ANATOMY OF THE CEREBELLUM AND SPINAL CORD

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I. CEREBELLUM

The cerebellum is critical for bodily equilibrium and posture. It coordinates the trajectory and smoothness of ongoing movements, including eye movements and motor speech, and regulates muscle tone. It is also important in motor learning. To do all this, the cerebellum integrates a massive variety of inputs (somatosensory, visual, vestibular, auditory, motor, and premotor) from the rest of the brain and spinal cord, and ultimately modulates motor signaling within the spinal cord and cerebral cortex. Impairment of cerebellar function causes ataxia, which is an impairment in the timing, trajectory, force, and smoothness of movements.

<u>Anatomic relationships to nearby structures</u>

The cerebellum is the largest structure in the posterior fossa. It is attached closely to the brainstem via superior, middle, and inferior peduncles, which also are the main conduits for information to and from the cerebellum. The inferior peduncle carries incoming spinal sensory and vestibular information. The middle peduncle carries incoming information originating in the cerebrum. The superior peduncle is the main output pathway of the cerebellum. The cerebellum forms the roof of the 4^{th} ventricle, which drains the ventricular system into the cisterna magna via the medial foramen of Magendie and the lateral foramina of Luschka.

Superiorly, the cerebellum is separated from the cerebral hemispheres by the tentorium cerebelli, a taut shelf of dura mater. Inferiorly, the cerebellar tonsils (part of the posterior lobe) descend behind the medulla toward the foramen magnum, and are variably positioned in different individuals according to developmental and acquired factors.

The cerebellum’s vascular supply is via the posterior inferior cerebellar arteries (PICA), anterior inferior cerebellar arteries (AICA), and superior cerebellar arteries (SCA).

Clinical correlations

The cerebellum's location near the brainstem and critical CSF flow pathways means that cerebellar lesions causing edema or mass effect (e.g. stroke, tumor) can be catastrophic. Obstruction of CSF outflow leads to non-communicating hydrocephalus and/or increased intracranial pressure. A swollen cerebellum can compress the brainstem anteriorly. In downward herniation, the cerebellar tonsils may squeeze the medulla, shutting down core cardiorespiratory function. Upward herniation of the cerebellum through the tentorium can compress the midbrain and nearby arteries.

Tonsillar protrusion to varying degrees below the foramen magnum can be in part developmental, as in Chiari malformation, or in benign tonsillar ectopia. Excessive tonsillar descent can also be due to cerebellar mass lesions, increased ICP, or relatively low pressure in the spinal CSF compartment.

<u>Intrinsic gross anatomy</u>

From rostral to caudal, the cerebellum is divided by major surface grooves into the anterior, posterior, and flocculonodular lobes. Transversely, the cerebellum is divided into a midline vermis and 2 lateral hemispheres. Moving from superficial to deep, the cerebellum comprises: 1) a cortex which is extensively folded into folia 2) a branching splay of white matter, and 3) several deep grey matter nuclei (dentate, globose, fastigial, and emboliform nuclei).

Clinical correlations

As an approximation, midline cerebellar structures regulate midline functions such as eye movements, speech, truncal stability, and gait. Lateral structures regulate precise limb movement, especially distally. Cerebellar localization is ipsilateral: left hemisphere controls left-sided limbs, and right hemisphere controls the right-sided limbs.

Functional and circuit anatomy
Though only 10% of the brain by weight, the cerebellum contains about 70 billion neurons.

Incoming information arrives in the cerebellum via climbing and mossy fibers. Much of this comes directly to the cerebellar cortex, whose many folia are oriented transversely, rather like an accordion. Cerebellar granule cell axons, by the billions, run parallel to the folia, contacting Purkinje cell dendritic trees which are flattened and oriented perpendicular to the folia. The single-cell layer of Purkinje cells represents the main source of output from the cerebellar cortex. Purkinje dendritic arbors are among the most elaborately branched in the nervous system, with as many as 200,000 synaptic inputs, allowing the integration of an immense amount of information from other parts of the CNS. The inferior olives are a particularly powerful input (via climbing fibers) to the Purkinje neurons.

A variety of interneurons facilitates these computations within the cortex. Purkinje neuronal axons project to the deep cerebellar nuclei, which in turn signal the final cerebellar output to the brainstem and thalamus.

While the above connectivity scheme is quite uniform throughout the cerebellum, there exist three functional subdivisions: vestibulocerebellum, spinocerebellum, and cerebrocerebellum.

The vestibulocerebellum has intimate bidirectional connections with the vestibular nucleus. It is, to a large extent, the flocculonodular lobe, and is critical for body equilibrium and eye movements. The spinocerebellum comprises much of the vermis, and the smaller deep nuclei. It processes sensory input from the spinal cord, to coordinate axial motor function, posture, and tone. The cerebrocerebellum comprises most of the lateral hemispheres and the dentate nucleus (the largest deep nucleus). It processes input from spinal cord and cerebral cortex, to facilitate precision limb movements and motor learning.

Direct cerebellar outflow is to several regions, including the reticular formation, olive, vestibular nuclei, red nucleus, and ventrolateral thalamus. This information ultimately heavily influences motor signaling within the spinal cord and cerebral cortex.

Clinical correlations
Because of the cerebellum's extensive connections with the rest of the brain, ataxia can result from extracerebellar disease. Limb ataxia can occur in focal lesions involving the midbrain and thalamus. In Friedreich ataxia, degeneration of spinal cord dorsal columns and spinocerebellar tracts causes ataxia even without direct involvement of the cerebellar cortex.

The dense and complex cerebellar neuropil is particularly sensitive to malfunction due to a variety of gene defects (30+ spinocerebellar ataxias), drugs and toxins (alcohol, lithium, anticonvulsants, calcineurin inhibitors, heavy metals), and autoimmune disorders (paraneoplastic, GAD65, gluten, and Hashimoto- related).

II. SPINAL CORD
The spinal cord carries motor signaling from the brain to the trunk and limbs, and somatosensory signaling from the trunk and limbs to the brain. It provides considerable autonomic innervation to the head, trunk, and limbs. Its intrinsic circuitry permits a variety of reflex actions, somatic and autonomic.

External anatomy
The vertebral canal encloses the spinal cord and cauda equina. Anteriorly, the canal is bound by the posterior longitudinal ligament. Posteriorly, it is protected by the ligamentum flavum. Moving toward the center of the canal, next lies the spinal epidural space, then the dura. In the spine, the arachnoid is closely applied to the dura, so that the subdural compartment is usually a theoretical space. Deep to the arachnoid lie the CSF and the cord itself, which is covered by the pia. Off the cord surface, the dorsal and ventral spinal nerve roots pass through the CSF. They take a sleeve of the outer meninges with them as they leave the intervertebral foramina for the periphery.

The spinal cord in adults extends from the foramen magnum to its tip, the conus medullaris, at the L1-2 level. Exiting it laterally are 31 pairs of spinal nerve roots, each named for the vertebral foramina at which it exits the spine. Roots C1 through C7 exit above their respective vertebrae; then C8 exits between C7 and T1 vertebrae; thereafter, the nerve roots exit below the respective vertebrae. Because the cord is so much shorter than the spine, cervical roots emerge relatively horizontally, and thoracic roots at a more oblique descent. Lumbosacral roots descend a steep 3 or more vertebral levels before they can exit the canal, well below the conus. This arrangement results in the cauda equina ("horse's tail") occupying the inferior portion of the spinal canal. A strand of pia called the filum terminale attaches the conus medullaris to the coccyx.

The spinal cord itself is expanded in its cervical and lumbar regions, as these regions contain more grey matter and transverse fiber volumes than the thoracic region.

The arterial supply of the spinal cord is largely via the anterior and posterior spinal arteries. The anterior spinal artery runs the length of the cord and irrigates the anterior two-thirds of it, including spinothalamic and lateral corticospinal tracts. The paired posterior spinal arteries irrigate the remainder, including the dorsal columns. These arteries arise from the vertebral system, but rely heavily on supplemental flow from the descending aorta, via a series of radicular arteries that arrive segment by segment through the intervertebral foramina.

Clinical correlations
The epidural space of the spine is a prime site for mass lesions causing cord or cauda compression, such as abscesses, tumors, and hematoma. Nearby bony structures, such as the vertebral bodies, can be a source for infectious and neoplastic lesions. Disease and degeneration of the bony spine, vertebral disks, and canal ligaments can also affect the spinal cord and nerve roots.

The spinal CSF space is continuous with that of the brain. Meningeal disease (infection, neoplasm, or inflammation) can selectively affect individual or multiple nerve roots, as well as the cord itself.

Canal lesions below the L2 vertebral body do not cause myelopathy, since the only neural structures below that point are lumbosacral nerve roots. A peripheral syndrome occurs instead, with flaccid weakness and areflexia (cauda equina syndrome).

Tethered cord syndrome, with excessive stretching of the cord, can result from an overly tight filum terminale. Aortic disease, including dissections and surgical repairs, can result in ischemia to the spinal cord, particularly in the thoracic segments, which rely heavily on arterial reinforcements form the aorta.

<u>Cross sectional anatomy</u>
At the very center of the spinal cord is the narrow central canal, a CSF channel continuous with the fourth ventricle. In the spinal cord, gray matter occupies an H-shaped central region, with white matter tracts on the periphery. At the dorsal horn, sensory information arrives from the periphery via dorsal roots. The dorsal root ganglia contain the cell bodies for these peripheral sensory neurons. Outgoing motor and autonomic signals exit anteriorly via paired ventral roots.

The widened anterior horn of the spinal grey matter contains lower motor neurons, whose axons innervate the skeletal muscles of the trunk and limbs. In the thoracic and lumbar cord there is a lateral bulge to the grey matter cross section: this is the intermediolateral column and contains preganglionic sympathetic neurons. In the sacral cord, this region contains preganglionic parasympathetic neurons.

There are numerous paired white matter tracts, ascending and descending. Most important for clinical localization are three: the anterior spinothalamic tracts, the lateral corticospinal tracts, and the posterior dorsal columns.

The spinothalamic tracts carry non-discriminatory tactile information up the cord. This includes pain, temperature, and crude touch or pressure. Critically, this sensory information decussates through the center of the cord soon after entering the cord at the dorsal horn, before it enters the spinothalamic tract. Thus, this tract carries information *contralateral* to the body half it serves. Somatotopically, cervical fibers are most medial while sacral fibers are most lateral.

The lateral corticospinal tracts carry motor information down the cord, and comprises upper motor neuron axons from the brain. This tract decussated in the caudal medulla, so in the cord is ipsilateral to the body half it serves. Somatotopically, cervical fibers are the most medial, while sacral fibers are the most lateral.

The dorsal columns (fasciculus cuneatus and gracilis) carry discriminatory tactile information up the cord. This includes position sense, vibration, two-point discrimination, and directional cutaneous sense (i.e., detecting the direction of an object moving on the skin). This tract decussates in the caudal medulla, so in the cord is ipsilateral to the body half it serves. In this tract, sacral fibers are the most medial and cervical fibers are most lateral.

Other tracts are functionally important, but not so from a localization standpoint. They include spinocerebellar, ventral corticospinal, rubrospinal, and vestibulospinal tracts. Details are beyond the scope of this review.

Clinical correlations

Based on the cross sectional involvement, sensorimotor deficits below the lesion can be predicted. Illustrative examples are anterior cord syndromes (e.g. infarction), hemi cord syndrome, and dorsal column syndromes. Central cord lesions of longitudinal extent (e.g. syrinx) can cause a suspended sensory loss to pin and temperature, and varying degrees of lower motor weakness (if the anterior horn is involved). Ascending and descending long tracts are relatively spared.

Severe autonomic dysfunction can result from major spinal cord lesions, particularly complete spinal cord injuries.

MAJOR REFERENCE, AND SUGGESTED FURTHER READING:

Brazis P., Biller J., and Masdeu J. Localization in Clinical Neurology. 7th ed. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins Health, 2016. Print.