SECTION I

1 Extraocular Muscle Anatomy and Innervation

This chapter outlines the anatomy of the extraocular muscles and their innervation and associated cranial nerves (II, V, VII and VIII).

There are four rectus and two oblique muscles attached to each eye. The rectus muscles originate from the Annulus of Zinn, which encircles the optic foramen and medial portion of the superior orbital fissure (Fig. 1.1). These muscles pass forward in the orbit and gradually diverge to form the orbital muscle cone. By means of a tendon, the muscles insert into the sclera anterior to the rotation centre of the globe (Fig. 1.2).

The extraocular muscles are striated muscles. They contain slow fibres, which produce a graded contracture on the exterior surface, and fast fibres, which produce rapid movements on the interior surface adjacent to the globe. The slow fibres contain a high content of mitochondria and oxidative enzymes. The fast fibres contain high amounts of glycogen and glycolytic enzymes and less oxidative enzymes than the slow fibres. The global layer of the extraocular muscles contains palisade endings in the myotendonous junctions, which are believed to act as sensory receptors. Signals from the palisade endings passing to the central nervous system may serve to maintain muscle tension (Ruskell 1999, Donaldson 2000).

Muscle pulleys

There is stereotypic occurrence of connective tissue septa within the orbit and stereotypic organisation of connective tissue around the extraocular muscles (Koornneef 1977, 1979). There is also stability of rectus extraocular muscle belly paths throughout the range of eye movement, and there is evidence for extraocular muscle path constraint by pulley attachment within the orbit (Miller 1989, Miller *et al*. 1993, Clark *et al*. 1999). High-resolution MRI has confirmed the presence of these attachments via connections that constrain the muscle paths during rotations of the globe (Demer 1995, Clark *et al*. 1997). CT and MRI scans have shown that the paths of the rectus muscles remain fixed relative to the orbital wall during excursions of the globe and even after large surgical transpositions (Demer *et al*.

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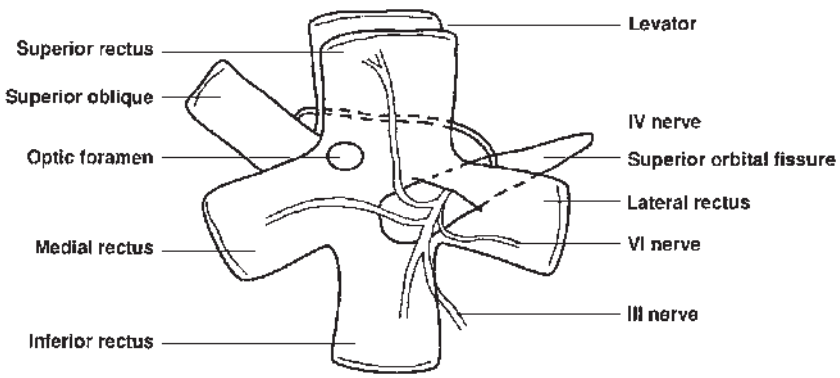

Figure 1.1 Orbital apex.

1996, Clark *et al.* 1999). It is only the anterior aspect of the muscle that moves with the globe relative to the orbit.

Histological studies have demonstrated that each rectus pulley consists of an encircling ring of collagen located near the globe equator in Tenon fascia attached to the orbital wall, adjacent extraocular muscles and equatorial Tenon fascia by sling-like bands, which consist of densely woven collagen, elastin and smooth muscle (Demer *et al.* 1995, Porter *et al.* 1996). The global layer of each rectus extraocular muscle, containing about half of all extraocular muscle fibres, passes through the pulley and becomes continuous with the tendon to insert on the globe. The orbital layer containing the remaining half of the extraocular muscle fibres inserts on the pulley and not on the globe (Demer *et al.* 2000, Oh *et al.* 2001, Hwan *et al.* 2007).

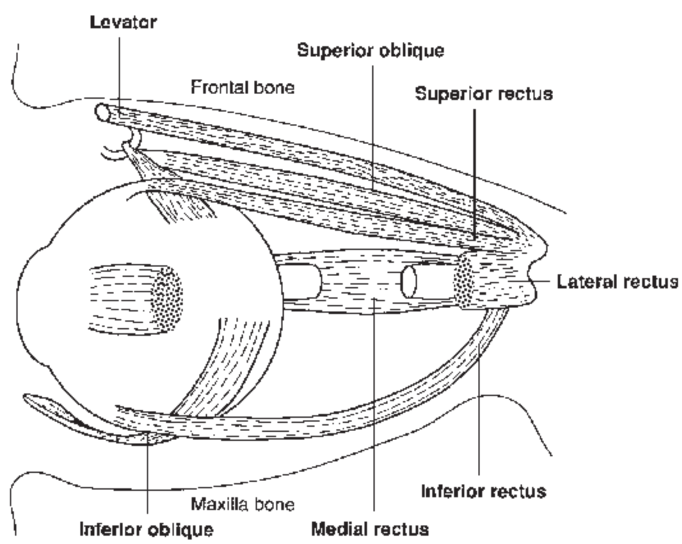

Figure 1.2 Extraocular muscles.

The orbital layer translates pulleys while the global layer rotates the globe through its insertion on the sclera. The inferior oblique muscle also has a pulley that is mechanically attached to the inferior rectus pulley (Demer *et al*. 1999).

The general arrangement of orbital connective tissues is uniform throughout the range of human age from foetal life to the tenth decade. Such uniformity supports the concept that pulleys and orbital connective tissues are important for the mechanical generation and maintenance of ocular movements (Kono *et al*. 2002).

Ocular muscles

Medial rectus muscle

This muscle originates at the orbital apex from the medial portion of the Annulus of Zinn in close contact with the optic nerve. It courses forward for approximately 40 mm along the medial aspect of the globe and penetrates Tenon's capsule roughly 12 mm from the insertion. The last 5 mm of the muscle are in contact with the eye and the insertion is at 5.5 mm from the limbus with a width of 10.5 mm. The muscle is innervated by the inferior division of the III nerve, which enters the muscle on its bulbar side. Its function is adduction of the eye (Fig. 1.3).

Lateral rectus muscle

This muscle arises by two heads from the upper and lower portions of the Annulus of Zinn where it bridges the superior orbital fissure. It courses forward for approximately 40 mm along the lateral aspect of the globe and crosses the inferior oblique insertion. It penetrates Tenon's capsule at roughly 15 mm from the insertion and the last 7–8 mm of the muscle is in contact with the eye. The insertion is at

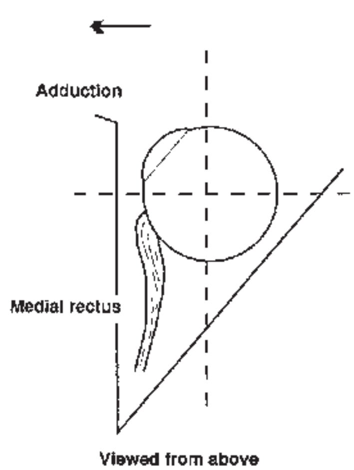

Figure 1.3 Medial rectus action.

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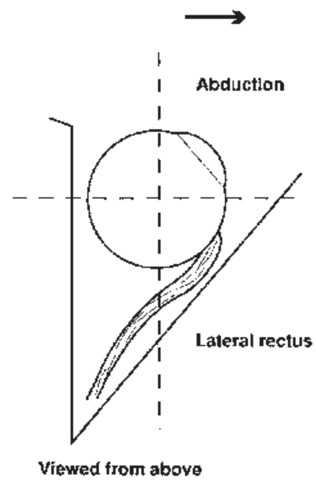


Figure 1.4 Lateral rectus action.

7 mm from the limbus with a width of 9.5 mm. The muscle is innervated by the VI nerve, which enters the muscle on its bulbar side. Its function is abduction of the eye (Fig. 1.4).

Superior rectus muscle

This muscle arises from the superior portion of the Annulus of Zinn and courses forward for approximately 42 mm along the dorsal aspect of the globe forming an angle of 23° with the sagittal axis of the globe. Superiorly, it is in close contact with the levator muscle. It penetrates Tenon's capsule at roughly 15 mm from the insertion and the last few mms of the muscle are in contact with the eye. The insertion is at 7.7 mm from the limbus with a width of 11 mm. The muscle is innervated by the superior division of the III nerve, which enters the muscle on its bulbar side. Its functions are elevation, intorsion and adduction of the eye (Fig. 1.5).

Inferior rectus muscle

This muscle arises from the inferior portion of the Annulus of Zinn and courses forward for approximately 42 mm along the ventral aspect of the globe forming an angle of 23° with the sagittal axis. It penetrates Tenon's capsule roughly 15 mm from the insertion and the last few millimetres of the muscle are in contact with the eye as it arcs to insert at 6.5 mm from the limbus. The width of insertion is 10 mm. The muscle is innervated by the inferior division of the III nerve, which enters the muscle on its bulbar side. Its functions are depression, extorsion and adduction of the eye (Fig. 1.6).

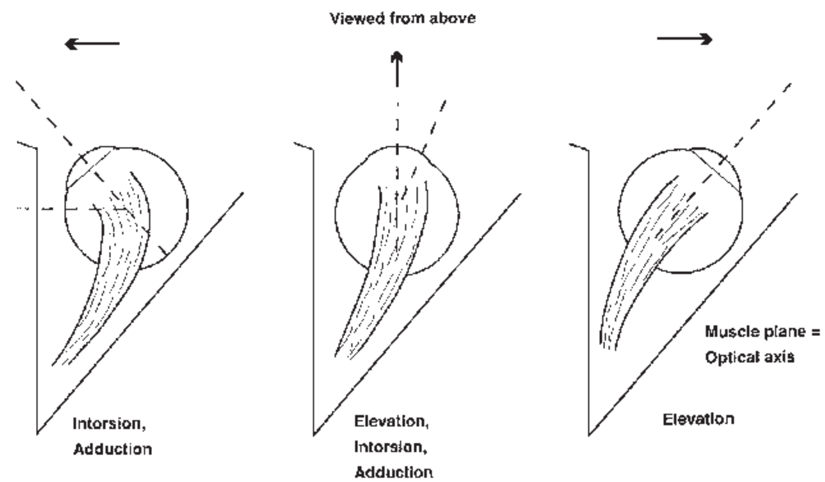


Figure 1.5 Superior rectus action. The course of the superior rectus is at an angle of 23° to the medial wall of the orbit. Actions in adduction are principally intorsion and adduction; in the primary position, actions are elevation, intorsion and adduction; action in abduction is principally elevation.

Superior oblique muscle

This muscle originates from the orbital apex from the periosteum of the body of the sphenoid bone, medial and superior to the optic foramen. It courses forward for approximately 40 mm along the medial wall of the orbit to the trochlea

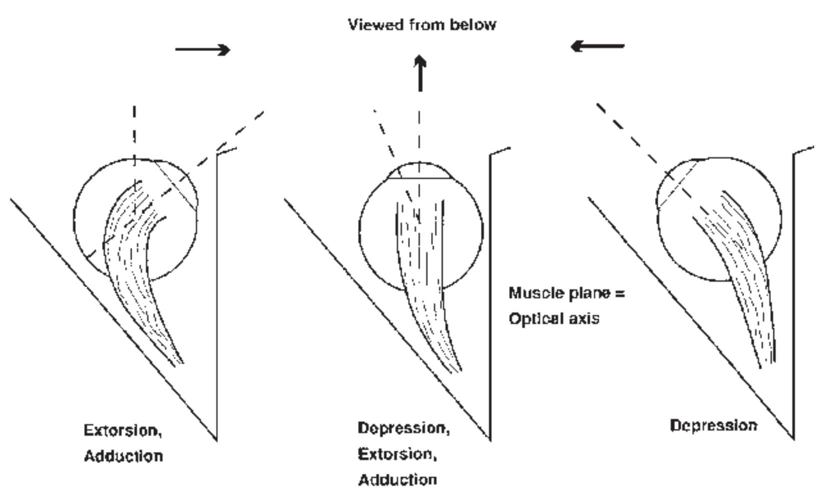


Figure 1.6 Inferior rectus action. The course of the inferior rectus is at an angle of 23° to the medial wall of the orbit. In adduction, the actions are principally extorsion and adduction; in the primary position, actions are depression, extorsion and adduction; action in abduction is principally depression.

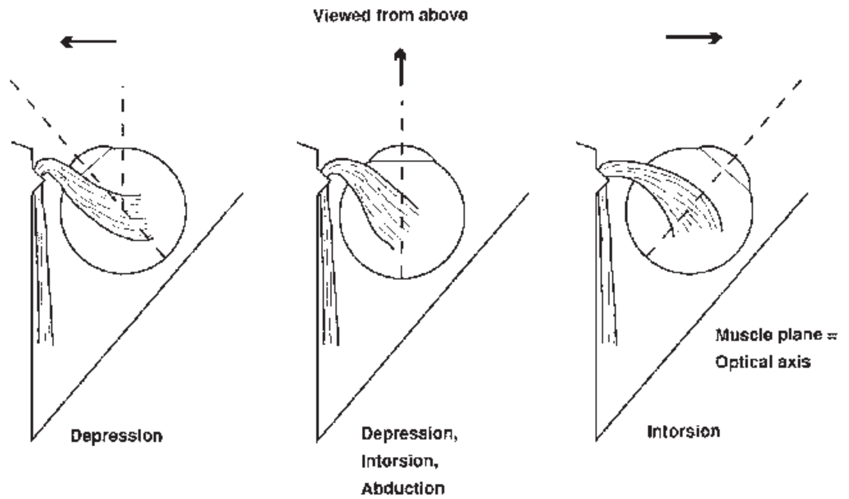


Figure 1.7 Superior oblique action. The course of the superior oblique tendon is at an angle of 51° to the medial wall of the orbit. Action in adduction is depression; in the primary position, actions are depression, intorsion and abduction; in abduction, action is intorsion.

(a V-shaped fibrocartilage that is attached to the frontal bone). The trochlear region is described by Helveston *et al*. (1982).

The muscle becomes tendonous roughly 10 mm posterior to the trochlea and is encased in a synovial sheath through the trochlea. From the trochlea, it courses posteriorly, laterally and downwards forming an angle of 51° with the visual axis of the eye in the primary position. It passes beneath the superior rectus and inserts on the upper temporal quadrant of the globe ventral to the superior rectus. Its insertion is fanned out in a curved line 10–12 mm in length. The muscle is innervated by the IV nerve that enters the muscle on its upper surface roughly 12 mm from its origin. Its functions are intorsion, depression and abduction of the eye (Fig. 1.7).

Inferior oblique muscle

This muscle arises from the floor of the orbit from the periosteum covering the anteromedial portion of the maxilla bone. It courses laterally and posteriorly for approximately 37 mm, forming an angle of 51° with the visual axis. It penetrates Tenon's capsule near the posterior ventral surface of the inferior rectus, crosses the inferior rectus and curves upwards around the globe to insert under the lateral rectus just anterior to the macular area. The muscle is innervated by the inferior division of the III nerve that enters the muscle on its bulbar surface. Its functions are extorsion, elevation and abduction of the eye (Fig. 1.8).

Figure 1.9 illustrates the muscle insertions in relation to the anterior segment of the eye. Figure 1.10 illustrates the positions of main action of each extraocular muscle and Table 1.1 illustrates all primary, secondary and tertiary muscle actions.

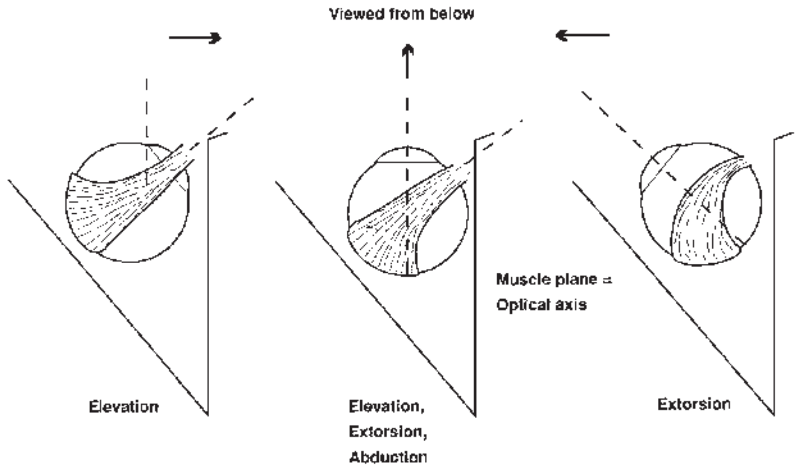


Figure 1.8 Inferior oblique action. The course of the inferior oblique is at an angle of 51° to the medial wall of the orbit. Action in adduction is elevation; actions in the primary position are elevation, extorsion and abduction; in abduction, action is extorsion.

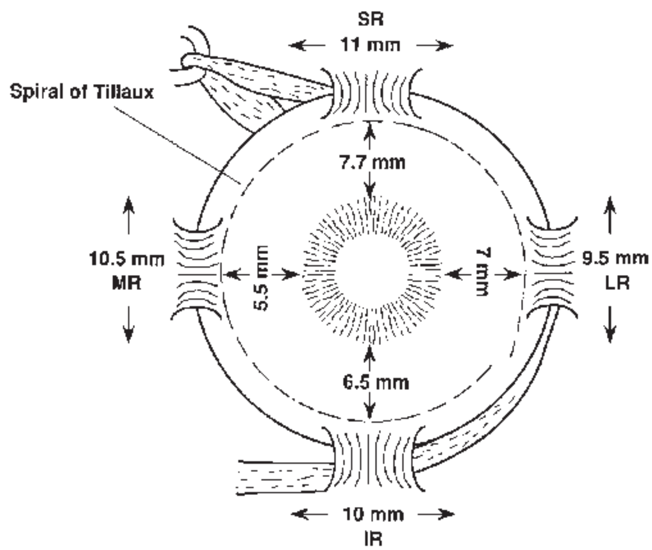
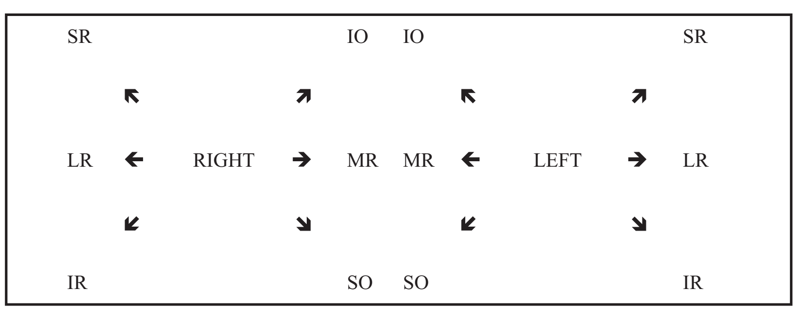


Figure 1.9 Extraocular muscle insertions. SR, superior rectus; MR, medial rectus; LR, lateral rectus; IR, inferior rectus.



SR	Superior rectus	IR	Inferior rectus	LR	Lateral rectus
MR	Medial rectus	IO	Inferior oblique	SO	Superior oblique

Figure 1.10 Cardinal positions of gaze – position of main action of extraocular muscles.

Table 1.1 Primary, secondary and tertiary extraocular muscle actions.

Muscle	Primary action	Secondary action	Tertiary action
Medial rectus	Adduction	–	–
Lateral rectus	Abduction	–	–
Superior rectus	Elevation, maximum in abduction	Intorsion, maximum in adduction	Adduction, maximum in adduction
Inferior rectus	Depression, maximum in abduction	Extorsion, maximum in adduction	Adduction, maximum in adduction
Superior oblique	Intorsion, maximum in adduction	Depression, maximum in abduction	Abduction, maximum in abduction
Inferior oblique	Extorsion, maximum in abduction	Elevation, maximum in adduction	Abduction, maximum in abduction

Levator palpebral superioris

This muscle originates from the under surface of the lesser wing of sphenoid bone above and in front of the optic foramen by a short tendon that blends with the origin of the superior rectus. It runs forward and changes directly from horizontal to vertical at the level of the equator of the globe. At approximately 10 mm above the superior margin of the tarsus, it divides into anterior and posterior lamellae. The anterior lamellae form the levator aponeurosis that is inserted into the lower third of the entire length of the anterior surface of the tarsus. Its fibres extend to the pre-tarsal portion of the orbit and skin. The posterior lamellae form Muller's muscle that is attached inferiorly to the superior margin of the tarsus.

Innervation

The extraocular muscles are innervated by the III, IV and VI nerves.

III nerve

The III nerve (third/oculomotor) supplies the superior rectus, inferior rectus, medial rectus, inferior oblique and levator muscles. Its visceral fibres innervate the ciliary muscle and sphincter pupillary muscle that synapse in the ciliary ganglion.

The nuclei are in the mesencephalon at the level of the superior colliculus. There is an elongated mass of cells that form the nuclei. Peripheral motor neurones innervate multiply innervated extraocular muscle fibres and central motor neurones innervate single innervated muscle fibres. Dorsal nucleus fibres pass to the ipsilateral inferior rectus, intermediate nucleus fibres pass to the ipsilateral inferior oblique, ventral nucleus fibres pass to the ipsilateral medial rectus, paramedian nucleus fibres pass to the contralateral superior rectus, central caudal nucleus fibres pass to both levator muscles, and the anterior median/Edinger-Westphal nucleus contains the parasympathetic fibres (Bienfang 1975). The nerve fibres emerge from the mesencephalon ventrally where they are closely associated with the posterior cerebellar and superior cerebral arteries. The nerve courses forward through the subarachnoid space to pierce the dura mater at the posterior clinoid process and enter the cavernous sinus.

The third cranial nerve pathway is supplied by branches of the basilar artery including the superior cerebellar arteries, posterior cerebral arteries, mesencephalic perforating arteries, collicular and accessory arteries in the midbrain; the thalamoperforating arteries supplemented by the superior cerebellar artery, posterior communicating artery and posterior cerebral artery in the proximal nerve pathway; and inferior cavernous sinus arteries, medial posterior choroidal artery and tentorial arteries in the distal nerve pathway (Marinkovic & Gibo 1994, Cahill *et al*. 1996).

IV nerve

The IV nerve (fourth/trochlear) supplies the superior oblique. The nucleus lies in the mesencephalon at the level of the inferior colliculus. The nerve fibres decussate (although about 3% do not decussate but retain ipsilateral projection) and emerge from the brainstem dorsally. The nerves curve around the brainstem and course forward through the subarachnoid space to pierce the dura mater and enter the cavernous sinus.

The fourth cranial nerve pathway is in close association or contact with branches of the basilar artery in the midbrain including the superior cerebellar artery, vernian artery and collicular artery. It is supplied by posterior cerebral artery and posterior communicating artery in its proximal pathway and by the internal carotid artery, medial posterior choroidal artery and tentorial arteries in the distal pathway (Marinkovic *et al*. 1996, Yousry *et al*. 2002).

VI nerve

The VI nerve (sixth/abducens) supplies the lateral rectus. The nucleus is situated in the pons in the floor of the IV ventricle near the midline, medial to VIII nucleus and proximal to the paramedian pontine reticular formation. The medial longitudinal fasciculus lies medial to the nucleus. The nerve fibres emerge from the brainstem ventrally and course forward and laterally over the petrous tip of the temporal bone and under the petrosphenoid ligament. The nerve pierces the dura mater to enter cavernous sinus. The nerve divides into two distinct trunks along its pathway between the brainstem and the lateral rectus muscle.

The sixth cranial nerve pathway is supplied with branches of the basilar artery including the anterior inferior cerebellar artery, posterior inferior cerebellar artery, pontomedullary artery and accessory arteries in the pons and clivus region. The distal pathway is supplied by the internal auditory artery, anterolateral artery and tentorial artery (Marinkovic *et al*. 1994, Yousry *et al*. 1999).

Common nerve pathways

The III, IV and VI nerves course forward together in the lateral aspect of the cavernous sinus entering the orbit through the superior orbital fissure. The III and VI nerves enter within the muscle cone.

The III nerve divides into the superior and inferior divisions. The superior division enters the superior rectus on its bulbar surface and passes through the muscle to terminate in the levator muscle. The inferior branch supplies the medial rectus, inferior rectus, and then passes beneath the optic nerve to the floor of the orbit and terminates in the inferior oblique. The terminal branch also sends a short branch to the ciliary ganglion. The VI nerve passes forward and laterally to enter the lateral rectus bulbar surface. The IV nerve enters through the superior orbital fissure laterally and superior to the Annulus of Zinn. It passes anteriorly and medially crossing the III nerve, levator muscle and superior rectus, and enters the superior oblique on its orbital surface.

Associated cranial nerves

Autonomic nerves

These nerves supply smooth muscles and source ganglia. Smooth muscles include the muscular blood vessels, Muller's muscle, pulley smooth muscle, sclera myofibroblasts and choroidal smooth muscle (Demer *et al*. 1997). Source ganglia include the pterygopalatine ganglion, ciliary ganglion and superior cervical ganglion.

Proprioceptive nerves

These nerves consist of palisade endings and spindles. Palisade endings innervate myotendonous cylinders at the termination of each multiply innervated global layer fibre in the rectus extraocular muscles (Lienbacher *et al*. 2011). Spindles are composed of several orbital layer myofibres and have nerve terminals within a very thin capsule.

II nerve

The II (optic) nerve serves the sensory function of vision. Its pathway commences in the eye at the receptor cells in the retina. There is a complex arrangement of nuclei and processes from three layers of photoreceptors, bipolar cells and ganglion cells. There are in the region of 1.2–1.5 million retinal ganglion cells and 105 million photoreceptors with an average ratio of 1 retinal ganglion cell to 100 photoreceptors. At the fovea, the ratio is 1:1 for retinal ganglion cells to photoreceptors.

Retinal ganglion cells include midget (parvocellular), parasol (magnocellular), koniocellular and other cells. Midget ganglion cells are responsible for slow conduction of impulses with low temporal resolution and require high contrast stimuli. Parasol ganglion cells are responsible for fast conduction of impulses with high temporal resolution and requiring low contrast stimuli. Midget cells have colour selectivity whereas parasol cells have little or no colour selectivity. Koniocellular cells have moderate conduction velocity and moderate sensitivity to light and spatial resolution. They have some colour selectivity and may have a role in motion detection and visual attention. Other cells include light reflex ganglions and photosensitive neurones.

Retinal ganglion cells pass in nerve fibre bundles to the optic discs and pass from each eye to the intracranial cavity along the optic nerves. The optic nerves merge in the optic chiasm where there is crossing of nasal retinal fibres. Ipsilateral temporal and contralateral nasal fibres pass along the optic tracts to the lateral geniculate nuclei where the first synapse of retinal nerve fibres occurs. The postsynaptic fibres then pass via the optic radiations to the visual cortex. The visual cortex (V1) occupies the calcarine sulcus in the occipital lobe and is the primary visual area.

V nerve

The V nerve (fifth/trigeminal) serves sensory and motor functions and the nuclei extend through the pons down into the medulla. The sensory nerve has three branches.

Sensory nerves

The ophthalmic division serves the sensory function to the lacrimal gland, conjunctiva, forehead, eyelids, anterior scalp and mucous membranes of the nose. The sensory fibres pass through the superior orbital fissure to the cavernous sinus and pass inferiorly to the trigeminal ganglion, which is located under the cavernous sinus in Meckel's cave (a groove in the skull). Fibres pass from the ganglion posteriorly to the pons to the trigeminal nuclei.

The maxillary division serves the sensory function to the cheeks, upper gums and teeth and lower eyelids. The sensory fibres pass through the foramen rotundum, underneath the cavernous sinus to the trigeminal ganglion and then onto the nuclei in the pons.

The mandibular division serves the sensory function to the teeth, gums of the lower jaw, pinna of ears, lower lip and tongue. The sensory fibres pass through the foramen ovale underneath the cavernous sinus to the trigeminal ganglion and then onto the nuclei in the pons.

Motor nerves

Motor fibres of the V nerve serve the muscles of mastication. The motor nuclei are located in the pons near the seventh nerve nuclei and aqueduct. Nerve fibres leave ventrally and medially and pass anteriorly to the trigeminal ganglion, through the foramen ovale to the muscles of mastication.

VII nerve

The VII nerve (seventh/facial) serves sensory and motor functions. The VII nerve has central connections to the motor face area of the cerebral cortex and the nuclei are divided into upper and lower halves. Corticobulbar fibres double decussate for the upper face but there is single decussation for lower face fibres.

Sensory fibres

Ganglion cells supply taste buds in the palate and tongue and sensory fibres are also present in the skin, in and around the external acoustic meatus. Fibres pass to the geniculate ganglion situated in the internal auditory meatus and pass back to the pons.

Motor fibres

The nuclei are located in the lateral part of the pons and fibres loop around the abducens nuclei, forming the facial colliculus, before leaving the pons ventrally. Fibres pass anteriorly and enter the internal auditory meatus. The nerve enters a narrow bony canal above the labyrinth and descends to the stylomastoid foramen where a branch supplies the stapedius muscle. It leaves the skull and supplies the facial muscles (frontal, zygomatic, buccal, mandibular marginal and cervical branches).

VIII nerve

The VIII nerve (eight/auditory) serves the sensory function of hearing and balance.

Cochlear nerve (hearing)

Receptor cells are hair cells in the organ of Corti. Fibres pass from the spiral ganglion along the Cochlear nerve through the internal auditory meatus to the cisterna pontis, to the inferior cerebellar peduncle and to the cochlear vestibular nuclei in the pons/medulla.

Vestibular nerve (balance)

Receptor cells are hair cells in the utricles, saccules and semicircular canals. Fibres pass from Scarpa's ganglion along the vestibular nerve through the internal auditory meatus to the cisterna pontis and to the vestibular nuclei in the pons/medulla. Within the internal auditory meatus, the vestibular and cochlear nerves are in close association with the facial nerve. Within the acoustic foramen and intracranial cavity, these nerves are closely associated with both the sixth and facial nerves.

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