Anatomical considerations

- ***The ear consists of the outer, the middle and the inner ear.***

◘ The **outer ear** consists of the pinna and the external auditory canal, directed medially and forwards to the eardrum or **tympanic membrane.** The tympanic membrane is shaped like a shallow funnel, with the tip of the funnel or umbo pointing inwards. It is lined by skin on the outside and mucous membrane on the inside.

◘ The **middle ear** is a cavity in the temporal bone filled with air and containing the three **ossicles:** the **malleus,** the **incus** and the **stapes.** The handle of the malleus (manubrium) is attached to the back of the tympanic membrane with its tip at the umbo; the head of the malleus articulates with the incus, the process of which articulates with the head of the stapes. The footplate of the stapes is attached to the wall of the **oval window** of the cochlea by an annular ligament, which is fixed firmly at a posterior point but is slightly loose otherwise, to allow for movement of the footplate.

✓ The air in the cavity of the middle ear communicates with the nasopharynx through the **Eustachian** or **auditory tube** and then with the outside air. The opening of the auditory tube in the nasopharynx is normally closed but it opens during chewing, swallowing and yawning, to allow equalization of pressure between the middle car and atmospheric pressure, i.e. on both sides of the tympanic membrane. A severe head cold may cause inflammation which closes off the auditory tube. The air trapped in the middle ear is partly absorbed, leading to atmospheric pressure pressing on the tympanic membrane and causing discomfort and reduced acuity of hearing.

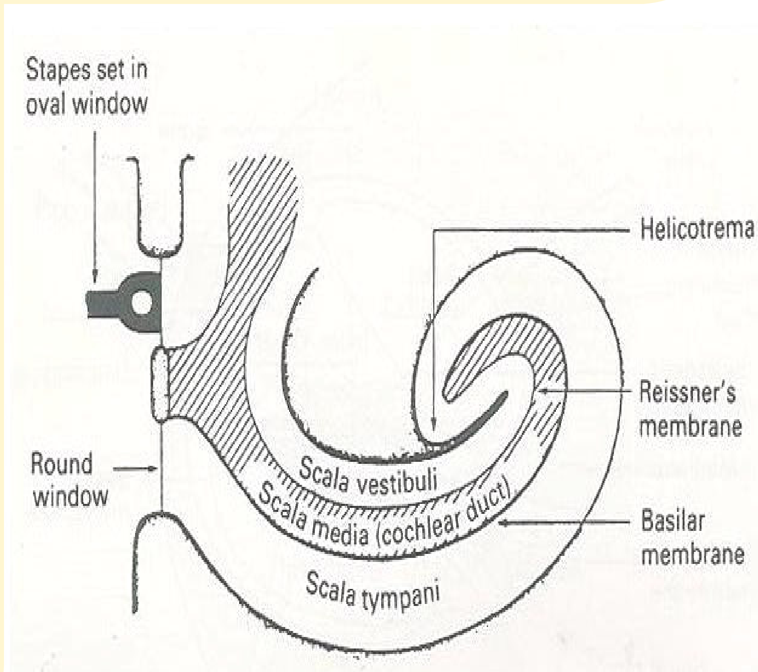
✓ *There are two small striated muscles in the middle ear:*

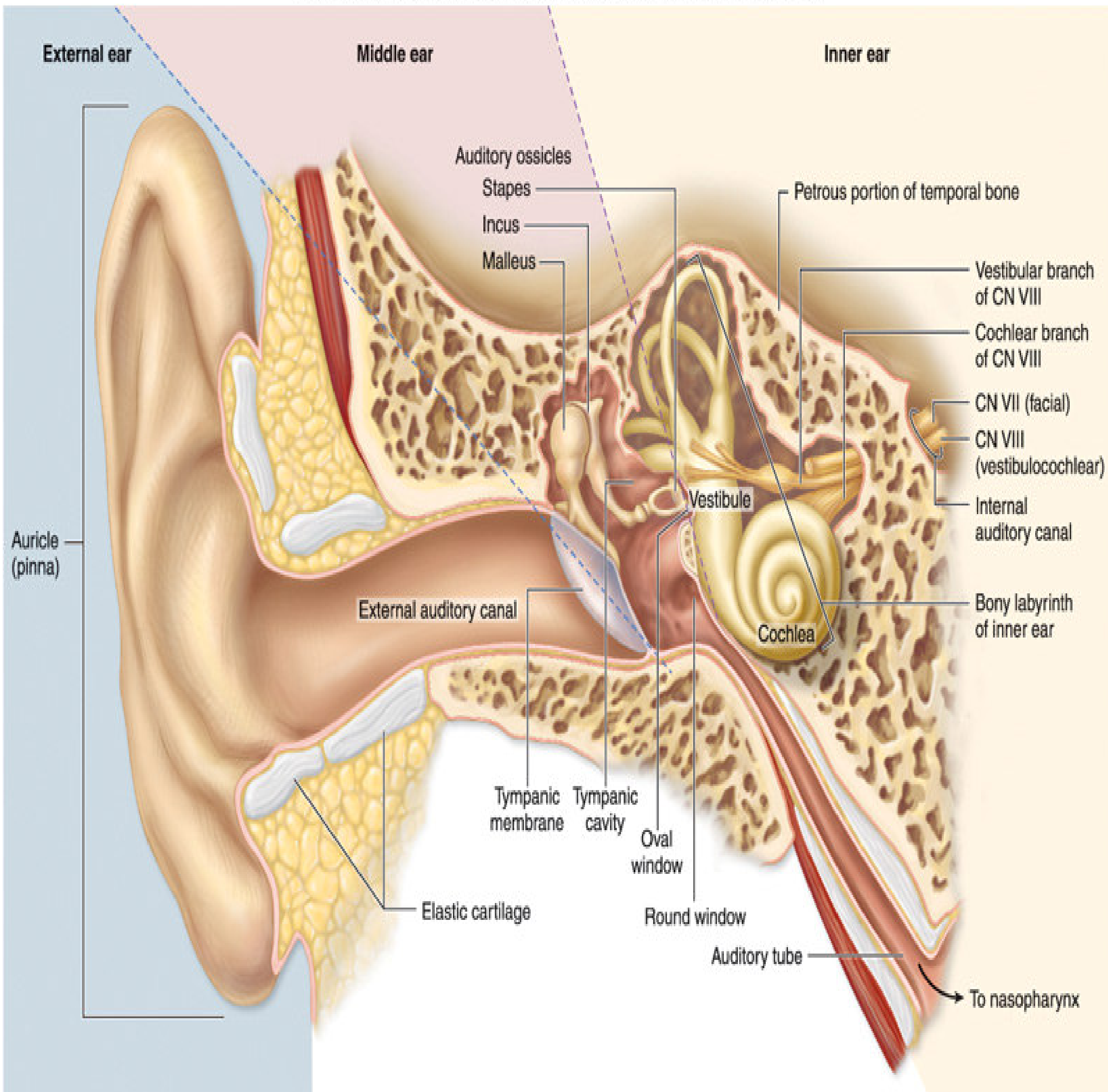
(i) the **tensor tympani,** attached to the neck of the malleus; when it contracts, it pulls (he drum medially; and

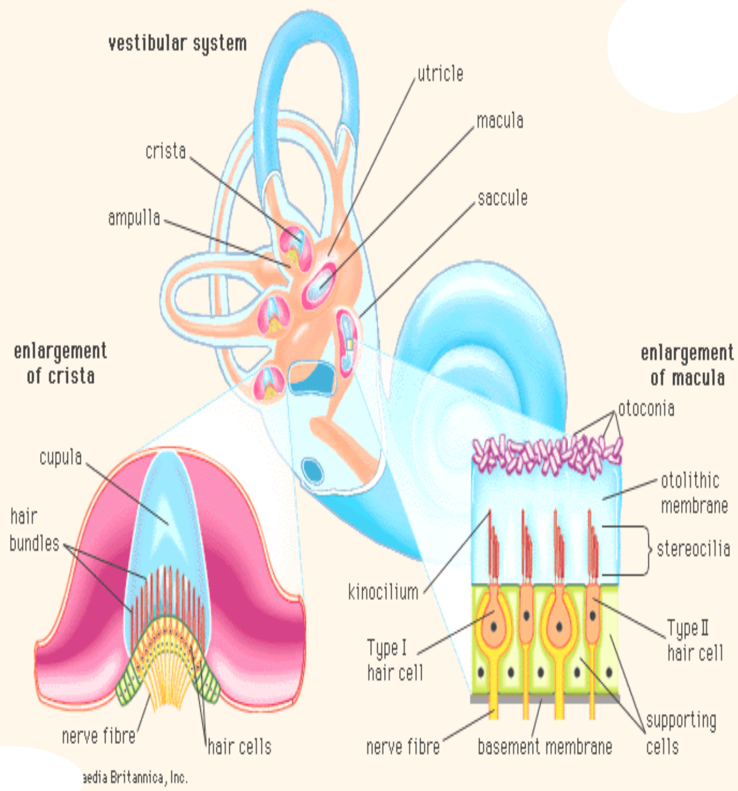
(ii) the **stapedius,** attached to the neck of the stapes; when it con-tracts, it tends to pull the footplate of the stapes out of the oval window. Simultaneous contraction of the two muscles reduces conduction of sound to the cochlea. Very loud sounds lead to reflex contraction of the tensor tympani and the stapedius, which thus reduces transmission of these loud sounds to the auditory receptors. This is termed the **tympanic reflex,** which is protective; however, it has a latent period of 40-160 ms, which makes it ineffective against brief sounds of high intensity.

The **inner ear** or labyrinth consists of the bony and membranous labyrinth. The bony part is a series of channels in the petrous part of the temporal bone, and membranes run inside the bony channels to form the **membranous labyrinth.** Between the bone and membranes is a fluid called **perilymph,** while inside the membranous labyrinth the fluid is **endolymph;** the two fluids do not mix. In the inner ear the **semicircular canals,** the **utricle** and the **saccule** are concerned with balance and are part of the vestibular system, which has been described in Chapter 16. The **cochlea** is concerned with hearing. In humans the cochlea is about 35 mm long; it is coiled spirally around a central bony pillar, called the modiolus, making two and three-quarter turns. Throughout its length it is divided into three chambers by two membranes; **Reissner's membrane** and the **basilar membrane** (Fig. 17.18). The upper chamber is called the **scala vestibuli,** which ends laterally at the oval window. The lower chamber is called the **scala tympani,** which ends laterally at the round window, which is closed by a **secondary tympanic membrane.** Between the two membranes is the **scala media** or **cochlear duct,** containing endolymph. Both the scala vestibuli and the scala tympani contain perilymph and communicate with each other at the apex of the cochlea (the helicotroma).

The receptors for hearing are hair cells which are found in **the organ of corti** , the organ of corti sits on the basilar membrane and extends from the base to the apex of the cochlea . between the rods of the corti is the tunnel of corti which contains perilymph . there is a single row **of inner hair cells** medial to the tunnel of corti and numbering 3500 . lateral to the tunnel of Corti are three rows of **outer hair cells** , numbering about 20,000 . the hair cells have process **(STEREOCILIA)** that pierce the tough reticular membrane . the process of outer but not inner , hair cells are embedded in the elastic **ribbonlile tectorial** membrane . nerve fibers , with cell bodies in spiral ganglion , branch extensive around the basses of the hair cells . there are 28,000 fibers in the auditory nerve . about 90-95% innervate the inner hair cells, while only about 5-10% supply the more numerous outer hair cells




External ear
Middle ear
Inner ear
Auditory ossicles
Stapes
Incus
Malleus
Petrous portion of temporal bone
Vestibular branch of CN VIII
Cochlear branch of CN VIII
CN VII (facial)
CN VIII (vestibulocochlear)
Internal auditory canal
Auricle (pinna)
Vestibule
External auditory canal
Cochlea
Bony labyrinth of inner ear
Tympanic membrane
Tympanic cavity
Oval window
Elastic cartilage
Round window
Auditory tube
To nasopharynx



Sound

Sound, unlike light, requires a medium to travel in. It travels in air at the speed of 344 m/s and at a faster speed in water. Sound travels in the form of waves, which, in their simplest form, can be represented as sine waves. There are two basic properties of sound waves:

(i) **amplitude,** which determines the *intensity* of sound or its *loudness*—the higher the amplitude, the greater the intensity of sound; and

(ii) **frequency,** or the number of cycles per second (Hz), which determines the *pitch* or tone of sound—the higher the frequency, the higher the pitch of sound.

✓ Intensity refers to the strength of the sound in physical terms, while loudness denotes appreciation of the sound intensity by the hearing apparatus. Loudness is affected by the frequency of sound (see Audibility below). Complex sounds with regularly repeating patterns are perceived as music, while sound waves of irregular frequency give a sensation of noise.

Sound intensity may be measured in terms of energy, in microwatts or ergs per second, or pressure, in dynes/cm". The range in intensity between the threshold of sound and the loudest sound that can be tolerated is very large. It would therefore be inconvenient to employ a linear

absolute scale to measure sound intensity in everyday life. A comparative logarithmic scale is employed, in which the basic unit is the bel (after A.G. Bell):

$$\text{bel} = \log \frac{\text{intensity of sound}}{\text{intensity of standard sound}}$$

Since intensity is directly proportional to the square of the sound pressure:

$$\text{bel} = 2 \log \frac{\text{pressure of sound}}{\text{pressure of standard sound}}$$

The bel is too large for everyday use and the decibel is used instead:

decibel (dB) = 0.1 bel

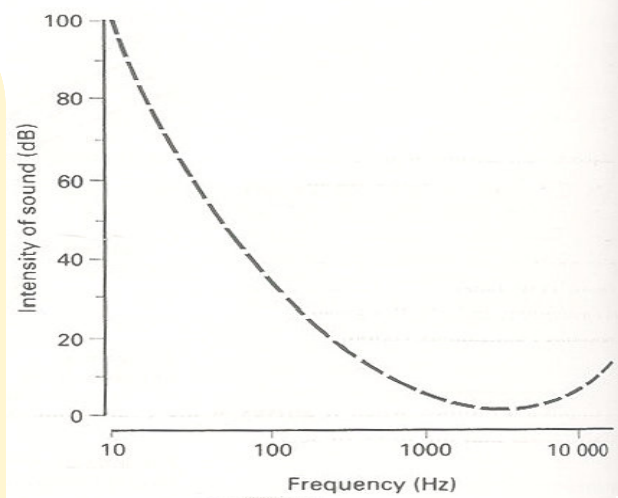
$$\text{Intensity of sound in decibels} = 20 \log \frac{\text{pressure of sound}}{\text{pressure of standard sou}}$$

The standard sound adopted as reference is the auditory threshold in healthy young people; in physical terms it is 0.000204 dynes/cm^2.

It should be noted that The decibel is a *logarithmic scale,* in which 0 dB refers to the auditory threshold, while a sound of 120 dB indicates a sound intensity 10^6 times that of the intensity of the auditory threshold.

Audibility

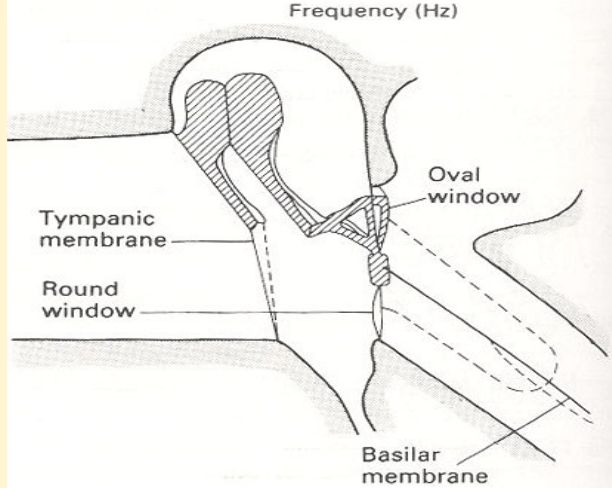
The human **audibility curve** shows that human hear sounds in the range of 20-20 000 Hz. Within this range, the threshold is lowest in the range 1000- 4000 Hz and greater at lower and higher frequencies. **Pitch discrimination** is best in the range 1000- 3000 Hz. Human beings can distinguish up to 2000 pitches and training can even improve on this, as musicians do. In ordinary conversation the average male voice has a frequency of about 120 Hz while that of the female voice is about 250 Hz. Very loud sounds are felt as well as heard and are also partly conducted through the bones of the skull.



The mechanism of hearing

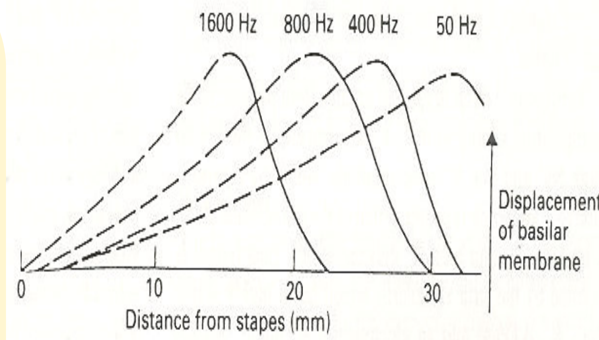
When sound waves strike the tympanic membrane, it vibrates with them but the vibration stops as soon as the sound ceases. Movement of the tympanic membrane is conducted through the ossicles TO the oval window of the cochlea (Fig). The ossicles constitute a system of levers which increases the force acting on the tympanic membrane by 1.3 times. Since the area of the tympanic membrane (about 50 mm^2) is approximately 17 times that of the oval window of the cochlea (3 mm^2), the pressure created by movement of the tympanic membrane is multiplied 17times when it arrives at the oval window. This means that the force of sound vibration is multiplied 1.3 x 17 times or 22 times when it arrives at the oval window. Indeed, it has been calculated that about 60% of the sound energy is transmitted to the cochlea, which is a high efficiency when considering the inevitable loss due to resistance.

Sound may be conducted to the cochlea either by air or through bone. **Air conduction** constitutes the normal situation, when sound waves travelling in air cause vibration of the tympanic membrane, which is transmitted by the ossicles to the oval window of the cochlea. In **bone conduction** the sound causes vibration of the bones of the skull, directly transmitting the sound vibrations to the cochlea, e.g. when the base of a vibrating tuning-fork is put on the mastoid process or the forehead. Under normal circumstances, air conduction is more efficient than conduction through bone.



As indicated in Fig., the footplate of the stapes rocks at the oval window like a hinged door fixed at a posterior point. This movement causes a pressure wave, which travels through the perilymph in the scala vestibuli and, through vibration of Reissner's membrane, to the endolymph of the scala media; this, in turn, conveys the wave to the perilymph of the scala tympani, through the vibration of the basilar membrane, and the wave eventually dies away at the round window of the cochlea. Normally the basilar membrane is not under tension. Stimulation of the hair cells is effected through vibration of the basilar membrane, on which the organ of Corti sits.

Like the arterial pulse wave, travelling waves in the cochlea reach a peak and then decline, to dissipate at the round window. High-frequency sounds reach a peak at the *base* of the cochlea, while low-frequency sounds peak at the *apex* of the cochlea, and medium frequencies peak in between with displacement of the basilar membrane closely following this pattern (Fig.). Nerve fibres from each part of the basilar membrane are distinct and signal the place at which the wave has peaked to the auditory cortex. This is the main mechanism for **discrimination of pitch** or tone of sound and has been referred to as the **place principle.** However, this principle does not explain discrimination between sound frequencies below 2000 Hz. It has been found that, in addition to this, sound frequencies from 20 to 2000 Hz arc also signalled to the cortex by having one burst of action potential synchronized with each sound wave, i.e. a **volley effect.** The place principle plus the volley effect has recently been referred to as the **duplex theory** of hearing.



Receptor potentials and the endocochlear potential

The hair cells are sitting on the basilar membrane with their upper ends fixed in the reticular lamina. Upper displacement of the basilar membrane moves the reticular lamina upwards and inward, while downward displacement of the basilar membrane moves the reticular lamina downward and outwards. The inward and outward movement of the reticular lamina causes a *shearing-force* in relation to the tectorial membrane and bends the stereocilia of the outer hair cells. The stereocilia of the inner hair cells arc bent by fluid movement under the tectorial membrane, to which they are not attached. Bending of the stereocilia of the hair cells alternately opens and closes cation channels at the lips of the stereocilia; entry of K^+ causes *depolarization,* while blocking K^+ entry causes hyperpolarization. The alternate depolarization and hyperpolarization constitute the hair cell **receptor potentials,** which thus change (transduce) the bending of the stereocilia into electrical energy. The receptor potential is directly proportional to the displacement of the basilar membrane and faithfully reproduces the characteristics of the sound. it probably releases a neurotransmitter that depolarizes the cochlear nerve endings, thus leading to action potentials in auditory nerve fibres.

Perilymph, which is formed mainly from plasma, has a composition similar to that of the extracellular fluid, with high Na^+ and low K+ concentrations, while the composition of endolymph is nearer to that of the intracellular fluid, with low Na^+ and high K^+ concentrations. Endolymph is formed by the stria vascularis, which has a highly active Na+. K+ ATPase and an electrogenic K+ pump. Studies with microelectiodes have shown that endolymph in the scala media has a positive potential (+80 mV) in relation to perilymph in either the seala vestibuli or the scala tympani; it is referred to as the *endocochlear potential.* Since the basilar membrane is relatively permeable to perilymph in the scala tympani. thetunneI of'Corti and consequently the bases of the hair cells are bathed in perilymph: the stereocilia of the hair cells are bathed in endolymph. As the resting potential inside the hair cells is -60 mV, the potential difference across the tips of the stereocilia is 140 mV (60mV + 80mV). This high potential may be important for increasing the sensitivity of the hair cells to stimulation.

Function of the hair cells

It has recently been recognized that the inner and outer hair cells have somewhat different functions. The stereo-cilia of the inner hair cells are not embedded in the tectorial membrane and are actually bent by fluid movement under the tectorial membrane as explained above. It is now clear that the inner hair cells arc the primary receptors for sound, transducing the fluid movement in the cochlea into action potentials in the auditory nerve. The outer hair cells, although far more numerous, stimulate only a small fraction of nerve fibres in the cochlear nerve. However, damage to these cells causes a significant loss of hearing. They seem to control the sensitivity of the inner hair cells. Retrograde (centrifugal) signals from the auditory cortex through the superior olivary nucleus to the proximity of the outer hair cells have been found to cause inhibition of their discharge and therefore to increase the sensitivity of adjacent hair cells to particular sound frequencies.

Pattern of impulse discharge in the auditory nerve and brain mechanisms

The pattern of the action potentials in the auditory nerve to the brain is responsible for the discrimination of pitch and loudness (intensity) of sound. At threshold sound intensity, an auditory nerve fibre discharges to one sound frequency, depending upon the point in the basilar membrane being stimulated. As the intensity increases, the range of sound frequencies and area of basilar membrane stimulated widens; this increases the number of stimulated hair cells, causing spatial summation of impulses and increased spike rate of the action potentials. Thus, *impulse frequency* in the auditory nerve principally signals *loudness.* As previously explained, *pitch* is mainly determined by the place in the basilar membrane which is maximally displaced. Also low sound frequencies between 20 and 2000 Hz are signaled by a synchronous pattern of nerve impulse discharge *{the volley effect).*

The basilar membrane is represented on the auditory cortex with low tones anterolaterally and high tones postero-medially. The *auditory cortex* is also concerned with sound *localisation.* **The auditory association areas**, adjacent to the primary auditory cortex are concerned with *interpreting* the meaning of the sound heard. In human beings a unilateral lesion affecting the primary auditory cortex will only slightly reduce hearing in the opposite ear because of the bilateral conical connections of the auditory pathways.

Sound localization

The main mechanism for sound localization involves using the two ears. Differences in the time of arrival of the sound wave at the two ears (time-lag), as well as the differences in loudness, by which the nearer ear heats louder than the other, are employed as clues for localization. The time-lag mechanism works best for frequencies below 3000 Hz; the difference in the sound intensity mechanism is best for frequencies above 3000 Hz. For people deaf in one ear, some localization is possible by making use of a clue resulting from transformation of the sound wave front by the angle of the pinna.

Masking

The presence of a background sound affects the ability to hear another sound in the environment, i.e. background noise can mask the sound *wholly* or partly. Masking is due to the fact that some of the receptors arc already stimulated and therefore refractory when the sound desired to be heard arrives. Masking is more effective when two sounds have similar rather than widely differing frequencies. Masking is present all the time in natural environments and is automatically taken into consideration, as when a speaker raises his/her voice in order to be heard.

Effect of noise on hearing:

Modern industrial societies are noisy and noise pollution is another environmental hazard.Exposure to sound intensities above 80 dB may result in damage to the outer hair cells, depending upon the extent of the intensity and the duration of exposure. The damage usually starts at about 4000 Hz, and the subject is usually unaware of any deficit. Then it affects lower frequencies and, when it reaches frequencies below 1000 Hz, the ability to hear normal conversation is impaired, inducing the victim to seek medical advice.

Deafness

Deafness may be classified, according to its cause, into **conduction deafness** and **nerve** or **perceptive deafness.**

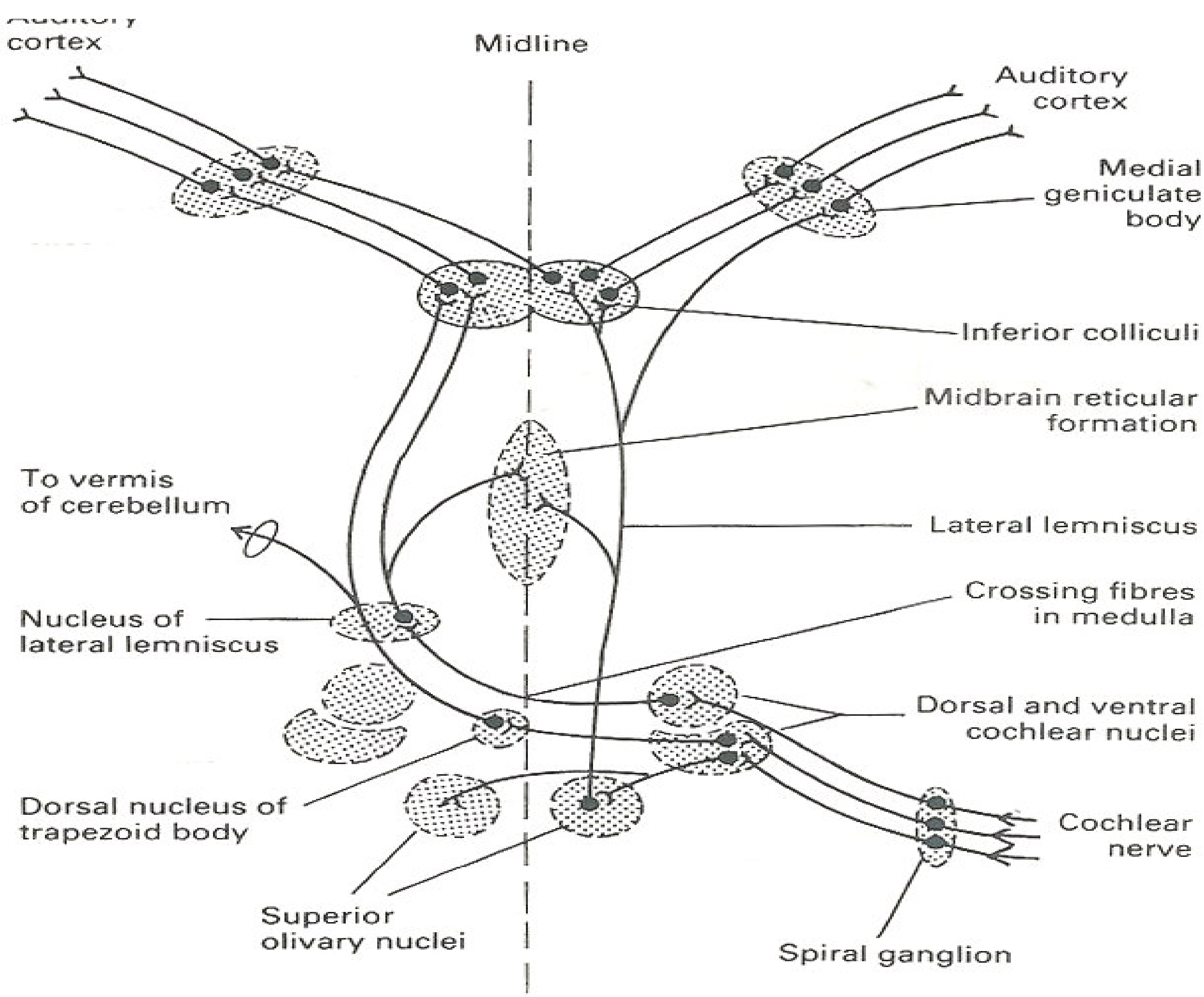
Conduction deafness is due to impairment of sound transmission through the external ear and middle ear. It may result from too much wax or a foreign body in the external auditory canal, repeated middle ear infections, a perforated drum, destruction of the ossicles or otosclerosis. Otosclerosis is a disease characterized by pathological fixation of the stapes in the oval window. Since the masking effect of background noise is greatly reduced, sounds are heard better by bone rather than by air conduction and sound frequencies are uniformly affected.

Nerve deafness may be congenital or may result from damage to the cochlea or auditory pathways. The cause may be toxic, e.g. administration of aminoglycoside antibiotics, such as streptomycin and gentamicin, or due to inflammation, e.g. cerebrospinal meningitis. Vascular lesions in the medulla or tumours, e.g. acoustic neuroma, may interrupt the auditory pathways and lead to some degree of deafness. In this connection, it should be remembered that the auditor)' pathways are characterized by bilateral representation and that, in contrast to vision, cortical lesions hardly ever result in deafness. In nerve deafness, hearing by both air and bone conduction is depressed.

The auditory pathways

The axons of the neurons that innervate the hair cells constitute the cochlear division of the 8th nerve and synapse in the **dorsal** and **ventral cochlear nuclei** in the medulla (Fig. 17.20). Second-order neurons arise from these and go to synapse in the olive and trapezoid body of the same and opposite side, with slightly more fibres crossing to the opposite side than those proceeding ipsilaterally. Fibres then ascend in the lateral lemniscus. Some fibres synapse in the **nucleus of the lateral lemniscus** and most of the fibres then proceed to synapse bilaterally in the **inferior colliculi** and then in the **medial geniculate bodies** of the thalamus. Some collaterals from the lateral lemniscus go directly to the **medial geniculate body**, while other collaterals enter the **reticular formation**. From the medial geniculate body, fibres are finally projected bilaterally to the **auditory cortex** Brodman's area 41, in the superior portion of the temporal lobe. There are auditory association areas adjacent to the primary auditory cortex. It should be noted that, once fibres leave the cochlear nuclei, they proceed *bilaterally* up to the cortex.

The auditory nerve also contains retrograde fibres which arise from the auditory cortex and reaches the cochlea through the superior olivary complex. These fibres are referred to as the **olivocochlear bundle**. The function of these retrograde or **centrifugal** signals is to inhibit specific areas of the organ of Corti and this sharpens attention to particular sounds, e.g. one instrument in an orchestra.



Tests of hearing and audiometry

The audiometer is an **instrument** which is used to determine the auditory threshold for sound frequencies which may range from 50 Hz to 16 000 Hz. Pure tones are delivered through earphones (air conduction) or directly through a vibrating piece on the mastoid bone (bone conduction). The test is conducted in a soundproof, or at least very quiet, room. The responses are plotted on a chart (audiogram) where 0 dB is the normal threshold and any hearing loss in dB is indicated for each frequency. An audiogram gives a measure of the hearing loss, shows the frequencies affected and, by comparing air conduction with bone conduction, gives an important clue as to whether the patient is suffering from conduction deafness or nerve deafness.

Before the audiometer became available, some simple tests using only a tuning-fork were used to differentiate between conduction and nerve deafness. These tests are still used by doctors as part of their examination of the ear.

Weber's test

The base of a vibrating tuning-fork is placed on the vertex of the skull. Normally, the sound should be heard equally well on both sides. In the case of unilateral *conduction deafness,* the sound is heard better (or lateralized) to the diseased side because of the absence of the masking effect of environmental noise on that side. In *nerve deafness* affecting one car, the sound is lateralized to the normal side.

Rhine's test

The base of the vibrating tuning-fork is placed on the mastoid process until the subject cannot hear by bone conduction; then the prongs of the fork arc held in the air near the ear. Normally, since air conduction is better than bone conduction, the subject will hear the vibration in the air after bone conduction is over, and this is referred to as a positive Rinne's test. If the subject does not hear the vibration in the air, the test is repeated but reversing the sequence, i.e. starting with the tuning-fork near the car and, after hearing the vibration in the air is over, the base of the tuning fork is placed on the mastoid process. Normally, the vibration should not be heard through bone after hearing by air has stopped. If it is, this means bone conduction is better than air conduction and Rhine's test is said to be negative in this case. A negative Rinne's test is thus indicative of *conduction deafness.* A positive Rinne's test with hearing loss is indicative of *nerve deafness.*

The End ☺