Vestibular System

Introduction:

The vestibular system is responsible for maintaining normal position of the eyes and head as external forces tend to displace the head from its "normal" position. Located within the inner ear, the vestibular apparatus is the sense organ that detects linear and angular accelerations of the head and relays this information to brainstem nuclei that elicit appropriate postural and ocular responses.

Note: Because [*force* = *mass* • *acceleration*] and because head mass is constant, detecting head acceleration is equivalent to detecting external force to the head.

Inner Ear Anatomy:

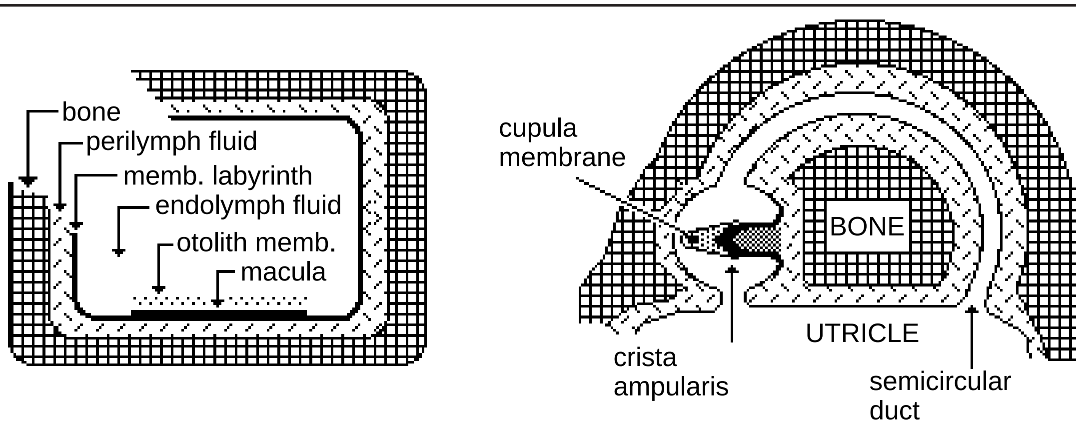
The inner ear is called the labyrinth because it consists of channels and chambers hollowed out within the temporal bone. The labyrinth has osseous and membranous components:

Osseous Labyrinth — tubes and chambers in the petrous part of the temporal bone that contain perilymph fluid and house the membranous labyrinth. The three osseous components are:

1) Cochlea — a spiral chamber that is related to hearing and will be discussed later

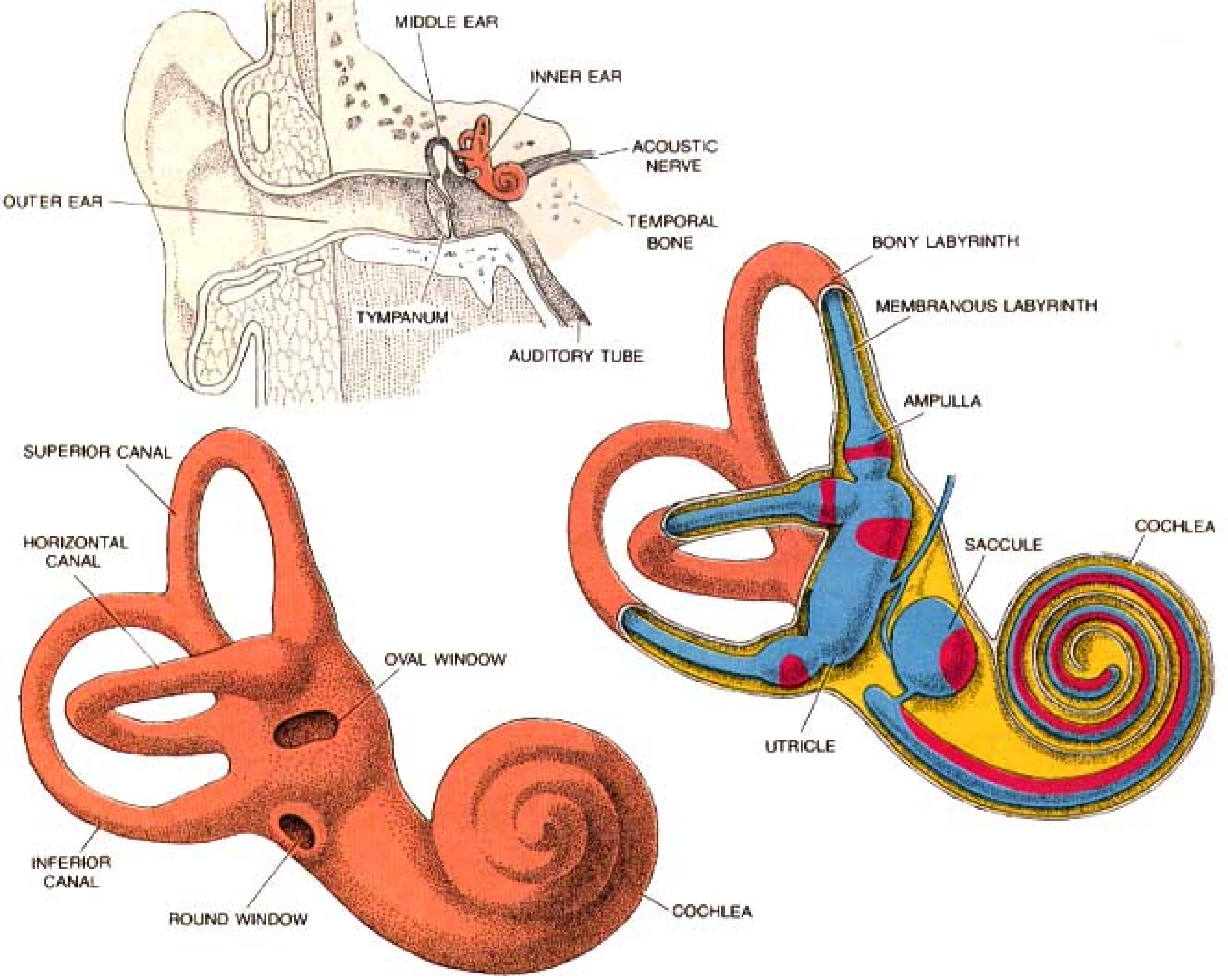
2) Vestibule — a large chamber adjacent to the middle ear

3) Semicircular Canals — three semicircular channels in bone, each semicircular canal is orthogonal to the other two



Schematic diagram of the osseous labyrinth containing the membranous labyrinth. The vestibule relationship (left) and the semicircular canal relationship (right) are shown.

Membranous Labyrinth — consists of interconnected tubes and sacs that are filled with endolymph, a fluid high in potassium. (Fluid outside the membranous labyrinth is perilymph, which is low in potassium and high in sodium like typical extracellular fluids.)


MIDDLE EAR
INNER EAR
ACOUSTIC NERVE
OUTER EAR
TEMPORAL BONE
TYMPANUM
AUDITORY TUBE
BONY LABYRINTH
MEMBRANOUS LABYRINTH
AMPULLA
SUPERIOR CANAL
HORIZONTAL CANAL
OVAL WINDOW
SACCULE
COCHLEA
UTRICLE
INFERIOR CANAL
ROUND WINDOW
COCHLEA

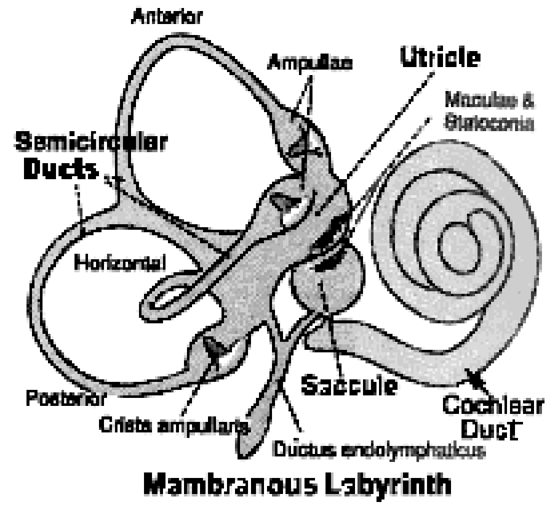
The membranous labyrinth, which contains the sense organ receptor cells, consists of the following components:

1) Cochlear Duct — related to hearing (will be discussed later).

2) Utricle — larger of two sacs located in the vestibule

3) Saccule — smaller of two sacs located in the vestibule

4) 3 Semicircular Ducts — each duct is located within one of the semicircular canals. Each duct has a terminal enlargement called an ampulla which contains a crista ampullaris, a small crest bearing sensory receptor cells.



Vestibular Apparatus:

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The vestibular apparatus consists of:

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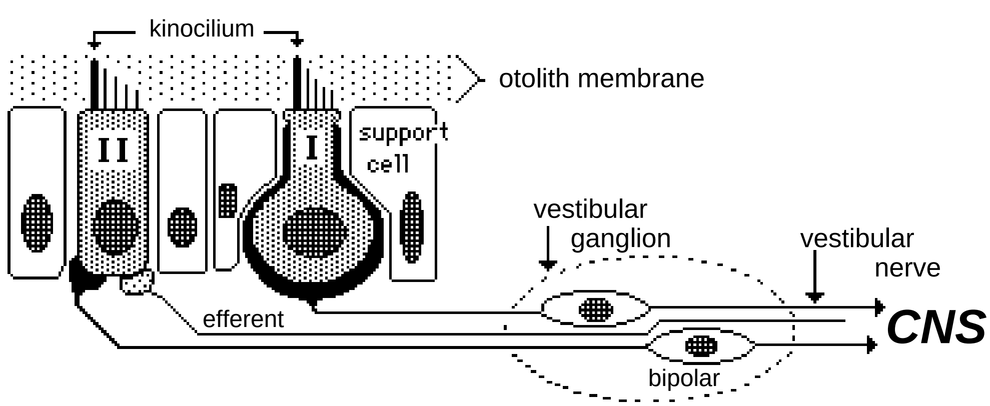
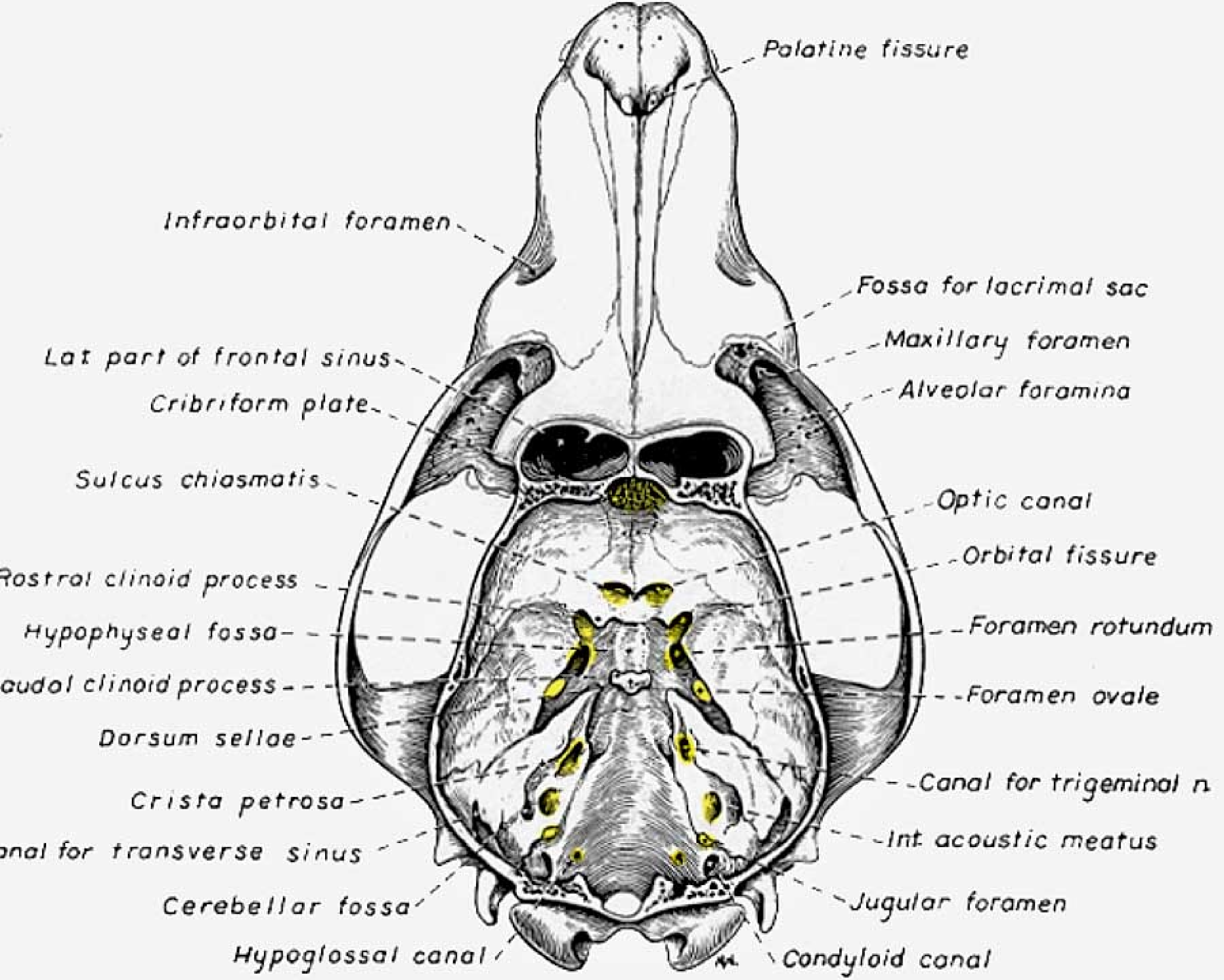
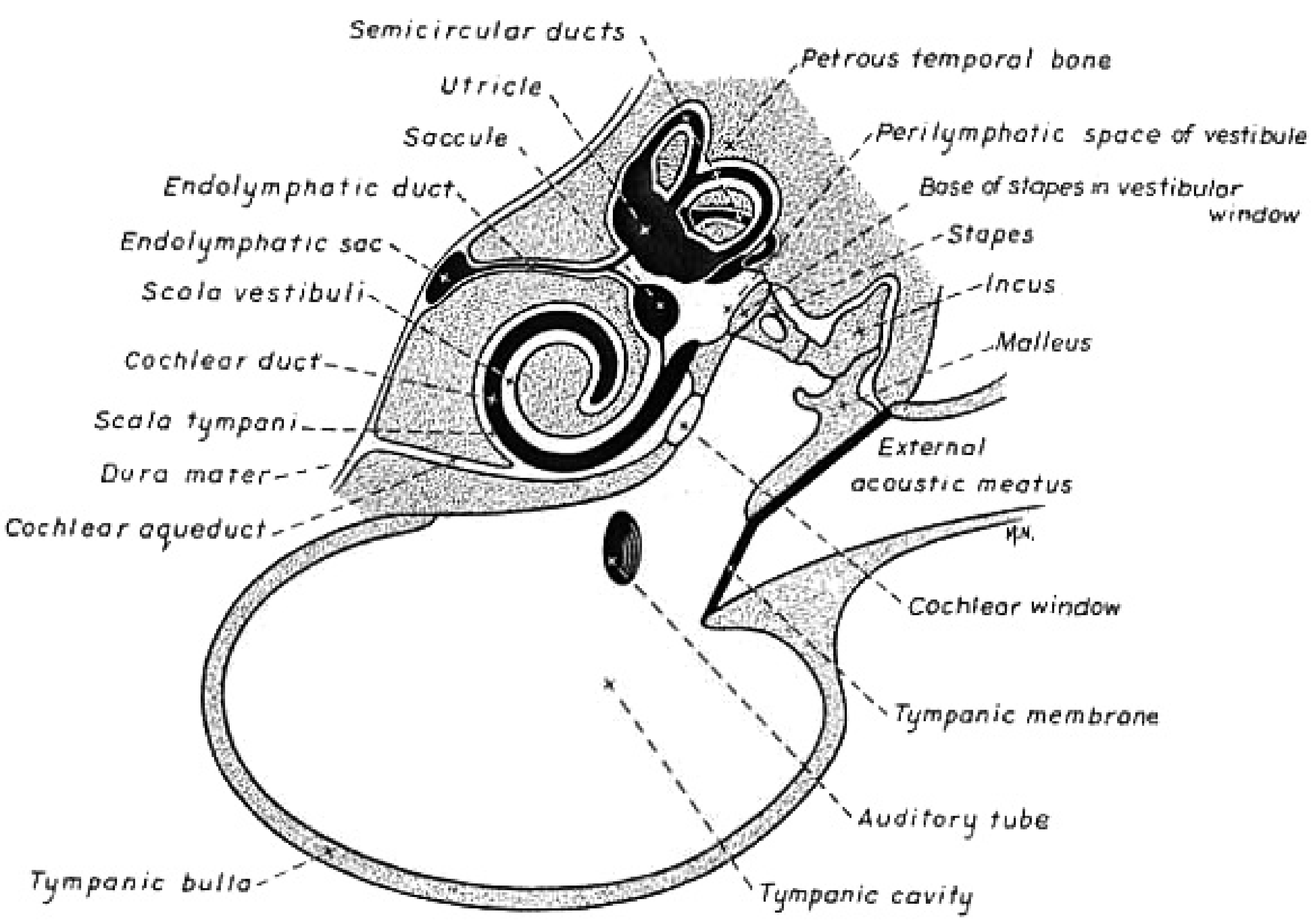


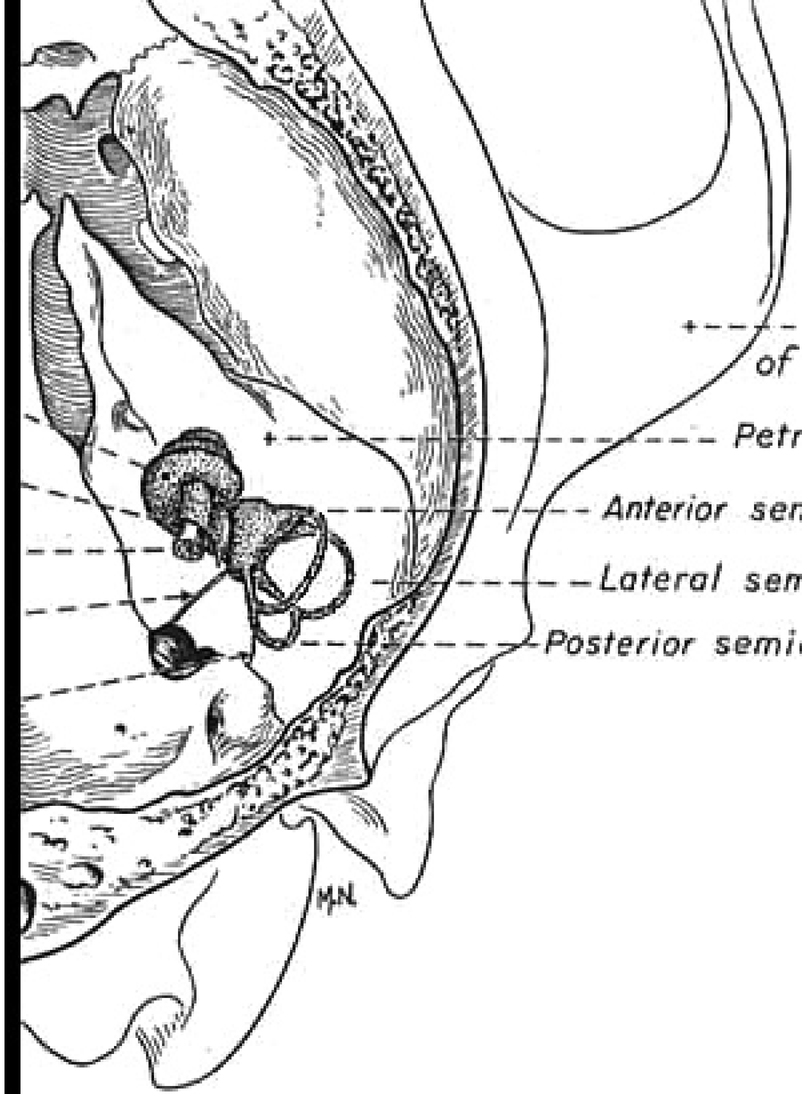
Schematic illustraion of a macula, including neurons of the vestibular nerve. Two types of receptor (hair) cells have stereocilia that extend into the overlying otolith membrane.



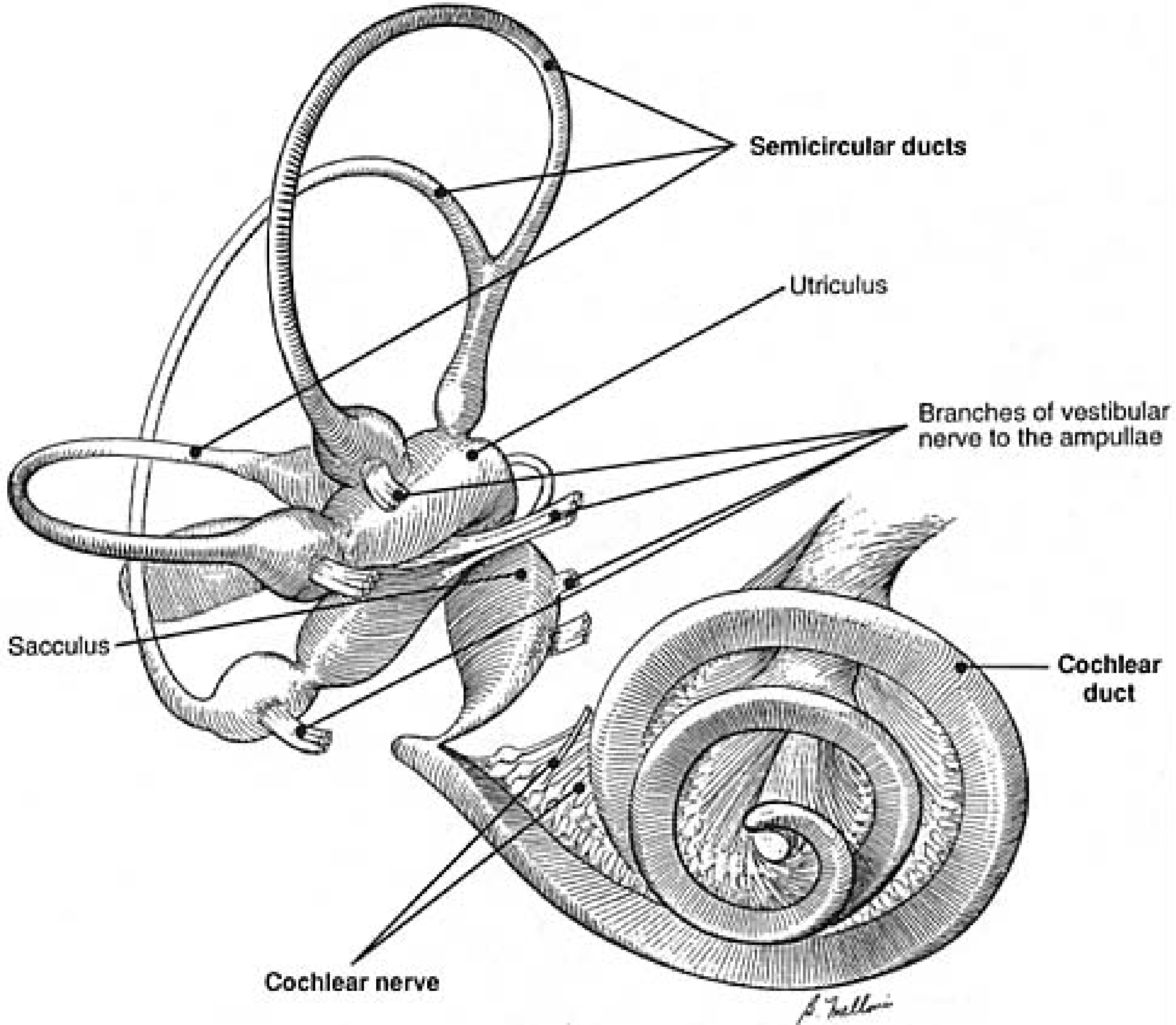
Palatine fissure
Infraorbital foramen
Fossa for lacrimal sac
Maxillary foramen
Lat part of frontal sinus
Alveolar foramina
Cribriform plate
Sulcus chiasmatis
Optic canal
Orbital fissure
Rostral clinoid process
Hypophyseal fossa
Foramen rotundum
audal clinoid process
Foramen ovale
Dorsum sellae
Canal for trigeminal n.
Crista petrosa
Int. acoustic meatus
anal for transverse sinus
Cerebellar fossa
Jugular foramen
Hypoglossal canal
Condyloid canal

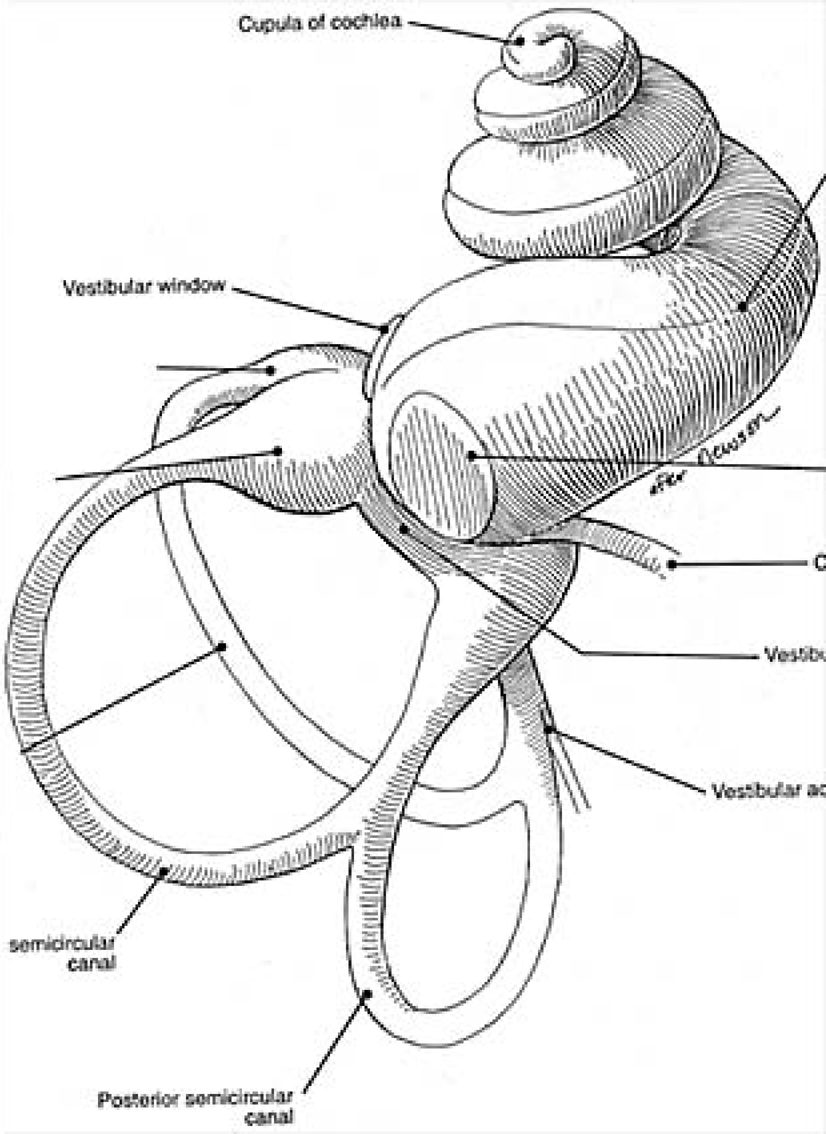


Semicircular ducts
Petrous temporal bone
Utricle
Saccule
Perilymphatic space of vestibule
Endolymphatic duct
Base of stapes in vestibular window
Endolymphatic sac
Stapes
Scala vestibuli
Incus
Malleus
Cochlear duct
Scala tympani
External acoustic meatus
Dura mater
Cochlear aqueduct
M.N.
Cochlear window
Tympanic membrane
Auditory tube
Tympanic bulla
Tympanic cavity



of
Petr
Anterior sem
Lateral sem
Posterior semi
M.N.


Semicircular ducts
Utriculus
Branches of vestibular nerve to the ampullae
Sacculus
Cochlear duct
Cochlear nerve


Cupula of cochlea
Vestibular window
semicircular canal
Posterior semicircular canal

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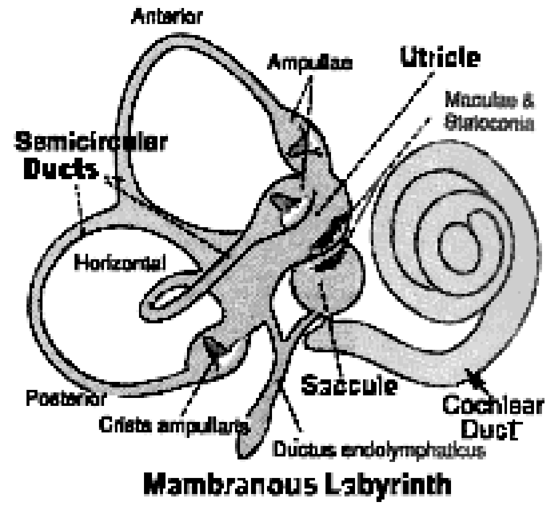

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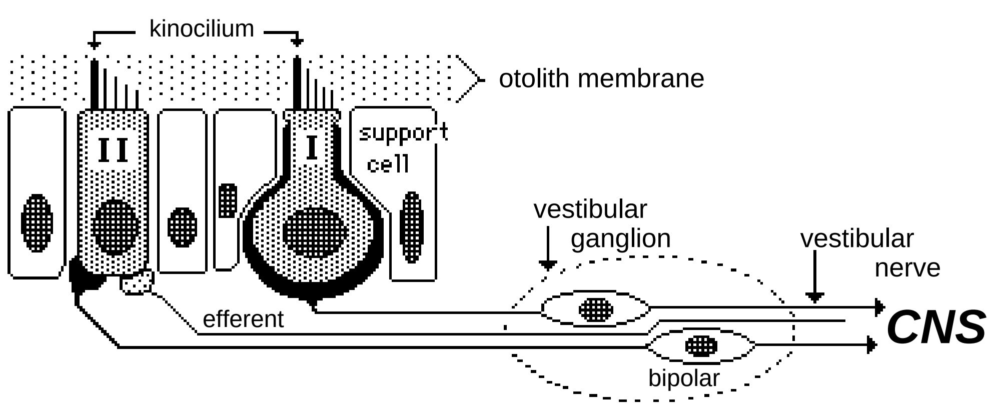
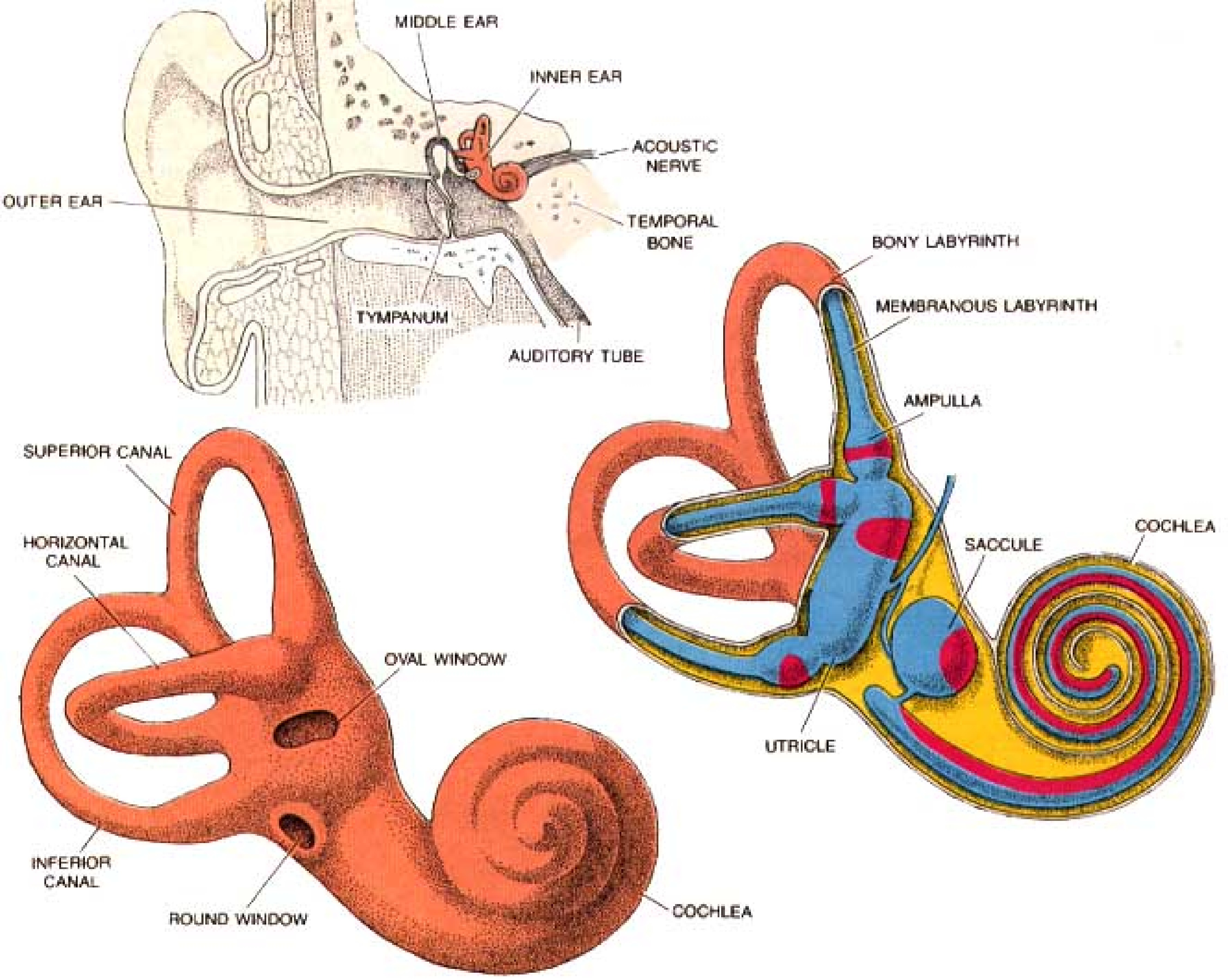


Schematic illustraion of a macula, including neurons of the vestibular nerve. Two types of receptor (hair) cells have stereocilia that extend into the overlying otolith membrane.


MIDDLE EAR
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UTRICLE
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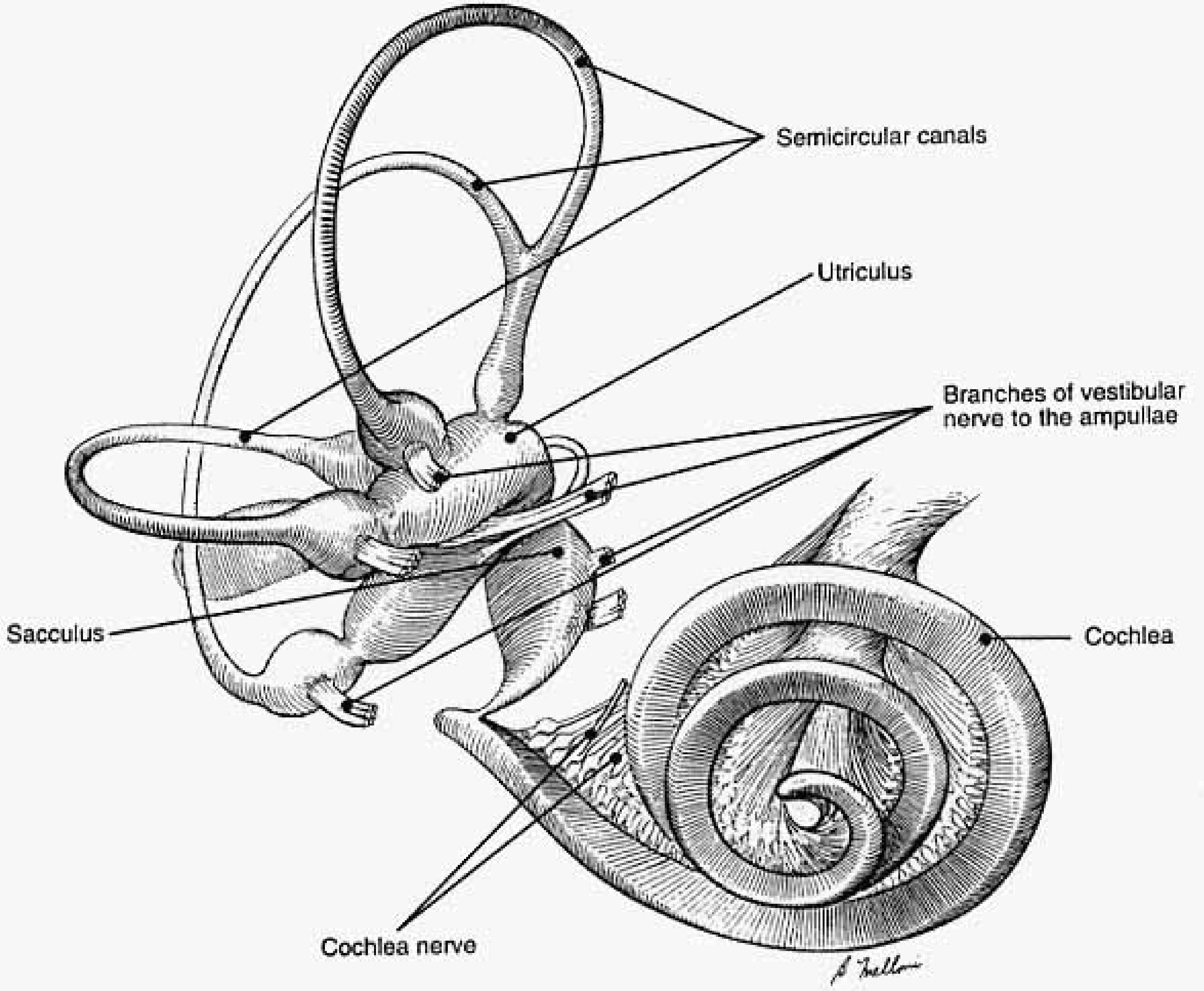
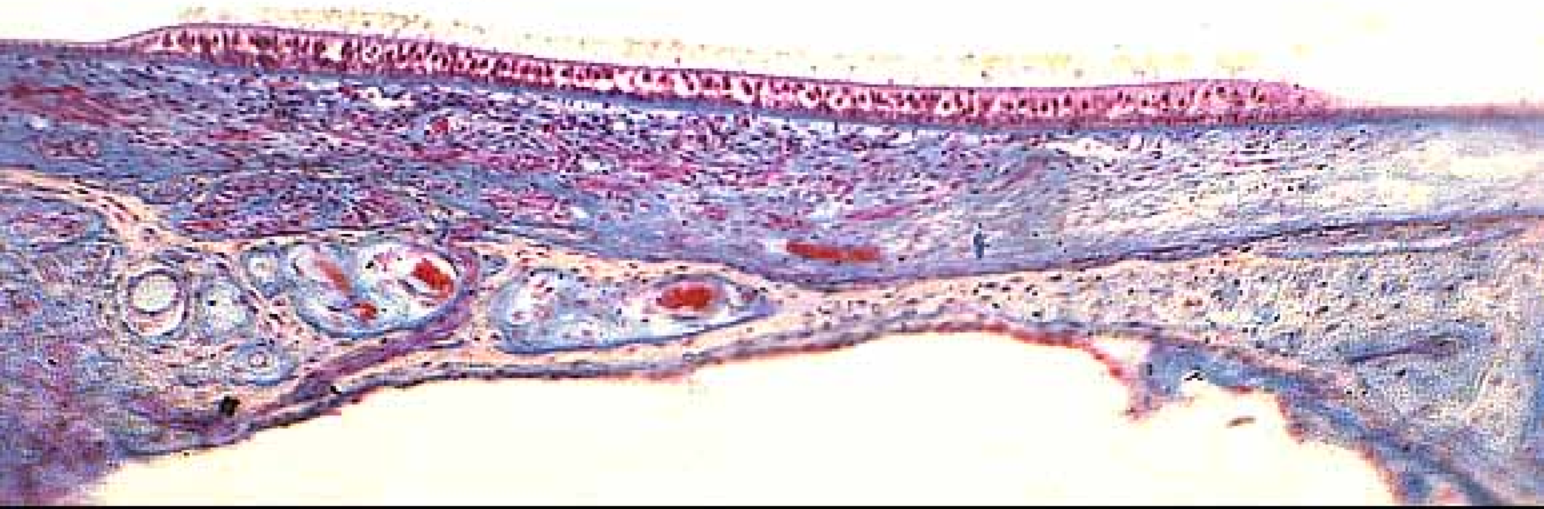
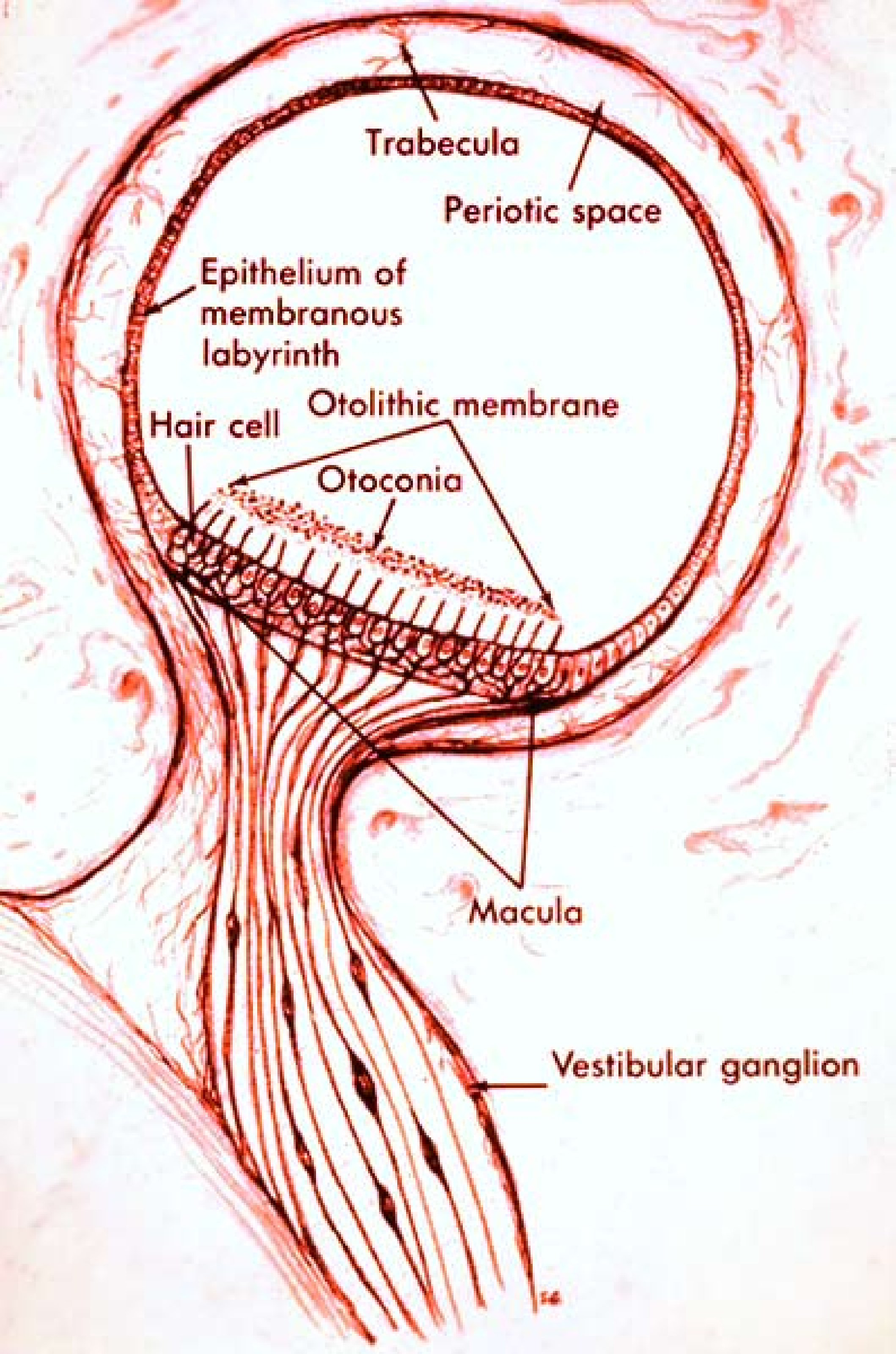
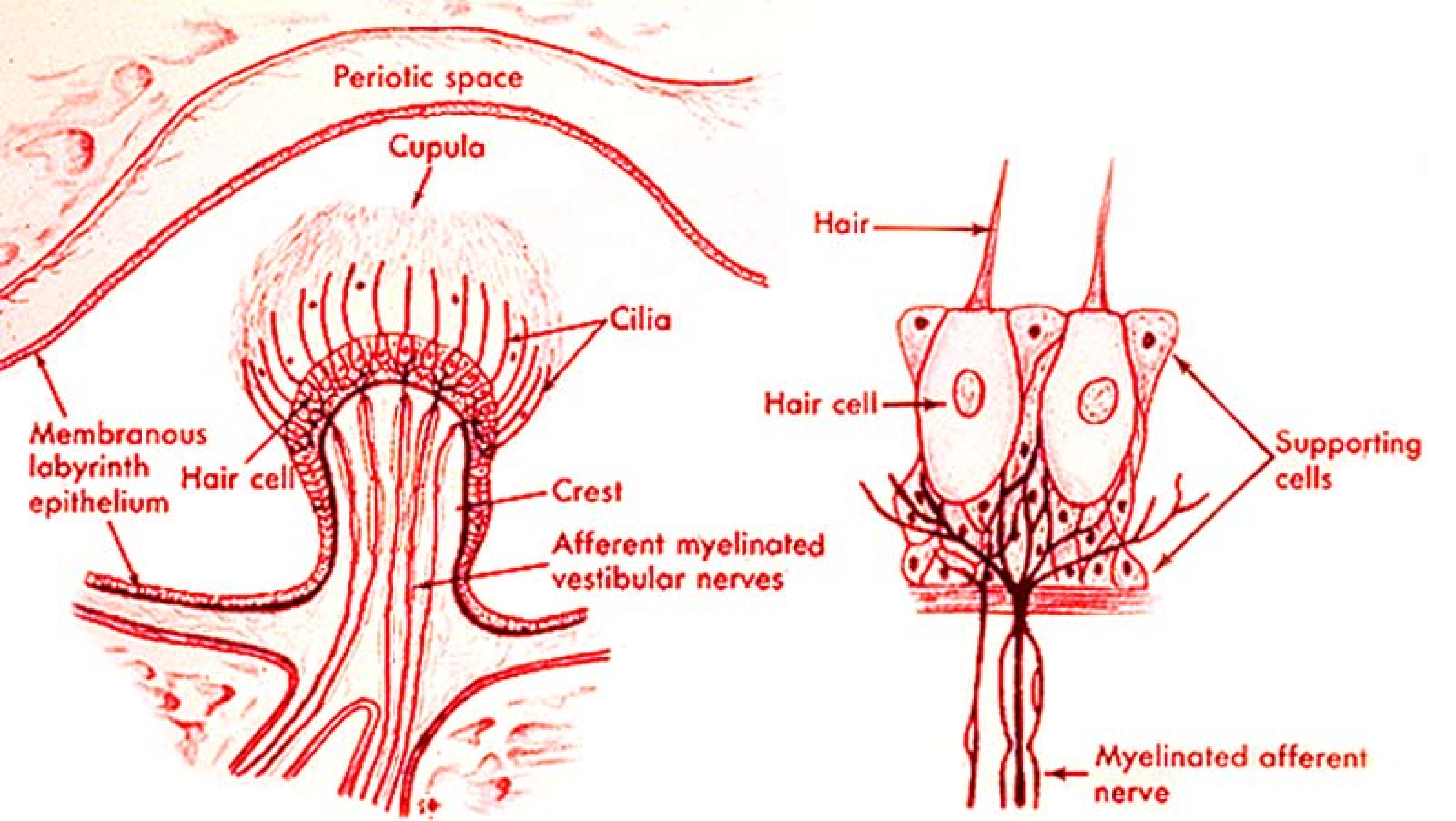

Semicircular canals
Utriculus
Branches of vestibular nerve to the ampullae
Sacculus
Cochlea
Cochlea nerve





Trabecula
Periotic space
Epithelium of membranous labyrinth
Otolithic membrane
Hair cell
Otoconia
Macula
Vestibular ganglion
56


Periotic space
Cupula
Cilia
Membranous
labyrinth
epithelium
Hair cell
Crest
Afferent myelinated
vestibular nerves
Hair
Hair cell
Supporting
cells
Myelinated afferent
nerve

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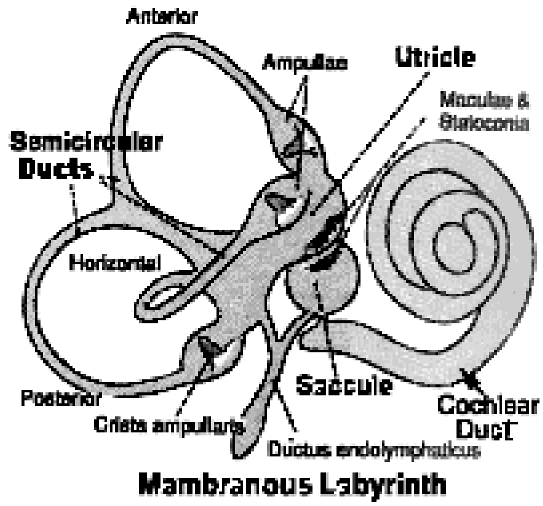

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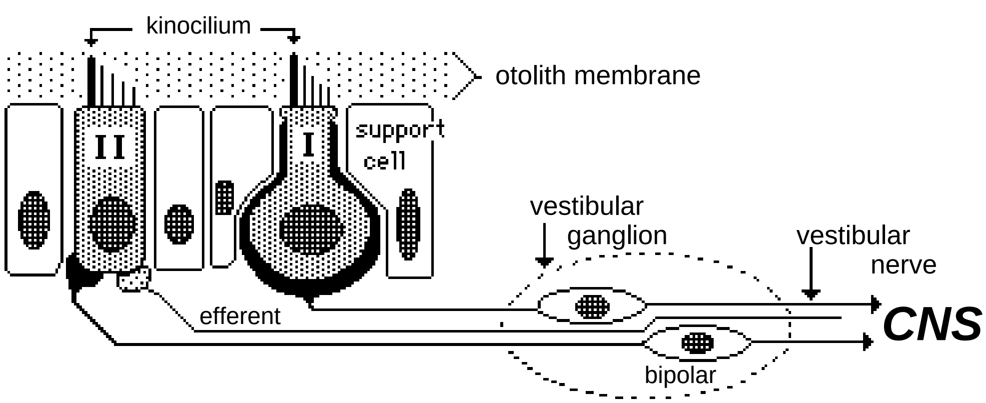

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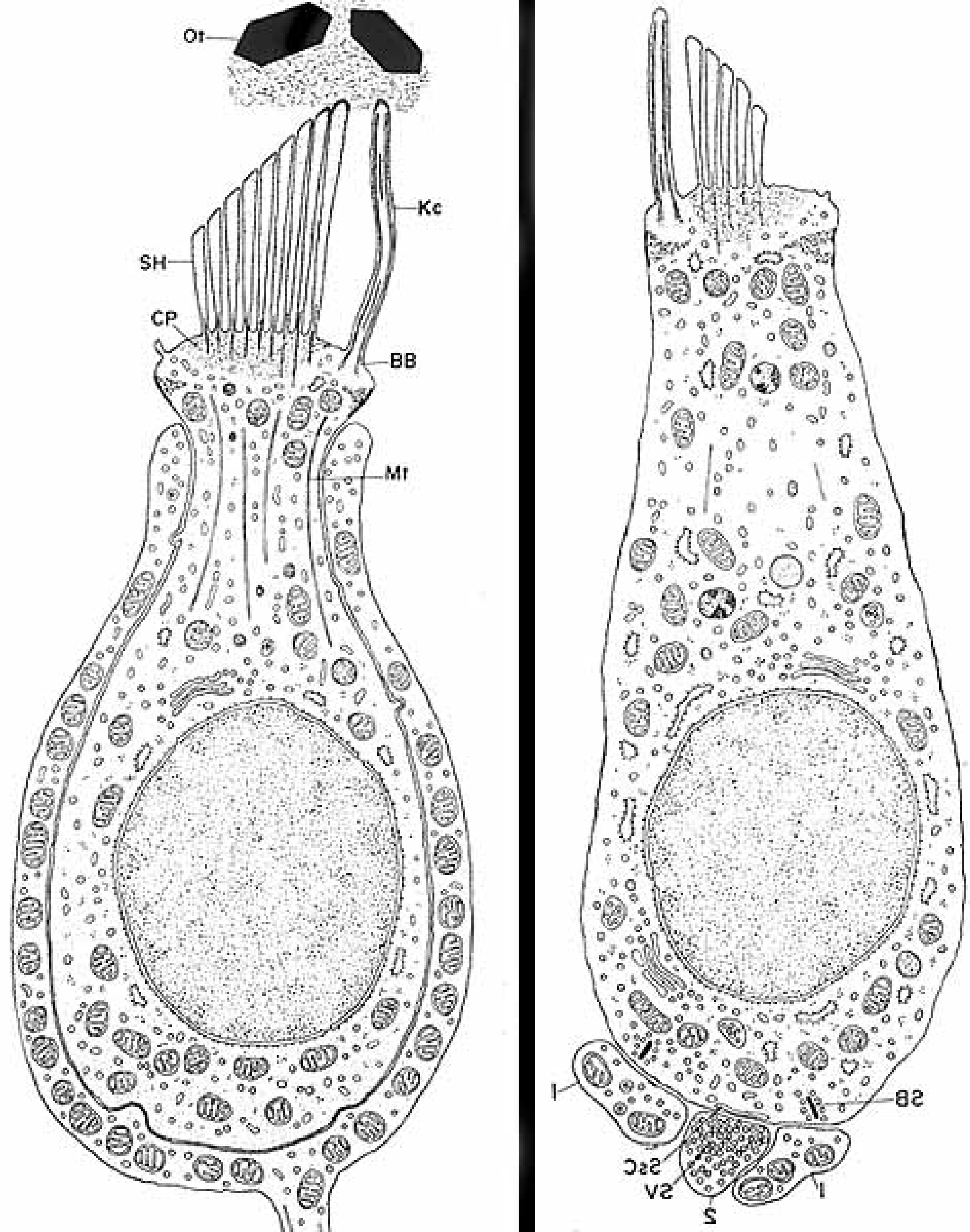
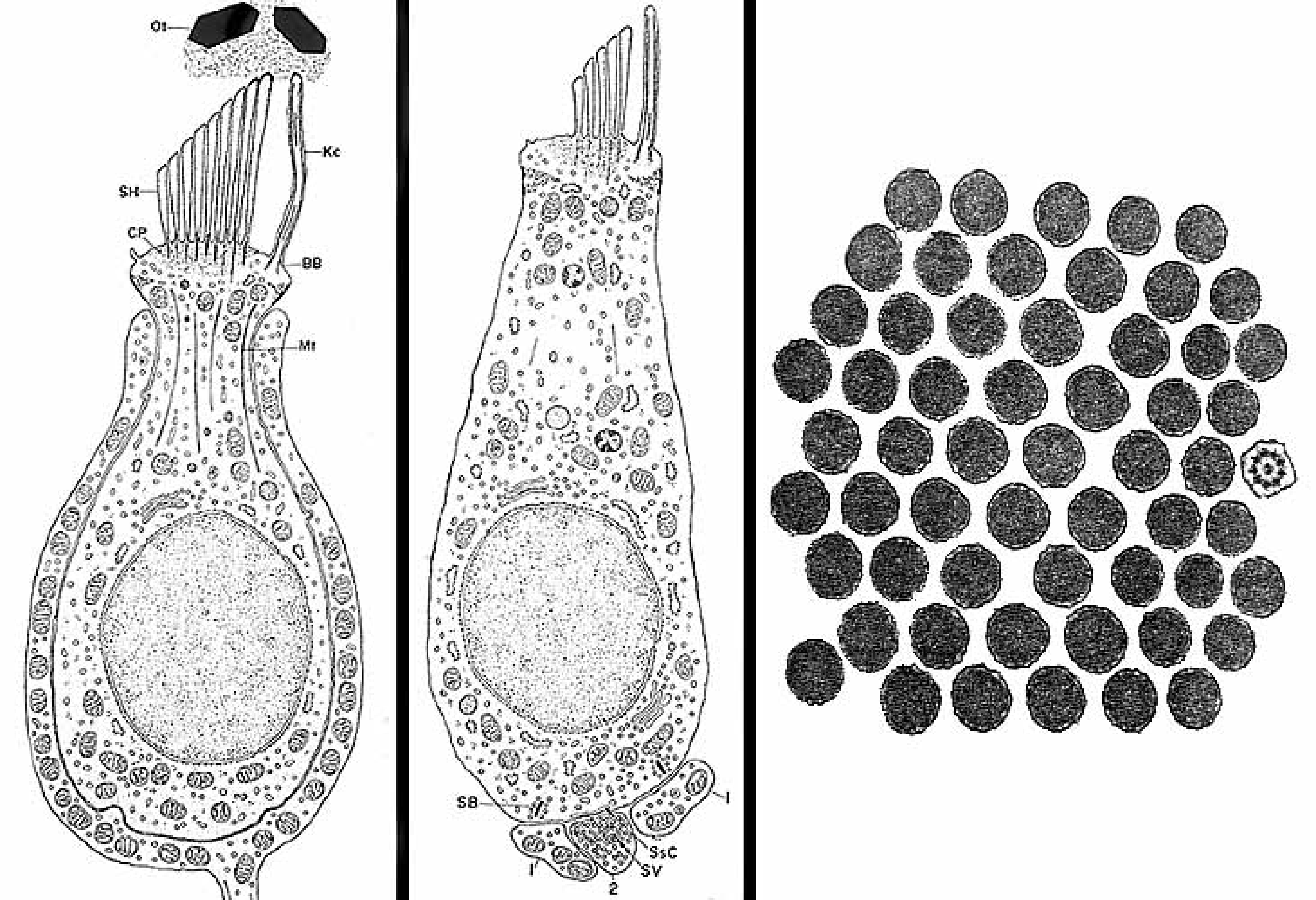
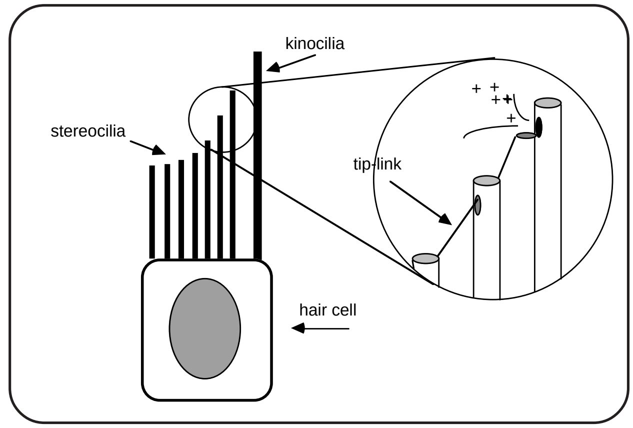

Ot
Kc
SH
CP
BB
Mt
1
SB
SsC
SV
2
1



Ot
Kc
SH
CP
BB
Mt
SB
I
SsC
SV
I'
2

Signal Transduction:

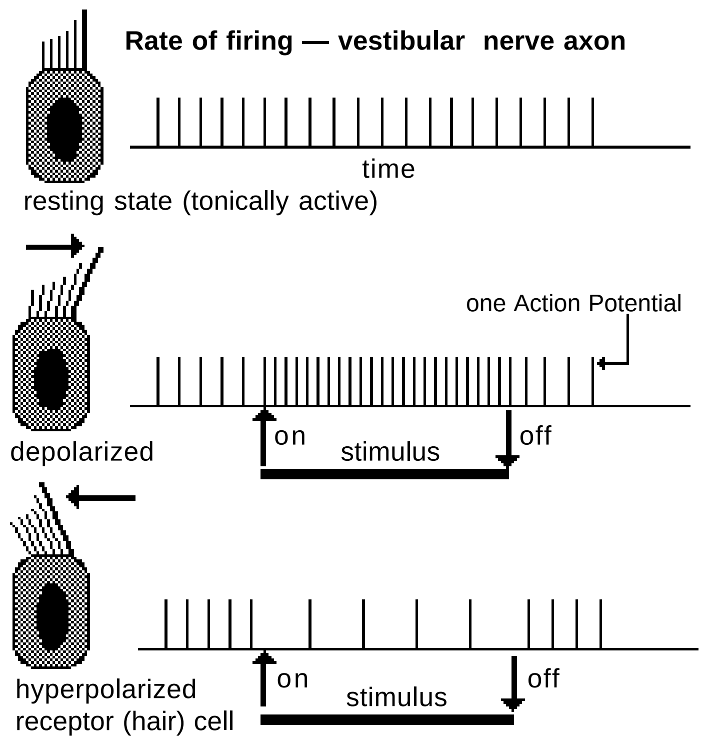


All components of the vestibular apparatus (each macula & crista ampullaris) have the same kind of sensory epithelium, composed of supporting cells and receptor (hair) cells. From the apical surface of each hair cell, stereocilia protrude into an overlaying membranes.

Membrane movement results in deflection of stereocilia. Deflection toward the kinocilium mechanically opens ion channels. This allows potassium ions to flow from the endolymph into the hair cell thus depolarizing the receptor cell membrane.

This depolarization (receptor potential) cause release of glutamate from the basolateral cell membrane of the receptor cell. The gluatamate neurotransmitter triggers action potentials in afferent axons of the vestibular nerve.

Deflection away from the kinocilium closes ion channels and reduces glutamate release.



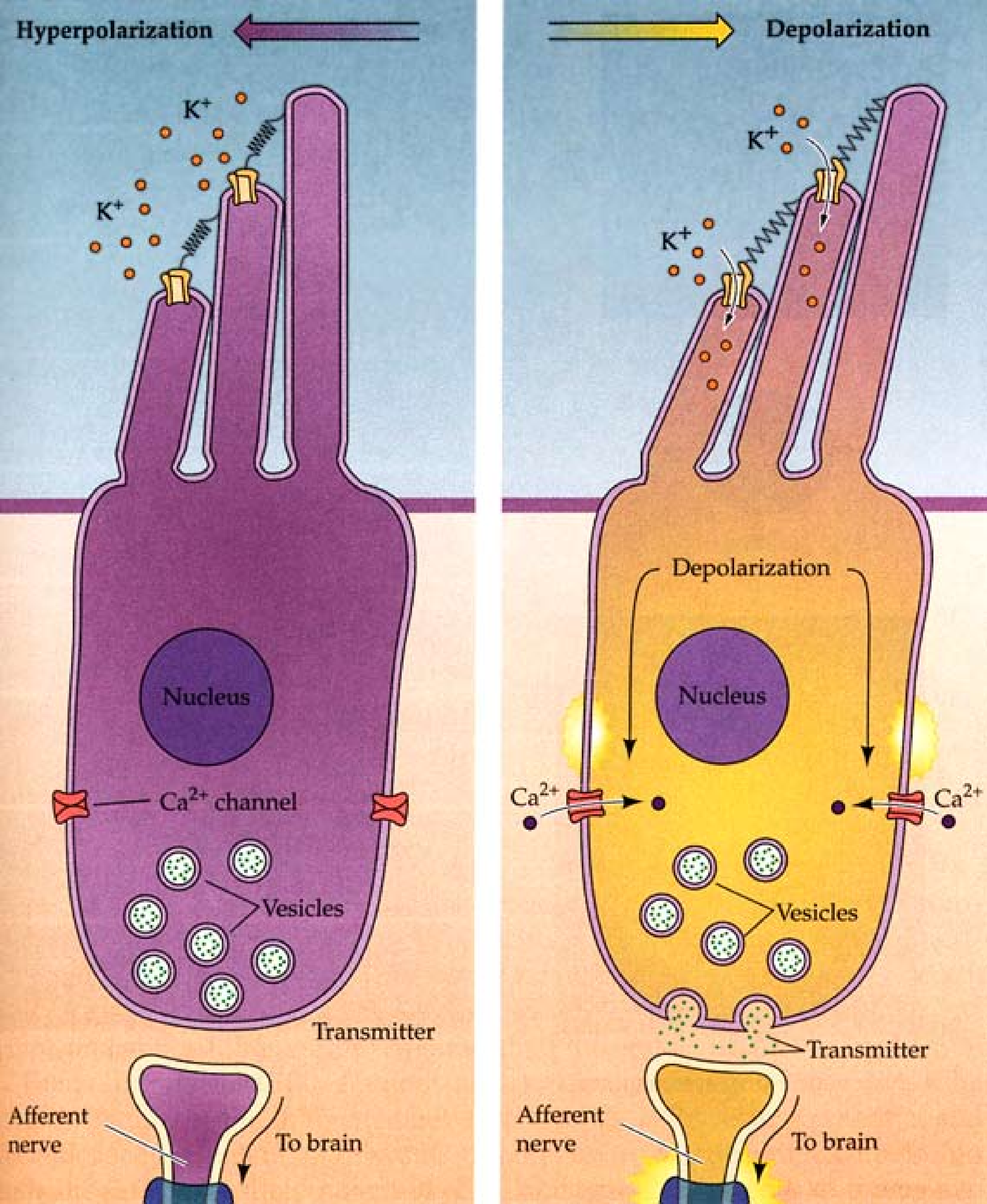
Crista Ampullaris. Stereocilia are embedded in a gelatinous membrane called a cupula. The cupula is moved by fluid inertia when the head rotates in the plane of a semicircular duct. The direction of head rotation is indicated by the relative amount of activity from the three semicircular ducts.

Macula. Stereocilia are embedded in a gelatinous membrane termed the otolith membrane because it contains calcium concretions (“ear stones”). Being denser than surrounding endolymph, the otolith membrane has more inertia than the fluid and it lags during linear acceleration or deceleration of the head.

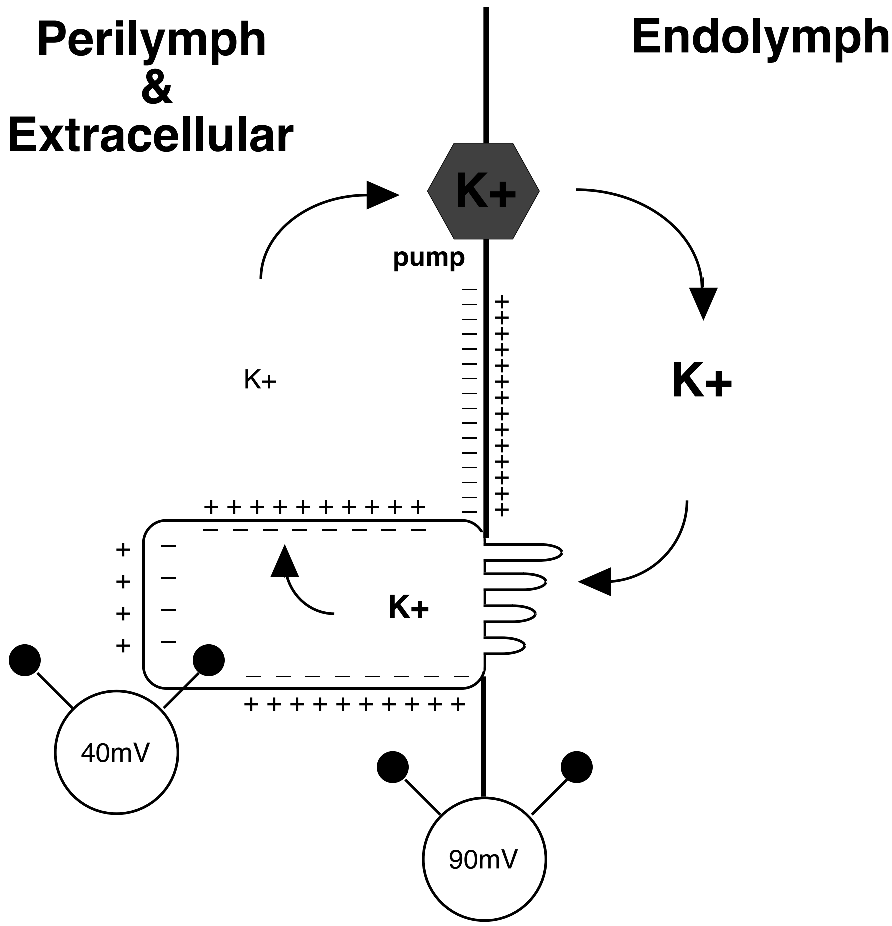
Notes:

1) Receptor cells are spontaneously active and vestibular nerve axons continually conduct action potentials to the brainstem. Thus, movement of sterocilia results in an ncrease or decrease in the rate of spontaneous activity.

2) Vestibular organs of each side are mirror images, a shift toward the kinocilia on one side results in a shift away from the kinocilia on the other side. Thus, spontaeous activity, which is bilaterally balanced under normal postural conditions, is quickly imbalanced during head acceleration.



Hyperpolarization
Depolarization
K+
K+
K+
K+
Nucleus
Ca2+ channel
Vesicles
Transmitter
Afferent nerve
To brain
Depolarization
Nucleus
Ca2+
Ca2+
Vesicles
Transmitter
Afferent nerve
To brain



Pressure waves of air (20 to 20,000 Hz in man; up to 40,000 Hz in the dog &100,000 Hz in the bat) can be interpreted as sound. Sound has subjective properties that correspond to parameters of physics:

pitch = wave frequency = Hz = Hertz = cycles/sec.,

volume = amplitude from the low point to the high point in a pressure wave, and

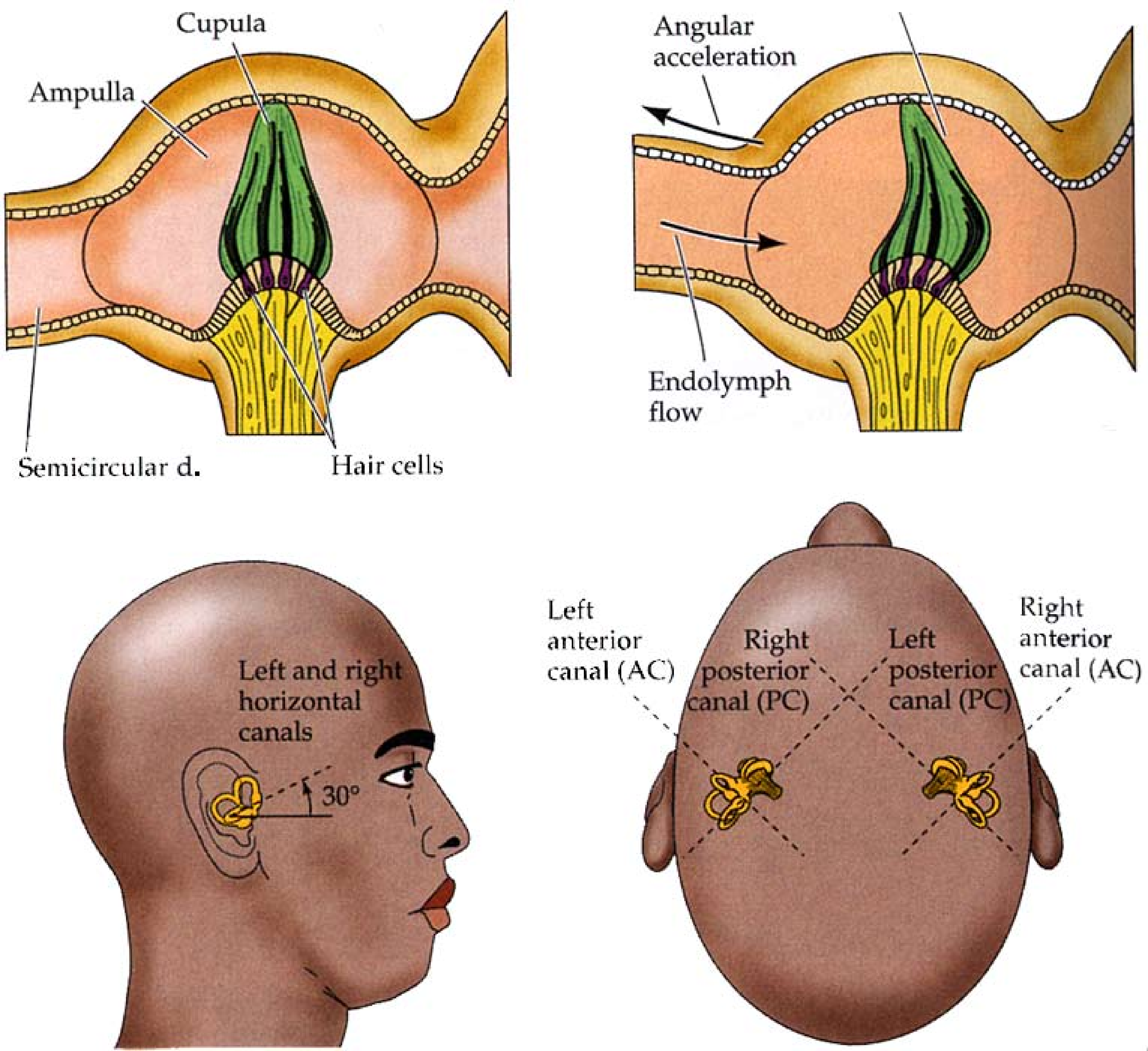
direction = location of the source of the sound waves.

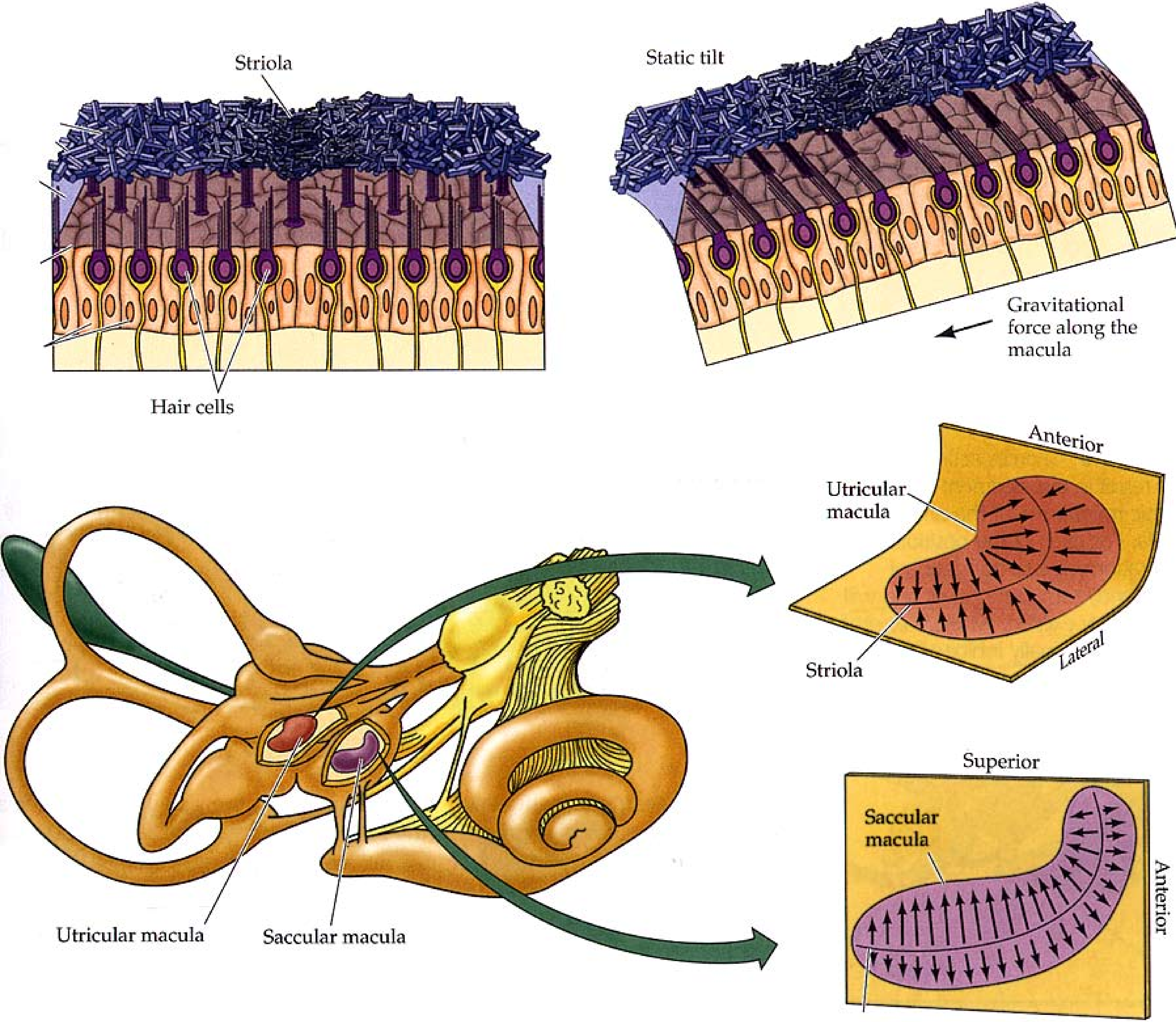
(Sound also has "color"— higher frequencies impart overtones which enable one to distinguish different instruments playing the same note at the same volume.)

Pitch — the brain deciphers pitch by determining which fibers of the cochlear nerve (which hair cells of the spiral organ; what place along the basilar membrane) are maximally active (for > 200 Hz). As the pitch (Hz) of a sound increases, the peak amplitude of basilar membrane displacement regresses, from the apex (longest fibers) toward the base (shortest fibers) of the cochlea. (*Place principle*: pitch is determined by the place of maximal amplitude displacement along the basilar membrane.)

Volume — the brain interprets volume as a function of the number of axons firing and the frequency of their action potentials. Increased volume (amplitude) will result in greater excursion of the basilar membrane, greater displacement of cilia, greater depolarization of receptor cells, and higher frequencies of action potentials in more cochlear nerve axons (whatever the pitch pattern of basilar membrane displacement).

Direction — at low frequencies, the brain uses the phase difference (time-lag) between inputs to right and left ears to determine which ear is closer to the source of the sound; at high frequencies, the head acts as a barrier resulting in an intensity difference between the near and far ear. (Also, the pinna may modify sound coming from different directions, and the animal can move its ears and head to assist in sound localization.)


Cupula
Ampulla
Semicircular d.
Hair cells
Angular acceleration
Endolymph flow
Left and right horizontal canals
30°
Left anterior canal (AC)
Right posterior canal (PC)
Left posterior canal (PC)
Right anterior canal (AC)



Striola
Static tilt
Hair cells
Gravitational force along the macula
Anterior
Utricular macula
Striola
Lateral
Superior
Saccular macula
Anterior
Utricular macula
Saccular macula

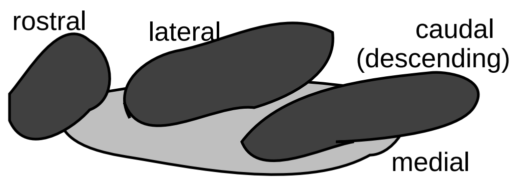
CNS Connections:

Vestibular nerve fibers (axons from neuron cell bodies of the vestibular ganglion) travel from the inner ear to the brain. They synapse in vestibular nuclei of the brainstem and in the nodulus or flocculus of the cerebellum.

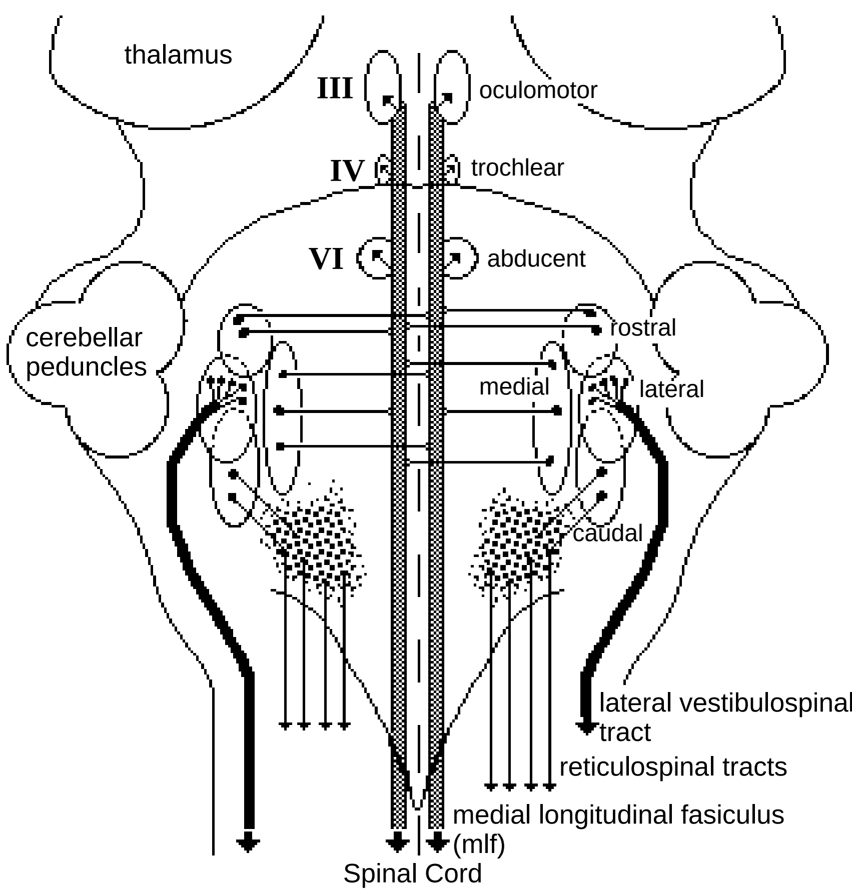
Vestibular nuclei:

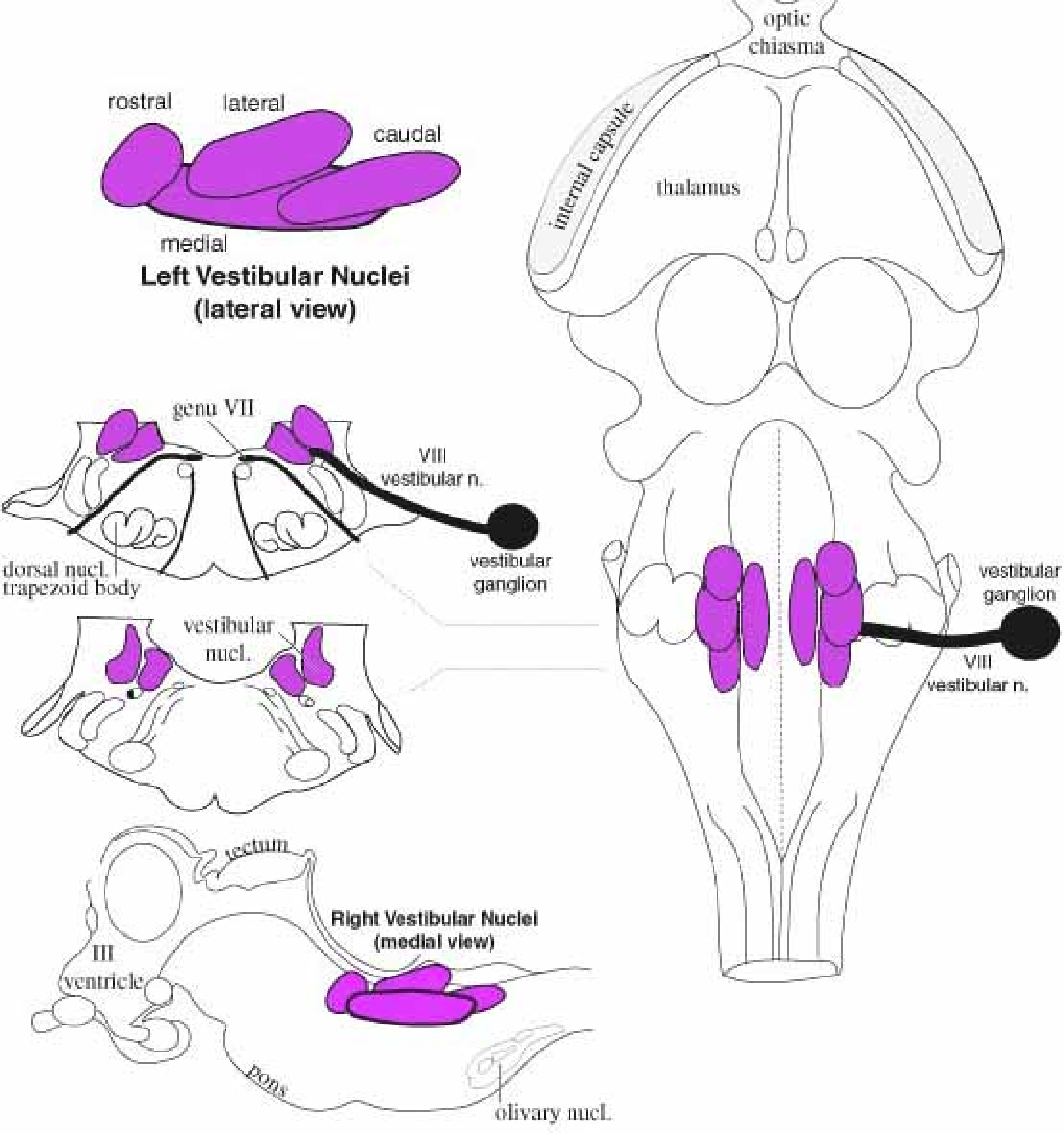
Four vestibular nuclei are located bilaterally in the medulla oblongata and pons. They receive input from the vestibular nerve and project to:

1) cerebellum,
2) reticular formation,
3) spinal cord via the lateral vestibulospinal tract (which activates limb extensor muscles via alpha and gamma neurons), and
4) neurons controlling eye (3, 4, and 6 cranial nerves) and neck (cervical spinal cord) muscles via the medial longitudinal fasciculus.

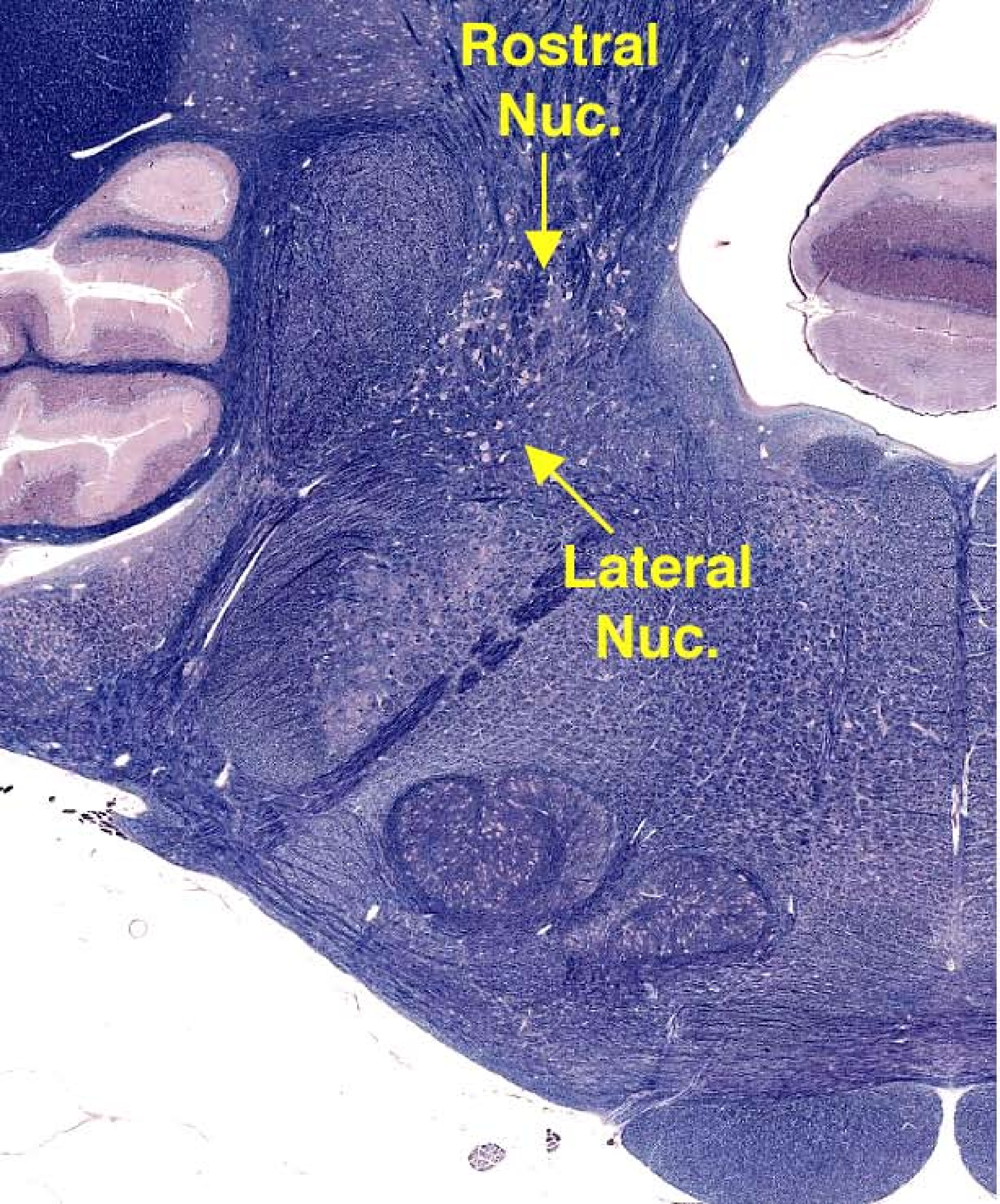
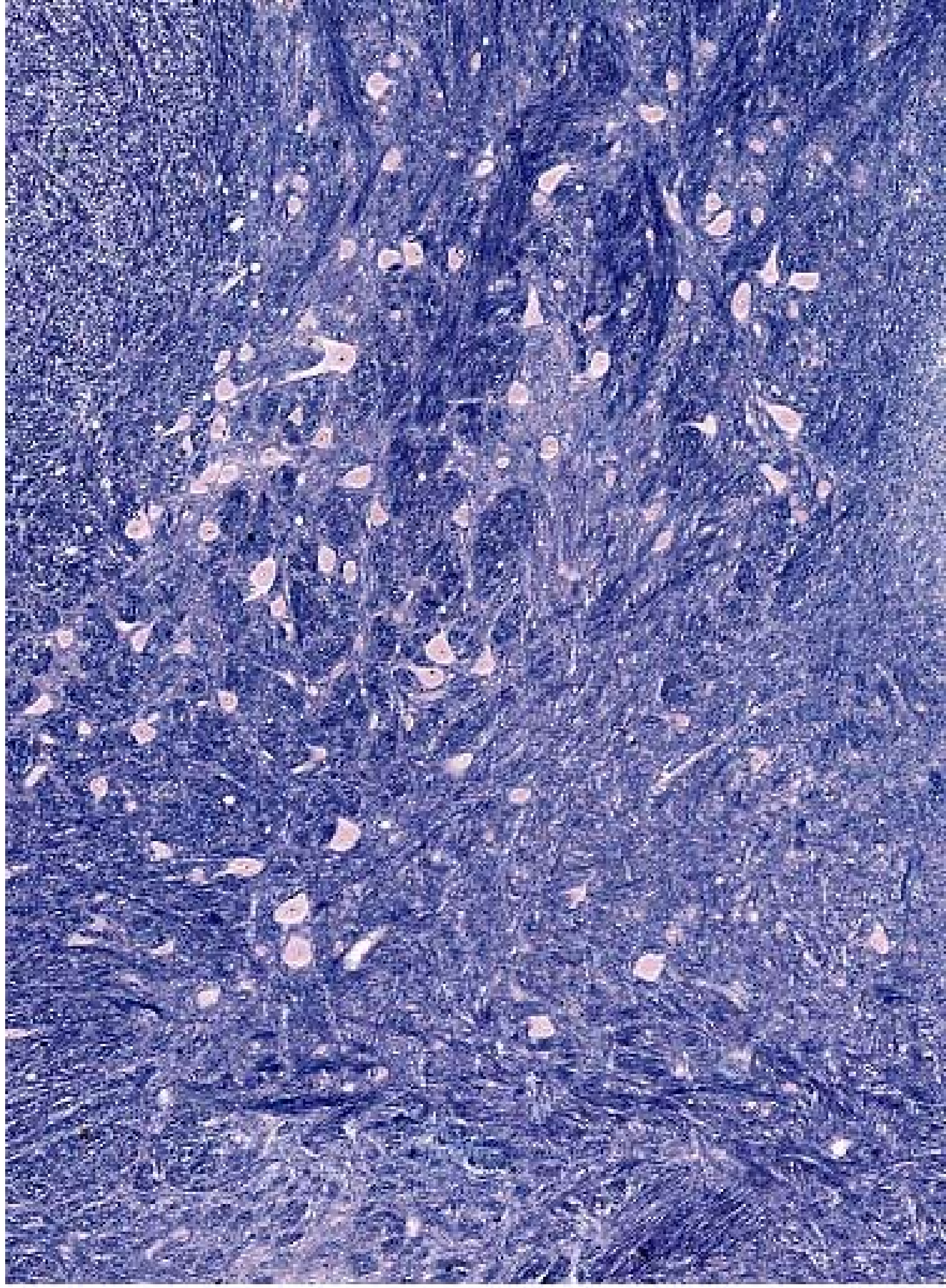


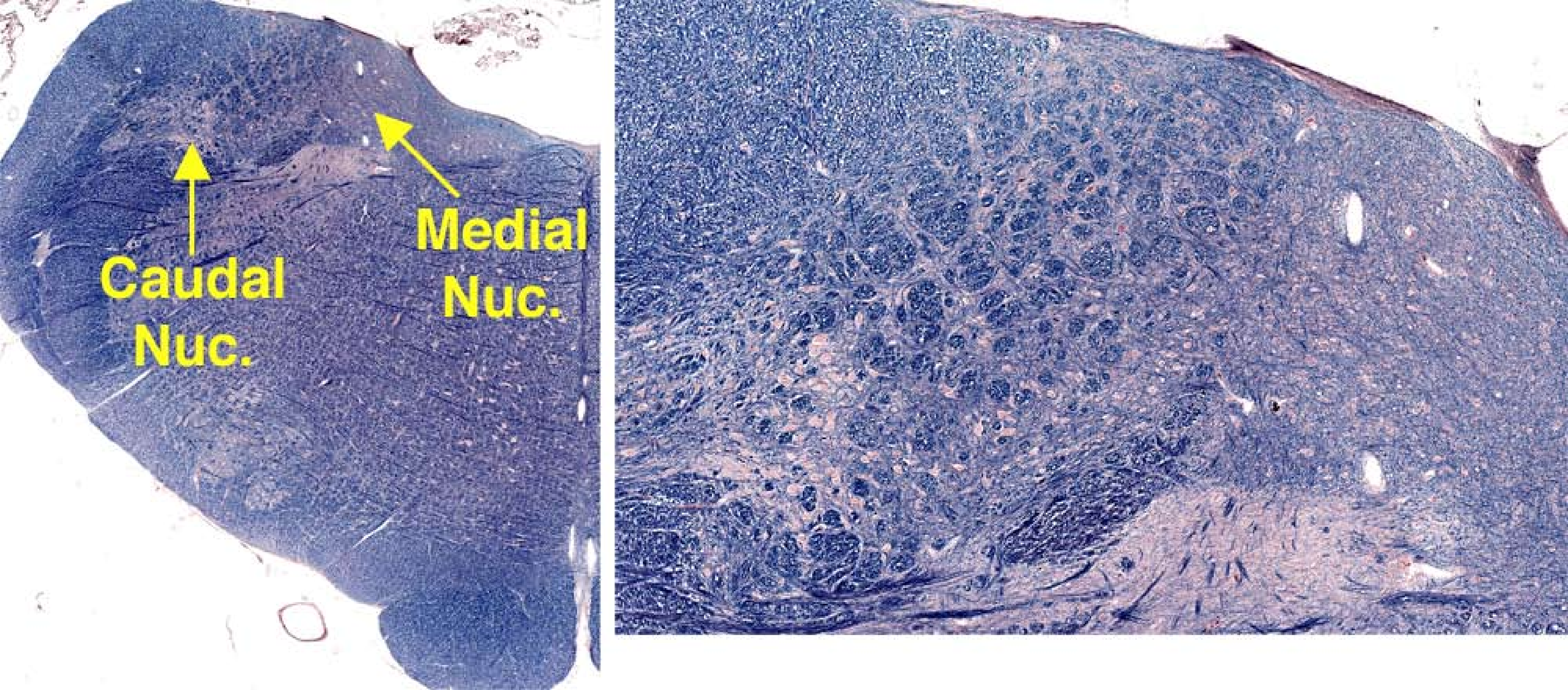
Four Vestibular Nuclei
(lateral view)

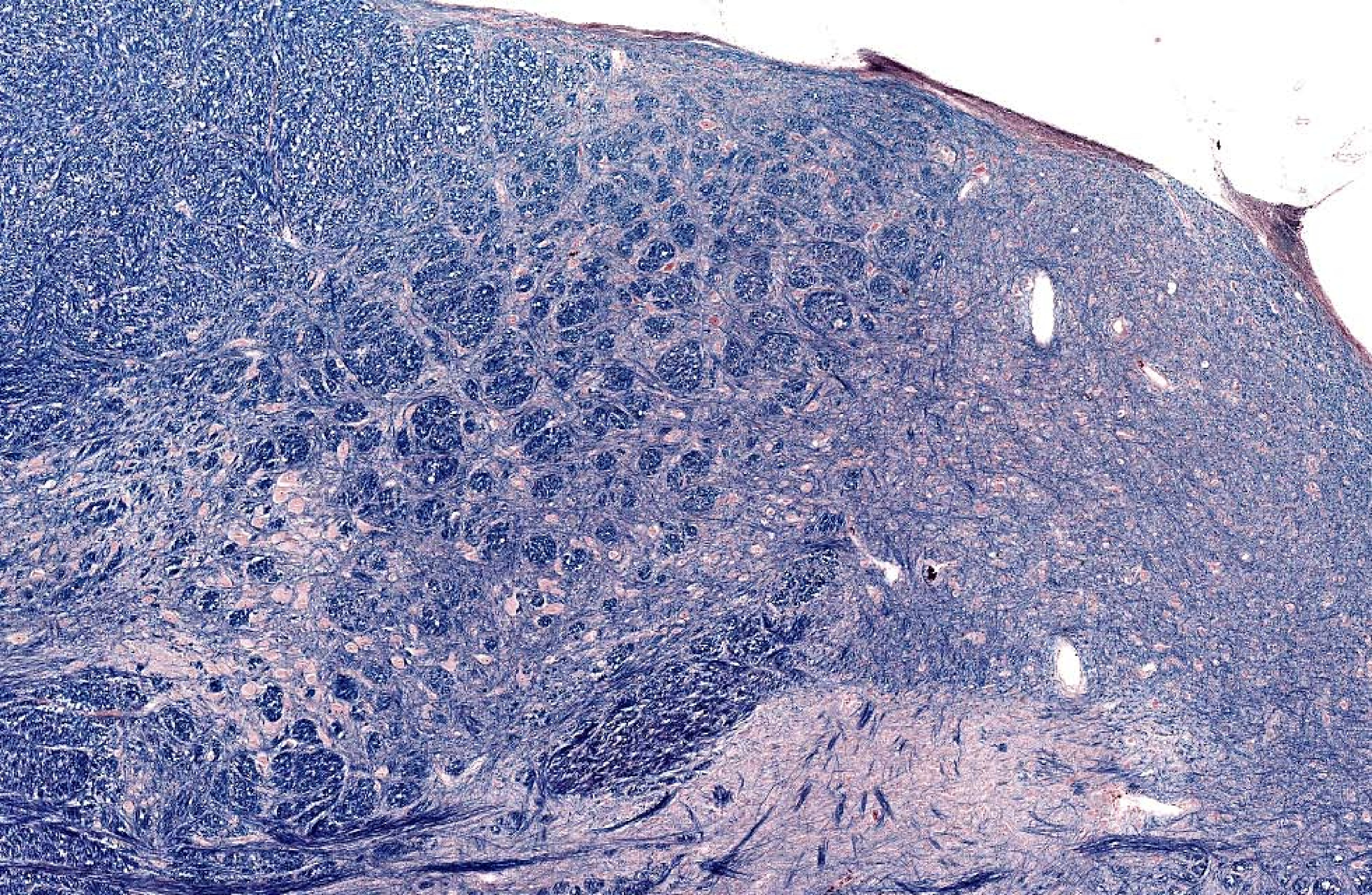


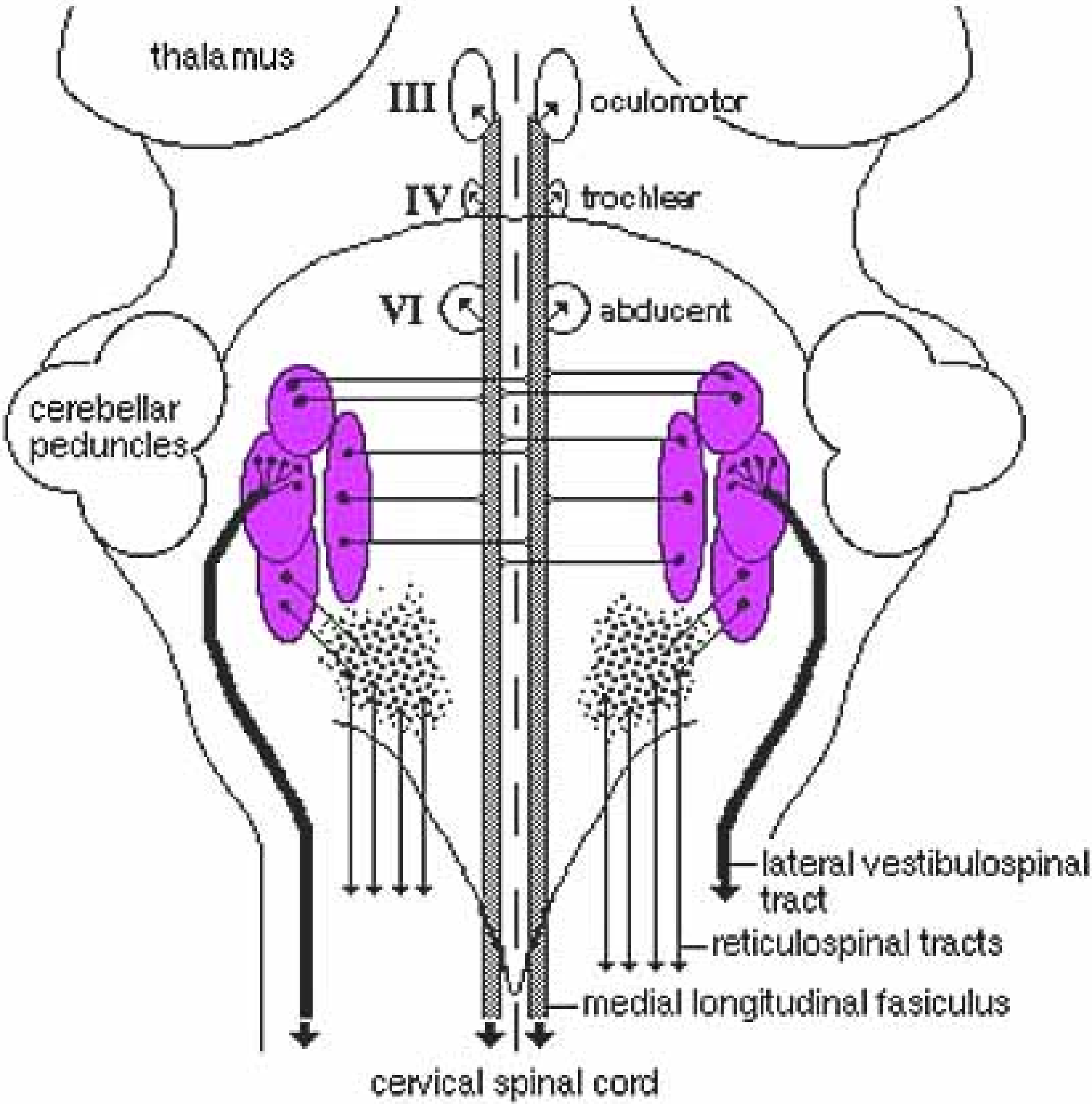


rostral
lateral
caudal
medial
Left Vestibular Nuclei
(lateral view)
optic
chiasma
internal capsule
thalamus
genu VII
VIII
vestibular n.
vestibular
ganglion
dorsal nucl.
trapezoid body
vestibular
nucl.
vestibular
ganglion
VIII
vestibular n.
tectum
Right Vestibular Nuclei
(medial view)
III
ventricle
pons
olivary nucl.


Rostral
Nuc.
Lateral
Nuc.



Caudal
Nuc.
Medial
Nuc.




thalamus
III
oculomotor
IV
trochlear
VI
abducent
cerebellar peduncles
lateral vestibulospinal tract
reticulospinal tracts
medial longitudinal fasiculus
cervical spinal cord

Vestibular Reflexes:

Effects on Eyes:

The eyes are shifted in a direction opposite to the direction that the head is accelerated, in order to maintain a stable visual field.

For example, head rotation to the right produces increased AP frequency in the right vestibular nerve and decreased frequency in the left. Vestibular nuclei on the right side dominate activity in the left abducens nucleus & right oculomotor nucleus, causing the eyes to move to the left.

In general, vestibular nuclei push the eyes contralaterally. When nuclear activity is balanced on each side the push is balanced and eyes are not shifted.

Effects on Neck and Limbs:

Analogous to eye control, the head is maintained in a normal posture by means of vestibular reflex control of neck muscles.

Vestibular nuclei influence extensor muscles in the limbs; extensor muscles are contracted on the side toward which the head is accelerating (to preclude falling).

Clinical considerations:

Lesions affecting the middle ear, vestibular apparatus, vestibular nerve, or vestibular nuclei are common. Such lesions produce imbalanced neural activity which leads to a vestibular syndrome.

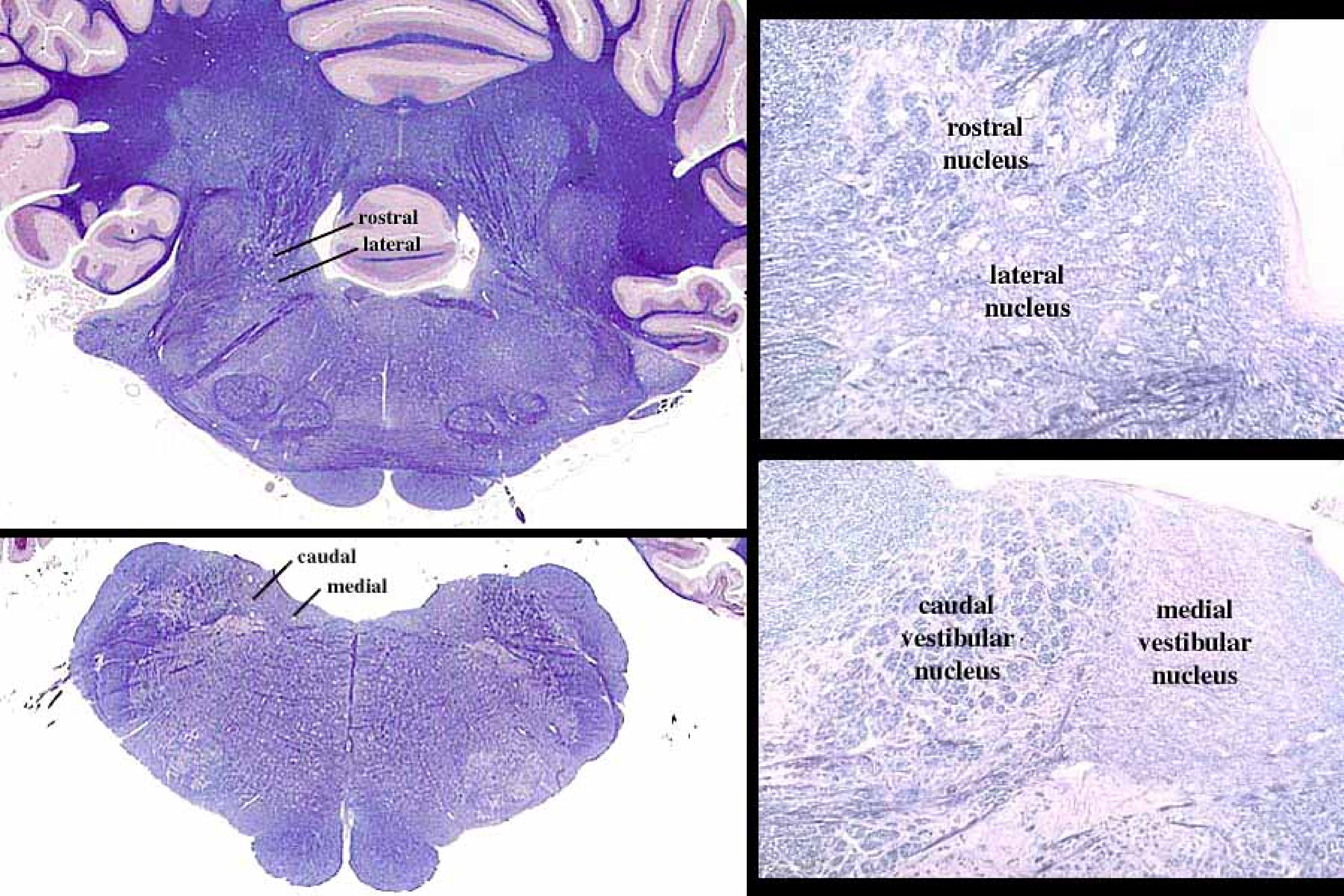
<u>Vestibular syndrome:</u> (you should be capable of diagnosing which side is lesioned)

- head tilt — lesion is on the "down ear" side
- stumbling, falling, rolling — direction is toward the lesion side
- nystagmus (oscillatory eye movement — abnormal when the animal is not rotating)
  — slow phase of nystagmus is directed toward the side of the lesion

Note: The normal (undamaged) side is more active than the lesioned (damaged) side. This imbalance causes reflexes to be expressed as if there were an "acceleration" toward the normal side. (During balanced vestibular activity, bilateral reflex effects cancel).

<u>Nystagmus</u> = eyes continuously shift: slowly to one side, then quickly back to center.

- *vestibular nystagmus* — is generated reflexly by vestibular nuclei in response to angular acceleration;
- *opticokinetic nystagmus* — is generated by cerebral cortex when focusing on moving objects, e.g., train passenger focussing on telephone poles.


rostral
lateral
caudal
medial
rostral nucleus
lateral nucleus
caudal vestibular nucleus
medial vestibular nucleus