Chapter 1: Anatomy and ultrastructure of the human ear

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Development of the human ear

In accordance with longstanding convention, the adult ear is here described in terms of its three portions, namely the outer, the middle and the inner ear. The inner ear, comprising the bony and membranous labyrinth with its central connections, arises from a set of structures quite distinct from those which give rise to the outer and middle ears. The development of the inner ear, which is the first organ of the special senses to become fully formed in man, is considered first, following a short, general description of the growth of the nervous system.

Prenatal development is divided into a number of separate periods. The first period extends from the time of implantation of the developing blastocyst into the uterine wall until an intraembryonic circulation has started to develop. During this short period of about 21 days, the three layers of ectoderm, mesoderm and endoderm develop to form a flat, elongated plate containing the notochord. This rod-like structure is derived from the ectodermal layers, and extends along the length of the embryonic disc from the buccopharyngeal membrane to the cloacal membrane, where ectoderm and endoderm are in direct contact. The second brief period of about 35 days, that is until the end of the eighth week, is termed the embryonic period. During this time there is rapid growth and cellular differentiation, so that by the fifty-sixth day all the major systems and organs are formed and the embryo has an external shape that is recognizably human. The remaining 7 months of gestation form the fetal period, during which there is rapid growth characterized by changes of shape, and by alterations in the position of one structure to another, rather than by the differentiation of new cell types.

During the embryonic period, the thickened mesoderm on each side of the notochord separates into paired cubical blocks called somites. The first occipital somite lies just behind the head end of the notochord, and no other somites develop further forward from this for the reason that here the mesoderm gives rise to, among other structures, the branchial (or pharyngeal) arches. Forty-one to forty-three more pairs of somites develop in a tailward direction during the first 9 days of the embryonic period.

The ectoderm not only assumes the shape of the underlying, developing mass of mesoderm but also thickens in the region of the notochord to form the midline neural plate. On each side of this plate, a longitudinal band of ectoderm called the neural crest develops. The neural plate subsequently sinks in to form the neural groove, the walls of which eventually close over to produce the neural tube surrounding the neural canal. While the neural groove is closing, the neural crest cells sink in from the surface to lie alongside the completed neural tube. At the head end, the neural tube undergoes rapid enlargement and dilatation to form the hindbrain, the midbrain and the forebrain. These last two extend forward past the notochord and buccopharyngeal membrane, which by now has broken down to allow the formation of the buccal cavity.

The neural crest cells, lying alongside the developing brain and spinal cord, develop into a chain of cell clusters which, at the head end of the embryo, form three groups:
trigeminal; facial and auditory; and glossopharyngeal and vagal. These clusters contain uni- or bipolar nerve cells and form the cranial sensory nerve ganglia. They link the peripheral sensory receptors with the afferent nuclei in the hindbrain. Motor nerve fibres arise directly from the cell bodies in the three efferent columns in the hindbrain and pass directly to striated muscles or, by way of a synapse, to non-striated muscle and glandular tissue.

The membranous labyrinth

When the embryo has reached the seventh somite stage (about 22 days), a thickening of the ectoderm forms just in front of the first occipital somite on each side of the still open neural groove. This thickening is the otic placode. The mesoderm surrounding this region proliferates and elevates the ectoderm around the placode, which subsequently sinks below the surface to become the otic pit. The ectoderm of the pit undergoes rapid growth, the mouth of the pit narrows and eventually closes, so that by the thirtieth somite (30 days) stage, an enlarging otocyst separated from the surface has been formed and lies anterior and medial to the combined facial and auditory cluster of neural crest cells. The geniculate ganglion migrates from this cluster leaving the auditory (vestibulocochlear) ganglion in close proximity to the otocyst.

Within 1 or 2 days, the otocyst has lengthened and an apparent infolding of the wall marks off a medial compartment, the endolymphatic duct, from a more lateral compartment, the utriculo-saccular chamber. This period is a time of rapid change, and complex alterations in the shape of different parts of the otocyst occur synchronously. The walls of the chamber grow inwards so that a number of constructions and folds appear, separating the utricle from the saccule. The major change is an ingrowth of the lateral wall assisted by a further enlargement of the initial fold (now called the utricular fold) that together separate the utricular chamber from the endolymphatic duct, and thus form the utricular duct. A lesser change is a separate ingrowth from the medial wall that divides the saccular chamber from the endolymphatic duct and thereby forms the saccular duct.

Meanwhile, the endolymphatic system is elongating in a medial direction towards the hindbrain; a proximal dilatation, the endolymphatic sinus, a middle, narrow endolymphatic duct and a widened distal endolymphatic sac are formed.

At the same time, other changes are occurring in the utricular chamber. At 35 days, three flattened hollow pouches push out approximately at right angles to each other, to form superior, posterior and lateral ridges. At the centre of each curved ridge, the opposing epithelial walls meet, fuse and break down to be replaced by the surrounding mesoderm. In this way, the superior ridge, at about 6 weeks, is transformed into the superior semicircular duct, with the transformation of the other two, the posterior before the lateral, taking place soon afterwards.

While the semicircular ducts are developing, and before the complete formation of the utricular and saccular duct has taken place, the saccule is putting out a single medially directed pouch which is the beginning of the cochlear duct. This grows medially and starts to coil, with the result that at the beginning of fetal life one coil is present, and by 25 weeks the adult form of two-and-one-half coils has been achieved. As the cochlear duct develops, it becomes isolated from the saccule by a construction called the ductus reuniens.
During this period of complex growth, other changes occur within the otocyst. Thickened epithelial areas develop in certain portions of its walls in relationship to the ingrowth of nerve fibres from the bipolar cells of the vestibulocochlear ganglion. The specialized areas of neuroepithelium are the maculae, the cristae and the organ of Corti.

The maculae

The maculae develop from the epithelium that overlies the areas where nerves enter the walls of the saccule and utricle. Two cell types differentiate: the sensory cells, with a single kinocilium and many stereocilia, projecting into the cavity of the otocyst; and the supporting cells. These latter cells appear to be responsible for the formation of the otoconia, although the early stages are not well understood. It seems likely that very small calcium-containing primitive otoconia are produced by the supporting cells and it is these that provide the nucleus for the multi-layered deposition of the calcite form of calcium carbonate to produce the mature otoconia with their characteristic shape (see section on adult anatomy). The supporting cells also produce a gelatinous matrix that subsequently forms the gelatinous layer of the definitive otoconial membrane. In the very early stages of otoconial formation in man this matrix is not present. However, by 14-16 weeks, the individual parts of the maculae have assumed an adult form with the sensory and supporting cells being overlaid by the mature otoconial membrane (see Lim, 1984, for an excellent review).

The crista of the semicircular ducts

At one end of each semicircular duct, a portion of the epithelial lining proliferates and heaps up to form the ridge-like crista. Differentiation into sensory and supporting cells occurs and this takes place on what will eventually become the convex side of the definitive semicircular canal. The membranous duct in this region enlarges to form the ampulla and, subsequently, a fibrogelatinous structure - the cupula - develops with the lumen. It probably originates from the supporting cells and is present in the 24-week old fetus. Both the cupula and the otoconial membrane (as well as the tectorial membrane) are extremely sensitive to distortion and shrinkage during routine histological preparation; therefore, the shape seen in such preparations does not represent that found in life. Especial care has to be taken to preserve the real shape and form of these structures.

As the ampulla enlarges, the crista grows with it, so that by the time it has reached its adult size, at about 23 weeks, it has become a curved ridge covering the floor and extending part way up the side walls of the ampulla.

The organ of Corti

The coils of the cochlear duct are initially circular in cross-section, but with the growth of the surrounding mesoderm, they are converted into a triangular form with a floor and an outer wall at right angles to each other, and a sloping roof completing the triangle. The epithelium lining this duct is originally stratified; however, in the roof, it undergoes regression through columnar, then cuboidal stages, changing finally into a simple squamous epithelium that remains as the lining of the future Reissner's membrane. The epithelium of the outer wall develops into the stria vascularis, a three-layered structure which rests on, and is supplied by, a highly vascular strip developed in the surrounding mesoderm. The epithelium
of the floor undergoes a series of spectacular changes to form the highly ordered organ of Corti. The structure of this is described in detail in the section on adult anatomy. During development, however, the stratified epithelium, under the influence of nerve terminals arriving from the cochlear ganglion, heaps up to form a ridge-like structure. This starts at about 11 weeks and the process is more rapid in the basal than the apical regions.

The future tectorial membrane, which is an ill-defined gelatinous membrane, develops and extends over the surface of the neuroepithelium. By 16 weeks, the ridge in the basal coil is more pronounced, so that an inner and outer sulcus are apparent. The inner sulcus is roofed in by the tectorial membrane, while in the outer sulcus the epithelial cells regress to a flattened low cuboidal form. Within the organ of Corti, sensory and supporting cells are developing. A space - the tunnel of Corti - appears within this mass of cells and separates the inner from the outer sensory cells. A cluster of stereocilia and a more laterally placed single kinocilium develop from the surface of each sensory cell, although the kinocilium subsequently degenerates and is not present in man at birth. The presence of the clusters of stereocilia has resulted in the sensory cells being called hair cells. The supporting cells become highly differentiated. Inner and outer pillar cells, on each side of the tunnel of Corti, give mechanical rigidity to the structure. Deiters' cells surround the base of the outer hair cells and send their processes up to the surface of the organ of Corti, which then expand to form the phalangeal processes which separate the upper surface of the outer hair cells. Hensen's and Claudius' cells form the lateral bulk of the organ of Corti, and it is to these that the tectorial membrane is attached laterally. The cells around the outer hair cells separate, so that definite spaces - the spaces of Nuel - develop and communicate with the tunnel of Corti.

As mentioned earlier, differentiation is occurring in a basal to apical direction, so that at any one time most stages of development can be seen in different parts of the cochlea as the duct is elongating. As the cochlear duct grows and coils, the cochlear ganglion also changes shape to complement the new form, to become known as the spiral ganglion. By 25 weeks, the organ of Corti and the spiral ganglion are complete, resembling those in the adult.

The bony labyrinth

Mesoderm surrounds the membranous labyrinth, and it is this which undergoes a series of changes that result in the formation of both the bony otic capsule and the perilymph spaces of the inner ear. The relatively unspecialized mesoderm of the presomite embryo becomes known as the mesenchyme in subsequent embryonic development as it undergoes differentiation into more specialized tissue. The mesenchyme surrounding the derivatives of the otocyst is initially quite dense and becomes chondrified to form the otic capsule. As the membranous labyrinth increases in size, the adjacent cartilage de-differentiates to form a loose periotic tissue. This subsequently regresses to form fluid-filled spaces adjacent to the most of the membranous structures. These are the perilymphatic spaces and they arise first in the region destined to become the vestibule. Subsequently, spaces develop around the cochlear duct, the scala tympani preceding the scala vestibuli. While this latter space is developing, other spaces form around the semicircular ducts so that the completed canals are formed. The perilymph space does not develop where vestibular and cochlear nerve fibres enter the sensory cell regions, and so these remain in close proximity to the cartilaginous otic capsule. Elsewhere, the developing perilymphatic spaces finally become continuous with the result that a tortuous but uninterrupted perilymph-filled space is formed.
The ossification of the remaining cartilaginous otic capsule takes place from 14 centres and begins in the fifteenth or sixteenth week. The last centre to begin ossification does so at 21 weeks, an indication that the otic capsule has, by this time, attained its maximum size. Each ossification centre develops as a three-layered structure comprising an inner periosteal layer, a central layer where mixed ossification of cartilage occurs and an outer periosteal layer. In the central layer, the cartilage cells enlarge, the matrix becomes calcified and the cells then shrink, atrophy and disappear leaving lacunae. Vascular invasion of the calcified cartilage occurs and osteogenic buds enter the lacunae and deposit an osseous lamina on the walls of the space. This is endochondral bone and its formation results in the development of a series of islands of bone enclosed in cartilage. Other osteoblasts derived from the vascular buds lay down endochondral bone on the surface of the remaining cartilage so that, with progressive growth, the vascular spaces are obliterated and the middle layer of the otic capsule will consist of one type of bone (intrachondral) embedded in another (endochondral), with remnants of calcified cartilage. Unlike all other cartilage-derived bones, no remodelling occurs, and the fetal architecture is maintained throughout life. The inner periosteal layers becomes greatly thickened by the laying down of interconnected plates of bone that form a dense hard petrous structure.

The 14 separate ossification centres fuse to form a single bony box, without the presence of a single suture line. (For a complete review, see Anson and Donaldson, 1981.) The interior of the bony labyrinth 'communicates' with the outside through seven or eight channels, and the facial nerve passing across and around it in a sulcus eventually becomes enclosed by a bony sheath on the lateral, tympanic aspect (Table 1.1).

The blood supply of the developing otic capsule comes mainly from the arteries of the tympanic plexus, which are supplied in turn predominantly by the stylomastoid arteries and its branches. The developing membranous labyrinth, however, is supplied almost entirely by branches of the internal auditory artery, and this pattern persists throughout life.

**The outer and middle ears**

The mesenchyme surrounding the primitive pharynx differentiates into paired maxillary and mandibular processes above and below the level of the buccopharyngeal membrane. Shortly after the appearance of these processes, the membrane breaks down and the buccopharyngeal cavity is formed. Behind the level of the membrane, the mesenchyme which surrounds the pharyngeal tube separates on each side into five or six bars running around the pharynx; these are the pharyngeal arches. In each arch, a bar of cartilage, together with its associated muscles, differentiates from the mesenchyme. The muscle is supplied by a nerve (one of the special visceral efferents) and the endoderm which covers the arch internally is supplied not only by the nerve of the arch (pre-trematic) but also by a branch from the arch behind (post-trematic). Each arch also has an artery associated with it, at least for a short while during embryonic development. Between successive arches, the endoderm of the pharynx forms pouches which come into contact with the covering ectoderm which has sunk between the arches as the pharyngeal grooves (or clefts). In land-living vertebrates, a thin layer of mesoderm intervenes between the pouch and the cleft which does not break down, so that true gill clefts are never formed.
Table 1.1 Development of communication channels passing through the bony labyrinth

<table>
<thead>
<tr>
<th>Channel</th>
<th>Description</th>
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<tr>
<td>Internal auditory meatus</td>
<td>Persisting channel in cartilage model around VII and VIII nerves</td>
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<tr>
<td>Subarcuate fossa</td>
<td>Persisting vascular channel</td>
</tr>
<tr>
<td>Vestibular aqueduct</td>
<td>Fifth and sixth ossification centres fuse around the endolymphatic duct</td>
</tr>
<tr>
<td>Cochlear aqueduct</td>
<td>Resorption of precartilage</td>
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<tr>
<td>Fossula ante fenestram</td>
<td>Resorption of precartilage</td>
</tr>
<tr>
<td>Fossula post fenestram</td>
<td>Resorption of precartilage</td>
</tr>
<tr>
<td>Oval window</td>
<td>Otic capsule becomes footplate of stapes and annular ligament</td>
</tr>
<tr>
<td>Round window</td>
<td>Persisting cartilage becomes round window niche and membrane.</td>
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</tbody>
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The first and second arches and their associated structures give rise to the middle and outer ears. Table 1.2 outlines the details of the derivatives of these arches.

The auricle

The development of the auricle begins with the appearance of six hillocks around the first pharyngeal groove between the first and second arches. Three hillocks develop on each side of the groove; but as growth proceeds they tend to become obscured, and of those of the first (mandibular) arch, only that which later forms the tragus can be obviously identified throughout the process. It seems that the bulk of the auricle is derived from the mesenchyme of the second (hyoid) arch, which extends around the top of the groove to form a flattened extension that subsequently becomes the helix (Streeter, 1922). The cartilage of the auricle extends inwards partially to surround the future external meatus. The rudimentary pinna has formed by 60 days and in the fourth month the convolutions have attained their adult form, although further generalized enlargement continues during the remaining months of gestation and in the postnatal period.

The external canal

The external canal develops from the upper portion of the first pharyngeal groove. This extends inwards as a funnel-shaped tube and the meatus deepens by proliferation of its ectoderm which forms an epithelial plug. The ectoderm at the depths of this plug is in contact with the endoderm of the first pharyngeal pouch for a short while before the mesenchyme intervenes to become the middle fibrous layer of the future tympanic membrane.

The ectodermal plug breaks down and a narrow slit forms between the future walls of the external meatus and the tympanic membrane which lies in an almost 'horizontal' plane during fetal development.

Within the mesenchyme around the external meatus, four small centres of ossification arise in the ninth week. These are destined to fuse and to become the tympanic ring (not an accurate name as it is never a complete ring) and, subsequently, the tympanic bone. The ring
develops a groove on its inner concave face, and this becomes the tympanic sulcus. The bony ring grows in diameter and extends laterally and inferiorly throughout fetal life to occupy the space between the mandibular fossa and the anterior surface of the developing mastoid bone, where it provides a sheath for the developing styloid process. By later fetal life, the tympanic plate is widely open and the definitive bony canal unformed. After birth, anterior and posterior bony prominences, which have developed on the inner aspect of the ring, grow inwards and eventually fuse to form the floor of the canal. As the tips of the processes fuse, a space surrounded by bone is created; this is the foramen of Huschke which is usually obliterated by adolescence. The completed tympanic bone, therefore, makes contact with the mastoid process and part of the squamous bone posteriorly, and with another portion of the squamous and part of the petrous bone anteriorly. The petrotympanic fissure between the more medial aspect of the tympanic bone and the mandibular fossa allows the passage of the chorda tympani nerve, the post-trematic nerve of the first arch. The tympanic ring is deficient superiorly in the external meatus and this is the tympanic incisura.

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<th>Table 1.2 Derivatives of 1st and 2nd branchial arches</th>
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<tbody>
<tr>
<td>Cartilage</td>
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<td>1st arch Derivatives</td>
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<td>2nd arch Derivatives</td>
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**The middle ear**

The cavity and lining of the middle ear cleft and eustachian tube arise from the expanding first pharyngeal pouch with probably some contribution at the medial end from the second. By the 4-week stage, the distal end lies against the ectoderm of the first pharyngeal groove and expands to form a flattened sac, the precursor of the tympanic cavity. Mesenchyme grows between the ectoderm and the endoderm to form the third layer of the future tympanic membrane. The slit-like space within the sac expands and, as it reaches the developing ossicles and otic capsule, the epithelium lining the sac is draped over the lateral (tympanic) portion of the labyrinth, the bodies of the ossicles, and their developing ligaments and muscular tendons, so that a complex and variable network of mucosal folds is formed. 'Pneumatization' of the meso- and hypotympanum is complete at 8 months, while the epitympanum and mastoid antrum have developed by birth. The spaces are not filled with air but with amniotic fluid, and this is replaced shortly after birth. The mastoid antrum, which is an extension of the epitympanum, has started to develop in mid-fetal life. A few mastoid
'air-cells' are present late in fetal life, but the bulk of their development occurs in infancy and childhood.

**The ossicles**

The outer lateral ends of the first (Meckel's) and second (Reichert's) arch cartilages lie, respectively, above and below the developing first pharyngeal pouch. Before these arch cartilages are fully defined, condensations in the mesenchyme occur in this region at about 4-5 weeks. As development proceeds, the condensations form cartilage models which, by 6.5 weeks, are well-defined as malleus, incus and stapes. By 5 weeks, the stapes can first be recognized as a circular mass at the end of the precursor of Reichert's (second arch) cartilage. Approximately 1.5 weeks later, this becomes annular as it is pierced by the first arch (stapedial) artery, and is now attached to the developing Reichert's cartilage by a membranous bar, the interhyale. At this time, the malleus and incus are developing from cartilage at the end of the precursor of Meckel's (first arch) cartilage. A groove represents the site of the future incudomalleolar joint, and the handle of the malleus and long process of incus are already apparent. By 7.5 weeks, the handle of the malleus lies between the layers of the developing tympanic membrane.

The stapes continues to grow and its ring-like shape is converted into the definitive arch-like stapedial form. It seems likely that the footplate of the stapes is formed primarily from the otic capsule, and that part of the stapedial ring which fuses with the otic capsule during ossification usually regresses. In the adult, therefore, the stapedial arches are derived from second arch cartilage, while the footplate is part of the labyrinthine capsule. Frequently, however, regression of the base of the stapedial ring is incomplete so that a dual origin for the mature footplate is possible. Ossification in the stapedial cartilage starts from a single centre at 4.5 months and is followed by a complex pattern of resorption, with the result that the base, the crura and the adjoining head are eventually hollowed out.

The malleus and incus start ossifying at the 4-month stage and progress is so rapid that, in the 25-week fetus, they are already of adult size and form.

The muscles of the tympanic cavity develop from the first and second arch mesenchyme to become the tensor tympani, which is supplied by a branch of the nerve of the first arch (mandibular), and the stapedius, which is supplied by the nerve of the second arch (facial). The pre-trematic nerve of the first arch is the chorda tympani and, with expansion of the tympanic cavity and resorption of the mesenchyme, its final course is within the layers of the tympanic membrane as it passes from the facial nerve to its destination in the floor of the mouth.

**The temporal bone**

The temporal bone is derived from four separate morphological elements that fuse with one another. The elements are the tympanic bone, already described previously, the squamous portion, the petromastoid complex, and the styloid process.

The squamous portion of the temporal bone, like the tympanic ring, develops in mesenchyme rather than in a preformed cartilage model. It is ossified from one centre that,
as early as 8 weeks, appears close to the root of the zygomatic arch, and extends radially and also into the arch itself. The posteroinferior portion grows down behind the tympanic ring to form the lateral wall of the fetal mastoid antrum.

The petromastoid is morphologically a single element, although it is conveniently described in the adult in two separate units, the petrous and mastoid bones. The development of the cartilaginous otic capsule of embryonic and fetal life has already been described. The rapid progression of ossification completes the formation of the bony labyrinth. However, changes in the outer periosteal layer continue. A cartilaginous flange grows downwards and outwards from the lateral part of the petrosal cartilages, above the tubotympanic cavity, to form the roof of the middle ear and of the lateral bony wall of the eustachian tube. A separate flange grows outwards below the developing middle ear cavity to form the jugular plate. The facial nerve, which lies in a sulcus on the lateral, tympanic, aspect of the otic capsule, is also enclosed by growth from the capsule. Other changes gradually occur in the outer layers of the capsule. The subarcuate fossa, which carried a leash of blood vessels and was as large as the internal meatus, becomes progressively smaller. Anteriorly, the outer periosteal layer enlarges to form the petrous apex.

The styloid process develops from two centres at the cranial end of Reichert's (second arch) cartilage). That part closest to the tympanic bone is the tympanohyal and its ossification centres appears before birth. It fuses with the petromastoid during the first year of life and is surrounded at its root by a portion of the tympanic bone. The ossification centre for the distal part - the stylohyal - does not appear until after birth and fusion with the tympanohyal does not occur, if at all, until after puberty.

The tympanic ring unites with the squamous portion shortly before birth, while the petromastoid fuses during the first year of life, so that tympanosquamous (anterior) and tympanomastoid suture lines are present in the bony external meatus. At birth, the tympanic annulus lies beneath the skull in an almost horizontal plane. By the third month, as a result of the upward and lateral rotation of the petrous bone, caused by rapid enlargement of the forebrain, the annulus appears on the inferolateral aspect of the skull, and it is not until some months later that its accessible oblique position is attained.

The mastoid portion of the petromastoid is at first flat, and the stylomastoid foramen with the facial nerve lies on the lateral surface behind the tympanic bone. With the development of air cells in the mastoid, its lateral portion grows downwards and forwards so that the stylomastoid foramen is carried on to the undersurface of the bone and the facial nerve canal elongates. During the second year of life, the portion of the squamous bone adjoining the petromastoid enlarged and grows downwards, thereby concealing some of the petrous portion which also enlarges downwards to form the mastoid tip. A squamopetrous suture line is usually visible on the outer surface of the mastoid process. Within this process, a variable extension of the antral air cells occurs and a septum may be left between deep and superficial air cells. This is Korner's septum and is a remnant of the petrosquamous suture line. As the tympanic bone and the mastoid process develop, the lateral surface of the temporal bone takes up its vertical adult position.
Anatomy of the human ear

For the purpose of anatomical description, the ear is divided into four separate portions. These are: the auricle (or pinna), the external auditory canal, the middle ear and its derivatives and, finally, the inner ear.

The auricle

The auricle (or pinna) projects to a greater or lesser angle from the side of the head and has some function in collecting sound (see Chapter 2). The lateral surface of the auricle has several prominences and depressions. The curved rim is the helix. At its posterosuperior aspect, a small auricular tubercle (Darwin’s tubercle) is often present. Anterior to and parallel with the helix is another prominence, the antihelix. Superiorly, this divides into two crura between which is the triangular fossa; the scaphoid fossa lies above the superior of the two crura. In front of the antihelix, and partly encircled by it, is the concha. The anterior superior portion of the concha is usually covered by the descending limb of the anterior superior portion of the helix (the crus of the helix). This region is the cymba conchae. It is the direct lateral relation to the suprameatal triangle of the temporal bone. Below the crus of the helix and opposite the concha, across the external auditory meatus, is the tragus, which is a small blunt triangular prominence. This points posteriorly and overlaps the orifice of the external canal. Opposite the tragus, at the inferior limit of the antihelix, is the antitragus. The tragus and antitragus are separated by the intertragic notch. The lobule lies below the antitragus and is soft, being composed of fibrous and adipose tissue. The medial (cranial) surface of the auricle has elevations corresponding to the depressions on the lateral surface, and possesses corresponding names - for example, the eminentia conchae.

The body of the auricle is composed of a thin plate of cartilage covered with skin, and it is connected to surrounding parts by ligaments and muscles. It is continuous with the cartilage of the external meatus.

The skin of the auricle is thin and closely adherent to the perichondrium on the lateral surface. There is a definite but thin layer of subdermal adipose tissue on the medial (cranial) surface. The skin is covered with fine hairs which have sebaceous glands opening into their root canals. The glands are most numerous in the concha and scaphoid fossa. On the tragus and intertragic notch coarse, thick hairs may develop in the middle-aged and older male.

The cartilaginous skeleton comprises a single piece of elastic fibrocartilage which is absent in the lobule and deficient between the crus of the helix and the tragus, that is in the anterior superior portion, where it is replaced by dense fibrous tissue. The cartilage, in the same way as cartilage elsewhere, is dependent on its perichondrium for supply of nutrients and removal of by-products. The cartilage is connected to the temporal bone by two extrinsic ligaments. The anterior ligament runs from the tragus and from a cartilaginous spine on the anterior rim of the crus of the helix to the root of the zygomatic arch. A separate posterior ligament runs from the medial surface of the concha to the lateral surface of the mastoid prominence. Intrinsic ligaments connect various parts of the cartilaginous auricle; that between helix and tragus has already been described and another runs from the antihelix to the postero-inferior portion of the helix.
Extrinsic and intrinsic muscles are, in the same way as ligaments, attached to the perichondrium of the cartilage. The extrinsic muscles are supplied by temporal and posterior auricular branches of the facial nerve and, while being functionally unimportant, they do give rise to the postauricular myogenic response following appropriate auditory stimulation (Gibson, 1978). There are three extrinsic muscles: auricularis anterior, superior and posterior, the last being supplied by the posterior auricular branch of the facial nerve. All three radiate out from the auricle to insert into the epicranial aponeurosis. The intrinsic muscles - six in number - are small, inconsistent and without useful function, other than that of entertaining children in those who possess the ability to alter the shape of the pinna.

Three arterial branches of the external carotid supply the auricle. The posterior auricular provides twigs that supply the medial (cranial) surface and, by extension around the helix, the extremities of the lateral surface. The anterior auricular branches of the superficial temporal supply the bulk of the lateral surfaces, and a small auricular branch from the occipital artery assists the posterior auricular in supplying the medial surface.

Many nerves make up the sensory supply of the auricle. Their distribution is variable and the overlap may be extensive. The essential features are described in Table 1.3.

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<tr>
<th>Nerve</th>
<th>Derivation</th>
<th>Region supplied</th>
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<tr>
<td>Greater auricular</td>
<td>Cervical plexus C2,3</td>
<td>Medial surface and posterior portion of lateral surface</td>
</tr>
<tr>
<td>Lesser occipital Auricular</td>
<td>Cervical plexus C2</td>
<td>Superior portion of medial surface Concha and antihelix Some supply medial surface (eminentia concha)</td>
</tr>
<tr>
<td>Auriculotemporal Facial VII</td>
<td>Vc mandibular</td>
<td>Tragus, crus of helix and adjacent helix Probably supplies a small region in the root of concha.</td>
</tr>
</tbody>
</table>

The lymphatic drainage from the posterior surface is to the lymph nodes at the mastoid tip, from the tragus and from the upper part of the anterior surface to the preauricular nodes, and from the rest of the auricle to the upper deep cervical nodes.

**The external auditory canal**

The external auditory canal extends from the concha of the auricle to the tympanic membrane. The distance from the bottom of the concha to the tympanic membrane is approximately 2.5 cm, although the length of the anterior canal wall is 1-1.5 cm more because of the length of the tragus, the obliquity of the tympanic membrane and the curvature of the canal wall. The supporting framework of the canal wall is cartilage in the lateral one-third and bone in the medial two-thirds. In adults, the cartilaginous portion runs inwards slightly upwards and backwards, while the bony portion runs inwards slightly downwards and forwards. The canal is straightened, therefore, by gently moving the auricle upwards and backwards to counteract the direction of the cartilaginous portion. In the neonate, there is virtually no bony external meatus as the tympanic bone is not yet developed, and the
tympanic membrane is more horizontally placed so that the auricle must be gently drawn downwards and backwards for the best view of the tympanic membrane.

In the adult, the lateral cartilaginous portion is about 8 mm long. It is continuous with the auricular cartilage and is deficient superiorly, this space being occupied by the intrinsic ligament between the helix and tragus. The medial border of the meatal cartilage is attached to the rim of the bony canal by fibrous bands.

The bony canal wall, about 1.6 mm long, is narrower than the cartilaginous portion and itself becomes smaller closer to the tympanic membrane. The anterior wall is longer by about 4 mm than the posterior wall because of the obliquity of the tympanic membrane. The medial end of the bony canal is marked by a groove, the tympanic sulcus, which is absent superiorly. Although the tympanic bone makes up the greater part of the canal, and also carries the sulcus, the squamous bone forms the roof. Therefore, there are two suture lines in the canal wall with the tympanosquamous anteriorly and the tympanomastoid posteriorly. Both these suture lines may be more or less developed; they project into the canal and the overlying skin is closely adherent. The tympanomastoid suture is a complex suture line between the anterior wall of the mastoid process, a portion of the squamous bone and the tympanic bone.

Apart from these intrusions into the canal, there are two constrictions: one at the junction of the cartilaginous and bony portions and the other, the isthmus, 5 mm from the tympanic membrane where a prominence of the anterior canal wall reduces the diameter. Deep to the isthmus, the anteroinferior portion of the canal dips forward so that a wedge-shaped anterior recess is formed between the tympanic membrane and the canal.

The skin of the external canal is continuous with that of the auricle and extends over the outer surface of the tympanic membrane. There is a definite subdermal layer in the cartilaginous portion, but in most of the bony segment this is very thin and the skin is adherent to the periosteum of the tympanic bone. In the superior portion of the deep meatus between the two suture lines, the subdermal layers are thickened and carry a leash of blood vessels. This is the vascular strip.

The skin itself has some properties not found in skin elsewhere. Instead of maturation occurring directly towards the surface there is lateral growth of the epidermis, with the consequence that layers of keratin are shed towards the surface opening of the external meatus (Johnson and Hawke, 1985). This is also true of the epidermal layers of the tympanic membrane, and Alberti (1964) has shown that migration occurs at the rate of about 0.05 mm/day, which is about the same rate of growth as that of fingernails.

The skin overlying the cartilaginous portion contains hairs and glands. The hairs are narrow and short and project towards the external opening of the meatus. The external surface of individual hairs has a series of overlapping 'scales' which are also directed externally.

The glands are of two types, ceruminous and sebaceous. The sebaceous glands are typical of sebaceous glands elsewhere and consist of a single wide duct from which arise a cluster of pear-shaped alveoli. Each alveolus consists of a basement membrane enclosing a mass of epithelial cells. The central cells, which contain fat, break down to form the
sebaceous material (sebum), and are in turn replaced by a proliferation of epithelial cells at the edge of the mass. The sebum passes along the ducts which nearly always open into hair follicles.

The ceruminous glands lie slightly deeper in the dermis and are simple coiled tubular structures lined with cuboidal secretory cells and surrounded by a myoepithelium. This contains smooth muscle, and its contraction compresses the duct which thus empties its contents into the root canal of the hair follicle from which these cells nearly always originate. The secretion is initially white and watery, but as it dries and is oxidized, it becomes sticky and semisolid, and thereafter slowly darkens in colour. The ceruminous glands are modified apocrine sweat glands and both react to the same stimuli. Adrenergic drugs, emotion resulting in an intrinsic release of adrenaline and noradrenaline, and mechanical manipulation, all result in a small increase in secretion.

**Wax (cerumen)**

The mixture of the products of the sebaceous and ceruminous glands results in the formation of wax, of which there are two distinct forms - dry and wet. Dry wax is yellowish or grey, and is dry and brittle, while wet wax is yellowish brown, and is wet and sticky. The type of wax possessed by an individual is probably monofactorially inherited with the wet phenotype dominant over the recessive dry type. The Japanese, other mongoloid populations and the American Indians tend to carry the recessive gene and, in general, to have dry wax, whereas in white and black populations, the wet gene predominates.

Wax contains various amino acids, fatty acids, lysozymes and immunoglobulins and is to some extent bactericidal, being especially potent at killing dividing bacteria (Stone and Fulghum, 1984).

**Blood supply and lymphatic drainage**

The arterial supply of the external meatus is derived from branches of the external carotid. The auricular branches of the superficial temporal artery supply the roof and anterior portion of the canal. The deep auricular branch of the first part of the maxillary artery arises in the parotid gland behind the temporomandibular joint, pierces the cartilage or bone of the external meatus, and supplies the anterior meatal wall skin and the epithelium of the outer surface of the tympanic membrane. Finally, auricular branches of the posterior auricular artery pierce the cartilage of the auricle and supply the posterior portions of the canal. The veins drain into the external jugular vein, the maxillary veins and the pterygoid plexus.

The lymphatic drainage follows that of the auricle.

**The middle ear cleft**

The middle ear cleft consists of the tympanic cavity (tympanum), the eustachian tube and the mastoid air cell system. Included in this section are the extensions of the air cell system into the anterior and posterior petrous apex.
The tympanic cavity

The tympanic cavity is an irregular, air-filled space within the temporal bone and contains the auditory ossicles and their attached muscles. Other structures run along its walls to pass through the cavity. For descriptive purposes, the tympanic cavity may be thought of as a box with four walls, a roof and a floor. The corners are not sharp and, therefore, the precise localization of features lying at the edge of one wall may not be possible with this model.

The lateral wall of the tympanic cavity

The lateral wall of the tympanic cavity is part bony and part membranous. The tympanic membrane forms the central portion of the lateral wall, while above and below there is bone, forming the outer lateral walls of the epitympanum and hypotympanum respectively. The lateral wall of the epitympanum also includes that part of the tympanic membrane lying above the anterior and posterior malleolar folds - the pars flaccida. This lateral epitympanic wall is wedge-shaped in section and its lower bony portion is also called the outer attic wall or scutum (Latin = shield). It is thin and its lateral surface forms the superior portion of the deep of the external meatus.

Three holes are present in the bone of the medial surface of the lateral wall of the tympanic cavity. The opening of the posterior canaliculus for the chorda tympani nerve is situated in the angle between the junction of the lateral and posterior walls of the tympanic cavity. It is often at the level of the upper end of the handle of the malleus, but a lower situation is very common. The opening leads into a small bony canal which descends through the posterior wall of the tympanic cavity. Near the tympanic opening, the chorda tympani lies anterior and lateral to the facial nerve; it descends obliquely to join the nerve, often at some point within the bone, but occasionally the channel remains separate and the two nerves join outside the skull. A branch of the stylomastoid artery accompanies the chorda tympani into the tympanic cavity.

The petrotympanic (Glasserian) fissure opens anteriorly just above the attachment of the tympanic membrane. It is a slit about 2 mm long which receives the anterior malleolar ligament and transmits the anterior tympanic branch of the maxillary artery to the tympanic cavity. The chorda tympani enters the medial surface of the fissure through a separate anterior canaliculus (canal of Huguier) which is short and is sometimes confluent with the fissure.

The tympanic membrane, forming the lateral wall of the mesotympanum and a small part of the epitympanum, separates the tympanic cavity from the external meatus. It is a thin, nearly oval disc, slightly broader above than below, forming an angle of about 55° with the floor of the meatus. Its longest diameter from posterosuperior to anteroinferior is 9-10 mm, while perpendicular to this the shortest diameter is 8-9 mm. Most of the circumference is thickened to form a fibrocartilaginous ring, the tympanic annulus, which sits in a groove in the tympanic bone, the tympanic sulcus. The sulcus does not extend to the roof of the canal which is formed by part of the squamous bone. From the superior limits of the sulcus, the annulus becomes a fibrous band which runs centrally as anterior and posterior malleolar folds to the lateral process of the malleus, the handle of which lies within the tympanic membrane. This leaves a small, rather squat, triangular region of tympanic membrane above the malleolar...
folds. It does not have a tympanic annulus at its margins, is lax and is called the pars flaccida. The pars tensa forms the rest of the tympanic membrane. It is taut and, when seen from the ear canal, is concave, with the maximal depression occurring at the inferior tip of the malleus handle (the umbo). However, each portion of the membrane, as the latter passes from the annulus to the umbo, is not flat but is gently curved, being slightly convex when seen from the external meatus.

The tympanic membrane has three layers: an outer epithelial layer, the epidermis, which is continuous with the skin of the external meatus; a middle, mainly fibrous layer, the lamina propria; and an inner mucosal layer continuous with the lining of the tympanic cavity.

The epidermis is divided into the stratum corneum, the stratum granulosum, the stratum spinosum and stratum basale. In main (Hentzer, 1969), the stratum corneum, which is the outermost layer, consists of between one and six compressed layers of almost acellular structures, without organelles but with recognizable membranes and intercellular junctions (desmosomes). The stratum granulosum contains one to three layers of cells with smooth borders, and interconnecting desmosomes. Keratohyaline granules and lamellar granules are present among occasional tonofilaments, but other cell constituents are lacking. The cells of the stratum spinosum, which are two or three layers deep, have prominent interdigitations with neighbouring cells to which they are bound by desmosomes. These cells contain bundles of tonofilaments, with mitochondria and ribosomes also present, but have a high nucleus to cytoplasm ratio. The stratum basale, which is the deepest layer, consists of a single layer of cells separated from the lamina propria by a basement membrane. Occasionally, prolongations of the deep surface of the cell extend down into the lamina propria. Nerve endings and melanin granules have not been seen in any of the cell layers of the epidermis.

The predominant feature of the lamina propria, in both the pars tensa and the pars flaccida, is the presence of collagen fibrils. In the pars tensa, the fibrils closest to the epithelial layer are usually in direct contact with the basement membrane of the epidermal layer, although in places a thin layer of loose connective tissue intervenes. These lateral fibres are radial in orientation, while the deeper ones are circular, parabolic and transverse. A loose connective tissue layer, containing fibroblasts, macrophages, nerve fibres (mainly unmyelinated) and many capillaries, lies between the deep layers of the lamina propria and the inner mucosal layer. Neither the capillaries nor the nerves appear to penetrate the basement membrane or enter the mucosal layer.

In the pars flaccida, the lamina propria is less marked, but it still contains collagen fibres although they appear to lie in an almost random orientation.

The mucosal epithelium of the pars tensa varies in height from a low simple squamous or cuboidal type to a pseudostratified columnar epithelium. The adjoining cell borders have marked interdigitations with tight junctions between the apices of the cells facing the tympanic cavity. The free surface of the cells - that is the surface facing the middle ear - possess numerous microvilli and, where the epithelium is cuboidal or columnar, cilia with the typical 'nine plus two' internal ultrastructure are found. These true cilia are patchy in their distribution and a continuous sheet, such as that which covers the respiratory mucosa of, say, the eustachian tube, is not found. No goblet cells have been found in this layer, but in cells without cilia, secretory granules are present. The cytoplasm and nuclei of the cells are
otherwise unremarkable. The mucosal layer is separated from the lamina propria by a basement membrane. In the pars flaccida, the overall picture is the same except that taller ciliated cells are not found.

**Blood supply of the tympanic membrane**

The arterial supply of the tympanic membrane is complex and arises from branches supplying both the external auditory meatus and the middle ear. These two sources interconnect through extensive anastomoses, but the vessels are found only in the connective tissue layers of the lamina propria. Within this layer there appears to be a peripheral ring of arteries connected by radial anastomoses, with one or two arteries that run down each side and around the tip of the malleus handle. The arteries involved include the deep auricular branch of the maxillary artery coming from the external auditory meatus; and, from the middle ear, the anterior tympanic branches of the maxillary artery, twigs from the stylomastoid branch of the posterior auricular and probably several twigs from the middle meningeal.

The venous drainage returns to the external jugular vein, the transverse sinus and dural veins and the venous plexus around the eustachian tube.

**Nerve supply of the tympanic membrane**

The nerves, in the same way as the blood vessels, run in the lamina propria and arise from the auriculotemporal nerve (Vc) supplying the anterior portion, from the auricular branch of the vagus (X), the posterior portion, and from the tympanic branch of the glossopharyngeal nerve (IX). The variations and overlap are considerable, but both the vascular supply and innervation are relatively sparse in the middle part of the posterior half of the tympanic membrane.

**The roof of the tympanic cavity**

The tegmen tympani is the bony roof of the tympanic cavity, and separates it from the dura of the middle cranial fossa. It is formed in part by the petrous and part by the squamous bone; and the petrosquamous suture line, unossified in the young, does not close until adult life. Veins from the tympanic cavity running to the superior petrosal sinus pass through this suture line.

**The floor of the tympanic cavity**

The floor of the tympanic cavity is much narrower than the roof and consists of a thin plate of bone which separates the tympanic cavity from the dome of the jugular bulb. Occasionally, the floor is deficient and the jugular bulb is then covered only by fibrous tissue and a mucous membrane. At the junction of the floor and the medial wall of the cavity there is a small opening that allows the entry of the tympanic branch of the glossopharyngeal nerve into the middle ear from its origin below the base of the skull (see Chapter 15).
The anterior wall of the tympanic cavity

The anterior wall of the tympanic cavity is rather narrow as the medial and lateral walls converge. The lower portion of the anterior wall is larger than the upper and consists of a thin plate of bone covering the carotid artery as it enters the skull and before it turns anteriorly. This plate is perforated by the superior and inferior caroticotympanic nerves carrying sympathetic fibres to the tympanic plexus, and by one or more tympanic branches of the internal carotid artery. The upper, smaller part of the anterior wall has two parallel tunnels placed one above the other. The lower opening is flared and leads into the bony portion of the eustachian tube which will be described in more detail later on in this chapter. The upper tunnel is separated from the eustachian tube by a thin plate of bone, and contains the tensor tympani muscle which subsequently runs along the medial wall of the tympanic cavity enclosed in a thin bony sheath. This muscle will also be further described in the section on the auditory ossicles.

The medial wall of the tympanic cavity

The medial wall separates the tympanic cavity from the inner ear. Its surface possesses several prominent features and two openings. The promontory is a rounded elevation occupying much of the central portion of the medial wall. It usually has small grooves on its surface and these contain the nerves which form the tympanic plexus. Sometimes the grooves, especially the groove containing the tympanic branch of the glossopharyngeal nerve, are covered by bone, with the consequence that small canals are present instead. The promontory covers part of the basal coil of the cochlea and in front merges with the anterior wall of the tympanic cavity.

Behind and above the promontory is the fenestra vestibuli (oval window), a nearly kidney-shaped opening that connects the tympanic cavity with the vestibule, but which in life is closed by the base of the stapes and its surrounding annular ligament. The long axis of the fenestra vestibuli is horizontal, and the slightly concave border is inferior. The size of the fenestra vestibuli naturally varies with the size of the base of the stapes, but on average it is 3.25 mm long and 1.75 mm wide. Above the fenestra vestibuli is the facial nerve and below is the promontory. The fenestra, therefore, lies at the bottom of a depression or fossula that can be of varying width depending on the position of the facial nerve and the prominence of the promontory.

The fenestra cochleae (round window), which is closed by the secondary tympanic membrane (round window membrane), lies below and a little behind the fenestra vestibuli from which it is separated by a posterior extension of the promontory, called the subiculum. Occasionally, a spicule of bone leaves the promontory above the subiculum and runs to the pyramid on the posterior wall of the cavity. This spicule is called the ponticulus. The fenestra cochleae, which faces inferiorly and a little posteriorly, lies completely under cover of the overhanging edge of the promontory in a deep niche and is, therefore, usually out of sight. The niche is most commonly triangular in shape, with anterior, posterosuperior and posteroinferior walls. The latter two meet posteriorly and lead to the sinus tympani. The average length of the walls of the niche are: anterior - 1.5 mm; superior - 1.3 mm; and posterior - 1.6 mm (Nomura, 1984). There is great variation in the depth of the niche and, to enable the secondary tympanic membrane to be seen, bone frequently has to be removed from
the anterior wall of the niche. Within the niche are mucosal folds or even complete membranes that partly or completely exclude the secondary tympanic membrane from view and may even be mistaken for it during surgery. In the adult, the secondary tympanic membrane lies almost horizontally in the roof of the niche. This membrane is not flat but curves towards the scala tympani of the basal coil of the cochlea, so that it is concave when viewed from the middle ear. It appears to be divided into an anterior and posterior portion by a transverse thickening within the membrane. The shape of the membrane varies, in different temporal bones, from round through oval and kidney-shaped to spatulate, with average longest and shortest diameters of 2.30 and 1.87 mm respectively.

The membrane consists of three layers: an outer mucosal, a middle fibrous and an inner mesothelial layer. The mucosal layer is rather like the mucosal layer of the primary tympanic membrane with flattened or cuboidal cells possessing microvilli and, occasionally, clusters of cilia on their surface. This layer is separated from the basement membrane by a single layer of loose connective tissue that often contains melanocytes. It is this layer that contains the capillaries and nerves. The rest of the middle layer, which forms the bulk of the membrane, contains fibroblasts and collections of collagen and elastic fibres. The fibres are not, however, ordered in the same way as in the pars tensa and do not form discrete bundles. The inner layer is a continuation of the cell layer lining the scala tympani. There are two or three layers of overlapping, flat mesothelial cells with wide intercellular spaces, but no tight junctions nor any connective tissue layer between this and the middle layer.

The membrane of the fenestra cochleae does not lie at the end of the scala tympani but forms part of its floor. The scala tympani terminates posterior and medial to the membrane. The ampulla of the posterior semicircular canal is the closest vestibular structure to the membrane and its nerve (the singular nerve) runs almost parallel to, and 1 mm away from, the medial attachment of the deep portion of the posterior part of the membrane. The membrane is therefore a surgical landmark for the singular nerve (Gacek, 1983).

The facial nerve canal runs above the promontory and fenestra vestibuli in an anteroposterior direction. It has a smooth rounded lateral surface that is occasionally deficient, and is marked anteriorly by the processus cochleariformis. This is a curved projection of bone, concave anteriorly, which houses the tendon of the tensor tympani muscle as it turns laterally to the handle of the malleus. Behind the fenestra vestibuli, the facial canal starts to turn inferiorly as it begins its descent in the posterior wall of the tympanic cavity.

The region above the level of the facial nerve canal forms the medial wall of the epitympanum. The dome of the lateral semicircular canal extends a little lateral to the facial canal and is the major feature of the posterior portion of the epitympanum. In well-aerated mastoid bones, the labyrinthine bone over the superior semicircular canal may be prominent, running at right angles to the lateral canal and joining it anteriorly at a swelling which houses the ampullae of the two canals. In front and a little below this, above the processus cochleariformis, may be a slight swelling corresponding to the geniculate ganglion, with the bony canal of the greater superficial petrosal nerve running for a short distance anteriorly.
The posterior wall of the tympanic cavity

The posterior wall is wider above than below and has in its upper part the opening (aditus) into the mastoid antrum. This is a large irregular hole that leads back from the posterior epitympanum. Below the aditus is a small depression, the fossa incudis, which houses the short process of the incus and a ligament connecting the two. Below the fossa incudis and medial to the opening of the chorda tympani nerve is the pyramid, a small hollow conical projection with its apex pointing anteriorly. It contains the stapedius muscle, the tendon of which passes forward to insert into the stapes. The canal within the promontory curves downwards and backwards to join the descending portion of the facial nerve canal. Between the promontory and the tympanic annulus is the facial recess. This is less marked lower down where the facial nerve canal forms only a slight prominence on the posterior wall. The facial recess is, therefore, bounded medially by the facial nerve and laterally by the tympanic annulus, but running through the wall between the two, with a varying degree of obliquity, is the chorda tympani nerve. This always runs medial to the tympanic membrane, which means that the angle between the facial nerve and the chorda allows access to the middle ear from the mastoid without disruption to the tympanic membrane. This angle can be small or large depending on the site of origin of the chorda from the facial nerve.

Deep to both the promontory and the facial nerve is a posterior extension of the mesotympanum - the sinus tympani. This extension of air cells into the posterior wall can be extensive, and Anson and Donaldson (1981) report that, when measured from the tip of the pyramid, the sinus can extend as far as 9 mm into the mastoid bone. The medial wall of the sinus tympani becomes continuous with the posterior portion of the medial wall of the tympanic cavity where it is related to the two fenestrae and the subiculum of the promontory.

The contents of the tympanic cavity

The tympanic cavity contains a chain of three small movable bones - the malleus, incus and stapes - two muscles, the chorda tympani nerve and the tympanic plexus of nerves.

The malleus

The malleus (hammer), the largest of the three ossicles, comprises a head, neck and three processes arising from below the neck. The overall length of the malleus ranges from 7.5 to 9.0 mm. The head lies in the epitympanum and has on its posteromedial surface an elongated saddle-shaped, cartilage-covered facet for articulation with the incus. This surface is constricted near its middle and the smaller inferior portion of the joint surface lies nearly at right angles to the superior portion. This projecting lower part is the cog, or spur, of the malleus. Below the neck of the malleus, the bone broadens and gives rise to the following: the anterior process from which a slender anterior ligament arises to insert into the petrotympanic fissure; the lateral process which receives the anterior and posterior malleolar folds from the tympanic annulus; and the handle. The handle runs downwards, medially and slightly backwards between the mucosal and fibrous layers of the tympanic membrane. On the deep, medial surface of the handle, near its upper end, is a small projection into which the tendon of the tensor tympani muscle inserts. Additional support for the malleus comes from the superior ligament which runs from the head to the tegmen tympani.
The incus

The incus articulates with the malleus and has a body and two processes. The body lies in the epitympanum and has a cartilage-covered facet corresponding to that on the malleus. The short process projects backwards from the body to lie in the fossa incudis to which it is attached by a short ligament. The long process descends into the mesotympanum behind and medial to the handle of the malleus, and at its tip is a small medially directed lenticular process which articulates with the stapes.

The stapes

The stapes consists of a head, neck, two crura (limbs) and a base or footplate. The head points laterally and has a small cartilage-covered depression for articulation with the lenticular process of the incus. The stapedius tendon inserts into the posterior part of neck and upper portion of the posterior crus. The two crura arise from the broader lower part of the neck and the anterior crus is thinner and less curved that the posterior one. Both are hollowed out on their concave surfaces. The two crura join the footplate which usually has a convex superior margin, an almost straight inferior margin and curved anterior and posterior ends. The average dimensions of the footplate are 3 mm long and 1.4 mm wide, and it lies in the fenestra vestibuli where it is attached to the bony margins of the labyrinthine capsule by the annular ligament. The long axis of the footplate is almost horizontal, with the posterior end being slightly lower than the anterior.

The stapedius muscle

The stapedius arises from the walls of the conical cavity within the pyramid and from the downward curved continuation of this canal in front of the descending portion of the facial nerve. A slender tendon emerges from the apex of the pyramid and inserts into the stapes. The muscle is supplied by a small branch of the facial nerve.

The tensor tympani muscle

This is a long slender muscle arising from the walls of the bony canal lying above the eustachian tube. Parts of the muscle also arise from the cartilaginous portion of the eustachian tube and the greater wings of the sphenoid. From its origin, the muscle passes backwards into the tympanic cavity where it lies on the medial wall, a little below the level of the facial nerve. The bony covering of the canal is often deficient in its tympanic segment where the muscle is replaced by a slender tendon. This enters the spoon-shaped processus cochleariformis where it is held down by a transverse tendon as it turns through a right angle to pass laterally and insert into the medial aspect of the upper end of the malleus handle. The muscle is supplied from the mandibular nerve by way of a branch, from the medial pterygoid nerve, which passes through the otic ganglion without synapse.

The chorda tympani nerve

This branch of the facial nerve enters the tympanic cavity from the posterior canaliculus at the junction of the lateral and posterior walls. It runs across the medial surface of the tympanic membrane between the mucosal and fibrous layers and passes medial to the
upper portion of the handle of the malleus above the tendon of tensor tympani to continue forwards and leave by way of the anterior canaliculus, which subsequently joins the petrotympanic fissure.

The tympanic plexus

The tympanic plexus is formed by the tympanic branch of the glossopharyngeal nerve and by caroticotympanic nerves which arise from the sympathetic plexus around the internal carotid artery. The nerves form a plexus on the promontory and provide the following:

1. Branches to the mucous membrane lining the tympanic cavity, eustachian tube and mastoid antrum and air cells.

2. A branch joining the greater superficial petrosal nerve.

3. The lesser superficial petrosal nerve, which contains all the parasympathetic fibres of IX. This nerve leaves the middle ear through a small canal below the tensor tympani muscle where it receives parasympathetic fibres from VII by way of a branch from the geniculate ganglion. The completed nerve passes through the temporal bone to emerge, lateral to the greater superficial petrosal nerve, on the floor of the middle cranial fossa, outside the dura. It then passes through the foramen ovale with the mandibular nerve and accessory meningeal artery to the otic ganglion. Occasionally, the nerve runs not in the foramen ovale but through a separate small foramen next to the foramen spinosum. Postganglionic fibres from the otic ganglion supply secretomotor fibres to the parotid gland by way of the auriculotemporal nerve.

The mucosa of the tympanic cavity

The middle ear mucosa is to some degree a respiratory mucosa carrying cilia on its surface and being able to secrete mucus (Sade, 1966). The extent of the mucociliary epithelium varies in normal middle ears, being more widespread in the young and ending at the line of the facial nerve in all ages. Above the facial nerve, that is in the epitympanum and mastoid, a flat non-ciliated epithelium, with only a very occasional mucus-producing cell, is found. The mucus comes from goblet cells and from mucous glands which are collections of mucus-producing cells linked to the surface by a short duct. In the middle ear, the glands are sometimes absent; however, in those ears where they are present, they tend to be clustered around the orifice of the eustachian tube, although they are never present in large numbers. Goblet cells eject mucus directly into the middle ear space and are in highest concentration close to the eustachian tube opening (Tos and Bak-Pedersen, 1976). Again, large numbers of goblet cells do not occur, but their presence is indicative of the potential ability of the middle ear mucosa to undergo changes typical of respiratory epithelium.

The mucous membrane lines the bony walls of the tympanic cavity, and it extends to cover the ossicles and their supporting ligaments in much the same way as the peritoneum covers the viscera in the abdomen. The mucosal folds also cover the tendons of the two intratympanic muscles and carry the blood supply to and from the contents of the tympanic cavity. These folds separate the middle ear space into compartments and the epitympanic space is only connected to the mesotympanum and is, therefore, ventilated only by way of
two small opening between the various mucosal folds - the anterior and posterior isthmus tympani. The mucosal folds have been described in detail by Proctor (1964).

**The blood supply of the tympanic cavity**

Arteries supplying the walls and contents of the tympanic cavity arise from both the internal and external carotid system. The overlap between branches is extensive and there is great variability in the supply between individuals. *Table 1.4* outlines the general distribution of the arterial supply although the anterior tympanic and stylomastoid arteries are the biggest. Because of the great variability of the blood supply, and the difficulty of interpretation of injected specimens, an 'average' view of the blood supply has been presented. Different authors give different names to what appear to be the same vessels, and attach varying importance to the contribution made by each. However, most authors believe that a major contribution to the supply of the stapes and incudostapedial joint comes from a plexus of vessels derived from the stylomastoid artery and which surrounds the facial nerve to enter the tympanic cavity by way of the pyramid or directly through its posterior wall. Additional vessels reach the stapes from the meshwork of arterioles on the promontory, and probably derive mainly from the anterior and inferior tympanic arteries.

*Table 1.4 Blood supply to the middle ear*

<table>
<thead>
<tr>
<th>Branch</th>
<th>Parent artery</th>
<th>Region supplied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior tympanic</td>
<td>Maxillary artery</td>
<td>Tympanic membrane, malleus and incus, anterior part of tympanic cavity</td>
</tr>
<tr>
<td>Stylomastoid</td>
<td>Posterior auricular</td>
<td>Posterior part of tympanic cavity, stapedius muscle</td>
</tr>
<tr>
<td>Mastoid</td>
<td>Stylomastoid</td>
<td>Mastoid air cells</td>
</tr>
<tr>
<td>Petrosal</td>
<td>Middle meningeal</td>
<td>Roof of mastoid, roof of epitympanum</td>
</tr>
<tr>
<td>Superior tympanic</td>
<td>Middle meningeal</td>
<td>Malleus and incus, tensor tympani</td>
</tr>
<tr>
<td>Inferior tympanic</td>
<td>Ascending pharyngeal</td>
<td>Mesotympanum</td>
</tr>
<tr>
<td>Branch from artery</td>
<td>Art of pterygoid canal</td>
<td>Meso- and hypotympanum</td>
</tr>
<tr>
<td>Tympnic branches</td>
<td>Internal carotid</td>
<td>Meso- and hypotympanum.</td>
</tr>
</tbody>
</table>

**The eustachian tube (auditory or pharyngotympanic tube)**

The eustachian tube is a channel connecting the tympanic cavity with the nasopharynx. In the adult, it is about 36 mm long and runs downwards, forwards and medially from the middle ear. There are two elements to the tube: a lateral bony portion arising from the anterior wall of the tympanic cavity, and a medial fibrocartilaginous part entering the nasopharynx. The tube is lined with respiratory mucosa containing goblet cells and mucous glands and having a carpet of ciliated epithelium. At its nasopharyngeal end, the mucosa is truly respiratory; but in passing along the tube towards the middle ear, the number of goblet cells and glands decreases, and the ciliary carpet becomes less profuse.
The bony portion is about 12 mm long and is widest at its outer tympanic end. It runs through the squamous and petrous portions of the temporal bone and gradually narrows to the isthmus which is the narrowest part of the whole tube, having a diameter of only 2 mm or less. The roof of the tube is formed by a thin plate of bone, above which is the tensor tympani muscle. The carotid artery, also separated by a plate of bone, lies medial to the tube. In cross-section, the tube is triangular or rectangular with the horizontal diameter being the greater.

The cartilaginous part of the tube is about 24 mm long and has a plate of cartilage forming its back (posteromedial) wall. At the upper border, the cartilage is bent forwards to form a short flange that makes up part of the front (anterolateral) wall. The rest of the front wall comprises fibrous tissue. The apex of the cartilage is attached to the isthmus of the bony portion, while the wider medial ends lies directly under the mucosa of the nasopharynx and forms the tubal elevation. The cartilage is fixed to the base of the skull in a groove between the petrous part of the temporal bone and the greater wing of the sphenoid. The groove terminates near the root of the medial pterygoid plate. In the nasopharynx, the tube opens 1-1.25 cm behind and a little below the posterior end of the inferior turbinate. The opening is almost triangular in shape and is surrounded above and behind by the tubal elevation. The salpingopharyngeal fold stretches from the lower part of the tubal elevation downwards to the wall of the pharynx. The levator palati, as it enters the soft palate, results in a small swelling immediately below the opening of the tube. Behind the tubal elevation is the pharyngeal recess or fossa of Rosenmüller. Lymphoid tissue is present around the tubal orifice and in the fossa of Rosenmüller, and may be prominent in childhood.

**Muscles attached to the eustachian tube**

The tensor palati muscle arises from the bony wall of the scaphoid fossa, the spine of the sphenoid and from along the whole length of the short cartilaginous flange that forms the upper portion of the front wall of the cartilaginous tube. From these origins, the muscle descends, converges to a short tendon that turns medially around the pterygoid hamulus and then spreads out within the soft palate to meet fibres from the other side in a midline raphe. The tensor palati separates the tube from the otic ganglion, the mandibular nerve and its branches, the chorda tympani nerve and the middle meningeal artery. It is supplied by the mandibular nerve.

The salpingopharyngeus is a slender muscle attached to the inferior part of the cartilage of the tube near its pharyngeal opening, and it descends to blend with palatopharyngeus.

The levator palati contains a few fibres that arise from the lower surface of the cartilaginous tube. This muscle, which also originates from the lower surface of the petrous bone, just in front of the opening for the entrance of the carotid, and from fascia forming the upper part of the carotid sheath, first lies inferior to the tube, then crosses to the medial side and spreads out into the soft palate. Both the salpingopharyngeus and the levator palati are supplied from the pharyngeal plexus.

The mechanism of tubal opening during swallowing and yawning is not well understood. The tensor palati probably plays a major role, assisted by the levator palati and
possibly by the salpingopharyngeus which is too slender to have much effect in raising the pharynx and larynx.

The tube is supplied by the ascending pharyngeal and middle meningeal arteries. The veins drain into the pharyngeal plexus and the lymphatics pass to the retropharyngeal nodes. The nerve supply arises from the pharyngeal branch of the sphenopalatine ganglion (Vb) for the ostium, the nervus spinosus (Vc) for the cartilaginous portion and from the tympanic plexus (IX) for the bony part.

**The aditus to the mastoid antrum**

This is a large irregular opening leading from the posterior epitympanum into the air-filled spaces of the mastoid antrum, often referred to as the aditus ad antrum. On the medial wall is the prominence of the lateral semicircular canal. Below and slightly medial to this is the bony canal of the facial nerve. The short process of the incus is closely related to these two structures, and the average distances between them are: seventh nerve to semicircular canal - 1.77 mm; seventh nerve to short process incus - 2.36 mm; and short process incus to semicircular canal - 1.25 mm (Anson and Donaldson, 1981).

**The mastoid antrum**

The mastoid antrum is an air-filled sinus within the petrous part of the temporal bone. It communicates with the middle ear by way of the aditus and has mastoid air cells arising from its walls. The antrum, but not the air cells, is well developed at birth and by adult life has a volume of about 1 mL - being 14 mm from front to back, 9 mm from top to bottom and 7 mm from side to side. The medial wall of the antrum is related to the posterior semicircular canal and more deeply and inferiorly is the endolymphatic sac and the dura of the posterior cranial fossa. The roof forms part of the floor of the middle cranial fossa and separates the antrum from the temporal lobe of the brain. The posterior wall is formed mainly by the bony covering of the sigmoid sinus. The lateral wall is part of the squamous portion of the temporal bone and increases in thickness during life from about 2 mm at birth to 12-15 mm in the adult. The lateral wall in the adult corresponds to the suprameatal (Macewen's) triangle on the outer surface of the skull. This region can be felt through the cymba conchae of the auricle and is defined by the supramastoid crest - which is the posterior prolongation of the upper border of the root of the zygoma - by a vertical tangent through the posterior margin of the external meatus and, finally, by the posterosuperior margin of the external meatus itself.

The floor of the mastoid antrum is related to the digastric muscle laterally and the sigmoid sinus medially, although in a poorly aerated mastoid bone these structures may be 1 cm away from the inferior antral wall. The anterior wall of the antrum has the aditus in its upper part, while lower down, the facial nerve passes in its descent to the stylomastoid foramen.

**The mastoid air cell system**

In the majority of the adult population, a more or less extensive system of interconnecting air-filled cavities arises from the walls of the mastoid antrum, and sometimes even from the walls of the epi- and mesotympanum. These air cells can extend throughout
the mastoid process and may be separated from the sigmoid sinus and posterior and middle cranial fossae by thin bone, which is occasionally deficient. Cells often extend medial to the descending portion of the facial nerve as the retrofacial cells, down to the digastric muscle as the tip cells, and around the sigmoid sinus as the perisinus cells. They can reach the angle between the sigmoid sinus and the middle fossa dura (the sinodural angle), and may even extend out of the mastoid bone into the root of the zygoma and into the floor of the tympanic cavity underneath the basal turn of the cochlea. Occasionally, the apex of the petrous bone is pneumatized (see following subsection).

These air cells, like the mastoid itself, are lined with a flattened non-ciliated squamous epithelium. Pneumatization can be very extensive, as described previously, when the mastoid process is referred to in terms such as cellular, well-aerated, or by some similar name. Alternatively, the mastoid antrum may be the only air-filled space in the mastoid process when the name acellular or sclerotic is applied. This condition occurs in perhaps 20% of adult temporal bones. In between these two forms are the so-called diploeic or mixed types where air cells are present but are interspersed with marrow-containing spaces that have persisted from late fetal life.

**The petrous apex**

The petrous apex is, surgically, the most inaccessible portion of the temporal bone, and has the shape of a truncated pyramid with a base and three sides making up the medial part of the bone. The base of this pyramid is formed, from front to back, by the canal for the tensor tympani and the carotid artery, by the cochlea, the vestibule and the semicircular canals. The superior surface is the floor of the middle cranial fossa extending forwards from the line of the superior semicircular canal (indicated by the arcuate eminence) to the foramen lacerum and the impression for the ganglion of the trigeminal nerve (V). The posterior surface forms the bony wall of the posterior cranial fossa and extends, again from back to front, from the endolymphatic sac and the line of the posterior semicircular canal to the pointed anterior tip of the petrous bone, from which arises the petroclinoid ligament. The junction between the superior and posterior surfaces is marked by the superior petrosal sinus, and the lower limit of the posterior surface is the suture line with the occipital bone. The third face of the pyramid has the jugular bulb and inferior petrosal sinus at its margins and the external opening of the carotid canal in the middle.

Two structures run through the petrous apex - the carotid artery and internal auditory meatus. The latter structures, on entering the posterior surface, divides the petrous apex into anterior and posterior parts. Chole (1985), from whom this description of the petrous apex is derived, reports that about 10% of normal human temporal bones have air cells within the anterior part, while perhaps 30% have a pneumatized posterior segment.

It is also of interest that the carotid artery loses its thick muscular medial layer as it enters the temporal bone from the neck, with the result that the mean thickness of the wall is only 0.15 mm. Sometimes, also, the medial bony wall of the eustachian tube is deficient or extremely thin, so that the carotid is separated from the mucosal lining of the tube by just a thin layer of fibrous connective tissue.
The internal auditory meatus

This is a short canal, nearly 1 cm in length and lined with dura, which passes into the petrous bone in a lateral direction from the cerebellopontine angle. It is closed at its outer lateral end, or fundus, by a plate of bone which is perforated for the passage of nerves and blood vessels to and from the cranial cavity. The meatus transmits the facial, cochlear and vestibular nerves and the internal auditory artery and vein.

Although various authors, having used different techniques for measurement, report dissimilar dimensions, on average the vertical diameter of the meatus in 90% of normal subjects lies between 2 mm and 8 mm, with an average of about 4.5 mm, and the difference between the two sides in an individual does not exceed 1 mm. The average length of the posterior wall is 8 mm, and the difference between the two sides does not exceed 2 mm (Valvassori and Pierce, 1964; Papangelou, 1972).

The bony plate separating the fundus from the middle and inner ears has a transverse crest on its inner medial surface. This is the crista falciformis and it separates a small upper region from a larger lower area. Above the crest and anteriorly is the opening of the facial canal carrying the facial nerve (VII). This is separated, by a small vertical ridge (Bill's bar), from the posterior region which transmits the superior vestibular nerve through several small foramina to the superior and lateral semicircular canals, to the utricle and a part of the saccule. Below the transverse crest, the cochlear nerve lies anteriorly and leaves the meatus through the cochlear area which comprises a spiral of small foramina and a central canal. The inferior vestibular nerve passes through one or two foramina behind the cochlear opening to supply the saccule. Just behind and below the inferior vestibular foramen is the foramen singulare which contains the singular nerve. This runs obliquely through the petrous bone close to the fenestra cochleae (round window) to supply the sensory epithelium in the ampulla of the posterior semicircular canal.

The inner ear

The inner ear, or labyrinth, lies in the temporal bone, and for descriptive purposes it is divided into a bony and membranous portion. The membranous labyrinth containing the sensory epithelium of the cochlea and vestibular structures lies within cavities surrounded by the bony labyrinth.

The bony labyrinth

This is derived from the inner periosteal layer of the otic capsule, and in adult life consists of a thin, but dense, bony shell surrounding the vestibule, the semicircular canals and the cochlea.

The vestibule

The vestibule is the central portion of the bony labyrinth and is a small flattened ovoid chamber lying between the middle ear and the fundus of the internal auditory meatus. It is about 5 mm long, 5 mm high, but only 3 mm deep. On its lateral wall is the opening of the fenestra vestibuli closed in life by the footplate of the stapes and its annular ligament. On the
medial wall anteriorly is the spherical recess which houses the macule of the saccule and which is perforated by small holes that carry fibres from the inferior vestibular nerve. Behind the spherical recess is a ridge named the vestibular crest. At its lower end, the ridge divides to encompass the cochlear recess which carries cochlear nerve fibres to the very base of the cochlea. Above and behind the crest is an elliptical recess which contains the macule of the utricle. Nerve fibres, destined for the utricle and superior and lateral semicircular canals, perforate the bony wall in an area close by which corresponds to the superior vestibular nerve region at the fundus of the internal auditory meatus. The opening of the vestibular aqueduct lies below the elliptical recess, and the aqueduct itself passes through the temporal bone to open in the posterior cranial fossa but outside of the dura. It carries the endolymphatic duct and several small blood vessels. The posterior wall of the vestibule contains five openings that lead into the semicircular canals. The anterior wall of the vestibule contains an elliptical opening into the scala vestibuli of the cochlea.

The semicircular canals

There are three semicircular canals - superior, posterior and lateral - situated above and behind the vestibule. Each occupies about two-thirds of a circle and the canals are unequal in length, although the lumen of each has a diameter of about 0.8 mm. At one end of each canal is a dilatation called the ampulla which contains the vestibular sensory epithelium and opens into the vestibule. For the superior and lateral canals, the ampullae are next to each other at their anterolateral ends, while the ampulla of the posterior canal lies inferiorly near the floor of the vestibule. The non-ampullated ends of the superior and posterior canals meet and join to form the crus commune which enters the vestibule in the middle of its posterior wall. The non-ampullated end of the lateral canal opens into the vestibule just below the crus commune.

In the two ears, the lateral canals lie nearly in the same plane which slopes downwards and backwards at an angle of about 30° to the horizontal when the individual is standing. The other canals are at right angles to this, so that the superior canal of one ear lies nearly parallel with the posterior canal of the other.

The lateral canal bulges the medial wall of the epitympanum, while the apex of the superior canal lies very close to the floor of the middle cranial fossa. The arcuate eminence of this portion of the petrous bone often, but not always, overlies this part of the superior canal.

The cochlea

The bony cochlea lies in front of the vestibule and has an external appearance rather like the shell of a snail. It is, however, a coiled tube, with the inside of one coil being separated from the lumen of an adjacent coil by a dense, but thin, bony wall. The shell has approximately two-and-one-half turns and its height is about 5 mm, while the greatest distance across the base is about 9 mm. The coils of the cochlea turn about a central cone or modiolus which arises from the cochlear nerve portion of the fundus of the internal auditory meatus, and points laterally and forwards, tapering from a wide base to a narrow apex. The apex of the cochlea, therefore, faces laterally and forwards towards the upper part of the medial wall of the tympanic cavity, while the basal coil forms the bulge of the promontory below this.
Arising from the modiolus is a thin shelf of bone that spirals upwards within the lumen of the cochlea as the bony spiral lamina. A membrane - the membranous spiral lamina - extends from the edge of the bony spiral lamina to the outer wall of the cochlea, thereby dividing each coil into two major portions - the scala vestibuli and scala tympani.

Conventional anatomical nomenclature becomes very difficult within the cochlea because of its coiled shape and orientation, so that a separate system has arisen which defines the position of structures relative to the modiolus which is thought of as rising vertically from base to apex. Structures close to the modiolus are inner or medial, while other more distant structures are outer or lateral. A coil at the apex is above or apical to a coil at the base, while within one coil a structure on the apical side of the spiral lamina is above one below it. The scala vestibuli, therefore, lies above the scala tympani. This has greatly simplified relating one structure to another, and the terminology will be continued in this chapter.

At the apex, the spiral lamina continues for a short distance as a spur or crescent that is not attached to the modiolus. There is, therefore, communication between the perilymph spaces each side of the spiral lamina, and this channel is called the helicotrema.

At the base of the cochlea, the scala vestibuli opens into the vestibule with the fenestra vestibuli and stapes footplate close by on the lateral wall of the vestibule. The scala tympani is a blind-ended tube, but has in its floor the fenestra cochleae (round window) closed by the secondary tympanic membrane (round window membrane). A small opening into the cochlear aqueduct also arises from the basal end of the scala tympani. This aqueduct runs through the petrous bone and into the posterior cranial fossa well below the internal auditory meatus, establishing a communication between the subarachnoid space and the scala tympani.

The modiolus contains many small canals that spread out to enter the bony spiral lamina. The most central canals carry fibres to and from the apical regions, while the outermost canals carry fibres from more basal parts of the cochlea. Close to the origin of the bony spiral lamina, these canals dilate to accommodate the bipolar ganglion cells of the spiral (cochlear) ganglion, and the confluence of the dilated spaces has given rise to the name of the spiral canal of the modiolus. The name is slightly misleading as only a few unmyelinated efferent nerve fibres run along this apparent canal, with the vast majority of acoustic nerve fibres running across it from the organ of Corti, by way of the spiral ganglion, to form the cochlear nerve in the modiolus.

Perilymph

As well as containing the membranous labyrinth, the bony labyrinth is filled with perilymph. The exact origin of this fluid is not known, although it resembles plasma, interstitial fluid and cerebrospinal fluid in its make-up with major differences occurring in the concentration and type of proteins present (see Chapter 2 for further details).

The membranous labyrinth

The membranous labyrinth is a series of communicating sacs and ducts derived from ectoderm and filled with endolymph. Within the walls of the membranous labyrinth, the
epithelium has become specialized to form the sensory receptors of the cochlear and vestibular labyrinth.

**The cochlear duct (scala media)**

The duct of the cochlea consists of a spirally arranged tube lying on the upper surface of the spiral lamina against the outer wall of the bony canal of the cochlea. The length of the cochlea, as measured by the length of the organ of Corti, varies enormously between individuals and much more than in experimental animals. The average length is around 34 mm (standard deviation about 2 mm) while the range is from 29 to 40 mm, which has interesting implications when the physiology of the cochlear function is considered (see Chapter 20. The length measurements are derived from the works of Retzius (1884), Bredberg (1968), Walby (1985) and Ulehlova, Voldrich and Janisch (1986).

The cochlear duct is triangular in section with a floor formed by the outer part of the bony spiral lamina and all of the membranous spiral lamina; with an outer wall lying against a fibrous thickening of the bony cochlear wall - the spiral ligament; and with a thin sloping roof - Reissner's membrane - that runs from the bony spiral lamina to the upper part of the outer wall. The scala vestibuli lies above the cochlear duct, the scala tympani below.

**The floor of the cochlear duct**

The inner part of the floor is formed by the bony spiral lamina which separates into two ridges one above the other. The upper ridge is the spiral limbus from which the tectorial membrane originates, while the lower ridge gives rise to the membranous spiral lamina and has acoustic nerve fibres running through it to the organ of Corti. The membranous spiral lamina has the flattened epithelium of the scala tympani on its underside, a fibrous middle layer and the organ of Corti on its upper surface. This is separated from the spiral limbus by the inner sulcus, and from the lateral wall by the outer sulcus. The organ of Corti is a ridge-like structure containing the auditory sensory cells and a complex arrangement of supporting cells. The sensory cells are arranged in two distinct groups as inner and outer ‘hair cells’. They are called hair cells because a cluster of fine filaments, resembling hairs, projects from the upper surface of each sensory cell. There is a single row of inner hair cells, although occasionally extra hair cells may be apparent, and also three, four or five irregular rows of outer hair cells, with frequent gaps where individual hair cells are absent. The distribution of hair cells is markedly different from that seen in rodents (guinea-pigs, rats, etc) where there is nearly always a highly regular arrangement.

Each hair cell consists of a body, which lies within the organ of Corti, and a thickened upper surface called the cuticular plate, from which projects a cluster of stereocilia or ‘hairs’. The stereocilia are not true cilia in that they do not have a central 'nine plus two' core of microtubules, but are more like large microvilli comprising a core of actin molecules packed in a paracrystalline array and covered with a cell membrane (Tilney, Derosier and Mulroy, 1980). The name ‘cilia’ is, therefore, inappropriate, but its use, like that of the term 'hair cell', has become entrenched in the literature and is unlikely to be replaced by a more convenient and correct term. The inner hair cells are separated from the outer ones by the tunnel of Corti. The bodies of the inner hair cells are flask-shaped, with a small apex and large cell body. The long axis of the cell is inclined towards the tunnel of Corti, and nerve fibres and nerve
endings are located around the lower half of the body. The stereocilia projecting from the thickened cuticular plate are arranged in two or three rows parallel to the axis of the cochlear duct. The shortest row of stereocilia is innermost, while the longest row is outermost. Along the length of the cochlear duct, the height of the longest stereocilia increases linearly with distance from the base, although the variation from base to apex is not great.

The body of the outer hair cell is cylindrical, with the nucleus lying close to the lower pole where afferent and efferent nerve endings are attached. The stereocilia that project from this have a different arrangement from those of the inner hair cells. There are several rows of stereocilia but the configuration varies from a W-shape at the base, through a V-shape in the middle coil, to an almost linear array at the apex. The number of stereocilia also decreases in the passage from base to apex, whereas the length increases although not in linear fashion (Wright, 1984). Within a single cluster of stereocilia, individual members are linked by short transverse fibrils, and the tips of shorter stereocilia have fine fibrillar extensions running laterally to adjoining longer stereocilia (Furness and Hackney, 1985). These linkages are also found between the stereocilia of both the inner hair cells and vestibular sensory cells. The role of these structures in cochlear mechanics is described in Chapter 2.

In the fetus and the newborn there are about 3500 inner hair cells and 13,000 outer hair cells (Bredberg, 1968), although the number of hair cells varies with the length of the cochlea, shorter cochleae having far fewer inner and outer hair cells. The distribution of hair cells, in terms of hair cell density related to place in the cochlea, can be plotted as a cytocochleogram, and it is found that with age there is a generalized reduction in the number of hair cells and an additional loss both at the base and, to a lesser extent, at the apex. These changes are most marked in the outer hair cells but are also found in the inner hair cell population.

The hair cells are supported within the organ of Corti by several types of specialized, highly differentiated cells. These are the pillar cells, Deiters' cells and Hensen's cells.

The tectorial membrane arises from the spiral limbus and extends over the organ of Corti to attach close to the Hensen cell region (Kronester-Frei, 1979). The membrane is an acellular gel-like matrix containing fibrillar strands, and is extremely sensitive to distortion and shrinkage during most preparation techniques. The tips of the longest stereocilia of the outer hair cells are attached to, or embedded in, the undersurface of the tectorial membrane and leave an impression on this surface. In adults, however, no impression or attachment of the inner hair cells has ever been noted.

The lateral wall of the cochlear duct

The lateral wall of the cochlear duct has three distinct zones: the stria vascularis above, the spiral prominence below and a transitional zone between the two. The stria vascularis forms the bulk of the lateral wall and consists of three cell layers. The marginal cells face the endolymph and are separated by the intermediate cells from a basal cell layer which is rich in capillaries. The marginal cells have a carpet of microvilli on their endolymphatic surface and tight junctions between neighbouring cells, so that the stria vascularis is effectively isolated from the endolymph. These cells are also rich in mitochondria, have an extensive Golgi apparatus and endoplasmic reticulum, and complex
foldings of their basal membranes, which interdigitate with the intermediate and basal cells. The stria is a metabolically active tissue and is thought to play an active role in the maintenance of the ionic composition and electrical potential of the endolymph.

**The roof of the cochlear duct (Reissner's membrane)**

Reissner's membrane is a thin membrane stretching from the bony spiral lamina to the upper part of the lateral wall of the cochlear duct. The endolymphatic surface consists of typical squamous epithelial cells with microvilli on their surface and joined together by tight junctions. A thin basement membrane separates these cells from those of the upper - scala vestibuli - side of the partition. These perilymphatic cells are thicker but have a dense cytoplasm only around the nucleus.

All of the cells lining the scala media are joined by tight junctions which effectively separate the endolymph from the outside and help in maintaining the unusual ionic content of this fluid (see Chapter 2 for details of the ionic constituents of endolymph).

**The vestibular labyrinth**

The vestibular labyrinth consists of a complex series of interconnecting membranous ducts and sacs which contain the vestibular sensory epithelium. Unlike the cochlea, the sensory epithelium is found in localized collections in the three ampullae of the semicircular ducts and in the maculae of the saccule and utricle. The saccule lies in the spherical recess near the opening of the scala vestibuli of the cochlea. It is almost globular in shape but is prolonged posteriorly where it makes contact with the utricle. In the anterior wall there is an oval thickening - the macula. The saccule is connected anteriorly to the cochlea by a narrow duct, the ductus reuniens. From the posterior part arises the endolymphatic duct. This is joined by the utriculosaccular duct at an acute angle, and continues medially through the vestibular aqueduct to end as a blind pouch, the endolymphatic sac. The junction between the endolymphatic and utriculosaccular ducts has a Y-configuration with the lower limb continuing to the sac.

The utricle is the larger of the two vestibular sacs and is irregularly oblong in shape, occupying the posterosuperior part of the bony vestibule. The lower part of the lateral wall of the pouch contains the comma-shaped macula, the plane of which lies at right angles to that of the macule of the saccule. Apart from the utriculosaccular duct, there are five openings into the utricle which correspond to the utricular ends of the semicircular ducts.

The three semicircular ducts are about 0.2 mm in diameter and resemble the bony canals. Each duct has an ampulla at one end, and within this the sensory cells are collected on a saddle-shaped ridge - the crista - that runs across the lumen.

**The vestibular sensory epithelium**

The sensory cells of the ampullae and maculae have the same structure and comprise type I and type II cells. Type I cells are flask-shaped with a rounded base and a short neck. The body is surrounded by a large goblet-shaped nerve terminal, or chalice, which often extends to enclose more than one type I cell. The upper surface of the cell is thickened in the
form of a cuticular plate and has a single kinocilium and between 20 and 100 stereocilia projecting from its surface. The kinocilium is slightly thicker than the stereocilia and has the internal structure of a true cilium with a 'nine plus two' arrangement of microtubules and an associated basal body and centriole. The stereocilia have the same internal structure as those of the cochlear sensory cells.

Type II cells are cylindrical in shape with the same collection of kino- and stereocilia as the type I cells. The cell body, however, is not surrendered by a nerve chalice but has many button-like nerve terminals associated with it. These button terminals are either granulated and thought to be efferent in origin, or non-granulated and presumed, conversely, to be afferent. The fibres arising from the type I cells are larger in diameter than those of the type II cells, and they are afferent. Efferent fibres to the type I cells appear to terminate on the nerve chalice itself rather than on the cell body.

The location of the kinocilium gives the sensory cells polarity and this is related to the changes that occur in the neural output when the ciliary bundle is deflected. Deviation in the direction of the kinocilium results in an increase in the resting output of nerve impulses of the afferent neurons, while deflection away from the kinocilium inhibits the resting discharge. The sensory cells are arranged in the cristae and maculae, so that there are strict patterns of orientation in the polarity of the cells (see Chapter 4 for further details and physiological relevance).

The sensory cells are surrounded by supporting cells. The apical surface of the supporting cells are covered with microvilli and it would appear that these cells have a secretory function. Close to the edges of the sensory cell regions of the cristae and maculae, and separated by a transitional zone in much the same way that the stria vascularis is separated from the organ of Corti, is a region occupied by 'dark cells'. These have an irregular surface, and resemble the marginal cells of the stria vascularis. Objects resembling degenerating otoconia are often found on the surface of the dark cells whose function is unclear but may, like the stria vascularis, have some role to play in the maintenance of the composition of the endolymph and, in addition, in the resorption of otoconia.

**Structures associated with the vestibular sensory cells**

In each ampulla, a gelatinous, wedge-shaped cupula sits astride the crista. The cupula, like the tectorial membrane, is extremely sensitive to alterations in its ionic environment and shrinks when standard preparative techniques are employed. In life, the cupula extends to the roof and lateral walls of the ampulla, and is attached firmly to each end of the crista. The rest of the dome of the ampulla also contains a loose fibrillar meshwork but there does appear to be a space between the cupula and the surface of the crista. The 'cilia' of the sensory cells project into this and the longest 'cilia' appear to enter the cupula. It seems most likely that during angular acceleration the cupula remains fixed, and the angle of the junction of the semicircular duct and the ampulla, along with the loose matrix within the dome of the ampulla, serve to direct endolymph into the subcupular space where deflection of the ciliary bundles occurs, with resulting stimulation or inhibition of the neural output of the sensory cells (Dohlman, 1981).
In each macula, a gelatinous material overlies the sensory cells, the ciliary bundles of which appear to project into a honeycomb meshwork in its undersurface. Embedded in the upper surface of the gelatinous layer are the otoconia. These have a characteristic shape with a barrel-shaped body and pointed ends. The size of the otoconia is not constant but varies across each macula. Small crystals are found near the central strip, or striola, and near to the margins, while the intervening zone has large, sometimes very large, crystals present in it. The term ‘otoconial membrane’ is used to describe the combination of the otoconia and the gelatinous membrane.

When the surface of the maculae is examined more closely, small globular bodies can be seen, apparently arising from the supporting cells. In experimental animals, these structures have a high calcium content and it has been suggested that the calcium of the otoconia is derived from its source (Harada, 1979). The otoconia are not static structures but appear to have a slow turnover with degenerating otoconia probably being resorbed by the dark cell regions (see Lim, 1984, for review).

The endolymphatic system

The endolymphatic system consists of a duct formed from the endolymphatic duct of the saccule and the utriculosaccular duct from the utricle, and a sac. The sac comprises three distinct portions. The proximal portion or isthmus is the first portion that is wider than the duct and lies within the bony vestibular aqueduct, as does the intermediate or rugose portion. The distal part of the sac is flattened and lies between the dura of the posterior fossa and the petrous bone. This arrangement is quite different from that found in most experimental animals where the rugose position, along with the distal position, is extradural.

The proximal part of the sac is lined with low cuboidal epithelium, whereas the intermediate, rugose, portion has a columnar epithelium that is extensively folded and, on cross-section, appears to consist of many small channels. The ultrastructural features suggest that the cells have an absorptive or secretory function. The distal part of the sac - that part which is surgically assessible - has a low cuboidal epithelium with no features suggestive of much metabolic activity, and an extremely narrow lumen as the opposing layers of the lining of the sac are frequently in contact (Lundquist et al, 1984).

Innervation of the cochlea

The cochlea is connected with the brainstem by afferent and efferent nerves. The afferent nerves, carrying sensory information to the brainstem, have their cell bodies in the spiral ganglion and their terminal dendrites make contact with the hair cells. The efferent nerves pass directly through the spiral ganglion, their cell bodies being located within the brainstem.

There are major differences in the make-up of the cochlear nerve and spiral ganglion between the frequently studied small mammals and man, and because of the difficulty in obtaining suitable material much remains to be learnt about the anatomy in man. Nevertheless, each cochlear nerve in young, normal individuals contains about 30,000 unmyelinated nerve fibres. These are virtually all afferent, as the efferent fibres travel initially in the superior vestibular nerve (see below). The afferent fibres pass through the modiolus to the spiral canal
where their cell bodies are found. Ninety-five per cent of the spiral ganglion cells are large type I cells, but unlike those found in other species the majority are unmyelinated as the afferent fibre loses its myelin sheath a short distance before entering the cell body. These type I cell bodies, both myelinated and unmyelinated, are bipolar and their terminal dendrites subsequently become myelinated for a short distance as they pass through the bony spiral lamina to reach the inner hair cells (Ota and Kimura, 1980). Each inner hair cell has about 10 dendrites synapsing around the lower part of the cell body.

The other 5% of spiral ganglion cells are small and may be myelinated or unmyelinated. The cell bodies can be unipolar or bipolar, and by analogy with animal work, it seems likely that the dendrites of these type II cells supply the outer hair cells. The fibres leave the spiral ganglion, run first across the floor of the tunnel of Corti and then descend the cochlea for up to 1 mm within an outer spiral bundle of nerve fibres before being distributed to 10 or more outer hair cells in various rows.

The efferent fibres are few in number and arise in both the homo- and contralateral superior olivary complex. They travel initially in the superior vestibular nerve which they leave in the internal auditory meatus to join the cochlear division by way of Oort's anastomosis. They enter the spiral canal within the modiolus and ascend or descend for a short distance. Some fibres subsequently supply the inner hair cells, while others run out across the tunnel of Corti as tunnel crossing fibres, to branch and terminate as large vesiculated nerve endings on several outer hair cells. The efferent innervation is most dense at the base of the cochlea but gradually diminishes towards the apex.

The other class of fibres entering the cochlea are adrenergic sympathetic fibres, some of which come from the superior cervical ganglion and are independent of the blood supply, whereas others originate in the stellate ganglion and arise from the plexus that surrounds the vertebral, basilar, anterior inferior cerebellar and labyrinthine arteries (see Spoendlin, 1984 for review).

The vestibular nerve

The vestibular nerve, like the cochlear nerve, contains afferent and efferent fibres as well as adrenergic sympathetic fibres. Unlike the cochlear nerve, however, there are a large number of efferent fibres and only 19,000 to 20,000 afferent fibres in the young adult. The calibre of the afferent fibres varies considerably between 2 and 15 microm (Spoendlin, 1972). The distribution of the various branches has already been described.

The vestibular ganglion (Scarpa's ganglion) contains the bipolar cell bodies of the afferent neurons as well as the efferent fibres that pass straight through. The ganglion lies at the lateral end of the internal auditory meatus partly covering the vestibular crest and being partially separated into a superior and inferior portion. Proximal to this, the vestibular nerve is a single bundle on its way to the brainstem by way of the cerebellopontine angle.

The central connections of the cochlear and vestibular nuclei are described in more detail in Chapter 2 (cochlear) and Chapter 4 (vestibular).
The blood supply of the labyrinth

The labyrinth is supplied principally from the labyrinthine artery which is usually a branch of the anterior inferior cerebellar artery, although it may arise directly from the basilar or even the vertebral arteries. The artery passes down the internal auditory meatus to divide into an anterior vestibular and a common cochlear artery, which subsequently divides into the cochlear artery and the vestibulocochlear artery.

The anterior vestibular artery supplies the vestibular nerve, much of the utricle and parts of the semicircular ducts.

The vestibulocochlear artery, on arrival at the modiolus, in the region of the basal turn of the cochlea, divides into its terminal vestibular and cochlear branches, which take opposite directions. The vestibular branch supplies the saccule, the greater part of the semicircular canals, and the basal end of the cochlea; the cochlear branch, running a spiral course around the modiolus, ends by anastomosing with the cochlear artery. The vestibular and cochlear branches both supply capillary areas in the spiral ganglion, the osseous spiral lamina, the limbus, and the spiral ligament.

In the internal auditory canal, the cochlear artery runs a spiral course around the acoustic nerve. In the cochlea, it runs a serpentine course around the modiolus, as the spiral modiolar artery, which is an end artery. Arterioles leave this artery, to run either into the spiral lamina or across the roof of the scala vestibuli. Both sets of arteries end in capillary networks either in the spiral lamina or the stria vascularis on the lateral wall of the cochlear duct. The capillaries from the lateral wall drain into venules which run under the floor of the scala tympani to empty into modiolar veins which run spirally down the modiolus. The apical regions are drained by way of an anterior spiral vein, while the basal regions drain into the posterior spiral vein. These two branches of the spiral vein join with the anterior and posterior branches of the vestibular vein, in the region of the basal turn, to form the vein of the cochlear aqueduct - the principal vein of the cochlea - which empties into the jugular bulb.

The vestibular labyrinth is drained from the anterior part by the anterior vestibular vein, which becomes the labyrinthine vein and accompanies the artery of the same name, usually ending in the superior petrosal sinus; and also from the posterior part by the vein of the vestibular aqueduct which passes alongside the endolymphatic duct to the sigmoid sinus.

This description of the vascular supply of the cochlea is based on the work of Axelsson (1968).

The facial nerve

The seventh cranial nerve - the facial or intermediofacial - is a mixed nerve containing:

1) motor fibres to the muscles of facial expression, the buccinator, stapedius, digastric and stylohyoid

2) taste fibres from the palate and anterior two-thirds of the tongue
(3) secretomotor parasympathetic fibres to the lacrimal and nasal glands, and to the submandibular and sublingual salivary glands

(4) sensory fibres supplying part of the concha of the auricle and sometimes an area of skin behind the ear and part of the mucous membrane in the supratonsillar recess.

The motor fibres have their cell bodies in the facial nucleus in the pons. The nucleus receives pyramidal fibres from the contralateral motor cortex and a smaller number from the same side. The contralateral fibres reach all of the nucleus, while the ipsilateral fibres supply those parts of the motor nucleus involved with innervating the forehead and the muscles around the eyes. Other fibres also relay on the facial motor nucleus and are involved in reflex movements. They come from the superior colliculus (an optic reflex centre), from the superior olive (acoustic reflex), as well as from sensory V nuclei and the nucleus of the solitary tract. The various inputs are involved in blinking and closing the eyes in response to strong light or touch on the cornea (corneal reflex), contraction and relaxation of the stapedius in response to sound, and sucking movements following the introduction of food into the mouth. Other fibres arrive from higher centres by way of the red nucleus, the mesencephalic reticular formation and probably the globus pallidus, and have been assumed to be involved with emotional facial movement.

The motor fibres leaving the facial nucleus do not pass directly out of the pons but first run medially and dorsally towards the floor of ventricle IV, turn around the nerve VI nucleus and then stream out laterally to leave the pons on the lateral aspect of the brainstem.

The sensory root of the facial nerve enters the brainstem as a separate nerve - the nervus intermedius. It carries the sensory fibres from the conchal skin and the supratonsillar recess, and the taste fibres from palate and tongue. The ganglion associated with these sensory fibres is the geniculate ganglion and the central processes of the unipolar ganglion cells leave the trunk of the facial nerve in the internal auditory meatus, as the nervus intermedius, to enter the brainstem at the lower border of the pons, and pass to the upper part of the nucleus of the solitary tract (tractus solitarius).

Secretomotor parasympathetic fibres also run in the nervus intermedius and have the superior salivatory nucleus as their origin.

At the fundus of the internal auditory meatus, the motor facial nerve - which, with the addition of the nervus intermedius, is now complete - enters the facial canal. In this canal, the nerve, surrounded by cerebrospinal fluid, runs between the cochlea anteriorly, the superior semicircular canal posteriorly and with the vestibule beneath it. This labyrinthine segment is the narrowest part of the facial canal with an average diameter of only 0.68 mm at the site of entry of the nerve (Fish, 1979). As the nerve reaches the medial wall of the epitympanic recess, it turns sharply backwards to make an angle of about 60° with the subsequent tympanic segment. At this turn - the geniculum - lies the geniculate ganglion which is a reddish asymmetric swelling.

The tympanic portion of the nerve now begins as it runs posteriorly on the medial wall of the tympanic cavity. The nerve is surrounded by a bony shell and stands out clearly just above the promontory and oval window recess, but below the prominence of the lateral
The anterior end of the tympanic portion is marked by the processus cochleariformis which is a stable landmark rarely eroded by disease. From this level, the nerve slopes downwards and backwards at an angle of about 30° from the horizontal. Above the oval window recess the nerve starts to curve inferiorly, and at the level of the pyramid enters the descending or mastoid portion of its intratemporal course. At this pyramidal turn, the short process of the incus always lies lateral to the nerve. In the descending portion, the nerve lies posterior and deep to both the tympanic annulus and the tympanomastoid suture line in the posterior wall of the external auditory meatus. This descending portion of the nerve lies deep within the mastoid portion of the temporal bone, rarely less than 1.8 cm from the outer surface of the bone in the adult.

The nerve emerges from the stylomastoid foramen to enter the neck. The posterior belly of digastric is attached to the digastric groove on the inferior surface of the mastoid process. This groove leads forwards to the stylomastoid foramen and the muscle provides a valuable landmark for the nerve. From the stylomastoid foramen, the nerve turns forward and passes laterally to the base of the styloid process and enters the parotid gland. Within the gland, the nerve separates into two primary divisions - an upper temporofacial and a lower cervicofacial. Each of these breaks up into several terminal branches which interconnect as the parotid plexus. From this plexus arise the terminal branches of the nerve.

During its course, the facial nerve makes communication with many other nerves, although the precise function of these is often unknown (Table 1.5).

**Table 1.5 Branches of communication of the facial nerve**

<table>
<thead>
<tr>
<th>Location</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal auditory meatus</td>
<td>Vestibulocochlear nerve</td>
</tr>
<tr>
<td>Geniculate ganglion</td>
<td>Greater petrosal nerve to pterygopalatine ganglion</td>
</tr>
<tr>
<td></td>
<td>Via lesser petrosal nerve to otic ganglion</td>
</tr>
<tr>
<td></td>
<td>Sympathetic plexus on middle meningeal artery</td>
</tr>
<tr>
<td>Facial canal</td>
<td>Auricular branch of vagus</td>
</tr>
<tr>
<td>At stylomastoid foramen</td>
<td>IX, X, greater auricular and auriculotemporal nerves</td>
</tr>
<tr>
<td>Behind the ear</td>
<td>Lesser occipital nerve</td>
</tr>
<tr>
<td>On the face</td>
<td>V nerve</td>
</tr>
<tr>
<td>In neck</td>
<td>Transverse cutaneous nerve of neck.</td>
</tr>
</tbody>
</table>

**Branches of the facial nerve**

**From the geniculate ganglion**

(1) Greater (superficial) petrosal nerve. This leaves the geniculate ganglion anteriorly, runs forwards and receives a twig from the tympanic plexus. It enters the middle cranial fossa outside the dura, and runs in a groove in the bone to pass beneath the trigeminal ganglion where it is joined by the deep petrosal nerve from the sympathetic plexus on the internal carotid artery. The nerve is now called the nerve of the pterygoid canal and it runs through this canal to end in the pterygopalatine ganglion. Taste fibres pass on without interruption in the palatine branches of the ganglion. The secretomotor fibres in the nerve synapse within the
ganglion and carry on by way of the zygomatic and lacrimal nerves to the lacrimal gland, and through the nasal and palatine nerves to the nasal and palatine glands.

**Branches within the facial canal**

(1) *Nerve to stapedius.* This arises from the facial nerve as the latter begins its descent, and reaches the muscle through a small canal in the base of the pyramid.

(2) *The chorda tympani.* This usually arises above the stylomastoid foramen but can occasionally leave the facial nerve outside the temporal bone and re-enter by way of a separate foramen. Its course in the middle ear has been described already and the nerve leaves the temporal bone by the petrotympanic fissure. It descends, sometimes grooving the medial surface of the spine of the sphenoid, and passes deep to the lateral pterygoid muscle to join the lingual nerve. The parasympathetic secretomotor fibres leave the lingual to enter the submandibular ganglion, which is suspended from the nerve by two fine neural filaments. The secretomotor fibres synapse within the ganglion and continue to supply the submandibular and sublingual salivary glands as well as other minor salivary glands in the floor of the mouth.

The majority of fibres in the chorda tympani are, however, taste fibres and these are derived from the mucous membrane of the presulcal part of the tongue but not from the vallate papillae which lie just in front of the sulcus.

**Branches in the neck and face**

(1) *The postauricular branch* arises close to the stylomastoid foramen and runs up between the external auditory canal and anterior surface of the mastoid. It has connections with other nerves as it continues on to supply the posterior auricular muscle, the intrinsic muscles of the posterior aspect of the pinna and the occipital muscle.

(2) *The digastric branch* also arises close to the stylomastoid foramen and supplies the posterior belly of the digastic.

(3) *The stylohyoid branch* supplies the stylohyoid muscle and arises near or in conjunction with the digastic branch.

**Branches from the parotid plexus**

These are highly variable, as is the site of division of the facial nerve into temporofacial and cervicofacial divisions. Nevertheless, five major branches are nearly always found.

(1) *Temporal branches* cross the zygomatic arch and supply intrinsic muscles on the lateral surface of the auricle and the anterior and superior auricular muscles. Other branches supply the frontal belly of the occipitofrontalis, the orbicularis oculi and corrugator.
(2) Zygomatic branches run parallel to the zygomatic arch and also innervate orbicularis oculi. Some of the lower branches may join with the buccal branches to form an infraorbital plexus which innervates the muscles in the middle part of the face.

(3) Buccal branches pass horizontally forward to the muscles of the middle part of the face. These include the procerus, orbicularis oculi, zygomaticus, levator anguli oris, levator labii superioris, buccinator, orbicularis oris and the small muscles of the nose.

(4) The mandibular branch runs forward below the angle of the mandible under platysma and then turns upwards and forwards to cross the mandible under cover of depressor anguli oris which it supplies. It continues onwards and supplies the orbicularis oris and other muscles of the lips and chin.

(5) The cervical branch leaves the lower part of the parotid gland and runs down the neck under cover of platysma which it supplies.

**Blood supply of the facial nerve**

The facial nerve is supplied by the anterior inferior cerebellar artery in its intracranial course, by the superficial petrosal branch of the middle meningeal artery, and by the stylomastoid branch of the postauricular artery in its intratemporal course. Outside the skull, the stylomastoid artery, the posterior auricular or occipital, the superficial temporal and transverse facial artery are all involved.

The veins form a plexus around the nerve, and efferent veins run from this through the nerve sheath to lie on its outer surface. From the intratemporal portion, the venous drainage leaves the canal at the stylomastoid foramen and at the geniculum where it enters the venae comitantes of the stylomastoid and superficial petrosal arteries respectively.