

## **Chapter 140: Cochlear Anatomy and Central Auditory Pathways**

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This chapter provides a brief review of the anatomy of the cochlea and its central auditory pathways. Since there is great similarity between the basic features of the human cochlea and those in a variety of animals, we have chosen the chinchilla as a representative animal model.

### **Historical Perspective**

Knowledge concerning the anatomy of the cochlea has long lagged behind that of other sensory systems because of its complexity and inaccessibility. The cochlea consists of delicate membranous structures that are suspended in fluids and surrounded by the hardest bone of the body. Because of these features, the two most useful methods to examine the membranous labyrinth are dissection of wholmount, surface preparations and radial sectioning. Alphonse Corti (1851) first described the organ of Corti using surface preparations and radial sections of the cochlear duct (Fig. 140-1). His drawings, although revealing postmortem artifact, provided many accurate details of important structures of the membranous labyrinth including the organ named in his honor. Corti's work inspired further studies by other investigators, including Reissner, Deiters, Boettcher, Claudius, Hensen, and particularly Retzius (1884), who produced exquisitely detailed drawings of the cochlea (Fig. 140-2). A comparison of Retzius' drawings with micrographs of the cochlea produced using current technology reveals the great accuracy of his observations.

Increased knowledge of the structure of the cochlea was paralleled by a better understanding of its function, and various theories of hearing were proposed during the same time period, including the resonance theory (Helmholtz, 1863) and the telephone theory (Rutherford, 1886). Subsequently, a number of investigators have substantially improved our understanding of the function and structure of the cochlea, including Bekesy (1960) for the traveling wave; Engstrom et al (1966) for systematic description of hair cell damage using a map called the cochleogram; Davis (1958) for the mechanoelectrical theory of hearing; and Smith (1954) for the ionic composition of endolymph, to name only a few outstanding individuals. Further details on the historical development of our knowledge of the anatomy and physiology of the cochlea has recently been provided by Hawkins (1988).

### **Cochlear Anatomy**

#### **Skull**

In the chinchilla (*C. laniger*) the cochlea lies within a large air-filled bulla (Fig. 140-3). The cochlea lies in a somewhat horizontal position relative to the axis of the skull. It is also apparent that the chinchilla cochlea has a thin otic capsule, has large round and oval windows, and is well defined from the surrounding temporal bone. These features, combined with a relatively long life span, a broad frequency range, and a high sensitivity to acoustic trauma are the primary reasons that the chinchilla has been an excellent animal model for hearing studies (Browning and Granich, 1978; Miller, 1970).

## **Osseous labyrinth**

The osseous labyrinth consists of bony structures that surround the internal membranous labyrinth and are best revealed in radial sections of the cochlea (Figs. 140-4 and 140-5). The otic capsule is thin toward the middle ear cavity and is connected via septa to an internal bony tube called the modiulus. These bony septa contain approximately three spirally arranged channels or scalae. The scala vestibuli begins at the oval window membrane and extends to the cochlear apex. It communicates, via the helicotrema, with the scala tympani, which then extends basally and ends at the round window membrane. These two scalae contain perilymph, which is an extracellular-like fluid containing a high Na<sup>+</sup> and low K<sup>+</sup> ion concentration. Between these two perilymphatic scalae is the scala media (Figs. 140-4 and 140-5). The scala media contains endolymph, which is an intracellular-like fluid containing a high K<sup>+</sup> and low Na<sup>+</sup> ion concentration (Smith, 1954). This channel is sealed at the cochlear apex but communicates with the endolymphatic compartments of the vestibular system via the ductus reuniens.

## **Membranous labyrinth**

The membranous labyrinth consists of channels containing cells and tissues that line the bony labyrinth of the cochlea and vestibular systems. In some places, such as Reissner's membrane, the membranous labyrinth is only two cells thick. The most specialized tissues of the cochlea, and the location of the sensory receptor cells, are within the membranous tissues of the scala media or the cochlear duct. The triangular-shaped cochlear duct can be divided into three regions: (1) Reissner's membrane, which forms a boundary between the scala media and the scala vestibuli (Figs. 140-4 to 140-6); (2) the lateral wall (Figs. 140-5 to 140-7), which includes the spiral ligament, stria vascularis, spiral prominence, and the external sulcus; (3) the basilar membrane and osseous spiral lamina, which forms a boundary between the scala media and the scala tympani and includes (Figs. 140-5 to 140-9) Claudius' cells; Boetcher's cells; organ of Corti, containing Hensen's cells, Deiters' cells, pillar cells, inner border cells, outer hair cells, and the inner hair cells; inner sulcus; and spiral limbus containing the interdental cells and tectorial membrane. Medial to the osseous spiral lamina lies Rosenthal's canal containing the spiral ganglion, which communicates with the modiulus (Figs. 140-4 and 140-5). Each of these tissues will be described in detail in the following sections.

### ***Reissner's membrane***

Reissner's or the vestibular membrane divides the scala media from the scala vestibuli by a three-layered structure consisting of two cell layers separated by a basal lamina (Figs. 140-5, 140-6, and 140-10). Reissner's membrane is attached medially to the modiolar edge of the spiral limbus and laterally to the spiral ligament at the apical edge of the stria vascularis. The cells facing endolymph have a low-cuboidal shape, exhibit numerous apical microvilli, and are sealed by tight junctions (see Fig. 140-10). A trilaminar basement membrane lies between the two cell layers. The cells facing perilymph have a squamous shape and are loosely joined together. Reissner's membrane appears to be freely permeable to water, but it restricts paracellular passage of large molecules into the endolymph through the tight junctions (Duvall and Sutherland, 1972; Konishi et al, 1984).

## *Lateral wall*

**Spiral ligament.** The spiral ligament forms most of the lateral wall of the cochlear duct and consists of loose connective tissues and cells rich in ion-transporting enzymes. Its lateral boundary is the inner surface of the otic capsule, and its medial boundary is formed by the stria vascularis and the spiral prominence (see Figs. 140-4 to 140-7). It extends into the scalae vestibuli and tympani and forms a lateral route of communication between these two perilymphatic channels. Anchoring cells, which may be able to exert tension on the basilar membrane, have recently been described at the junction of the spiral ligament and the otic capsule (Henson and Henson, 1988; Henson et al, 1985). The matrix of the spiral ligament primarily contains fibroblast-like cells (type I and II; Takahashi and Kimura, 1970) and numerous extracellular filaments (Figs. 140-7 and 140-11). The fibroblast type I cell predominates in the spiral ligament; however, two other cell types, fibroblast type II and the external sulcus cells, occur in the spiral ligament near the spiral prominence. The type II fibroblast cells have been shown to contain Na<sup>+</sup>, K<sup>+</sup>-ATPase, and carbonic anhydrase ion-transporting enzymes (Lim et al, 1983; Schulte and Adams, 1989).

**Stria vascularis.** The stria vascularis forms the endolymphatic border of the cochlear duct (Figs. 140-6, 140-7, and 140-12). It extends from the attachment of Reissner's membrane to the spiral prominence. In the chinchilla its average length is 25.22 mm, and its area, width, and thickness decrease toward the cochlear base (Santi and Muchow, 1979). It is a somewhat stratified epithelium containing primarily three cell types (marginal, intermediate, and basal cells) and intraepithelial capillaries (Fig. 140-12). The stria vascularis also contains melanocyte, pericyte, and endothelial cells. In the chinchilla the volume density of the four primary components of the stria vascularis are, respectively, 0.53, 0.21, 0.16, and 0.1 (Santi et al, 1983). The marginal cells appear to be the primary functional units of the stria vascularis and probably produce the positive DC endocochlear potential and the low-sodium, high-potassium ion concentration of cochlear endolymph (Smith et al, 1954; Tasaki and Spyropoulos, 1959; Tasaki et al, 1954). They are the only cells that directly face the endolymph, and their basolateral surface is convoluted into numerous mitochondria-packed folia that are rich in Na<sup>+</sup> and K<sup>+</sup>-ATPase (Kerr et al, 1982; Schneider et al, 1987; Schulte and Adams, 1989). The intermediate cells, melanocytes, and intraepithelial capillaries occupy the middle layer of the stria vascularis. The intermediate cells are stellate-shaped, electrolucent cells that appear to have phagocytic activity. They have also been reported to contain carbonic anhydrase enzyme activity (Lim et al, 1983). The capillaries are formed by nonfenestrated endothelial cells that are surrounded by a dense homogeneous basement membrane (Fig. 140-13). This basement membrane is probably formed by the fusion of epithelial and endothelial basement membranes during development (Kikuchi and Hilding, 1966). The capillaries are also invested by pericyte cells. The basal surface of the stria vascularis is sealed from paracellular transport of materials by several layers of tightly interdigitated basal cells. These cells may contain lipid inclusions and have apical processes that interdigitate with processes of the marginal and intermediate cells.

**Spiral prominence.** The spiral prominence is a spirally directed ridge of tissue between the stria vascularis and the basilar membrane (see Figs. 140-6 to 140-8 and 140-13). It is covered by a single layer of cuboidal-shaped epithelial cells that lie on a basement membrane. The connective tissue matrix of the spiral prominence contains omega-shaped capillary loops and numerous fibroblast type II cells (see Figs. 140-6 to 140-8 and 140-13).

Rootlike processes of the external sulcus cells also occur in the matrix of the spiral prominence. Because of the high concentration of fibroblast type II cells and the omega-shaped capillary loops in the spiral prominence, the function of this tissue is most likely to be ion transport.

**External sulcus.** The open channel formed by the spiral prominence and the Claudius' cells of the basilar membrane is called the external sulcus. The external sulcus lie beneath the Claudius' cells and send long, rootlike processes into the matrix of the spiral prominence and the spiral ligament (see Figs. 140-6 to 140-8). These cells are rich in organelles but have an electron-lucent cytoplasm (see Fig. 140-11). A thick basement membrane occurs along the root-like processes. These cells have also been reported to contain carbonic anhydrase (Lim et al, 1983).

### *Basilar membrane*

The basilar membrane extends from the lateral edge of the osseous spiral lamina to its insertion into the spiral ligament in a wedge-shaped tissue called the basilar crest (Figs. 140-6 and 140-8) (Iurato, 1962). It is primarily composed of connective tissue and is fundamentally important for the tonotopicity of the cochlea. Its spiral length averages 31.5 mm in the human and 18.3 mm in the chinchilla (Bohne and Carr, 1979; Hardy, 1938). Its width increases toward the cochlear apex from 150 to 450 microm in the human and from 230 to 370 microm in the chinchilla (Lim, 1980; Wever, 1938).

Its width is divided into a medial pars arcuata and a lateral pars pectinata (see Fig. 140-6). The pars arcuata primarily consists of radial filaments that split to form two bundles (in the cochlear base) that extend through the pars pectinata and into the spiral ligament. Amorphous material that has been shown to be rich in the glycoprotein fibronectin (Santi et al, 1989) lies between the fiber bundles and comprises a large portion of the pars pectinata (Figs. 140-14 and 140-15). In the chinchilla, the thickness of the pars pectinata decreases toward the apex from 16.5 to 5 microm because of a decrease in the thickness of the amorphous material (Lim, 1980). Changes in the width and thickness of the basilar membrane along its length are responsible for the propagation of the traveling wave and the frequency-specific maximal vibrations of the membrane.

The scala tympani surface of the basilar membrane is contiguously covered by spindle-shaped, spirally directed, mesothelial cells that form the tympanic covering layer (see Figs. 140-6 and 140-8). A spirally directed vessel, called the vas spirale, may occur beneath the inner tunnel of Corti (see Fig. 140-9). However, this vessel appears to be rudimentary, and the exchange of metabolites of the organ of Corti appears to occur via diffusion of perilymph through the basilar membrane and spaces of Nuel (Duvall and Sutherland, 1972; Kimura and Ota, 1974).

**Claudius' cells.** Claudius' cells are cuboidal-shaped cells that cover the endolymphatic side of the basilar membrane and extend along the width of the basilar membrane from Hensen's cells to the spiral prominence (see Figs. 140-6 to 140-8). Claudius' cells resemble the inner sulcus cells with their prominent spheric nuclei and empty-looking cytoplasm. Their apical surface contains short microvilli and their borders are sealed on their endolymphatic surface by tight junctions. Their basal pole has direct contact with the basilar membrane except

where intervening Boettcher's cells occur. Claudius' cells form a tight cellular border between endolymph of the scala media and perilymph of the scala tympani.

**Boettcher's cells.** Boettcher's cells lie between the basal surface of the Claudius' cells and the apical portion of the basilar membrane (see Figs. 140-6 to 140-8). Boettcher's cells occur most frequently in the cochlear base and decrease in number completely toward the apex. They form a single layer of cuboidal-shaped cells and often occur in clusters of cells. Their cytoplasm contains a rich complement of organelles, and their density is much greater than Claudius' cells. Their laterobasal borders contain microvilli and form channels containing fibronectin above the basilar membrane (Fig. 140-15). Their function may be to produce fibronectin and other matrix components for the basilar membrane. They may also be involved in fluid transport since they appear to contain carbonic anhydrase (Lim et al, 1983).

### *Organ of Corti*

The organ of Corti consists of a spiral array of alternating sensory hair cells and supporting cells that are supported by the basilar membrane and overlaid by the tectorial membrane (Figs. 140-2, 140-9, and 140-16). The primary function of the organ of Corti is to convert mechanical vibrations of the basilar membrane to neural impulses that are transmitted to the brain. In addition, recent evidence suggests that the hair cells, in concert with efferent innervation from the brain, are able to mechanoelectrically tune the output of sensory information from the organ of Corti (Brownell, 1985; Siegel and Kim, 1982).

The organ of Corti consists of the following lateral to medial components (Iurato, 1961): Hensen's cells, outer tunnel of Corti, three to four rows of outer hair cells, Deiters' cells with phalangeal processes, spaces of Nuel, outer pillar cells, inner tunnel of Corti, inner pillar cells, inner hair cells, inner phalangeal cells, and inner border cells (see Figs. 140-9 and 140-16). A rigid platelike structure, called the reticular lamina, is formed by the apical processes of the supporting and sensory cells of the organ of Corti. Most of the structures of the organ of Corti change as a function of distance along the basilar membrane. Toward the cochlear apex, increases occur in the radial area of the organ of Corti, the length of the inner and outer hair cell bodies and their stereocilia, the angle and width of the apical surface of the organ of Corti relative to the basilar membrane, the length of the pillar cell head plates, and the height of Hensen's cells.

The organ of Corti can best be examined using surface preparations and radial sections. From surface preparations, degenerated or damaged hair cells can be assessed as a function of distance along the length of the cochlear duct, and a map, called a cochleogram or cytochleogram, can be constructed (Engstrom et al, 1966). Cytochleograms are essential to determine the relationship between hair cell loss/damage and a frequency-specific decrease in hearing threshold. Each structure of the organ of Corti, beginning with the lateral supporting cells, will be described in the following sections.

## Supporting cells

**Hensen's cells.** Hensen's cells form the lateral border of the organ of Corti but are not part of the reticular lamina (see Figs. 140-9, 140-15, and 140-16). They consist of several rows of tall columnar cells that increase in height toward the cochlear apex. Their nuclei occur high in their cytoplasm, and not all of these cells make direct contact with the endolymphatic space. In some species, such as the guinea pig, Hensen's cells contain large, lipid inclusions. Between the last row of outer hair cells and Hensen's cells is a fluid-filled space, the outer tunnel of Corti, which in some animals (for example, gerbil and kangaroo rat) is quite large.

**Deiters' cells.** Deiters' cells support the outer hair cells at their base and apex (see Fig. 140-9). They are attached to the basilar membrane and form a cuplike process around the basal pole of the outer hair cell. The cuplike process is open at the base to allow attachment of the afferent and efferent nerve terminals to the outer hair cell body. In addition, a thin process containing microtubules and filaments, the phalangeal process, branches off the Deiters' cell body and extends obliquely to the apical process of adjacent outer hair cells. This dumbbell-shaped process joins together four different outer hair cells in a rigid platelike array called the reticular lamina (see Fig. 140-16). In the chinchilla the slope of the reticular lamina relative to the plane of the basilar membrane increases from 3.5 degrees at the base to 35 degrees in the cochlear apex (Lim, 1980). The fluid-filled spaces between the outer hair cell bodies and the phalangeal processes of the Deiters' cells are the spaces of Nuel.

**Pillar cells.** The inner and outer pillar cells oppose each other and form the inner triangular-shaped tunnel of Corti and portions of the reticular lamina (see Figs. 140-9, 140-15, and 140-16). Each pillar cell has a broad base containing a spheric nucleus and a slender apically directed process containing microtubules and actin filaments. At the level of the reticular lamina each apical process of the cell forms a flattened rectangular-shaped head plate. The inner head plates lie above the outer head plates and form the endolymphatic surface of the inner tunnel. Phalangeal processes of the inner pillar cells also separate the inner hair cells laterally. Phalangeal processes of the outer pillar cells travel to the endolymphatic surface to laterally separate the first row of the outer hair cells. The basilar membrane, spaces of Nuel, and the inner tunnel of Corti probably contain perilymph (Duvall and Sutherland, 1972).

**Inner border and phalangeal cells.** The inner border and phalangeal cells separate the inner sulcus cells from the medial surface of the inner hair cells (see Figs. 140-9 and 140-15). The inner border cells form the most medial edge of the organ of Corti. The apical processes of the inner phalangeal cells separate the innerhair cells laterally from one another and medially from the inner border cells. However, the inner phalangeal cells do not separate the inner hair cells from the inner pillar cells at the level of the reticular lamina. Basally, the inner phalangeal cells envelop the unmyelinated nerve fibers associated with the inner hair cell.

## Sensory cells

**Stereocilia.** Both the inner and outer hair cells contain apical stereocilia that are fundamentally important for hair cell transduction. Stereocilia increase in length from the cochlear base toward the apex and laterally across the rows of the outer hair cells (Figs. 140-16 and 140-17). Inner hair cell stereocilia are approximately twice as thick and are more club shaped than outer hair cell stereocilia. Stereocilia are not true cilia but are long, stiff microvilli that extend from the cuticular plate of the hair cell. The stereocilia are graded in length across the rows with the longest row being the most lateral.

The stereocilia are connected to one another within the bundle by two sets of linking filaments (Fig. 140-17) (Osborne et al, 1984; Pickles et al, 1984). Lateral cross-links attach the stereocilia to one another within and between the rows. Vertical or tip links occur between the tips of the shorter stereocilia and shafts of the longer stereocilia. The vertical cross-links may be part of the transduction channels of the hair cells (Hudspeth, 1983; Pickles et al, 1984). The rigid structure of the stereocilia is due to the axially directed, polarized actin filaments within the stereocilia (Flock and Cheung, 1977; Slepecky et al, 1981; Tilney et al, 1980). The actin filaments of each stereocilium form a compact bundle or rootlet that enters the filamentous cuticular plate of the hair cell body. Mature cochlear hair cells, unlike vestibular hair cells, do not contain a kinocilium; however, a remnant of the kinocilium, the basal body, occurs in an electron-lucent area in the cuticular plate and is present in cochlear hair cells. The outer hair cell stereocilia bundle forms a V- or W-shaped pattern whose angle becomes more acute toward the cochlear apex and from the first to the third row of hair cells. The apical surface of the hair cells contains a bundle of six or seven rows of stereocilia. The inner hair cell stereocilia form a slightly curved bundle of three or four rows of stereocilia. The tips of the stereocilia of the longest row of the outer but not the inner hair cells appear to be attached to the undersurface of the tectorial membrane (Kimura, 1966). Evidence for attachment of the outer hair cell stereocilia to the tectorial membrane comes from occasional electron microscope observation of direct connections between the stereocilia and the tectorial membrane and numerous observations of stereocilia imprints in the undersurface of the tectorial membrane (Fig. 140-18).

**Outer hair cells.** The outer hair cells are cylindrically or test tube shaped and are attached, within the organ of Corti, at their apical and basal ends by Deiters' cells and their phalangeal processes (see Figs. 140-6, 140-9, and 140-19). There are approximately 13,400 outer hair cells in the human and 10,400 in the chinchilla. The outer hair cells are positioned within the reticular lamina in a medial to lateral orientation. The cells increase in length toward the apex (that is, 14 to 55 microm) and laterally across the rows (that is, 20 to 55 microm). Along the inner plasma membrane there are several layers of subsurface cisternae that extend the length of the cell from the cuticular plate to the nucleus (see Figs. 140-19 and 140-20). Beneath the cuticular plate, whorls of subsurface cisternae may occur that have been called Hensen's bodies. Some of the parallel stacks of the subsurface cisternae are interrupted by pores, and a 30 to 50 nanom network of filaments lies between the cisternae and the cell membrane (Fig. 140-20) (Holly and Ashmore, 1988). The function of the subsurface cisternae is not yet well defined, but it has been suggested to be involved in motile properties of the outer hair cells (Evans, 1990).

Numerous mitochondria and other organelles lie near the subsurface cisternae, which leaves the central cytoplasm of the hair cell appearing organelle sparse. A spheric nucleus is located at the basal end of the cell and occupies most of the width of the cell. Numerous mitochondria of decreasing size occur below the nucleus of the cell body (Fig. 140-21). Deiters' cell process forms a cuplike attachment to the basolateral end of the outer hair cell. The extreme basal end of the outer hair cell is occupied by several small afferent nerve endings and 6 to 10 large, vesicle-filled efferent endings (Fig. 140-21) (Spoendlin, 1988). The cytoplasm adjacent to the efferent but not the afferent endings exhibits a single layer of subsurface cisternae.

***Inner hair cells.*** The inner hair cells are similar to vestibular and lateral line hair cells but differ in several important aspects from the outer hair cells. They form a single row of flask-shaped cells that are tightly surrounded by supporting cells (Figs. 140-9, 140-22, and 140-23). Their large, spheric nucleus occupies the middle portion of the cell, and there are only a few layers of subsurface cisternae along their inner plasmalemma. Their organelles, particularly vesicles, are scattered throughout their cytoplasm. At the basal pole of the inner hair cell are numerous synaptic endings. Adjacent to each afferent ending occurs a presynaptic bar or ribbon in the cytoplasm of the hair cell. The efferent endings are larger, are filled with vesicles, and make synaptic contact with the afferent fibers rather than the inner hair cell body.

### ***Inner sulcus***

The inner sulcus is a spirally directed open channel bounded by the lateral edge of the spiral limbus, by the medial edge of the organ of Corti, and apically by the tectorial membrane (Figs. 140-6, 140-9, and 140-24). The inner sulcus cells resemble Claudius' cells by their cuboidal shape and empty-looking cytoplasm. Their apical surface exhibits short microvilli, and the cells are connected together by tight junctions.

### ***Spiral limbus***

The spiral limbus is a spirally directed shelf of vascularized connective tissue that overlies the medial region of the osseous spiral lamina (see Figs. 140-5, 140-6, and 140-24) (Iurato, 1960). At its most medial edge, Reissner's or the vestibular membrane is attached. Its lateral edge forms a wedge-shaped prominence called the tooth of Huschke that extends over a channel formed by the inner sulcus cells. The endolymphatic surface of the spiral limbus is covered by a thin extracellular matrix called the limbal portion of the tectorial membrane. Directly beneath the limbal portion of the tectorial membrane lies the epithelial cells that are called interdental or T cells. They are T-shaped cells whose apical surface forms broad plates across the apical surface of the spiral limbus. They form radial rows that are apparent in surface preparations (see Fig. 140-1). The connective tissue matrix of the spiral limbus contains fibroblast-like cells, vascular elements, and extracellular filaments.



### *Tectorial membrane*

The tectorial membrane is an acellular, extracellular matrix that overlies the spiral limbus, inner sulcus, and the organ of Corti (see Figs. 14-6, 140-9, 140-18, and 140-24). It consists primarily of fibrous materials and appears to be hydrated with endolymph (Iurato, 1960). According to Lim (1982), the tectorial membrane can be divided into six regions: limbal layer, fibrous matrix, marginal band, cover net, Hensen's stripe, and Hardesty's membrane (see Fig. 140-9). The limbal layer is thin and directly overlies the interdental cells of the spiral limbus. This layer expands out over the inner sulcus and forms a wedge-shaped main body called the fibrous matrix. It contains straight, unbranched 10 nm filament bundles of type II collagen intermingled with a finer network of filaments (Arima et al, 1990; Hasko and Richardson, 1988). Type II collagen appears to be the predominant protein of the tectorial membrane, but the tectorial membrane also contains lesser amounts of other collagens (types V and IX) and unidentified glycoproteins (Khalkhali-Ellis et al, 1987; Santi et al, 1990; Steel, 1985; Thalmann et al, 1986, 19987). On the endolymphatic surface, radial strands of material, the cover net, extend out toward the margin of the membrane in an obliquely apical direction. The lateral margin of the membrane forms a discontinuous net of material called the marginal band. On the organ of Corti surface of the tectorial membrane a thin poorly defined region of material, called Hardesty's membrane, overlies the outer hair cells (see Figs. 140-9 and 140-18). Hensen's stripe forms a prominent triangular-shaped substructure that overlies the inner hair cells.

### *Osseous spiral lamina*

The osseous spiral lamina is a spirally directed thin shelf of bone that extends from the modiolus to the medial attachment of the basilar membrane (see Figs. 140-5, 140-6, and 140-9). The interior of the spiral lamina forms a channel and a pathway for the nerve fibers that travel to and from the organ of Corti. The spiral lamina is broad in the cochlear base and narrows toward the apex. At its lateral margin the bone becomes thinner and perforated by channels called the habenulae perforata where the nerve fibers lose their myelination and enter the organ of Corti (see Fig. 140-9). The spiral lamina also forms the structural base for the spiral limbus and the inner sulcus and its cells. The inner hair cells also rest on the most lateral edge of the osseous spiral lamina.

### **Vascular Supply**

The labyrinthine artery enters the internal auditory meatus with cranial nerve VIII as a branch of the anterior inferior cerebellar artery. The labyrinthine artery branches to form the common cochlear artery and the anterior vestibular artery. In animals the common cochlear artery ascends the modiolus as the spiral modiolar artery, which gives off numerous branches toward the cochlear apex. In humans the common cochlear artery gives off two branches: the spiral modiolar artery, which travels apically, and the vestibulocochlear artery, which vascularizes the lower basal cochlear turn. The spiral modiolar artery gives off two coiled branches (that is, the radiating arterioles) that travel apically over the scala vestibuli and basally to vascularize the spiral ganglion and spiral limbus. The radiating arterioles of the scala vestibuli give rise to capillaries of the scala vestibuli and the stria vascularis (see Figs. 140-12 and 140-13), omega-shaped loops of the spiral prominence (see Fig. 140-8 and 140-13), and arteriovenous anastomoses of the spiral ligament. The cochlea is drained by the spiral

modiolar vein, which originates as a confluence of the venules of the lateral wall, spiral limbus, and spiral ganglion (Axelsson and Lipscomb, 1975; Axelsson and Ryan, 1988; Smith, 1954).

### **Cochlear Innervation**

The cochlea is innervated by three types of nerve fibers: autonomic, afferent, and efferent. Autonomic nerve fibers do not appear to be present within the organ of Corti but are associated with blood vessels and nerve fibers of the modiolus and spiral lamina (Ross, 1973; Spoendlin, 1988).

### **Organ of Corti**

The inner and outer hair cells are innervated by both afferent and efferent nerve fibers; however, their pattern is quite different (Fig. 140-25) (Smith, 1975; Spoendlin, 1988). Approximately 90% of the afferent nerve fibers end in synaptic boutons directly on the inner hair cell bodies. The remaining 10% of the afferent nerve fibers innervate the outer hair cells. The afferent synapses appear to be of the chemical type, but the transmitter substance is not known (Fex and Altschuler, 1986). Efferent nerve fibers also innervate the inner and outer hair cells differently. Efferent synapses do not usually synapse directly on the inner hair cell body but end on their afferent nerve fibers near the cell body. On the other hand, large efferent synaptic boutons end directly on the base of the outer hair cell body. The efferent synaptic transmitter appears to be acetylcholine (Fex and Altschuler, 1986).

Myelinated afferent and efferent nerve fibers travel through the osseous spiral lamina in a radial direction to the organ of Corti (Fig. 140-25). At the lateral edge of the spiral lamina all the nerve fibers lose their myelin sheath and travel through perforations in the bone, called habenula perforata, to enter the organ of Corti. As the unmyelinated nerve fibers enter the organ of Corti, the inner hair cell afferents travel directly to the cell body. The afferents of the outer hair cells travel across the tunnel of Corti and then travel, between the Deiters' cells as the outer spiral bundle, in a spiral direction toward the cochlear base for approximately 0.6 mm. The fibers then form collaterals that innervate approximately 10 outer hair cells across the three rows.

The efferent nerve fibers travel in a spiral direction within Rosenthal's canal in a bundle called the intraganglionic spiral bundle. From this bundle, radially directed fibers branch to innervate the organ of Corti. Efferent nerve fibers that innervate the inner hair cells form a spiral bundle near the base of the hair cell called the inner spiral bundle. The number of fibers in this bundle increases toward the cochlear apex. These fibers give rise to *en passant* synaptic contacts on the afferent nerve fibers of the inner hair cell. Other efferent nerve fibers enter the inner tunnel of Corti and travel in a spiral, and then radial, direction across the tunnel to innervate the outer hair cells. Efferent innervation of the outer hair cell decreases toward the apex and across the three rows (Spoendlin, 1988).

## **Spiral ganglion**

The neuron cell bodies that innervate the inner and outer hair cells are located in the spiral ganglion (Fig. 140-26). The bony channel that contains these cell bodies travels in a spiral direction toward the apex of the cochlea and is called Rosenthal's canal (see Fig. 140-4). Within the spiral ganglion are myelinated nerve fibers that originate from the afferent bipolar cell bodies and the en passant efferent nerve fibers that are contained in a discrete bundle called the intraganglionic spiral bundle. Autonomic nerve fibers also travel through the spiral ganglion (Spoendlin, 1988).

In mammals, two types (that is, types I and II) of afferent cell bodies can be differentiated (Fig. 140-26) within the spiral ganglion (Kellerhals et al, 1967; Spoendlin, 1988). Approximately 90% of the spiral ganglion neurons are type I cells, and the remaining 10% are type II. The type I cell bodies can be distinguished by their bipolar shape, large spheric nucleus, and conspicuous Nissle substance. The type I cell bodies are ensheathed by approximately 50 lamellae of myelin and innervate the inner hair cells (Spoendlin, 1988). The type II cell bodies have a pseudounipolar shape and a smaller size, an eccentric lobulated nucleus in some species, and a more filamentous cytoplasm. The type II cell bodies have a thin myelin sheath (that is, they are unmyelinated) and innervate the outer hair cells. In the human, the numbers of myelinated and unmyelinated cell bodies are approximately equal; however, the majority population of large unmyelinated neurons (type I) appear to innervate inner hair cells or both inner and outer hair cells (Ota and Kimura, 1980).

## **Central Auditory Pathways**

### **Cranial nerve VIII**

In humans cranial nerve VIII originates from four separate nerve branches: the superior vestibular, saccular, posterior ampullary, and cochlear nerve. These nerves are found in separate bony channels within the otic capsule and travel with the facial and intermediate nerves inside the internal auditory canal (IAC). The IAC is divided by the transverse falciform crest into superior and inferior compartments. The facial, intermedius, and superior vestibular nerves travel in the superior part, and the saccular and cochlear nerves travel in the inferior part.

The cochlear nerve fuses with the vestibular branches within the IAC or at the porus acousticus (Fisch, 1970, 1978; House, 1961). Within the IAC the saccular portion of the vestibular nerve gives rise to the vestibulocochlear anastomosis (anastomosis of Oort) that inserts in the longitudinal fissure of the cochlear nerve (Arnesen and Osen, 1984). After the two nerves fuse, a cleavage plane between the cochlear and vestibular component usually persists (Silverstein et al, 1986). The cochlear nerve fibers follow a spiral course and have a cochleotopic organization. The fibers for the basal turn are situated peripheral to the deeper fibers that innervate the apical turn of the cochlea (Arnesen and Osen, 1978).

The relationship between the cochlear and vestibular nerves changes from the most lateral end of the IAC to the cerebellopontine angle (CPA); the two nerves rotate 90 degrees from the labyrinth to the brain stem, and the cochlear nerve, which is anterior and inferior within the IAC, enters the brain stem posterior and lateral to the vestibular nerve. Most of the

rotation occurs within the IAC (Glasscock et al, 1984; Silverstein, 1984; Silverstein et al, 1986). A histologic section of cranial nerve VIII in the CPA shows that even if there is a complete separation between the two nerves, the cochlear nerve contains a variable number of vestibular fibers that are characterized by a larger diameter (Natout et al, 1987; Rasmussen, 1940).

Cranial nerve VIII separates into two roots and enters the brain stem at the pontomedullary junction. The cochlear division is separated from the vestibular division by the cerebellar peduncle (Bebin, 1968). The cochlear nerve passes over the restiform body and enters the anteroventral cochlear nucleus on its ventromedial surface. Each fiber bifurcates, within the nerve root, in a descending branch that innervates the posteroventral and dorsal cochlear nuclei and in an ascending branch that innervates the anteroventral cochlear nucleus (Moore and Osen, 1979). In many mammals the intranuclear portion of the cochlear nerve often contains scattered neurons (root neurons), distinct from the other cells of the nuclear complex, arranged in rows or small groups between the densely packed fascicles of fibers (Harrison and Irving, 1965, 1966; Harrison and Warr, 1962; Merchan et al, 1988; Webster and Trune, 1982). The vestibular fibers pass below the restiform body and penetrate the trapezoid body to proceed dorsally into the brain stem (Brodal, 1981; Moore and Osen, 1979).

### **Cochlear nuclei and acoustic striae**

The cochlear nuclei (CN) represent the first and obligatory relay for all of the afferent auditory fibres. The nuclei are located bilaterally at the pontomedullary junction, lateral to the point of entry of the eighth nerve. After removal of the cerebellar hemisphere, they are visible in the floor of the lateral recess of the fourth ventricle (Moore and Osen, 1979). The CN are generally recognized as consisting of two major subdivisions: the ventral cochlear nucleus (VCN) and the dorsal cochlear nucleus (DCN). The VCN is structurally classified into the anteroventral cochlear nucleus (AVCN) and the posteroventral cochlear nucleus (PVCN). The AVCN is further subdivided into anterior and posterior divisions (Brawer et al, 1974; Moore and Osen, 1979).

Each subdivision consists of a distinctive set of cell types, highly heterogeneous between species, that receive a complete topographic projection from the auditory nerve. Five neuronal classes are generally accepted, based on cell morphology: spheric and globular bushy cells and multipolar, octopus, pyramidal, and granule cells.

The AVCN is mainly characterized by the bushy cells that occupy a preeminent position in the mammalian auditory pathway. The bushy cells have a spheric shape in the anterior division of the AVCN and a globular shape in the posterior division. The multipolar cells (stellate neurons) represent the major morphologic population in the central region of the VCN and are characterized by stellate perikarya (Moore and Osen, 1979; Osen, 1969a; Rhode and Smith, 1982). The PVCN is characterized mainly by octopus cells, with the cell body covered by spicules and long paired dendrites oriented orthogonally to the incoming cochlear nerve fibers (Brugge and Geisler, 1978; Moore and Osen, 1979; Osen, 1969a). These neurons seem to respond to the onset of repetitive acoustic stimuli. In the cat the posterior and anterior divisions are further separated by a granule cell lamina (Osen, 1969a). The DCN is characterized by pyramidal (large fusiform) and granule cells. In many mammals this nucleus has a laminated organization. The pyramidal cells contribute to form the five layers

of the dorsal nucleus (Lorente de No, 1933; Mugnaini et al, 1980). Their axons give off collaterals containing synaptic terminals within the nucleus (Smith and Rhode, 1985). The granule cells are small neurons with two or three short dendrites. Horseradish peroxidase (HRP) studies suggest that all or at least the majority of the granule cell axons project within the layers of the DCN and traverse the apical dendrites of the pyramidal and stellate cells (Mugnaini et al, 1980). In humans the DCN has lost the laminar organization and the pyramidal cells are irregularly distributed (Moore and Osen, 1979). Many of the smaller neurons of this nucleus are intrinsic inhibitory neurons frequently connected to the pyramidal cells (Phillips, 1988). Small and stellate neurons are also present in different layers of this nucleus.

The bushy cells of the VCN receive afferent fibers from the cochlear nerve by way of synaptic endings termed end-bulbs of Helde (Osen, 1969b). They are characterized by fingerlike extensions that encapsulate the cell body, particularly for the low-frequency neurons (Rouiller et al, 1986). Only a small number of these synapses make contact with cell bodies so that they preserve temporal information transmitted by auditory nerve fibers (Brugge, 1991; Phillips, 1988). The bushy cells of the AVCN anterior division are innervated by larger and more complicated variety of end-bulbs than the posterior division (Brawer and Morest, 1975; Rouiller et al, 1986). The stellate, octopus, and pyramidal neurons receive numerous boutonlike synaptic contacts from primary afferent fibers (Brawer and Morest, 1975; Brawer et al, 1974). The octopus cells, in sharp contrast to the bushy cells, are innervated from a great number of cochlear fibers (Osen, 1969b). The DCN receives a considerable number of fibers from the PVCN and sends tonotopic projections to the AVCN. These projections may play a major role in shaping the physiologic response characteristics of many cochlear nucleus cells (Lorente de No, 1981; Osen, 1969b, 1970; Snyder and Leake, 1988; Warr, 1972; Wickesberg and Oertel, 1988).

The distribution of the nerve fibers throughout the CN follows a regular cochleotopic order. Each subdivision of the CN contains a relatively complete neural representation of the cochlear frequency range (Evans, 1975; Evans and Nelson, 1973). The axons from the basal end of the cochlea project most dorsally and those from the apical end most ventrally in each of the three major subdivisions (Phillips, 1988; Sando, 1965). For each cell there is usually a single frequency to which the neuron is most sensitive (the characteristic frequency) (Liberman, 1982).

The axons of the second-order neurons form three main bundles: the ventral acoustic stria (VAS, trapezoid body), the intermediate acoustic stria (IAS, stria of Helde) and the dorsal acoustic stria (DAS, stria of Monakow) (see Figs 140-27 and 140-28). The VAS originates from the spheric and globular cells of the VCN and courses medially and rostrally across the medulla to reach the lateral superior olive, the medial superior olive, the medial nucleus of the trapezoid body, and the inferior colliculus (Neely et al, 1986; Oliver, 1987). The IAS originates mainly from the octopus cells of the PVCN and projects ipsilaterally, bilaterally, or contralaterally to the ventral nucleus of the trapezoid body, lateral superior olive, and the periolivary region, which gives rise to the olivocochlear bundle (Osen, 1969b; Thompson and Thompson, 1987, 1991; Warr, 1969, 1972, 1982). The DAS is essentially a crossed pathway by which the cells in the DNC project to the nuclei of the lateral lemniscus and the central nucleus of the inferior colliculus (Fernandez and Karapas, 1967; Osen, 1972).

## Superior olivary complex and olivocochlear bundle

The superior olivary complex (SOC) is located in the caudal pons immediately dorsal to the pontine gray (Brodal, 1981). This nuclear complex consists of the medial nucleus of the superior olive (MSO), the lateral nucleus of the superior olive (LSO), the medial nucleus of the trapezoid body (MNTB), and the periolivary nuclei (PON). The PON consists of three principal groups of cells that curve around the MSO and LSO and are collectively referred to as the dorsomedial preolivary nucleus (DMPO), the dorsal preolivary nucleus (DPO), and the dorsolateral preolivary nucleus (DLPO) (Brugge, 1991; Phillips, 1988; Pickles, 1982). The morphology of the SOC and the organization and location of cochlear efferents vary considerably in different mammals. In fact, the LSO and MSO are both prominent in nonprimate species, while in humans, the MSO predominates and the lateral nucleus is small or vestigial (Luxon, 1981; Moore and Moore, 1971; Strominger and Hurwitz, 1976).

The MSO is characterized by bipolar neurons with two densely tufted dendrites arranged in a transverse plane (Cant and Casseday, 1986; Goldberg and Brown, 1968; Osen, 1969a; Stotler, 1953; Warr, 1966, 1982). The LSO contains multipolar neurons with flattened two-dimensional dendritic fields that run for considerable distances in a rostrocaudal direction (Scheibel and Scheibel, 1974). The MSO receives ipsilateral and contralateral innervation from both VCN via the ventral acoustic stria (Cant and Casseday, 1986; Warr, 1966, 1982). The lateral dendrites of the bipolar neurons receive axon terminals from the ipsilateral AVCN, and those on the medial side derive their input from the contralateral AVCN (Cant and Casseday, 1986; Goldberg and Brown, 1968; Osen, 1969a; Stotler, 1953; Warr, 1966, 1982). The incoming axons branch predominantly within horizontal layers (Morest, 1973; Scheibel and Scheibel, 1974; Schwartz, 1984). The ipsilateral inputs to the LSO are almost exclusively excitatory and come via the trapezoid body from all the subdivisions of AVCN and PVCN (Cant and Casseday, 1986; Osen, 1969a; Stotler, 1953; Tsuchitani and Boudreau, 1966; Warr, 1966, 1982). In the cat, the small spheric cells of the AVCN are the major contributors to this pathway (Osen, 1969a). The projection from the PVCNs to the ipsilateral LSO is topographically organized with the dorsal and ventral PVCNs projecting to the extreme lateral and medial limbs of the LSO. This neural pathway preserves the tonotopic organization of the afferent CN input to the LSO with axons from high-frequency sensitive areas terminating in the medial limb and from lower-frequency areas in the lateral limb (Thompson and Tompson, 1987). The contralateral inputs arise from globular bushy cells of the caudal AVCN and rostral PVCN via the MNTB (Moore and Goldberg, 1966; Rasmussen, 1964; Tolbert et al, 1982).

The MNTB receives projections from the ipsilateral PVCN and projections from globular cells in the contralateral AVCN via specialized calyx-type endings that partially encapsulate the MNTB cell body (Morest, 1973; Tolbert et al, 1982; Warr, 1982). It is thought that the MNTB cells serve as inhibitory interneurons between the opposite cochlear nucleus and the LSO (Tolbert et al, 1982; Warr, 1982).

The PONs receive afferent input from the CN over the three acoustic striae (Fernandez and Karapas, 1967; Morest, 1968, 1973; Warr, 1966, 1969, 1972, 1982). The periolivary region also receives descending inputs from the inferior colliculus and collateral fibers projecting to MNTB (Faye-Lund, 1986; Moore and Goldberg, 1966; Morest, 1973; Rasmussen, 1964). The MSO and LSO are tonotopically organized with a prevalence of

low-frequency neurons in the MSO (Goldberg and Brown, 1968; Guinan et al, 1972; Phillips, 1988; Tsuchitani and Boudreau, 1968). The LSO appears to be more sensitive to high-frequency stimuli (Guinan et al, 1972; Tsuchitani, 1977; Tsuchitani and Boudreau, 1966). Neurons from the SOC are among the first to receive and process binaural input, and the different pattern of binaural convergence on LSO and MSO may play a role in the interaural temporal and intensity disparities and therefore for mechanisms underlying binaural spatial hearing (Phillips, 1988).

The SOC sends ascending fibers to the nuclei of the lateral lemniscus and the inferior colliculus via the lateral lemniscus (Glendenning et al, 1981). The SOC also sends descending fibers to the hair cells of the organ of Corti via the olivo-cochlear bundle (OC) (Fig. 140-27). The initial description of this pathway was described by Rasmussen (1946, 1953). The OC bundle is divided in two parts, a lateral (LOC) and a medial (MOC) olivocochlear system (Warr, 1975; Warr and Guinan, 1979).

The myelinated medial OC system originates from large neurons located outside the LSO in the medial periolivary cell groups and projects to the contralateral outer hair cells. These cell groups receive direct afferents from the CN and afferents from neurons projecting to the MNTB, arising from the contralateral PVCN (Osen, 1969a; Thompson and Thompson, 1991; Warr, 1969, 1982).

The unmyelinated lateral OC system originates from small cells in the lateral margin of the SOC and projects ipsilaterally to terminate as small contacts located on the afferent terminals of the cochlear nerve fibers innervating inner hair cells (Aschoff and Ostwald, 1988; Tokunaga, 1988; Warr, 1975; Warr and Guinan, 1979). Both fiber systems travel dorsomedially, and the MOC fibers cross the midline below the floor of the fourth ventricle to join the LOC fibers (Osen and Roth, 1969). The MOC system in its route gives off collaterals that innervate the ventral cochlear nucleus (Brown et al, 1988; Liberman and Brown, 1986; Rasmussen, 1967). The ipsilateral and contralateral systems travel peripherally with the inferior division of the vestibular nerve to join the cochlear nerve at the vestibulocochlear anastomosis (VCA) of Oort (Arnesen and Osen, 1978, 1984; Rasmussen, 1953). The VCA, which bridges the vestibular and cochlear nerves in the fundus of the internal acoustic meatus, contains the majority of the olivo-cochlear fibers with little contamination of other fiber categories (Arnesen and Osen, 1984). These descending connections, particularly the crossed fibers, may serve to modulate cochlear sensitivity to the sound, possibly by influencing the contractile properties of the outer hair cells (Brownell, 1985; Geisler, 1986).

### **Lateral lemniscus**

The lateral lemniscus is the major ascending pathway, located rostrally close to the lateral surface of the brain stem, and connects the cochlear nuclei and the superior olivary complex to the inferior colliculus. Associated with the lateral lemniscus are three principal groups of cells: the ventral (VLL), intermediate (ILL), and dorsal (DLL) nuclei of the lateral lemniscus.

The VLL receives fibers mainly from the contralateral VCN and a smaller contributions from the SOC and the DCN (Glendenning et al, 1981; Warr, 1969, 1972), so that it responds largely to stimulation of the contralateral ear (Brugge et al, 1970). The ILL receives fibers from the contralateral VCN, the ipsilateral MNTB, and small fibers from the contralateral DLL (Glendenning et al, 1981). The DLL receives the same projections that ascend to the inferior colliculus (Glendenning et al, 1981; Oliver, 1987; Shneiderman et al, 1988). The DLL receives afferents from the ipsilateral MSO and bilateral LSO with fewer fibers from the contralateral VCN (Glendenning et al, 1981). The DLLs on each side of the brain are interconnected via the commissure of Probst (1902). These fibers emerge from the DLL and cross the midline immediately below the medial longitudinal fasciculus to synapse in the dorsal nucleus of the opposite side. Part of these fibers distributes to the central nucleus of the inferior colliculus (Goldberg and Moore, 1967). Oliver and Shneiderman (1989) suggested the possibility that this pathway participates in an inhibitory reciprocal relationship (Fig. 140-28).

The nuclei of the lateral lemniscus are tonotopically organized with low frequencies located dorsally and high frequencies located ventrally (Aitkin et al, 1970; Ryan et al, 1982)). The efferent projections of the nuclei of the lateral lemniscus have their principal target in the central nucleus of the inferior colliculus (Goldberg and Moore, 1967). The DLL also sends bilateral projections to the superior colliculi and descending fibers to the SOC (Goldberg and Moore, 1967; Kudo, 1981; Shneiderman et al, 1988; Tanaka et al, 1985). The VLL sends descending fibers to the DMPO and the ventral nucleus of the trapezoid body (Whitley and Henkel, 1984).

### **Inferior colliculus**

The inferior (posterior) colliculi (ICs) are bilateral, mesencephalic structures that form with the superior colliculi part of the tectum of the brain stem. They serve as a principal relay station for the ascending auditory pathways and process acoustic information on its way from the lower brain stem to the medial geniculate body and then to the auditory cortex (Geniec and Morest, 1971; Morest, 1965b; Rasmussen, 1964). The ICs consists of three main cell groups: the central nucleus of the inferior colliculus (ICC), the external nucleus of the inferior colliculus or dorsal cortex (ICX) located caudal and ventral to the ICC, and the pericentral nucleus (ICP) surrounding the medial rostral and lateral aspects of the ICC.

The ICC is the largest and most prominent nucleus of the IC and is subdivided into dorsomedial and ventrolateral parts on the basis of dendritic orientation, cell size, and fiber connection (FitzPatrick, 1975; Osen, 1972). The ICC is characterized by a laminar organization with the obliquely vertical layers extending anteroposteriorly (Geniec and Morest, 1971; Gonzalez-Hernandez et al, 1989; Morest, 1964a; Oliver and Morest, 1984; Rockel and Jones, 1973). The principal cell types, based on Golgi staining, are the disk-shaped neurons. The laminae are formed by the fibers of the lateral lemniscus, dendrites, axons, and collaterals of the disk-shaped neurons and the ascending projections from the CN. The stellate neurons are the second neuronal type with dendrites that do not follow the laminar arrangement but send axons over several layers (FitzPatrick, 1975; Geniec and Morest, 1971; Gonzalez-Hernandez et al, 1989; Herrera et al, 1987, 1988; Oliver and Morest, 1984). The ICX has a cortical structure with four layers. The dorsal layer contains neurons whose dendrites cross the layers to varying extents. Each of the successively deeper layers contains predominantly



larger cells (Morest and Oliver, 1984). The ICP includes commissural, dorsomedial, lateral, and ventrolateral nuclei and the nucleus of the rostral pole, with a large variety of cell composition (Morest and Oliver, 1984).

The ICC receives most of the ascending information from the lower brain stem (Fig. 140-28). It receives input from both CN, the SOC, nuclei of the lateral lemniscus, and descending afferents from the auditory cortex. The DCN projects directly to the ICC, while indirect inputs project from the VCN through the SOC and the nuclei of the lateral lemniscus (Adams, 1979; Cant, 1982; Oliver, 1987; Osen, 1972). The ICC receives ipsilateral and contralateral projections from the MSO and LSO and ipsilateral projections arise from the MNTB and PON (Adams, 1979; Warr, 1975). The ICC receives inputs from both DLL (Kudo, 1981; Shneiderman et al, 1988). The inputs coming from the VLL appear to project mainly to the ventrolateral part (Adams, 1979; Brunso-Bechtold et al, 1981; Kudo, 1981; Roth et al, 1978; Whitley and Henkel, 1984). The descending projections arise largely from the primary auditory cortex, and the dorsomedial part receives relatively heavier projections than the anteroventral part (Rockel and Jones, 1973). The ICX receives direct input from the telencephalon and the CN, the dorsal and ventral nucleus of the lateral lemniscus, but no input from the SOC. ICX also receives collaterals from the emerging fibers of the ICC both from the inferior brachium and the commissure of the inferior colliculus (Goldberg and Moore, 1967) and from the dorsal column nuclei (Hand and Van Winkle, 1977). The ICP receives projections from the auditory cortex (Jones and Rockel, 1973), the lateral tegmental system (Henkel and Schneiderman, 1988; Morest, 1965b), and minor projections from the DLL (Oliver, 1984; Shneiderman and Henkel, 1987; Shneiderman et al, 1988). Further, there are projections from somatosensory centers to the external nucleus of the IC. Other afferents come from nonauditory and nonsomatosensory centers: hypothalamic nuclei, lateral part of substantia nigra, central periaqueductal gray, deep layer of the superior colliculus, nucleus sagulum, paragigantocellular nucleus, and the spinal cord.

The ICC shows a tonotopic organization with a regular progression of best frequencies from low to high as the registration progresses from the dorsal to the ventral position with isofrequency laminae congruent with the orientation of the dendritic laminae (FitzPatrick, 1975).

The main efferent projections of the IC travel to the medial geniculate body via the brachium of the IC, but the IC also sends projections to the contralateral IC via the commissure of the inferior colliculus (Faye-Lund, 1986; Moore and Goldberg, 1966; Paloff et al, 1989). Additional projections travel to the periaqueductal gray and to deep layers of the caudal superior colliculus, the contralateral inferior brachium, and terminate in the parabrachial region, the interstitial nucleus of the inferior brachium, and the lateral part of the posterior thalamic group (Moore and Goldberg, 1963, 1966). Descending fibers project via the lateral lemniscus to the VLL, the medial PON, lateral PON, retroolivary region, and contralateral DCN (Andersen et al, 1980b; Borg, 1983; Faye-Lund, 1986; Moore and Goldberg, 1966; Rasmussen, 1964).

## Medial geniculate body

The medial geniculate body (MGB) is a relay station in the ascending auditory pathways, intercalated between the fibers of the brachium of the IC and the auditory cortex (Fig. 140-28). The MGB is found in the thalamus medial to the lateral geniculate body in humans and ventral to it in cats (Brodal, 1981). The MGB is divided on the basis of its cytoarchitecture into ventral, medial, and dorsal divisions.

The ventral division occupies most of the ventrolateral quadrant of the MGB. It consists of three architectonically distinct nuclei: the ventral nucleus (pars lateralis), the ovoid nucleus (pars ovoidea), and the marginal zone. The ventral division is characterized by Golgi type I and II cells. The Golgi type I cells (projection cells) represent the main neurons; they have a tufted dendritic branching pattern and long axons projecting beyond the nucleus of origin. The Golgi type II cells (interneuronal cells) have short axons with dendro-dendritic synapses on the dendrites of the principal neurones (Morest, 1964b). Although both types of neurons receive contacts from afferent axons of the brachium of the inferior colliculus and descending projections of the cortex, only the principal neurons send axons to the auditory cortex (Morest, 1975). This nucleus is characterized by a laminar organization as seen in transverse or horizontal sections. These laminae are formed by three sources: the ascending fibers from the brachium of the inferior colliculus, extrinsic axons probably of cortical origin that cross the laminae obliquely, and the collateral system of Golgi type II axons (Morest, 1965a, 1975; Winer, 1985). The medial division occupies the ventromedial quadrant of the MGB. It is the most heavily myelinated division and contains morphologically heterogeneous neurons with both tufted and radiate dendrite patterns, more scattered and larger than in the other subdivisions. The dorsal division, which is the largest of the three parts, occupies the entire caudal extremities of the MGB. Two main areas, distinct on the basis of cytoarchitecture and connections, can be recognized. The dorsal nucleus consists of three subdivisions: the superficial dorsal, dorsal, and deep dorsal. The second area is subdivided into suprageniculate and posterior limitans nuclei. It is typified by two kinds of principal neurons, stellate and bushy cells, and diffuse axodendritic afferent contacts (Morest, 1964b; Morest and Winer, 1986). In Nissl-stained material, the dorsal division has some of the smallest cells of the MGB and in restricted areas, large neurons (Morest, 1964b; Winer and Morest, 1983).

All the three subdivisions of the MGB receive ascending projections from the nuclei of the IC and descending fibers from the auditory cortex (Andersen et al, 1980c; Imig and Morel, 1984; Moore and Goldberg, 1963, 1966; Morest, 1965a). The ascending projections that travel to the ventral division course parallel to the laminae and contact perikarya and dendrites in dense clusters of knobby branches (Morest, 1964b). The medial division receives fibers from the fastigial nucleus (Carpenter, 1960), the superior colliculus (Altman and Carpenter, 1961; Morest, 1965b), and the vestibular system (Mickle and Ades, 1954). The dorsal division receives afferents from the lateral tegmental system (Morest, 1965b; Morest and Winer, 1986; Winer and Morest, 1984). This connection could be involved in the interplay of somesthetic, auditory, visceral, and visual impulses in the midbrain and the integrated polysensory activity in the posterolateral thalamic complex and associated cortex (Morest, 1965b).

The ventral division of the MGB is tonotopically organized, and Imig and Morel (1985) recognized at least seven zones with different tonotopic organizations. The ventral and ovoid nuclei of the ventral division project to the primary auditory cortex and the anterior auditory field next to it (Morest, 1964b), whereas neurons from the dorsal part seem to project to overlying cortical areas (Andersen et al, 1980a; Middlebrooks and Zook, 1983; Winer, 1977). The ascending projections of the medial nucleus include every subdivision of the auditory cortex, without obvious topography (Morest, 1964b; Winer, 1985; Winer and Morest, 1983) and subcortical areas of the basal forebrain (LeDoux et al, 1985). The posterior nucleus projects in an overlapping manner to the auditory cortex. The principal targets are the cortical area AII and beside it, but consistent projections also arise to the insular cortex, and temporal cortex, and the ventroposterior auditory field (Winer, 1985).

### **Auditory cortex**

The auditory cortex is divided, based on cytoarchitecture, fiber connections, and physiologic properties, into a primary auditory cortex and associated auditory regions that receive acoustic and other sensory inputs.

In humans the primary auditory cortex (Brodmann's areas 41 and 42) is located in the upper bank of the temporal lobe and is surrounded by specific auditory and nonspecific association areas (Brodmann's areas 22 and 52) (Fig. 140-29, A). Its cytoarchitecture histologically resembles the other primary cortical sensory areas. The association areas connect the primary cortex to frontal and temporoparietal regions, concerned with language and speech, and with the somesthetic and vision areas (Luxon, 1981). The auditory cortex of the cat is located on the lateralside of the hemisphere below the suprasylvian sulcus (Brodal, 1981). In primates and cats the auditory cortex contains a number of fields that were differentiated for the first time by Woolsey (1960) on the basis of cytoarchitecture and physiologic studies, including primary (AI), secondary (AII), posterior (P), ventroposterior (VP), and anterior (A) auditory fields (Fig. 140-29, B).

The primary auditory cortex of the cat has a reciprocal connection with the medial geniculate body, whereas geniculocortical fibers travel to all different fields (Merzenich et al, 1982; Morel and Imig, 1987). The major input arises from the ventral division of the medial geniculate body (Morel and Imig, 1987). The primary auditory cortex is characterized by a tonotopic and binaural organization with the high frequencies represented rostrally, in the middle ectosylvian gyrus, and low frequencies represented caudally, in the dorsal part of the ectosylvian gyrus (Imig et al, 1982; Morel and Imig, 1987).

The posterior and ventroposterior acoustic areas are located caudal and ventral to AI. Low frequencies are represented in the dorsal position of the posterior ectosylvian sulcus, adjoining the lowest best frequencies of AI. The high frequencies of the posterior area are located ventrally. The anterior auditory field (Knight, 1977) is located on the rostral border of AI, and its representation of highest best frequencies is contiguous to AI, whereas the lowest best frequencies are situated rostroventrally. Studies combining microelectrode mapping and axonal tracing demonstrated that each cortical field receives a different pattern of thalamic projections and is reciprocally connected with the other three fields by cortico-cortical connections (Imig et al, 1982; Morel and Imig, 1987).

Surrounding fields AI, A, P, and VP is a peripheral belt of auditory responsive cortex that includes the second (AII), temporal (T), dorsoposterior (DP), and ventral (V) areas. This peripheral belt contains neurons responsive both to acoustic and visual stimuli and is tonotopically organized in its most auditory portion. The visual belt that surrounds the auditory area receives input from extrastriate visual areas (Bowman and Olsen, 1988; Imig et al, 1982; Reale and Imig, 1980).

The auditory cortex gives off three main descending pathways to the thalamus, midbrain, and pons. Each auditory cortical area projects to the sources of its afferent fibers in the medial geniculate body, establishing short feedback loops (Andersen et al, 1980b; Imig and Morel, 1984). The primary auditory cortex also projects bilaterally to the central and ipsilaterally to the pericentral nucleus of the inferior colliculus (Andersen et al, 1980c; Diamond et al, 1969) and to the corpus striatum (Webster, 1965). In the cat a feedback loop is also present that connects the primary cortex with the thalamic reticular nucleus (Andersen et al, 1980b; Diamond et al, 1969; van Noort, 1969). The non-primary cortex projects to the medial and lateral parts of the pericentral nucleus of the IC, to the tegmental system (Andersen et al, 1980b; Diamond et al, 1969; van Noort, 1969). This last pathway is involved in a feedback loop that sends back projections to the auditory cortex via the suprageniculate nucleus (Oliver and Hall, 1978a, 1978b).