast to human temporal bone, rat temporal bone does not have an internal auditory meatus fundus with separation by bony bars. Instead, there are two openings inferior and anterior to the subarcuate fossa and the one located supero-anterior to the other contains an oblique bony bar that separates the opening into two with the anterior one passing the facial nerve and the posterior one passing the superior vestibular nerve bundle supplying the macula of utricle and ampullas of the lateral and superior semicircular canals. The other opening is the conduit for the auditory nerve bundle that travels to the cochlear modiolus and the inferior vestibular nerve bundle that travels backward to supply the macula of saccule and the ampulla of posterior semicircular canal (Fig. 1C and D). Medial to the junction of the petrosal and occipital bones is a curved bony decompression that contains the sigmoid sinus. Anterior to the sigmoid sinus knee is a bony fissure housing the endolymphatic sac.

The underneath aspects of the temporal bone that connects to the sphenoid and occipital bones is consisted of the ventral tympanic bulla, bottom of petrosal bone, tip of mastoid and paracondylar process. The pharyngeal opening of Eustachian tube can be seen anterior to the tympanic bulla and near the sphenoid bone (Fig. 1E and F).

3. Middle ear of the rat

The tympanic membrane forms the central part of rat middle ear cavity lateral wall and separates the cavity from the ear canal. The membrane can be divided into pars tensa and pars flaccida (Fig. 2A and B). The pars tensa is attached to the annulus in the tympanic sulcus via fibrous cartilage. Its lateral layer is stratified squamous epithelium continuing from skin of the ear canal and inner layer is part of the mucosa covering the entire tympanic cavity. Sandwiched between the two layers is fibrous tissue arranged in radiating or circular patterns. Above the tympanic notch is the pars flaccida that is attached to the temporal squama and comprised of only a skin and a mucosa layer. The part of tympanic cavity above the tympanic membrane is called the epitympanum, the part under the tympanic membrane the hypotympanum and the part posterior to the tympanic membrane the posterior tympanum, while the part between the upper and lower border of the tympanic membrane is called the mesotympanum. There is a 120° angle between the ear canal floor and tympanic membrane, giving the tympanic membrane an oval shaped and semitransparent appearance with a cone of light reflex in the infero-anterior quadrant when viewed from the ear canal with a light source. There is a depression in the center of the membrane, called the umbo. The prominence superior and anterior to the umbo and near the boundary of pars tensa is the malleolar prominence, and between which and the umbo, the malleolar stria from the manubrium behind the membrane is visible. The curve lines anterior and posterior to the malleolar prominence separate pars tensa and pars flaccida (Fig. 2A and B).

The medial wall of rat middle ear cavity is also the lateral wall of the inner ear. The protrusion in the center is called promontory which is the lateral wall of cochlear turns. Superior and posterior to the promontory are the oval and round windows. The oval window is sealed by the stapedial footplate and annular ligament. Medial to the oval window are the vestibular cavity and cochlear vestibular scala. The round window niche is situated lower than oval window and sealed off by the round window membrane at its bottom. On its medial side is the scala tympani. Above the oval window is the horizontal segment of facial canal and anterior to it is the bony canal that contains tensor tympani whose tendon is attached to the medial side of the manubrium (Fig. 2C and D). Inferior and anterior to the promontory is the opening of the Eustachian tube (Fig. 2C and D).

The roof of the middle ear cavity is the tegmen tympani, which is part of the petrosal bone and forms the floor of the middle cranial fossa that houses the temporal lobe. The anterior and inferior walls of the middle ear cavity form part of the skull base. Behind the stapes and on the posterior wall of the middle ear cavity is the pyramidal eminence, from which the stapedius muscle extends forward to connect to the stapes.

The ossicular chain in the tympanic cavity consists of the malleus, incus and stapes. The malleus is comprised of (from above down) the head, collum, long process, short process and manubrium. Different from the human and other mammals, rat malleus long process assumes a near right angle from the manubrium and there is a protrusion from the collum toward the curved lower side of the head, forming a transparent plate (Fig. 3). The manubrium is embedded between the fibrous and mucosal layers of the tympanic membrane. The incus is comprised of a body, a long limb and a short limb (Fig. 3). The anterior side of its body forms the incudomalleolar joint with the head of malleus. Its short limb is attached to the posterior wall of epitympanum via a ligament and its long limb forms the incudostapedial joint with the head of stapes via the

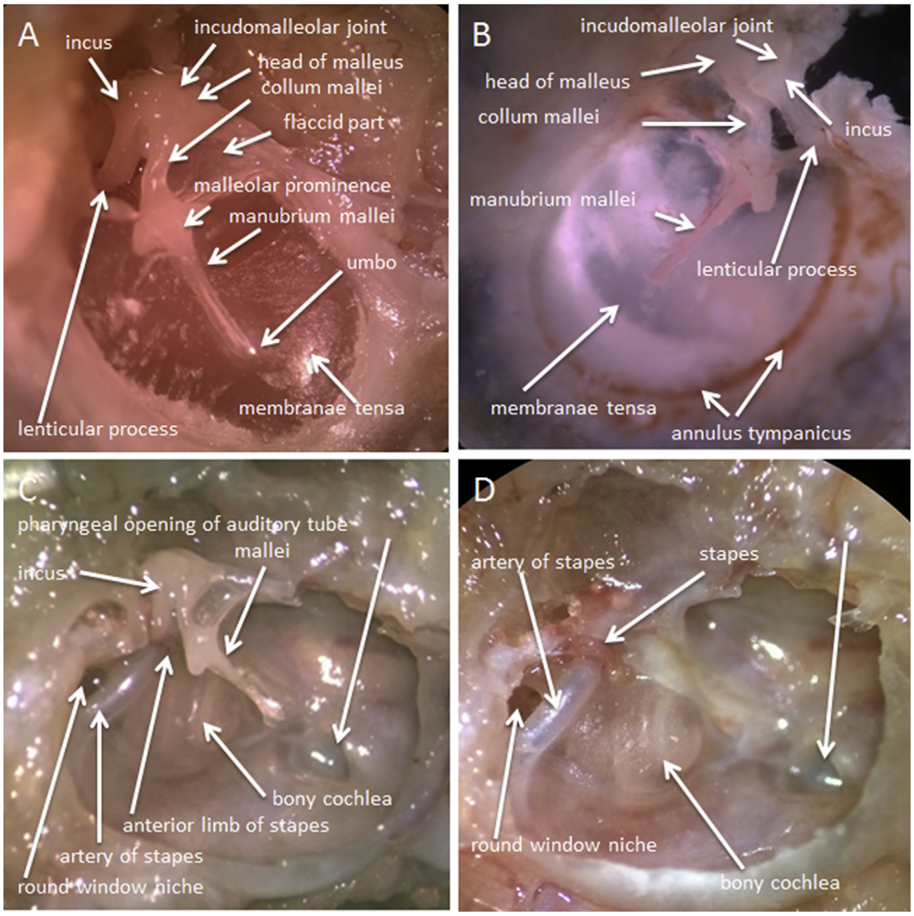

Fig. 2. The lateral and medial walls of rat middle ear cavity. A. Lateral view of tympanic membrane. B. Medial side of tympanic membrane. C. Medial wall of rat tympanic cavity. D. View of medial wall of tympanic cavity without malleus and incus.

lenticular process. The stapes is shaped like a stirrup and is comprised of the head, neck, anterior crus, posterior crus and foot plate (Fig. 3). The footplate is connected to the oval window via the annular ligament. In rats, similar to mice but different from humans and a number of other mammals including some rodents, there is a stapedial artery traveling downwards between the anterior and posterior cruses and footplate (Fig. 2C and D). In addition to connections among the ossicular joints and to the tympanic membrane and oval window, the ossicular chain is also suspended in the tympanic cavity via the tensor tympani, stapedius muscle, superior, anterior and lateral ligaments of the malleus and posterior ligament of the incus.

4. Rat inner ear

The bony shell of the inner ear is called osseous labyrinth (Fig. 4A), which contains the membranous labyrinth similar to

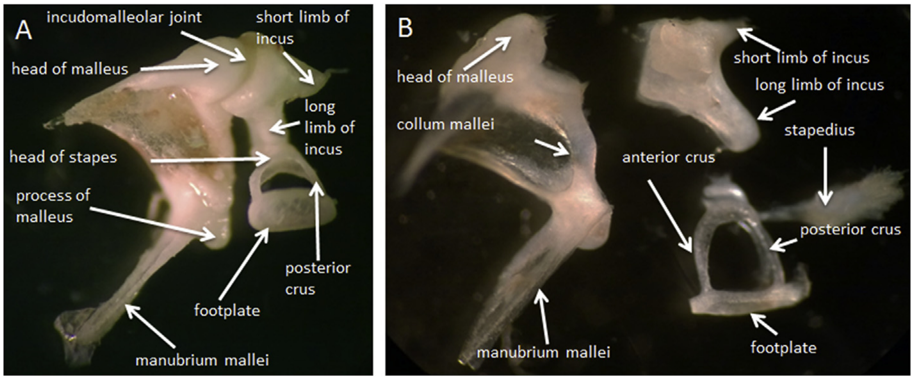

Fig. 3. Rat ossicular chain. A. Entire ossicular chain and joints. B. Separated ossicular bones.

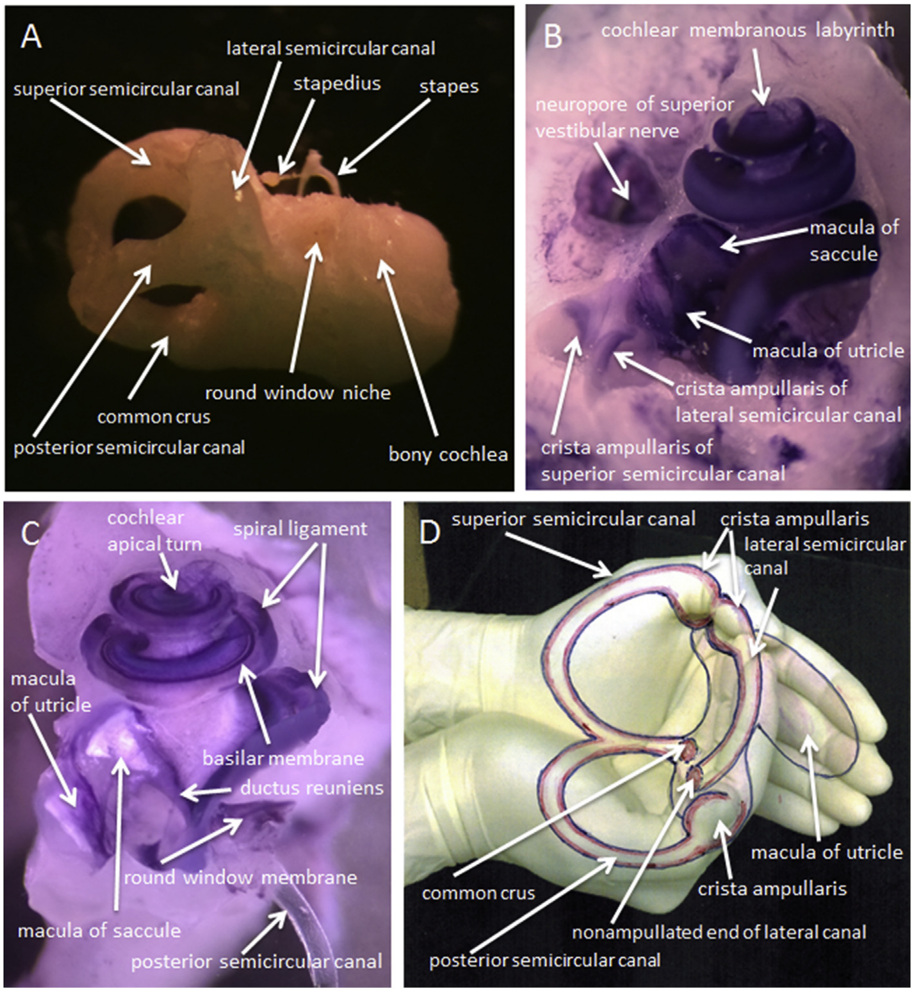

Fig. 4. Osseous and membranous labyrinth in rat. A. Osseous labyrinth. B. Exposure of cochlear membranous labyrinth, saccule and utricle in vestibular cavity and membranous ampullae of superior and lateral semicircular canals. C. Exposure of cochlear basilar membrane, maculae of saccule and utricle, and ampulla of posterior semicircular canal. D. Hand gestures depicting relations among utricle and three semicircular canals.

the bony labyrinth in shape and suspended in the perilymph. The inner ear is divided into the cochlea and vestibule that senses sounds and position changes respectively.

The snail shaped cochlea is positioned anterior to the vestibule and comprised of two and half turns of a spiraling bony tube around an axis called the modiolus. In a normal body position, the apex of the cochlea points inferiorly and anteriorly. However, for the purpose of description, we position the cochlea such its apex points up in this text. The osseous spiral lamina from the modiolus spirals up toward the apex from the base. The basilar membrane between the spiral lamina medially and basal ampulla on the spiral ligament laterally divides the bony cochlear tube into two cavities, with the one below the basilar membrane is named as the scala tympani. The cavity above the basilar membrane is further divided by the Reissner's membrane that extends from the spiral limbus on the osseous spiral lamina on the cochlear basilar membrane to the vestibular crest of the spiral ligament into the scala vestibuli and scala media (or cochlear duct), respectively (Fig. 4B). Similar to other mammals, the cochlear duct in rats is a triangle tube with the basilar membrane, Reissner's membrane and spiral ligament as its boundaries and is filled with the endolymph. The fluid inside scalae vestibuli and tympani is perilymph and communicates with the subarachnoid space via the cochlear aqueduct situated in the basal turn inferior and posterior to the round window niche. The scala vestibuli and scala tympani are connected through the helicotrema at the apex.

Sitting on the middle part of the basilar membrane, the organ of Corti contains the inner and outer hair cells as well as supporting cells and senses vibration of the basilar membrane. The space inside the organ of Corti is filled with cortilymph that is similar to the perilymph. From the cuticular plate, the stereocilium inserts into the tectorial membrane extending from the vestibular lip of the basilar membrane. As the tectorial and basilar membranes attach to different locations on the spiral lamina, the rocking movement of the basilar membrane when vibrating causes a shearing motion between the two membranes, causing deflection of the stereocilium and hence excitation of the hair cells. Both efferent and afferent nerve fibers travel through the hole of habenula perforata on the rim of osseous spiral lamina to connect the organ of Corti.

Spiral ganglion neurons are located in the Rosenthal's canal in the modiolus. Central axons from spiral ganglion neurons, as well as efferent nerve fibers, enter the center of the modiolus and on to the intracranial pathways via openings on the inner wall of Rosenthal's canal.

In rats, the vestibular cavity is situated in the center of the bony labyrinth (Fig. 4A). At the center of its lateral wall, the oval window is covered by the stapes and annular ligament. Its roof borders the epitympanum, posterior wall the subarcuate fossa and medial wall the posterior cranial fossa. Its floor is part of the bottom of petrosal bone.

Within the spherical recess on the medial wall of the vestibular cavity, there is the macula of saccule facing the oval window (Fig. 4B). Its surface is covered by a gelatinous otolithic membrane with an otoconial layer on the top containing crystal-like otoliths. The kinocilia and stereocilia are inserted into the otoconial layer of the otolithic membrane, which bend upon acceleration/deceleration of the head on the sagittal plane due to otolith inertia, inducing stimulation to the hair cells on macular of saccule. Nerve fibers carrying signals from types I and II hair cells in the macular groove pass through small openings in the middle macular cribrosa on the bony wall to arrive at inferior vestibular neurons located at the bottom of the internal auditory canal. The lower part of saccule is connected to the cochlear duct via the ductus reuniens on the lateral side, and to the endolymphatic sac via the vestibular aqueduct on the medial side.

Located in the upper back part of the vestibular cavity at the medial wall, the elliptical recess houses a dumbbell shaped utricle (Fig. 4B), filled with endolymph. In the upper anterior wall of utricle there is an area of thickened epithelium, macula of utricle, containing sensory hair cells. On the surface of macula of utricle, the kinocilia and stereocilia of hair cells are inserted into the otoconial membrane. These hair bundles bend and stimulate hair cells in response to side way head movement in the horizontal plane, whose supplying nerve fibers pass through the superior macular cribrosa on the medial vestibular cavity wall to arrive at the superior vestibular ganglion.

Five openings connect the utricle to the three semicircular canals (Fig. 4C), three at the ampullas, one at the lateral semicircular canal crus and one at the common crus. The bony semicircular canals contain membranous semicircular canals of similar shapes and suspended in the perilymph via connective tissue trabeculae. The membranous semicircular canal is filled with endolymph. In each ampulla, there is a crista, which is covered by sensory hair cells. The location of saddle shaped crista is perpendicular to semicircular canal circling and lie in the convex side of semicircular canal. The distribution of sensory hair cells on the crista of lateral semicircular canal are saddle shaped like humans. However, the sensory epithelium on the crista of posterior and superior canal are divided by a transverse bar of cylindrical cells into two zones. This is very different from humans and other mammals and its significance is yet to be determined. Similar to hair cells in the saccule and utricle, the hair bundles on top of hair cells in the ampulla are attached to the cupula, a sail shaped gelatinous structure covering the ampulla whose inertia causes position shifting of hair bundles in response to head movement, thus generating excitation of hair cells and subsequently the release of neural impulses. The three semicircular canals align with three planes perpendicular to each other. An easy way to memorize their relations is to hold the fingers together and put them at a right angle to the palm. To show positions of semicircular canals in the right ear, point the right hand fingers and palm upward and left hand fingers and palm to the right while having the two hands touching each other by their medial sides. In this hand position, the left palm represents the plane of the superior semicircular canal, left hand fingers the plane of utricle macula, right palm the plane of lateral semicircular canal, and right hand fingers the plane of superior semicircular canal, while the thumbs indicate locations of the ampullas (Fig. 4D). Rotation in the plane of each semicircular canal will cause relative position shifting of the cupula and subsequently excitation of hair cells in the specific canal more than those in other canals. Nerve endings at the base of hair cells send signals along nerve fibers that travel through cribrosa on the back side of bony ampulla to arrive at either the superior or inferior vestibular ganglions. At the lower corner of the wall behind the utricle macula, there is a communication channel from saccule to the sinus of the endolymphatic duct by the saccular duct. The utricular duct leaves the inferior part of the utricle via a cleft-shaped opening to enter the sinus of endolymphatic duct. The endolymphatic duct drains the endolymph to the endolymphatic sac via the vestibular aqueduct.

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References

Allman, B., Manohar, S., Lewicki, L., et al., 2011. Auditory cortex neuronal death and hippocampal neurogenesis following blast-induced traumatic brain injury. Abstr. Assoc. Res. Otolaryngol. 34, 154.

Ding, D., Jiang, S., 1989. In: Manual of Techniques for Inner Ear Anatomy and Histology Study in Guinea Pigs. Xuelin Press Shanghai, pp. 24–35.

Ding, D., Salvi, R., 2005. Review of cellular changes in the cochlea due to aminoglycoside antibiotics. Volta Rev. 105, 407–438.

Ding, D., Li, M., Jiang, S., et al., 2001. Anatomy of temporal bone and inner ear. In: Inner Ear Morphology. Heilongjiang Science and Technology Press, Haerbin, pp. 10–17.

Ding, D., Jiang, H., McFadden, S.L., et al., 2004. Ethacrynic acid is the key for opening of the blood-labyrinth barrier. Chin. J. Otol. 2, 42–47.

Ding, D., Qi, W., Yu, D., et al., 2009. Ototoxic effects of mefloquine in cochlear organotypic cultures. J. Otol. 4, 29–38.

Ding, D., Wang, P., Jiang, H., et al., 2009. Gene expression in cisplatin ototoxicity and protection with p53 inhibitor. J. Otol. 4, 15–24.

Ding, D., Jiang, T., Qi, W., et al., 2010. Chapter 1 inner ear anatomy. In: Inner Ear Science. China Science and Technology Press, Beijing, pp. 1–8.

Ding, D., Someya, Sh, Jiang, H., et al., 2011. Detection of apoptosis by RT-PCR array in mefloquine-induced cochlear damage. Chin. J. Otol. 6 (1), 1–8.

Ding, D., Roth, J., Salvi, R., 2011. Manganese is toxic to spiral ganglion neurons and hair cells in vitro. Neurotoxicol. 32, 233–241.

Ding, D., Allman, B.L., Salvi, R., 2012. Review: ototoxic characteristics of platinum antitumor drugs. Anat. Rec. Hob. 295, 1851–1867.

Ding, D., Jiang, H., Fu, Y., et al., 2012. Ototoxic effects of carboplatin in organotypic cultures in chinchillas and rats. J. Otol. 7 (2), 92–101.

Ding, D., Qi, W., Yu, D., et al., 2013. Addition of exogenous NAD$^+$ prevents mefloquine-induced neuroaxonal and hair cell degeneration through reduction of caspase-3-mediated apoptosis in cochlear organotypic cultures. PloS One 8 (11) e79817.

Ding, D., Jiang, H., Fu, Y., et al., 2013. Ototoxic model of oxaliplatin and protection from nicotinamide adenine dinucleotide. J. Otol. 8 (1), 22–30.

Ding, D., Salvi, R., Roth, J., 2014. Cellular localization and developmental changes of the different isoforms of divalent metal transporter 1 (DMT1) in the inner ear of rats. BioMetals 27 (1), 125–134.

Ding, D., Salvi, R., Roth, J., 2014. Cellular localization and developmental changes of Zip8, Zip14 and transferrin receptor 1 in the inner ear of rats. Biometals 27 (4), 731–744.

Engstrom, H., 1951. Microscopic anatomy of the inner ear. Acta Otolaryngol. 40, 5–22.

Engstrom, H., Engstrom, B., 1971. The inner ear. J. Otolaryngol. Soc. Aust. 3, 307–316.

Engstrom, H., Sjostrand, F.S., 1954. The structure and innervation of the cochlear hair cells. Acta Otolaryngol. 44, 490–501.

Engstrom, H., Bergstrom, B., Ades, H.W., 1972. Macula utriculi and macula sacculi in the squirrel monkey. Acta Otolaryngol. Suppl. 301, 75-1.

Engstrom, H., Engstrom, B., Watanuki, K., 1979. The labyrinth of the American bullfrog. Adv. Otorhinolaryngol. 25, 1–6.

Ewert, D.L., Lu, J., Li, W., et al., 2012. Antioxidant treatment reduces blast-induced cochlear damage and hearing loss. Hear Res. 285 (1–2), 29–39.

Fu, Y., Ding, D., Jiang, H., et al., 2012. Ouabain-induced cochlear degeneration in rat. Neurotox. Res. 22, 158–169.

Gulya, A.J., Schuknecht, H.F., 1995. Anatomy of the Temporal Bone with Surgical Implications, second ed. Parthenon Pub. Group, New York.

Hellstrom, S., 1982. Salcarvation of the. Anatomy of the rat middle ear. A study under the dissection microscope. Acta Anat. 112 (4), 346–352.

Huang, X., Xiao, H., Wang, J., 2003. An anatomy and histology study of rat endolymphatic sac. Acta Anat. Sin. 34 (3), 327–329.

Judkins, R.F., Li, H., 1997. Surgical anatomy of the rat middle ear. Otolaryngol. Head Neck Surg. 117 (5), 438–447.

Kraus, K.S., Ding, D., Jiang, H., et al., 2011. Relationship between noise-induced hearing-loss, persistent tinnitus and growth-associated protein-43 expression in the rat cochlear nucleus: does synaptic plasticity in ventral cochlear nucleus suppress tinnitus? Neuroscience 194, 309–325.

Liu, H., Ding, D., Jiang, H., et al., 2011. Ototoxic destruction by co-administration of kanamycin and ethacrynic acid in rats. J. Zhejiang Univ. Sci. B 12, 853–861.

Liu, H., Ding, D., Sun, H., et al., 2014. Cadmium-induced ototoxicity in rat cochlear organotypic cultures. Neurotox. Res. 26 (2), 179–189.

Mencher, G.T., Novotny, G., Mencher, L., et al., 1995. Ototoxicity and irradiation: additional etiologies of hearing loss in adults. J. Am. Acad. Audiol. 6 (5), 351–357.

Nicotera, T.M., Ding, D., McFadden, S.L., et al., 2004. Paraquat-induced hair cell damage and protection with the superoxide dismutase mimetic m40403. Audiol. Neurotol. 9, 353–362.

Qi, W., Ding, D., Salvi, R., 2008. Cytotoxic effects of dimethyl sulphoxide (DMSO) on cochlear organotypic cultures. Hear. Res. 236, 52–60.

Schuknecht, H.F., 1974. Pathology of the Ear. Harvard University Press, Cambridge, Mass, pp. 21–96.

Wang, Z., Hao, L., Li, Z., et al., 2008. Anatomy Atlas of Wistar Rat. Shandong Science and Technology Publishing Hourse, Jinan, pp. 4–9.

Wei, L., Ding, D., Salvi, R., 2010. Salicylate-induced degeneration of cochlea spiral ganglion neurons-apoptosis signaling. Neuroscience 168, 288–299.

Wei, L., Ding, D., Sun, W., et al., 2010. Effects of sodium salicylate on spontaneous and evoked spike rate in the dorsal cochlear nucleus. Hear. Res. 267, 54–60.

Wu, X., Ding, D., Sun, H., et al., 2011. Lead neurotoxicity in rat cochlear organotypic cultures. J. Otol. 6, 45–52.

Yang, A., Wang, P., Pan, W., 1985. Anatomy and Histology of Rat. Science Press, Beijing, pp. 6–16.

Zhang, Q., Tian, P., Xu, M., et al., 2008. A study of microanatomy of temporal bone in rat. Chin. J. Otol. (4), 464–467.