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Review Article

An Updated Terminology for the Internal Ear with Combined Anatomical and Clinical Terms

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ABSTRACT

Here we report a recent revision of the terminology in the Chapter Sense Organs (*Organa sensuum*) of the Terminologia Anatomica and the Terminologia Histologica that addressed the internal or inner ear, and which the Neuroanatomy Working Group of the Federative International Programme for Anatomical Terminology (FIPAT) of the International Federation of Associations of Anatomists (IFAA) updated thoroughly. After extensive discussions within FIPAT, and consultation with the IFAA Member Societies, these parts of the TA and TH were merged to form Chapter 3 of the newly established Terminologia Neuroanatomica, which currently stands alone. Since validation at the IFAA Executive Meeting, September 22, 2016, in Göttingen, Germany, the TNA has been placed on the FIPAT website open section as part of the official FIPAT Terminology. August 9, 2019, the TNA was accepted at the 19th World Congress of the IFAA in London as its official terminology for the nervous system and the sense organs. This review presents an overview of the updated terminology for the internal or inner ear used in the TNA, compares anatomical and clinical terms to bridge the gap between both approaches, and provides brief descriptions and illustrations. We adopt a recent proposal for combining name recognition with anatomical description, aiming at a short and clear nomenclature. Consequently, this review also presents an overview of eponyms associated with the human inner ear over the years. In Tables, the changes in terminology are further explained.

Keywords: Terminology internal ear; Vestibular labyrinth; Cochlear labyrinth; Spiral organ; Inner ear; Eponyms

INTRODUCTION

Recently, the Neuroanatomy Working Group of the Federative International Programme for Anatomical Terminology (FIPAT) of the International Federation of Associations of Anatomists (IFAA) revised and updated the official anatomical terminology in the Chapter Sense Organs (*Organa sensuum*) of the Terminologia Anatomica [1] and the Terminologia Histologica [2] thoroughly. After extensive discussions within FIPAT, and consultation with the IFAA Member Societies, these parts of the TA and TH were merged to form Chapter 3 of the newly established Terminologia Neuroanatomica [3], which currently stands alone. Since validation at the IFAA Executive Meeting, September 22, 2016, in Göttingen, Germany, the TNA has been placed on the FIPAT website's open section as part of the official FIPAT Terminology.

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August 9, 2019, the TNA was accepted at the 19th World Congress of the IFAA in London as its official terminology for the nervous system and the sense organs. An illustrated version was published in 2018 [4]. This review presents an overview of the updated terminology for the internal or inner ear used in the TNA, compares anatomical and clinical terms to bridge the gap between both approaches, and provides brief descriptions and illustrations of most structures. A recent proposal combining name recognition with anatomical description [5] was adopted. Consequently, this review also presents an overview of eponyms associated with the human inner ear over the years.

The various terms in the TNA are presented in six columns: Latin official term, Latin synonym(s), English official term with British and American spelling, respectively, English synonym(s), and Notes with Related terms and Eponyms. British English and American English are used as equivalent official English terms. Here, American English terms are used with the Latin terms in italics. Synonyms are mentioned as second terms both for the English and Latin terms. The Tables presents most of the terms in use in four columns: English terms (*official and synonyms*), Latin terms (*official and synonyms*), Eponyms and Clinical terms. Infrequent structures are placed between parentheses.

The Tables included in this paper are systematically partonomic tables. Each indentation in their hierarchies is the expression of a part_of relation when an anatomical entity A is indented below B, it means A part_of B. Plural terms strictly define the maximal set of the entity mentioned strictly hair cells is the set of all hair cells. The part_of relation between two plural terms is interpreted as subset of in the spiral organ; Border cells subset_of cells of cochlear duct. The usage of upper-case letters is absent in the terminology and has no meaning, except at the level of presentation, but with quite variable rules between authors. Therefore, all terms proper names are presented in lower-case letters.

For the description of the various structures, McVay [6], Geneser [7], O'Rahilly [8], Lang [9], Schuknecht [10], Williams [11], Merchant and Nadol [12], Janfaza et al. [13] and Rask-Andersen et al. [14] were of great help. For the eponyms, the works of Pagel [15], Politzer [16], Dumesmil and Bonnet-Roy [17], Dobson [18], Hübotter [19], Lustig et al. [20] and Mudry [21] were consulted.

THE INTERNAL EAR IN OVERVIEW

The internal or inner ear (*auris interna*) consists of a bony and a membranous part. The bony labyrinth (*labyrinthus osseus*) consists of a communicating system of cavities and channels in the petrous part of the temporal bone (Figures 1 and 2). It encloses a corresponding system of membranous sacs and ducts, the membranous labyrinth (*labyrinthus membranaceus*). The bony labyrinth communicates with the tympanic cavity through two openings: (1) the vestibular or oval window (*fenestra vestibuli or fenestra ovalis*); and (2) the cochlear or round window (*fenestra cochleae or fenestra rotunda*). The vestibular window is closed by the base of the stapes, so that vibrations of the auditory ossicles are transmitted to the perilymph of the internal ear. The cochlear window is closed by the secondary tympanic membrane (*membrana tympani secundaria*) or round window membrane, which dissipates acoustic energy initially transmitted through the oval window. The internal ear is innervated by the vestibular nerve (*nervus vestibularis*) and the cochlear nerve (*nervus cochlearis*) and vascularized by the labyrinthine artery (*arteria labyrinthi*), usually a terminal branch of the anterior inferior cerebellar artery [10,22] and shows a large number of variations. As to the use of eponyms for the internal ear, the extensive studies on cochlear anatomy by Scarpa [23], von Sömmerring [24] and Retzius [25,26] did not earn them an eponym, apart for Scarpa on the helicotrema and the vestibular ganglion. The term organ of Corti was introduced by von Kolliker (o with Umlaut) [27]. Most of the German anatomists studying the cochlear organ gave an eponym to a part of this organ [16,21].

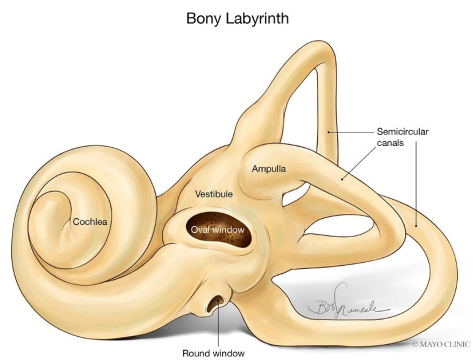

Figure 1: The bony labyrinth, outer view [4].

The bony labyrinth

The Vestibule and the Semicircular Canals: The bony labyrinth (*labyrinthus osseus*) has three parts (Figure 1 and Table 1) the vestibule (*vestibulum*), which continues posteriorly into three semicircular canals (*canales semicirculares*), anterior or superior, lateral or horizontal and posterior, and anteriorly into the cochlea (*cochlea*). Although the lateral semicircular canal is often referred to as the horizontal canal, its plane rests 30 degrees of the true horizontal. The semicircular canals detect angular acceleration as part of the vestibulo-ocular reflex. The bony labyrinth contains the perilymph (*perilympha*) in the perilymphatic space (*spatium perilymphaticum*), surrounding the membranous labyrinth. The semicircular canals are each enlarged near one end as the bony ampulla (*ampulla ossea*), the remaining narrow majority of the semicircular canals are termed the ampullary bony limbs (*crura ossea ampullaria*). The limbs of the anterior and posterior semicircular canals are fused before their transition into the vestibule as the common bony limb (*crus osseum commune*) or common crus, whereas the lateral semicircular canal opens separately as the single bony limb (*crus osseum simplex*). The vestibule contains the saccule (*sacculus*) in a small spherical or saccular recess (*recessus sphericus or recessus saccularis*), and the utricle (*utriculus*) in the elliptical or utricular recess (*recessus ellipticus or recessus utricularis*), responsible for detecting vertical and horizontal linear acceleration, respectively. At places, the walls of the vestibule are perforated by several minute foramina (Figure 2) the maculae cribrosae (*maculae cribrosae*). The spherical recess contains the macula cribrosa media (*macula cribrosa media*), transmitting vestibular fibers to the saccule (*the saccular nerve*). Behind the recess is the oblique vestibular crest (*crista vestibularis*) ending in the pyramid of the vestibule (*pyramis vestibuli*). The ridge encloses a small depression, the cochlear recess (*recessus cochlearis*), perforated by fibers of the cochlear nerve. The pyramid and the adjoining part of the elliptical recess contain the macula cribrosa superior (*macula cribrosa superior*) for nerve fibers to the utricle and the ampullae of the superior and lateral semicircular ducts (*the utriculoampullary or superior vestibular nerve*). In otologic surgery, the macula cribrosa superior is known as "Mike's dot" (after Michael E. Glasscock III, M.D.). It is an important landmark for translabyrinthine resection of an acoustic neurinoma. The macula cribrosa inferior (*macula cribrosa inferior*) contains vestibular fibers for the ampulla of the posterior semicircular duct (*the posterior ampullary or inferior vestibular nerve*).

Table 1: The Bony labyrinth.

English terms	Latin terms	Eponyms	Clinical terms
Bony labyrinth	**Labyrinthus osseus**		
Vestibule	**Vestibulum**		
Elliptical recess; utricular recess	Recessus ellipticus; recessus utricularis		
Vestibular canaliculus ; vestibular aqueduct	Canaliculus vestibuli; aqueductus vestibuli		
Internal opening of vestibular canaliculus	Apertura interna canaliculi vestibuli		
Vestibular crest	Crista vestibuli		
Pyramid of vestibule	Pyramis vestibuli		
Spherical recess; saccular recess	Recessus sphericus; recessus saccularis		
Cochlear recess	Recessus cochlearis		
Maculae cribrosae	Maculae cribrosae		
Macula cribrosa superior	Macula cribrosa superior		Mike's dot
Macula cribrosa media	Macula cribrosa media		
Macula cribrosa inferior	Macula cribrosa inferior		
Semicircular canals	**Canales semicirculares**		
Anterior semicircular canal	Canalis semicircularis anterior		Superior canal
Anterior bony ampulla	Ampulla ossea anterior		
Posterior semicircular canal	Canalis semicircularis posterior		
Posterior bony ampulla	Ampulla ossea posterior		
Common bony limb	Crus osseum commune		Common crus
Ampullary bony limbs	Crura ossea ampullaria		
Lateral semicircular canal	Canalis semicircularis lateralis		Horizontal canal
Lateral bony ampulla	Ampulla ossea lateralis		
Simple bony limb	Crus osseum simplex		
Cochlea	**Cochlea**		
Cochlear cupula	Cupula cochleae		
Base of cochlea	Basis cochleae		
Spiral canal of cochlea	Canalis spiralis cochleae		
Osseous spiral lamina	Lamina spiralis ossea		
Vestibular lamella	Lamella vestibularis		
Tympanic lamella	Lamella tympanica		
Habenula perforata	Habenula perforata		
Cochlear canaliculus ; cochlear aqueduct	Canaliculus cochleae ; aqueductus cochleae	canal of Cotugno	
Internal opening of cochlear canaliculus	Apertura interna canaliculi cochleae		
Cochlear septum	Septum cochleae		
Modiolus of cochlea	Modiolus cochleae		
Base of modiolus	Basis modioli		
Lamina of modiolus	Lamina modioli		
Spiral canal of modiolus	Canalis spiralis modioli	canal of Rosenthal	
Longitudinal canals of modiolus	Canales longitudinales modioli		
Scala vestibuli	Scala vestibuli		
Helicotrema	Helicotrema	orifice of Scarpa	
Scala tympani	Scala tympani		
Internal acoustic meatus	**Meatus acusticus internus**		Internal auditory canal
Internal acoustic pore	Porus acusticus internus		Internal acoustic opening
Fundus of internal acoustic meatus	Fundus meatus acustici interni		Fundus
Transverse crest	Crista transversa		
Facial area	Area nervi facialis		
Vertical crest	Crista verticalis		Bill's bar
Superior vestibular area	Area vestibularis superior		
Inferior vestibular area	Area vestibularis inferior		
Singular foramen	Foramen singulare		
Cochlear area	Area cochlearis; area cochleae		

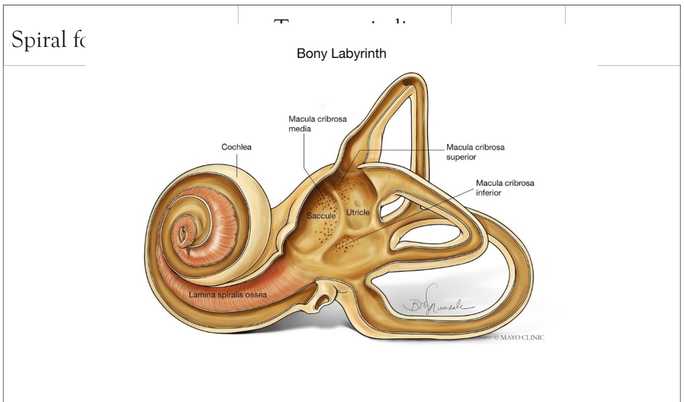

Figure 2: The bony labyrinth, inner view [4].

The Vestibular Canaliculus: A fine bony canal, the vestibular canaliculus (*canaliculus vestibuli*), earlier known as the vestibular aqueduct (*aqueductus vestibuli*) begins in the elliptical recess as the internal opening of the vestibular canaliculus (*apertura interna canaliculi vestibuli*) and opens as the external opening of the vestibular canaliculus (*apertura externa canaliculi vestibuli*) onto the posterior surface of the petrous part of the temporal bone, about midway between the internal acoustic meatus and the sigmoid sulcus [6,28]. The wall of the vestibular canaliculus is formed around the pre-existent part of the membranous labyrinth, the endolymphatic, which ends as the endolymphatic sac (*saccus endolymphaticus*).

The Cochlea: The cochlea is a spirally wound cavity with approximately 2.5 turns, which resembles the shell of a common snail with its base (*basis cochleae*) facing the internal acoustic meatus and its apex (*cupula cochleae*) pointing anterolaterally towards the upper part of the medial wall of the tympanic cavity. The "hook" region (*regio uncinata*) is defined as the most basal part of the cochlear tube, which forms a hook-like structure [29-31]. This part contains the cul-de-sac of the endolymphatic space where the osseous spiral lamina, the spiral ligament and the basilar membrane merge. The cochlea consists of a central, cone-shaped pillar of bone, the modiolus (*modiolus cochleae*) around which a bony canal, the spiral canal of the cochlea (*canalis spiralis cochleae*), is wound spirally for some two and a half turns, described as apical, middle and basal coils. The base of the modiolus is perforated by numerous apertures that continue into fine canals along the long axis of the modiolus, the longitudinal canals of the modiolus (*canales longitudinales modioli*). These house the branches of the cochlear nerve. From the modiolus, a thin bony shelf, the osseous spiral lamina (*lamina spiralis ossea*), extends out into the lumen of the cochlea from base to apex. The longitudinal canals of the modiolus (*canalis spiralis*) have an expansion, and all of the expansions form a spirally wound canal, the spiral canal of the modiolus in which the cochlear ganglion is found.

The Osseous Spiral Lamina: The osseous spiral lamina (*lamina spiralis ossea*) consists of a vestibular lamella (*lamella vestibularis*) and a tympanic lamella (*lamella tympanica*), and in between the habenula perforata (*habenula perforata*). The habenula perforata, a perforated rein, contains about 4,000 openings [26], the foramina nervosa [32], through which the fibers of the cochlear nerve pass. The osseous spiral lamina extends only about halfway into the lumen of the cochlea and thereby incompletely divides the cochlea into two smaller canals (Figure 3), the upper or lateral scala vestibuli (*scala vestibuli*) and the lower or medial scala tympani (*scala tympani*). The two scalae communicate at the apex of the cochlea through an opening, the helicotrema [23]. The scala vestibuli begins in the vestibule in the basal part of the cochlea, whereas the scala tympani begins at the cochlear or round window. The separation of the two scalae is completed by a connective tissue membrane, the basal lamina or basilar membrane [33], which extends from the free edge of the osseous spiral lamina to the outer wall of the cochlea. At its attachment to the external wall of the cochlea, the periosteum is thickened in the form of the basal or spiral crest (*crista basilaris or crista spiralis*).

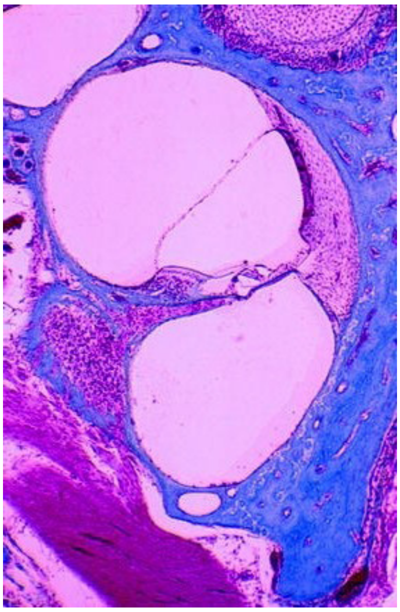

Figure 3: Photomicrograph of the human cochlea.

The Cochlear Canaliculus: A bony channel, the cochlear canaliculus [34], earlier known as the cochlear aqueduct (*aqueductus cochlearis*), begins close to the scala tympani as the internal opening of the cochlear canaliculus (*apertura interna canaliculi cochleae*) and opens as the external opening of the cochlear canaliculus (*apertura externa canaliculi cochleae*) onto the inferior surface of the petrous part of the temporal bone, anterior to the jugular fossa [6,28,35]. The cochlear canaliculus is of secondary formation produced through the resorption of precartilage of the developing otic capsule. It contains the perilymphatic duct (*ductus perilymphaticus*), earlier known as the periotic duct (*ductus perioticus*), and is filled with a loose meshwork of connective tissue (*trabeculae perilymphaticae*).

The Membranous Labyrinth: The membranous labyrinth (*labyrinthus membranaceus*) can be divided into vestibular and cochlear components. The vestibular labyrinth (*labyrinthus vestibularis*) comprises the statoconial sacs, the utricle and the saccule within the vestibule, and the three semicircular ducts within the bony semicircular canals. Moreover, the endolymphatic duct (*ductus endolymphaticus*) and the endolymphatic sac (*saccus endolymphaticus*) are included in the vestibular labyrinth. The cochlear labyrinth (*labyrinthus cochlearis*) is formed by the membranous cochlear duct or scala media (*ductus cochlearis or scala media*), which is situated in the bony cochlea.

The Vestibular Labyrinth: The vestibular labyrinth (*labyrinthus vestibularis*) consists of an enlargement, the utricle (*utriculus*), a smaller vesicle, the saccule (*sacculus*), and three narrow semicircular ducts (*ductus semicirculares*) that emerge from the utricle (Table 2). The utricle and the saccule are connected via the narrow utriculosaccular duct (*ductus utriculosaccularis*). From the utriculosaccular duct the endolymphatic duct (*ductus endolymphaticus*) arises, passes inside the vestibular canaliculus or vestibular aqueduct, and ends as the endolymphatic sac (*saccus endolymphaticus*), which is thought to be responsible for endolymph resorption. The semicircular ducts are oriented orthogonal to each other; there are lateral or horizontal, anterior or superior and posterior ducts (*ductus semicircularis lateralis, -anterior or superior, and – posterior*; Figure 2). The vestibular part of the membranous labyrinth is connected via the saccule with the auditory part by a thin tube, the ductus reuniens (*ductus reuniens*) [36]. The lateral wall of the utricle and the medial wall of the saccule contain a thickening, the macule of the utricle (*macula utriculi*) and the macula of the saccule (*macula sacculi*), containing vestibular hair cells. The maculae are covered by the statoconial or otolithic membrane (*membrana statoconiorum*), composed of outer and inner sheaths (*stratum externum membranae statoconiorum and stratum internum gelatinosum membranae statoconiorum*). The membrane contains cylindric crystals of calcium carbonate known as statoconia (*statoconia*) or otoconia. In the middle of the statoconial membrane, a stripe (*striola*) is found.

Table 2: The Vestibular Labyrinth.

English terms	Latin terms	Eponyms	Clinical terms
Vestibular labyrinth	**Labyrinthus vestibularis**		
Utricle	**Utriculus**		
Utricular recess	Recessus utricularis; recessus utriculi		
Saccule	**Sacculus**		
Semicircular ducts; membranous semicircular ducts	**Ductus semicirculares**		
Anterior semicircular duct	Ductus semicircularis anterior		
Anterior membranous ampulla	Ampulla membranacea anterior		
Posterior semicircular duct	Ductus semicircularis posterior		
Posterior membranous ampulla	Ampulla membranacea posterior		
Common membranous limb	Crus membranaceum commune		
Ampullary membranous limbs	Crura membranacea ampullaria		
Lateral semicircular duct	Ductus semicircularis lateralis		
Lateral membranous ampulla	Ampulla membranacea lateralis		
Simple membranous limb	Crus membranaceum simplex		
Maculae	**Maculae**		
Macula of utricle	Macula utriculi		
Macula of saccule	Macula sacculi		
Statoconial membrane; otolithic membrane	Membrana statoconiorum		
Outer sheath of statoconial membrane	Stratum externum membranae statoconiorum		
Statoconium; otolith	Statoconium		otocomium
Inner sheath of statoconial membrane; gelatinous layer of statoconial membrane	Stratum internum membranae statoconiorum		
Striola	Striola		
Ampullary crest	**Crista ampullaris**		
Ampullary groove	Sulcus ampullaris		
Ampullary cupula	Cupula ampullaris		
Semilunate plane	Planum semilunatum		
Cells of vestibular labyrinth	**Cellulae labyrinthi vestibularis**		
Vestibular hair cells; vestibular sensory cells	Vestibulocyti; cellulae sensoriae pilosae		
Type 1 vestibular hair cells; type 1 vestibular sensory cells	Vestibulocyti typi I; vestibulocyti piriformes		
Type 2 vestibular hair cells; type 2 vestibular sensory cells	Vestibulocyti typi II; vestibulocyti columnares		
Vestibular supporting cells	Vestibulocyti sustenantes		
Utriculosaccular duct	**Ductus utriculosaccularis**		
Utricular duct	Ductus utricularis		
Saccular duct	Ductus saccularis		

Endolymphatic duct	Ductus endolymphaticus		
Endolymphatic sac	Saccus endolymphaticus		
Ductus reuniens	Ductus reuniens	duct of Hensen	
Nonsensory surface; unspecialized surface	Membrana nonsensoria labyrinthi		

Each semicircular duct contains a sensory end-organ ridge or crest (*the ampullary crest, crista ampullaris*) that rests inside an enlargement near one end of the canal, the lateral, anterior and posterior membranous ampulla (*ampulla membranacea lateralis*) anterior and posterior, and contains the vestibular hair cells. At either end of each ampullary crest, the epithelium forms a crescent-shaped thickening, the semilunate plane (*planum semilunatum*). The rest of the vestibular labyrinth is formed by the nonsensory surface (*membrana nonsensoria labyrinthi*).

Vestibular Hair Cells: Two types of vestibular hair or sensory cells (*vestibulocyti or cellulae sensoriae pilosae*) can be distinguished [37,38] (1) type I vestibular hair or sensory cells (*vestibulocyti typi I or vestibulocyti piriformes*) and (2) type II vestibular hair or sensory cells (*vestibulocyti typi II or vestibulocyti columnares*). Type I hair cells are flask-shaped, have a round base, a spherical nucleus, and are surrounded by an afferent nerve calix (*calix nervosus afferens*) from the vestibular nerve. Type II hair cells are cylindrical with an oval nucleus and without an afferent nerve calix surrounding the nerve cell body. Both types I and II vestibular hair cells have an apical cuticular plate (*lamina cuticularis apicalis*) and a stereociliary bundle consisting of stereocilia (*stereocilia vestibulocyti*). Vestibular supporting cells (*vestibulocyti sustenantes*) lack stereocilia and a cuticular plate.

The Cochlear Labyrinth: The cochlear labyrinth (*labyrinthus cochlearis*) is formed by the cochlear duct or scala media [39], which contains the spiral organ of Corti, resting on the basal lamina or basilar membrane (Figure 3 and Table 3). It is filled with endolymph (*endolympha*), which is rich in potassium and has the characteristics of intracellular fluid. The cochlear duct ends blindly at the apex of the cochlea as the cupular cecum (*caecum cupulare*) and at the vestibule as the vestibular cecum (*caecum vestibulare*). The vestibular surface of the cochlear duct (*paries vestibularis*), located superiorly, consists of the vestibular membrane [39] and angles downwards from lateral to medial, making the cochlear duct wedge shaped on cross section. The external surface (*paries externus*) is formed by the spiral ligament (*ligamentum spirale*), the thickened periost of the cochlea at the level of the cochlear duct. Its main part is specialized as the stria vascularis (*stria vascularis*), which produces the endolymph. The spiral prominence (*prominentia spiralis*) is a highly vascularized thickening of the connective tissue of the spiral ligament, containing the vas prominens (*vas prominens*). The outer spiral sulcus (*sulcus spiralis externus*) separates the stria vascularis from the spiral organ. It is covered by the root cells of the cochlea (*cellulae radiculares cochleae*).

Table 3: The cochlear labyrinth.

English terms	Latin terms	Eponyms	Clinical terms
Cochlear labyrinth	**Labyrinthus cochlearis**		
Cochlear duct; scala media	**Ductus cochlearis; scala media**	Canal of Reissner	
Vestibular surface	Paries vestibularis		
Vestibular membrane	Membrana vestibularis	Membrane of Reissner	
Simple squamous epithelium of vestibular membrane	Epithelium simplex squamosum membranae vestibularis		
Lamina propria of vestibular membrane	Lamina propria membranae vestibularis		
Vestibular squamous cell layer	Lamina cellularum squamosarum vestibularium		
External surface	Paries externus		
Stria vascularis	Stria vascularis		
Marginal epithelium of stria vascularis	Epithelium marginale striae vascularis		
Marginal cells of stria vascularis	Cellulae marginales striae vascularis		
Intermediate melanocytes of stria vascularis	Cellulae melanocyticae intermediae striae vascularis		
Basal cells of stria vascularis	Cellulae basales striae vascularis		
Capillary plexus of stria vascularis	Plexus capillaris striae vascularis		
Spiral prominence	Prominentia spiralis		
Vas prominens	Vas prominens		
Spiral ligament	Ligamentum spirale		
Type 1 fibrocytes of spiral ligament	Fibrocyti typi I ligamenti spiralis		
Type 2 fibrocytes of spiral ligament	Fibrocyti typi II ligamenti spiralis		
Type 3 fibrocytes of spiral ligament	Fibrocyti typi III ligamenti spiralis		
Outer spiral sulcus	Sulcus spiralis externus		
Root cells of cochlea	Cellulae radiculares cochleae		
Tympanic surface; spiral membrane	Paries tympanicus; membrana spiralis		

Basal crest; spiral crest	Crista basilaris; crista spiralis		
Basal lamina; basilar membrane	Lamina basilaris; membrana basilaris	spiral membrane of Duverney	
Vas spirale	Vas spirale		
Spiral limbus	Limbus spiralis		
Tympanic lip	Labium tympanicum limbi spiralis		
Foramina nervosa	Foramina nervosa	foramina of Morgagni	habenula perforata
Vestibular lip	Labium vestibulare limbi spiralis		
Acoustic teeth	Dentes acustici	teeth of Huschke	
Interdental cells	Epitheliocyti interdentales		
Inner spiral sulcus	Sulcus spiralis internus		
Tectorial membrane	Membrana tectoria	membrane of Corti	
Inner stripe of tectorial membrane	Linea interna membranae tectoriae	stripe of Hensen	
Outer stripe of tectorial membrane	Linea externa membranae tectoriae	membrane of Hardesty; stripe of Kimura	
Vestibular cecum	Caecum vestibulare		
Cupular cecum	Caecum cupulare		

The Spiral Organ: The spiral organ [40] is located on the tympanic surface, the inferior or medial wall of the cochlear duct. It contains hair cells, supporting cells and border cells (Figure 4 and Table 4). The cochlear hair cells [40] are the sensory receptor cells of which there is a single row of inner hair cells (*cochleocyti interni*) and three rows of outer hair cells (*cochleocyti externi*). They exhibit a tonotopic distribution: receptors sensitive to high frequencies are located near the cochlear base and those sensitive to low frequencies near the cochlear apex. The supporting cells (*epitheliocyti sustenantes*) include the inner and outer pillar cells, also known as rods of Corti, which are separated by the inner tunnel [40] extending along the whole length of the cochlea, and the inner and outer phalangeal cells. The border cells (*epitheliocyti limitantes*) include inner and outer sulcus and border cells. The cochlear hair cells and part of the supporting cells are overlaid by the gelatinous tectorial membrane [40]. The connective tissue of the limbus forms teeth-like protrusions, the auditory teeth [41], which are separated by deep furrows. Toward the cochlear duct, the auditory teeth are covered by a simple epithelium, formed by the interdental cells (*epitheliocyti interdentales*). The tectorial membrane is anchored to the interdental cells of the vestibular lip of the spiral limbus. At the site of the inner hair cells, the inner stripe of the tectorial membrane [36] is found, a thickening of the tectorial membrane. Here, the tectorial membrane is anchored to the inner phalangeal and border cells [42,43]. More externally, the outer stripe of the tectorial membrane [44,45] is found. Here, the tallest rows of the outer hair cells are embedded in the tectorial membrane [45].

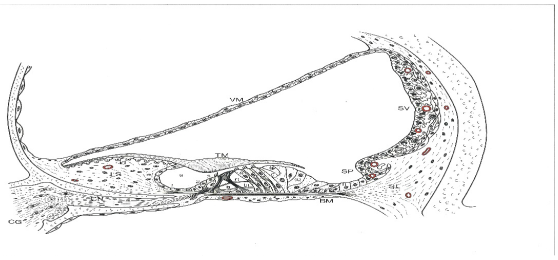

Figure 4: The spiral organ of Corti [4,10]. Abbreviations: *a* inner spiral tunnel, *b* inner tunnel of Corti, *BM* basal lamina, *bt* basal tunnel fiber (afferent), *c* outer tunnel, CG cochlear ganglion, *CN* cochlear nerve, *id* interdental cells, *LS* spiral limbus, *rt* radial tunnel fiber (efferent), *SL* spiral ligament, *SP* spiral prominence, *SV* stria vascularis, *TM* tectorial membrane, *VM* vestibular membrane, *1* inner sulcus cell, *2* inner border cell of Held, *3* inner phalangeal cell, *4* inner hair cell, *5* inner pillar cell, *6* outer pillar cell, *7, 9* outer phalangeal cells of Deiters, *8* outer hair cell, *10* outer border cell of Hensen, *11* outer sulcus cell of Claudius, *12* basal external glandular cell of Boettcher.

Table 4: The spiral organ.

English terms	Latin terms	Eponyms	Clinical terms
Spiral organ	**Organum spirale**	Organ of Corti	
Cells of cochlear duct	**Cellulae ductus cochlearis**		
Border cells	Epitheliocyti limitantes		
Inner sulcus cells; cuboidal inner sulcus cell	Epitheliocyti limitantes sulci interni		
Inner/internal border cells	Epitheliocyti limitantes interni	Inner border cells of Held	
Outer/external border cells	Epitheliocyti limitantes externi	Outer border cells of Hensen	
Basal external glandular cells	Epitheliocyti glandulares externi basales	Glandular cells of Boettcher	
Outer sulcus cells, cuboidal outer sulcus cells	Epitheliocyti limitantes sulci externi	Epithelial cells of Claudius	
Supporting cells	Epitheliocyti sustenantes		
Inner/internal pillar epithelial cells	Epitheliocyti interni pilae	Rods of Corti	
Outer/external pillar epithelial cells	Epitheliocyti externi pilae	Rods of Corti	
Inner/internal phalangeal epithelial cells	Epitheliocyti phalangei interni		

Outer/external phalangeal epithelial cells	Epitheliocyti phalangei externi	Epithelial cells of Deiters	
Cochlear hair cells	Cochleocyti	Hair cells of Corti	
Inner hair cells	Cochleocyti interni		
Outer hair cells	Cochleocyti externi		
Reticular membrane	Membrana reticularis		
Tunnels	**Cuniculi**		
External tunnel	Cuniculus externus	Tunnel of Held	
Inner tunnel	Cuniculus internus	Tunnel of Corti	
Intermediate tunnel; pilar-hair cell space	Cuniculus intermedius	Tunnel/space of Nuel	
Vestibulocochlear ganglia	**Ganglia vestibulocochlearia**		
Cochlear ganglion; spiral ganglion	**Ganglion cochleare; ganglion spirale**	Ganglion of Corti	
Bipolar neurons of cochlear ganglion	Neura bipolaria ganglii cochlearis		
Outer spiral ganglion cells; nonmyelinated perikarya; type II cells	Perikarya nonmyelinata	Type II neurons of Spoendlin	
Inner spiral ganglion cells; myelinated perikarya; type I cells	Perikarya myelinata	Type I neurons of Spoendlin	
Satellite cells of cochlear ganglion	Gliocyti ganglionici ganglii cochlearis		
Radial fibers of cochlear ganglion	Neurofibrae radiales ganglii cochlearis		Note: Afferent from type I ganglion cell
Basilar fibers	Neurofibrae basilaris		Note: Efferent, olivocochlear fiber
Spiral fibers of cochlear ganglion	Neurofibrae spirales ganglii cochlearis		Note: Afferent from type II ganglion cell
Inner spiral bundle	Fasciculus spiralis internus		
Outer spiral bundle	Fasciculus spiralis externus		
Vestibular ganglion	**Ganglion vestibulare**	Ganglion of Scarpa	
Bipolar neurons of vestibular ganglion	Neura bipolaria ganglii vestibularis		
Large neurons of vestibular ganglion	Neura magna ganglii vestibularis		
Small neurons of vestibular ganglion	Neura parva ganglii vestibularis		
Satellite cells	Gliocyti ganglionici ganglii vestibularis		

Sulcus, Border and Supporting Cells: The sulcus, border and supporting cells of the spiral organ are arranged from the inner spiral sulcus in an external direction (Figure 4 and 5): (1) the inner or cuboidal inner sulcus cell (*epitheliocytus limitans sulci interni*); (2) the inner or internal border cell (*epitheliocytus limitans internus*) or inner border cell of Held [46, 47]; (3) the inner or internal phalangeal cell (*epitheliocytus phalangeus internus*); (4) the inner or internal pillar cell (*epitheliocytus internus pilae*) or rod of Corti [40]; (5) the outer or external pillar cell (*epitheliocytus externus pilae*) or rod of Corti [40]; (6) the outer or external phalangeal cell (*epitheliocytus phalangeus externus*) or epithelial cell of Deiters [48]; (7) the outer or external border ell (*epitheliocytus limitans externus*) or border cell of Held {36]; (8) the basal external glandular cell (*epitheliocytus glandularis externus*) or glandular cell of Boettcher [49], restricted to the basal turn (Figure 5), and (9) the outer or cuboidal sulcus cell (*epitheliocytus limitans sulci externi*) or supporting cell of Claudius [50]

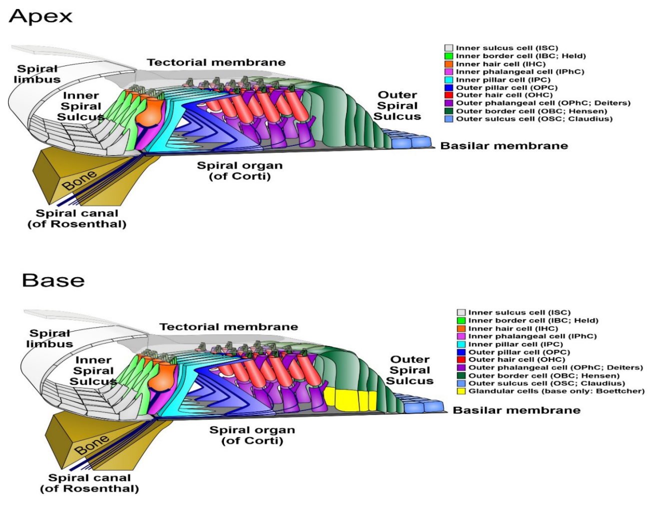

Figure 5: The cellular components of the spiral organ of Corti in its apex (a) and base (b) [5].

The supporting cells all rest on the basal lamina of the epithelium that separates the epithelial cells of the spiral organ from the connective tissue of the epithelium. At their free surface, the cochlear hair, pillar and phalangeal cells are interconnected by junctional complexes, light-microscopically with the appearance of a continuous thin membrane, the reticular membrane [27]. In the epithelium of the spiral organ, several clefts or tunnels (*cuniculi*) exist between the lateral cell surfaces: (1) the inner or internal tunnel [40] (2) the intermediate tunnel [51] (3) the outer or external tunnel [46,47].

Cochlear Hair Cells: In humans, there are 12,000 outer hair cells (*cochleocyti externi*) in three rows at the basal turn of the cochlea, increasing to four to five rows in the middle and apical turns, and 3,500 inner hair cells (*cochleocyti interni*) in a single row [26,44,52]. On their apical side, the cochlear hair cells contain contractile proteins, including an actin cuticular plate or apical cuticle (*lamina cuticularis*), and about 100 stereocilia, graded in length in a row of stereocilia (*ordo stereociliorum*), which extend to the overlying tectorial membrane. The stereocilia of the cochlear hair cells (*stereocilia cochleocyti*) are composed of the active contractile proteins actin and myosin [53,54]. The cochlear hair cells are innervated by the peripheral processes of bipolar ganglion cells in the cochlear ganglion. The afferent fibers from the hair cells pass from the spiral organ through small openings called foramina nervosa [32] in the osseous spiral lamina into the modiolus, also known as habenula perforata (*habenula perforata*). Their cell bodies are located within the spiral canal of the modiolus [55] as the cochlear or spiral ganglion. Their central processes form the cochlear nerve and terminate in the cochlear nuclei of the brain stem.

The transition from hair cell activity to neural activity occurs within the cochlea. Activation of the stereocilia results in changes in the intracellular potential that leads to the release of a neurotransmitter from synaptic vesicle clusters at the base of the cochlear hair cells. Opposite such a cluster of synaptic vesicles, bulbous nerve terminals are found on the outer surface of the cell wall. Six to eight such terminals are present on the base of each inner hair cell, and a smaller number on each outer hair cell [56]. These terminals continue as short unmyelinated processes, forming the dendritic segment (*peripheral process*) of cochlear nerve fibers. They become myelinated when they enter the osseous spiral lamina. Here, they reach their cells of origin, the ganglion cells of the cochlear ganglion. The hair cells are also innervated by the olivocochlear bundle [57] from the periolivary nuclei in the brain stem, which form the basilar fibers (*fibrae basilares*).

Inner and Outer Sections of the Spiral Organ: Recently, Fritzsch and Elliott [5] proposed to divide the spiral organ of Corti into an inner and an outer section, separated by the inner tunnel of Corti, and taking into account ultrastructural details and their functional significance [44,58-60]. The inner section is the sound-receiving section and includes the inner sulcus cells, inner border cells, inner hair cells, inner pillar cells and inner phalangeal cells. In this subdivision, the neuronal processes of the type I ganglion cells, receiving input from the inner hair cells, are termed the inner spiral ganglion cells. Apart from transient expansion of some inner spiral neurons into the outer section during development [61] and under certain conditions of disorganization of hair cells [62], these neuronal processes of type I spiral ganglion cells remain within the inner section. The lateral olivocochlear system of inner ear efferent fibers remains also restricted to the inner section [63,64] and should be renamed inner olivocochlear efferents.

The outer section is regarded as the sound-amplifying section and includes the outer pillar cells, the outer hair cells, the outer phalangeal cells, the outer border cells and the outer sulcus cells. As for the inner section, the afferent and efferent innervation should be renamed to reflect their exclusive projection to outer hair cells [65,66]. Therefore, type II spiral ganglion cells, receiving input from the outer hair cells, become the outer spiral ganglion cells and the medial olivocochlear system the outer olivocochlear efferents.

Neural Components of the Internal Ear: The neural parts of the internal ear are the cochlear ganglion, the vestibular ganglion, the vestibular nerve and the cochlear nerve (Figure 6).

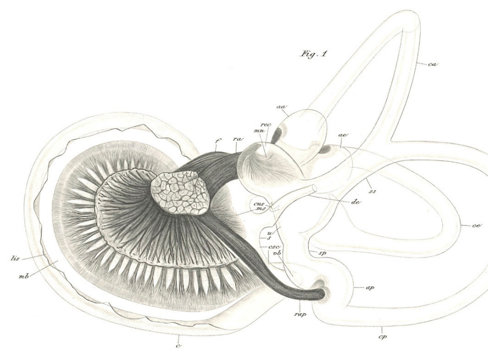

Figure 6: Neural components of the internal ear as present in the membranous part of a five-months-old fetus [40]. Abbreviations: *aa* ampulla anterior, *ae* ampulla externa, *ap* ampulla posterior, c cochlea membranacea, *ca* canalis membranaceus anterior, *ce* canalis membranaceus externus, *cp* canalis membranaceus posterior, *cr* crista acustica ampullaris, *cus* canalis utriculoampullaris, de ductus endolymphaticus, *f* nervus facialis, *lis* ligamentum spirale, *mb* membrana basilaris, *ms* macula acustica sacculi, *mu* macula acustica utriculi, *ra* ramus anterior, *raa* ramus ampullae anterioris, *rae* ramus ampullae externae, *rap* ramus ampullae posterioris, *rb* ramulus basilaris, *rec* recessus utriculi, *rs* ramus sacculi, *ru* ramus recessus utriculi, *s* sacculus, *sp* sinus utriculi posterior, *ss* sinus utriculi superior, *u* utriculus.

The Cochlear or Spiral Ganglion: The cochlear or spiral ganglion [40] extends only halfway from the base of the cochlea (*basis cochleae*) to the apex, the cochlear cupula (*cupula cochleae*). Therefore, the peripheral processes, reaching the cochlear hair cells in the apical and middle coils of the cochlea, extend down through the modiolus to reach the most apical ganglion cells. In humans, there are about 35,000 bipolar neurons of the cochlear ganglion [67,68]. Two types are found, the majority of which (90-95%) are type I cells (*myelinated perikaryon, perikaryon myelinatum*), contacting inner hair cells via radial fibers (*neurofibrae radiales*), recently renamed inner spiral ganglion cells [5]. The unmyelinated peripheral processes of the remaining 5%-10%, the type II cells (*nonmyelinated perikaryon, perikaryon nonmyelinatum*), recently remamed outer spiral ganglion cells [5], contact the outer hair cells via spiral fibers (*neurofibrae spirales*), arranged as inner and outer spiral bundles (*fasciculus spiralis internus, externus*). The central processes of both types of ganglion cells form the cochlear nerve [69].

The Vestibular Ganglion: The vestibular ganglion [23] is found outside the bony labyrinth within the internal acoustic meatus. Its superior and inferior parts continue into the superior and inferior parts of the vestibular nerve that identifies an intermediate part receives fibers from the saccule [70].

The Eight Cranial Nerve: The eighth cranial nerve, colloquially referred to as vestibulocochlear nerve (*nervus vestibulocochlearis*;

Figure 6) enters the internal acoustic meatus (*meatus acusticus internus*) or internal auditory canal through the internal acoustic opening (*porus acusticus internus*). The vestibular branche projects exclusively to vestibular nuclei to innervate four subdivisions: the lateral vestibular nucleus (LVN), the medial vestibular nucleus (MVN), the superior vestibular nucleus (SVN) and the deesecending vestibular nucleus (DVN). The cochlear branch enters the cochlear nucleus separate from the vestibular projection. The cochlear nerve splits into three divisions: the anterio-ventral cochlear nucleus (AVCN), the postero-ventral cochlear nucleus (PVCN) and the dorsal cochlear nucleus (DCN). The internal acoustic meatus ends blindly as the fundus of the internal acoustic meatus (*fundus meatus acustici interni*), a thin cribriform plate of bone separating the cochlea and the vestibule from the internal acoustic meatus (Figure 7). The transverse crest (*crista transversa*) divides the fundus into two regions: a superior and an inferior region. The superior region is divided by a vertical crest [11] into an anterior, facial area (*area nervi facialis*) for the facial nerve, and a posterior, superior vestibular area (*area vestibularis superior*) for the superior part of the vestibular nerve, also known as the utriculoampullary or superior vestibular nerve (*pars superior, nervus utriculoampullaris or nervus vestibularis superior*), which divides into (1) the utricular nerve (*nervus utricularis*), also previously known as the ramus saccularis superior (2) the anterior ampullary nerve (*nervus ampullaris anterior*) and (3) the lateral ampullary nerve (*nervus ampullaris lateralis*). The inferior region consists of (1) the inferior vestibular area (*area vestibularis inferior*) for the saccular or posterior vestibular nerve (*nervus saccularis or nervus vestibularis posterior*) of the inferior part of the vestibular nerve (*pars inferior*) (2) the singular foramen (*foramen singulare*), a small opening for the posterior ampullary or inferior vestibular nerve (*nervus ampullaris posterior or nervus vestibularis inferior*), also part of the inferior part of the vestibular nerve and (3) the cochlear area (*area cochlearis*) with the coiled spiral foraminous tract (*tractus spiralis foraminosus*) for the cochlear nerve.

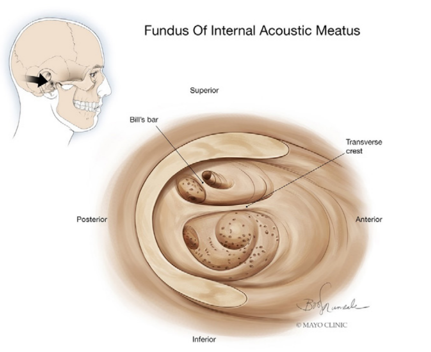

Figure 7: The fundus of the internal acoustic meatus [4].

The Cochlear or Vestibulocochlear Anastomosis: The cochlear or vestibulocochlear communicating branch (*ramus communicans cochlearis*) or anastomosis of Oort [71] is an interconnection between the vestibular and cochlear nerves through which olivocerebellar fibers pass to the cochlea to innervate the inner and outer hair cells.

Vessels of the internal ear

The Labyrinthine Artery: The internal ear is supplied by the labyrinthine artery (*arteria labyrinthi*), also known as the internal auditory artery, which usually is a branch of the anterior inferior cerebellar artery (*arteria cerebelli inferior anterior*) from which it courses into the internal acoustic meatus (Figure 8). The labyrinthine artery divides into two main branches [72-77], (1) the anterior vestibular artery (*arteria vestibularis anterior or arteria vestibuli*) and (2) the common cochlear artery (*arteria cochlearis communis*), which divides into (a) the vestibulocochlear artery (*arteria vestibulocochlearis*) (b) the proper or main cochlear artery (*arteria cochlearis propria*) and (c) the spiral modiolar artery (*arteria modioli spiralis*). The vestibulocochlear artery further divides into: (a) a variable anterior vestibular branch (*ramus vestibularis anterior*) (b) the posterior vestibular branch (*ramus vestibularis posterior*) and (c) the cochlear branch (*ramus cochlearis*).

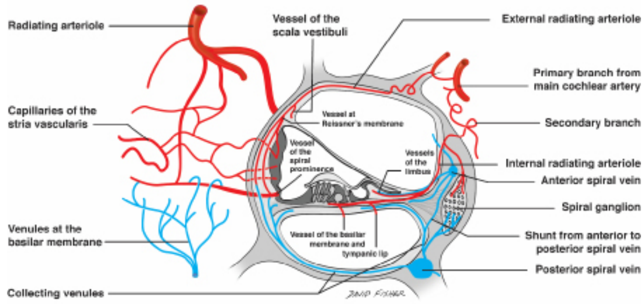

Figure 8: Principal arteries of the internal ear [79, 81].

Usually, the proper cochlear artery supplies three-fourths of the cochlea, whereas the cochlear branch of the vestibulocochlear artery supplies the basal one-fourth of the cochlea [78]. The anterior vestibular artery supplies the macula of the utricle, a small part of the macula of the saccule, the ampullary crests and the membranous ducts of the superior and lateral semicircular canals. The posterior vestibular branch supplies the macula of the saccule, the ampullary crest and the membranous duct of the posterior semicircular canal, and the inferior surfaces of the utricle and saccule. The proper cochlear artery enters the central canal of the modiolus and gives off several primary and many secondary branches. The radiating arterioles are further ramifications and consist of two sets: (1) for the structures of the external wall and (2) for the structures of the internal wall of the cochlea [79,80].

Veins from the Internal Ear: The veins from the internal ear take another course than that of the arteries, especially in the cochlea (Figure 8). The main venous channels of the cochlea are the anterior and posterior spiral veins. The posterior spiral vein (*vena spiralis posterior*) drains the cochlear ganglion, the external wall of the cochlear duct, and the scala tympani. The anterior spiral vein (*vena spiralis anterior*) drains the osseous spiral lamina and the scala vestibuli. The spiral veins join near the basal end of the cochlea to form the common modiolar vein (*vena modioli communis*). The vestibulocochlear vein (*vena vestibulocochlearis*) joins the common modiolar vein to form the vein of the cochlear aqueduct (*vena aqueductus cochleae*), also previously described as the inferior cochlear vein. This main venous channel enters a bony canal, coursing very near the cochlear canaliculus (*canaliculus cochlearis*) or canal of Cotugno [34], and drains into the inferior petrosal sinus [35]. Labyrinthine veins or internal auditory veins (*venae labyrinthi*), accompanying the labyrinthine artery, drain the apical and middle coils of the cochlea and empty into the inferior petrosal sinus via the interior acoustic meatus.

The anterior vestibular vein (*vena vestibularis anterior*) drains the utricle and the ampullae of the superior and lateral semicircular canals [82]. The posterior vestibular vein (*vena vestibularis posterior*) drains the saccule, the ampulla of the posterior semicircular canal and the basal end of the cochlea. The vestibular veins join, receive the vein of the cochlear window (*vena fenestrae cochleae*), and form the vestibulocochlear vein. The semicircular ducts are drained by veins of the semicircular ducts (*venae ductuum semicircularium*), passing toward the ampullae to form the vein of the vestibular aqueduct (*vena aqueductus vestibuli*), which accompanies the endolymphatic duct in the vestibular canaliculus and drains into the sigmoid sinus. Various studies of the venous drainage of the internal ear show great variations.

CONCLUSION

In this review, we present a terminology for the anatomy and histology of the internal ear and its components that has been revised extensively and updated with a comparison of anatomical and clinical data. This terminology is based on Chapter 3 of the Terminologia Neuroanatomica derived from the Chapter Sense Organs of the Terminologia Anatomica and the Terminologia Histologi. The updated terminology presents a new approach to anatomical terminology that combines anatomical and histological terms with brief descriptions and illustrations, as an example for the other parts of the human body. In this review, eponyms and clinical terms are included and a new subdivision of the spiral organ of Corti into an inner, sound-receiving section and an outer, sound-amplifying section is advocated.

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AUTHOR CONTRIBUTIONS

Conceptualization: H.J.tD., B.F. and D.K.; data acquisition and analysis: H.J.tD., B.F., K.E., D.K., M.C., B.I., V.T., J.B., R.S.T. and R.B.; drafting of the manuscript: H.J.tD. and B.F.; critical revision: D.K., M.C., B.I., V.T., K.E., J.B., R.S.T. and R.B. All authors approved the final version of the manuscript.

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