Brief review of the anatomy of the head, spine, brain, and spinal cord.

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The first goal of this chapter is to acquaint the reader with the gross anatomy and landmarks of the skull, spine, brain, and spinal cord in order to facilitate an accurate description of lesions. The second goal is to provide a succinct review of the clinical manifestations associated with lesions of specific regions of the brain and spinal cord.

Scalp

The scalp is the cover of the skull and consists of several layers including the external skin and hair, subcutaneous tissue, the galea or epicranial aponeurosis, and the periosteum. The galea provides attachment to the occipitalis and frontalis muscles. Over the squamous portion of the temporal bone, the temporalis muscle is inserted between the periosteum and the subcutaneous tissue. The subcutaneous tissue of the scalp is richly vascularized and can bleed profusely. The space between the galea and the periosteum constitutes a cleavage plane that allows the scalp to be stripped from the skull (i.e., in order to expose the skull for opening during autopsy). Blood can also dissect and enter into this space giving origin to a subgaleal hematoma.

Skull

The skull or cranium is the compartment that contains and protects the brain. The skull consists of an inferior platform or base of the skull and a dome, known as the calvarium or vault. The calvarium is marked by three major sutures, i.e. sagittal; coronal; and lambdoid, which are closed in the adult, but remain partially open in newborns and infants and form the anterior (bregma), posterior (lambda), and lateral fontanelles. The base of the skull is divided by the sphenoid and petrous ridges into three tiers denominated by the anterior, middle, and posterior fossae. The
inferior surface of the frontal lobes, also known as orbito-frontal region, rests on the anterior fossa. The floor of the anterior fossa, which is also the roof of the orbit, is a very thin lamina of bone that can fracture easily. For example, the floor of the anterior fossa may fracture due to the contrecoup impact of the brain in falls with occipital impacts (blow-out fracture) (Hirsch and Kaufman, 1975). The temporal lobes lie on the middle fossa, and the cerebellum on the posterior fossa (the occipital lobes rest on the tentorium, as described below). At the center of the middle fossa lies the sella turcica, the seat of the pituitary gland. The surface of the anterior and middle cranial fossae is very irregular, characterized by multiple bony ridges and small orifices through which blood vessels and nerves enter and exit the skull. The posterior fossa consists of an inclined central plane, known as the clivus, over which lies the brain stem, and two lateral and posterior concave expansions that contain the cerebellar hemispheres. The foramen magnum is at the bottom of the posterior fossa, allowing the passage of the neuroaxis and marking the transition of the medulla into the cervical cord. Unlike the anterior and middle cranial fossae, the surface of the posterior fossa is smooth. It is important to realize that the same bones that form the base of the skull harbor multiple air-filled cavities known as sinuses. For example, the sphenoidal sinus is under the sella and the frontal sinuses are under the anterior fossa. These sinuses, the frequent site of inflammation and infection, represent potential sources for infections to extend into the skull, meninges, and brain. This potential is greatly enhanced by fractures of the base of the skull. Notably, fractures of the base of the skull may result in communication between the subarachnoid space and the paranasal sinuses or the nose. In this way, a fracture of the anterior fossa may result in a leak of cerebrospinal fluid through the nose.

The calvarium is formed by the fusion of the frontal, parietal, temporal, and occipital bones. The bones of the calvarium are formed by two layers or tables of compact bone (diploe) with an intermediate layer of trabeculated bone which contains a plexus of veins. The cranial dura mater is attached to the internal surface of the skull in such a way that fractures of the calvarium can lacerate the dura or dural vessels. The most common mechanism for the development of epidural hemorrhage is a fracture of the squamous portion of the temporal bone with laceration of branches of the middle meningeal artery. The blood under pressure dissects the dura from the bone and forms a lens-shaped hematoma that compresses the brain.
Meninges

The brain and spinal cord are wrapped by three layers of connective tissue known collectively as meninges, including the dura mater, arachnoid, and pia mater.

Dura mater
The skull is lined internally with a tough layer of connective tissue designated the dura mater. The dura mater has two major reflections: the falx, which runs vertically in the interhemispheric fissure, separating the cerebral hemispheres; and the tent of the cerebellum, which has an approximately horizontal orientation and separates the dorsal surface of the cerebellum from the inferior surface of the occipital lobes. A large opening, the tentorial notch, is present in the center of the tentorium for the passage of the brain stem. Accumulations of blood or exudates may occur between the dura mater and the skull, known as epidural lesions, or between the dura mater and the brain, designated subdural lesions. Sometimes in newborns, intradural hemorrhages are noted within the two layers of the falx.

The dura mater also forms the walls of the venous sinuses that drain the brain into the jugular arteries. These sinuses include the superior and inferior sagittal, transverse, straight, and sigmoid sinuses. The cavernous sinus, which runs lateral to the sella, drains via the ophthalmic veins and pterygoid plexus into the veins of the face.

Leptomeninges
The brain is covered by two delicate layers of connective tissue known as leptomeninges. The pia mater which is the most internal layer adheres to the brain tissue and follows intimately the contour of the cortical mantle, thus covering from the crown of the gyri to the bottom of the sulci. Although delicate in appearance, the pia is an effective barrier that can prevent infectious agents and inflammatory exudates from extending directly from the subarachnoid space into the brain parenchyma. The arachnoid, placed between the pia and the dura mater, is also a thin and translucent membrane, like a cobweb, that covers the surface of the brain bridging over the sulci of the cerebral cortex. The normal translucency of the arachnoid can be obscured by hemorrhage, exudates, or fibrosis. Between the pia and the arachnoid is the subarachnoid space. This space,
which is continuous with the subarachnoid space surrounding the spinal cord, contains the cerebrospinal fluid, communicates with the ventricular system via the orifices of Lushka and Magendie (fourth ventricle), and projects into the brain parenchyma along perivascular sleeves known as Virchow-Robin spaces. The arachnoid has specialized structures designated arachnoid granulations that project from the subarachnoid space into the superior sagittal sinus for absorption of the cerebrospinal fluid into the venous system.

The vessels at the surface of the brain are contained within the subarachnoid space; thus, hemorrhages are frequent within this space. Dilation and congestion of the vessels at the surface of the brain are frequently observed in autopsy specimens. These findings are non-specific and should be considered as such.

From a functional perspective, it is important to recognize that inflammatory processes and hemorrhages of the subarachnoid space have the potential to cause fibrosis of this space and hinder the normal circulation of the cerebrospinal fluid and its absorption into the superior sagittal sinus. This situation may result in enlargement of the ventricular system known as communicating hydrocephalus.

**Brain**
The brain can be divided into three major components: the cerebrum, brain stem, and cerebellum. Afferent and efferent connections of the brain travel in 12 pairs of cranial nerves.

**The cerebrum** consists of two cerebral hemispheres joined by the corpus callosum and thalamus. Each cerebral hemisphere encompasses the frontal, temporal, parietal, and occipital lobes. The external layer of the cerebral hemispheres is the cortex, a mantle of gray matter a few millimeters thick that covers large expanses of myelinated white matter. The cerebral cortex is characterized by multiple infoldings that give origin to a fairly stereotyped pattern of many plateaus (gyri) and grooves (sulci and fissures). The dorsal surface of the brain is known as the convexity and the ventral surface is designated the base of the brain. At the base of the brain we encounter the major arteries that supply the brain and the 12 pairs of cranial nerves. The cerebral cortex is fairly homogeneous throughout the cerebrum, 2 to 3 mm thick, and well-demarcated
from the subjacent white matter. In the occipital lobe, the primary visual or calcarine cortex (Brodmann’s area 17) can easily be identified by a prominent white myelinated layer or line of Gennari. In the mesial aspect of the temporal lobe, the neocortex (with six layers) is replaced by the entorhinal cortex, which merges medially into the hippocampus. The hippocampus is an elongated structure, approximately 7 to 8 cm, wrapped in myelinated fibers that runs along the temporal horn of the lateral ventricle. In coronal sections, the hippocampus is nearly round and is characterized by two interlocking lamellae of granule cells (fascia dentate) and pyramidal neurons. Immediately rostral to the hippocampus, and also abutting the temporal horn of the lateral ventricle, is the amygdala, a nucleus that forms part of the limbic system. At the core of the cerebral hemispheres lie several nuclei of gray matter surrounding the ventricular system. These nuclei include the basal ganglia, thalamus, and hypothalamus. The basal ganglia consist of the putamen, caudate, and globus pallidum. The thalamus is large expanse of gray matter on the banks of the third ventricle and it is bound laterally by the posterior limb of the internal capsule. The thalamus extends from its anterior nucleus, at the level of the foramina of Monro, to its most posterior nucleus or pulvinar, at the level of the splenium of the corpus callosum. Under the thalamus there are two important structures: the hypothalamus and the subthalamic nucleus. The hypothalamus extends along the walls of the third ventricle from the level of the anterior commissure, rostrally, to the mammillary bodies, caudally. The subthalamic nucleus is a lens- or almond-shaped nucleus that occupies an oblique position under the thalamus, above the substantia nigra, and lateral to the red nucleus. The ventricular system in the cerebral hemispheres encompasses the two lateral ventricles connected by the foramina of Monro to the midline third ventricle, which in turn communicates with the fourth ventricle via the aqueduct of Sylvius. Within the ventricular cavities is the choroid plexus, a richly vascularized and amorphous tissue that is attached to the ependymal lining and secretes the cerebrospinal fluid. This fluid exits the ventricular system into the subarachnoid space via two sets of foramina, Lushka and Magendie, located in the fourth ventricle.

The brainstem is divided into midbrain, pons, and medulla. The midbrain is the most rostral division. Its roof or tectum consists of the superior and inferior colliculi, immediately dorsal to the aqueducts of Sylvius, which connects the third ventricle in the cerebrum and the fourth ventricle in the pons. Other important structures in the midbrain are the periaqueductal gray
matter, the nuclei of cranial nerves III and IV, substantia nigra, red nuclei, the superior cerebellar peduncles and their decussation, and the cerebral peduncles. The pons consists of a basal portion or basis pontis that contains ascending, descending, and decussating fibers, and the tegmentum that contains the reticular activating system, and the nuclei of cranial nerves V, VI, VII, and VIII. The tegmentum of the pons constitutes the floor of the fourth ventricle. The medulla contains the pyramids, inferior olivary nuclei, vestibular nuclei, and the nuclei of cranial nerves IX, X, XI, and XII.

The cerebellum, located in the posterior fossa behind the brainstem, consists of two lateral hemispheres flanking a thin midline vermis. The surface of the cerebellum is formed by a thin layer of gray matter with thin and long infoldings that generates a pattern known as folia. Under the folia is the white matter, abundant in the hemispheres but scant in the vermis. In the depth of the white matter lie the deep gray nuclei: dentate, globosus, emboliform, and fastigial. The dentate nucleus is the largest and the more lateral one, and is easily identified. The other are smaller, occupy more medial positions, and are better examined under the microscope.

The cranial nerves connect the brain with the body and the world. All of these nerves arise from the base of the brain, except for the IV pair (trochlear) which originate from the tectum of the midbrain, but promptly swing around the brain stem to join the other cranial nerves at the base. All cranial nerves are peripheral nerves; thus, they are myelinated by Schwann cells. The exception is the optic nerve, which is really a projection of the brain and is myelinated by oligodendrocytes.

The olfactory nerve (I) is composed of many tiny nerves that pierce through the cribiform plates of the ethmoid bone to reach the olfactory epithelium in the back of the nose. The olfactory nerves arise from the olfactory bulbs, which project into the cerebral cortex via the olfactory tracts. The olfactory nerves, bulbs, and tracts are frequently injured in head trauma. The optic nerve axons arise from the ganglion cells of the retina, travel in the optic nerves, chiasm and optic tracts, and project to the lateral geniculate body, a thalamic nucleus. The III cranial nerve (oculomotor) arises from the midbrain and its functions include innervation of extraocular muscles and pupillary constriction. The IV cranial nerve (trochlear) also arises
from the midbrain and innervates the superior oblique muscle. The **V cranial nerve (trigeminal)** has a very long nucleus that extends from the pons to the medulla. This nerve provides cutaneous sensation to the face and most of the scalp, and motor innervation to muscles of mastication (masseters and pterygoids). The **VI cranial nerve (abducens)** with its motor neurons in the caudal pons, exits close to the midline in the pontomedullary junction and innervates the lateral rectus muscle. The III, IV, V, and VI cranial nerves course in part within the cavernous sinus. The **VII cranial nerve (facial)** arises from motor neurons in the caudal pons, its axons loop around the VI cranial nerve nucleus, forming the knee of the facial nerve, and exit the pons laterally into the cerebellopontine angle. The VII cranial nerve innervates the muscles of the face and the platysma. The **VIII cranial nerve (auditory)** originates from neurons in the pons, its axons emerge from the lateral aspect of the pons into the cerebello-pontine angle to enter into the internal auditory canal. The **IX (glossopharyngeal), X (vagus), and XI cranial nerves** originate from neurons in the dorsolateral medulla and their rootlets exit the neuroaxis behind the inferior olive. These nerves innervate the muscles of the pharynx and larynx and their impairment may result in dysphonia and dysphagia. The latter is a risk for aspiration. The **XII (hypoglossal) cranial nerve** originates from motor neurons in the dorsal medial medulla and its axons emerge from the base of the medulla between the inferior olives and the pyramids. The hypoglossal innervates the tongue.

**Blood supply of the brain**

The brain, and in particular its gray matter, has a high metabolic rate and therefore requires a very substantial blood supply. The brain represents approximately 2% of the body weight but it receives 25% of the cardiac output. Arterial blood reaches the brain through the internal carotid arteries (anterior circulation) and vertebral and basilar arteries (posterior circulation). These arteries reach the base of the brain and form an anastomotic system known as circle of Willis. From this circle arise the anterior, middle and posterior cerebral arteries, which supply the cerebrum. Each artery has a superficial territory supplied by circumferential branches and deep territory supplied by the penetrating branches of the middle and posterior cerebral arteries. The zones where the territories of two arteries meet are known as watershed zones, which are more susceptible to ischemia when perfusion fails (The arterial circulation of the brain will be described in more detail in the chapter on vascular lesions.)
The veins of the brain have very thin walls and do not have valves. The cerebral cortex and immediately subjacent white matter drain into superior, middle, and inferior cerebral veins, which, via the anastomotic veins of Trolard (superior) and Labbé (inferior), drain into the superior sagittal and transverse sinuses, respectively. The deep structures of the cerebrum are drained by the terminal and choroid veins, which form the internal cerebral vein. The two internal cerebral veins join to form the vein of Galen, which drains into the straight sinus. The veins of the cerebellum drain into the transverse, superior petrosal, and occipital sinuses.

**Spinal Cord**

**External features.** Contained within the spinal canal, the spinal cord extends for approximately 30-35 cm from the cervicomedullary junction to the conus medullaris. The spinal cord gives origin to 31 pairs of spinal nerves formed by the joining of dorsal and ventral roots. In adults, the cord ends approximately at the level of the disc between the L1 and L2 vertebrae. The subarachnoid space extends beyond that level, however, and reaches the space between the S1 and S2 vertebrae, thus allowing for the performance of spinal taps without the risk of damaging the cord itself. The cord is anchored laterally to the dura by means of the denticulate ligaments, which intercalate their processes between the spinal roots. The cord is roughly cylindrical, with a dorsal medial sulcus and a ventral median fissure, and enlargements at the cervical and lumbar levels. These enlargements accommodate the expanded gray matter necessary to innervate the upper and lower extremities. Similar to the brain, the spinal cord is covered by three layers of meninges: pia, arachnoid, and dura mater. The pia is intimately adherent to the external surface of the cord. The subarachnoid space is continuous with the subarachnoid space surrounding the brain, is filled with cerebrospinal fluid, and contains arteries, veins, and spinal roots. The subarachnoid space forms a lateral sleeve around the roots as they pierce across the dura. The space between the arachnoid and the dura (subdural) is virtual, but the epidural space is real and filled with adipose tissue. For this reason, the spinal epidural space is suitable for the instillation of analgesic drugs and even to the installation of catheters. The pathologist and the anesthesiologist should be aware that although the dura mater is a tough fibrous membrane, it is only microns apart from the subarachnoid space; therefore, there is a risk that epidural anesthesias may leak and the anesthetic solution may extend into the subarachnoid space, with ominous consequences (i.e., cardiorespiratory arrest).
Internal features  In contrast to the brain, in the spinal cord the gray matter is internal and the white matter is external. The central gray matter is roughly shaped as the letter “H” with ventral and dorsal horns and a gray commissure. At the center of this commissure is the central canal lined with ependymal cells. The ventral horns harbor the lower motor neurons, the axons of which exit the cord in the ventral or motor roots on their way to innervate muscles of the extremities, trunk, and diaphragm. Since the innervation of the large number of muscles in the extremities requires large numbers of motor neurons, the ventral horns are more robust at the cervical and lumbar levels compared with the thoracic level. The dorsal horns contain sensory neurons and relay the inputs of axons of the dorsal or sensory roots. These dorsal root axons have their origin in neurons of the dorsal root ganglia, the axons of which bifurcate into peripheral and central axons. The peripheral axon innervates receptors in skin or muscles. The central axon enters the cord via the dorsal root and either ascends via the posterior columns to the nuclei gracilis and cuneatus of the medulla, or forms synapses with neurons in the dorsal horn, which in turn give origin to axons that decussate via the gray commissure to ascend in the spinothalamic tract.

The spinal white matter is divided into dorsal, lateral, and ventral columns, which contain ascending and descending fibers. For making clinical pathological correlations, the most important fascicles to remember are: corticospinal, gracilis and cuneatus, and spinothalamic. The corticospinal fascicle or tract, travels in the lateral columns, originates in the cortical (upper) motor neurons of the opposite cerebral hemisphere, and innervates the spinal (lower) motor neurons. The integrity of the corticospinal tract is critical for voluntary movements; its damage results in ipsilateral weakness or paralysis, hyperreflexia, and extensor plantar response (Babinski). The posterior columns include the fasciculi gracilis (medial) and cuneatus (lateral) which carry axons that originate in ipsilateral dorsal root ganglia neurons and project to the nucleus gracilis and cuneatus in the dorsal medulla. These fibers subserve the perception of vibration and position sense. Impairment of the posterior columns results in ipsilateral loss of vibration and proprioception. The spinothalamic fascicles ascend in the lateral and ventral columns and carry fibers that originate in the opposite ventral horns. These fibers subserve the perception of pain and temperature; their damage results in contralateral loss of pain and temperature perception two or three spinal levels below the lesion.
Blood supply  External examination of the spinal cord reveals a single anterior spinal artery and two posterior spinal arteries interconnected by fine anastomoses. The anterior spinal artery is formed at the cervicomedullary junction by two descending branches of the vertebral arteries. As the anterior spinal artery descends along the ventral sulcus of the cord, it receives multiple anastomotic branches that arise from posterior intercostal arteries originating from the descending aorta. One of the most important of these branches is known as the arteria magna of Adamkewicz and it arises from the T10, T11, or T12 intercostal arteries in most subjects. The artery of Adamkewicz is easily damaged during surgical procedures of the thorax and retroperitoneum. Lesions of the descending aorta, such as dissecting aneurysms, as well as their repair, carry the risk for ischemic injury of the low thoracic and high lumbar cord.

FUNCTIONAL NEUROANATOMY

We will review here certain functions of the nervous system and the neuroanatomical structures that subserve them. These concepts are particularly pertinent for establishing clinical pathological correlations.

Consciousness

Consciousness is a brain function that has two components: wakefulness or alertness and awareness of self and environment, also known as the content of consciousness (Plum and Posner, 1980; Stevens and Bhardwaj, 2006). Awareness includes several brain functions such as attention, sensation and perception, memory, and motivation (Young and Pigott, 1999). Awareness cannot occur without wakefulness, but wakefulness may be observed in the absence of awareness, for example in subjects in vegetative status (Stevens and Bhardwaj, 2006). Wakefulness depends on the integrity and function of the ascending reticular activating system (ARAS), whereas awareness depends on the integrity of the cerebral cortex and its subcortical connections. Therefore, consciousness depends on the integrity and functional interaction of both brainstem and cerebral structures. Alterations of consciousness may result not only from
structural lesions of the brain, but from pharmacological, toxic, metabolic, or electrical (seizures) derangements.

In this section, we first review structures that constitute the anatomical substrate of consciousness and then we will discuss alterations of consciousness.

**Ascending reticular activating system (ARAS).** This is a network of neurons that extends throughout the brain stem, from the medulla to the midbrain and projects rostrally into the thalamus and hypothalamus to activate the cerebral cortex. In the pons, the reticular formation is localized in the tegmentum and in the midbrain in the periaqueductal region. (Moruzzi and Magoun, 1995). Neurons of the ARAS have diverse neurotransmitters including acetylcholine, glutamate, noradrenaline, serotonin, dopamine, and histamine (Zeman, 2001). Functional or structural lesions of the reticular formation impair the activation of the cerebral cortex and can cause decreased levels of wakefulness or coma (Parvizi and Damasio, 2003).

**Thalamus.** The thalamus contains the rostral end of the reticular activating system; it is also a major relay station for all sensory systems. Thus, the thalamus is the direct source of most inputs to the cerebral cortex. For these reasons, lesions of the thalamus have the potential to cause lessened degrees of alertness or even coma. In contrast to the reticular formation in the pontine tegmentum, where fairly small lesions can lead to coma, in the thalamus the lesions have to be more extensive to impair consciousness. These lesions, frequently the consequence of massive hemorrhages or transtentorial herniations, may be unilateral but tend to produce bilateral distortions of the thalamic structures because of pressure effects.

**Cerebral cortex.** Localized lesions of the cerebral cortex may produce various specific neurologic deficits, but do not alter significantly the level of consciousness. For this to happen, a substantial proportion of the cerebral cortex must be impaired bilaterally. Importantly, this impairment of the cortex could be functional and reversible, or structural with very limited or no reversibility. Among the former, a typical example is a narcotic overdose, in which the coma can be reverted by the administration of naloxone. In contrast, if a subject suffers hypoxic-ischemic
damage of the cerebral cortex, i.e., widespread pseudolaminar necrosis, then the coma or vegetative state cannot be reversed.

**Alterations of consciousness**

The forensic pathologist should be acquainted with the clinical terminology used to describe alterations of consciousness. Descriptive terms such as stupor, obtundation, and lethargy are still in use, but may become the source of confusion, because these terms may have different meanings for different observers. For this reason, it is better to use an objective instrument to measure the level of consciousness. Currently, the Glasgow Coma Scale (GCS) (Table 2) is widely used by clinicians to assess the level of consciousness of patients (Teasdale and Jennett, 1974). Although originally designed for patients with traumatic brain injury, the GCS is now used for all types of brain pathologies. In this scale, a score of 15 is normal and a score ≤8 corresponds to coma. Of note, this scale is useful not only because of its objectivity, but also for its predictive value for survival and recovery of function in patients.

<table>
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<th>Table 2: Glasgow Coma Scale</th>
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<tr>
<td><strong>Motor responses (M)</strong></td>
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<td>Follow commands</td>
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<td>Localizes pain</td>
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<td>Withdraws to pain</td>
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<td>Flexion</td>
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<td><strong>Verbal response (V)</strong></td>
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<td>Confused speech</td>
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<td>Inappropriate words</td>
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<td>None</td>
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<td><strong>Eye opening (E)</strong></td>
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<td>Spontaneous</td>
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**Coma.** This is a state characterized by complete loss of both alertness and of awareness. Comatose patients do not open their eyes, speak, or move spontaneously. According to the GCS, coma is defined by a score ≤8, motor ≤4, verbal ≤3, and eye opening ≤2. The loss of consciousness in coma is prolonged and arbitrarily it should last for more than an hour. This is in contrast to the transient loss of consciousness experienced in syncope or concussion, which lasts for minutes. Lesions that cause coma involve the cerebrum or cerebral cortex bilaterally or the ARAS, or both.

**Concussion.** The term concussion alludes to a transient interruption of consciousness after head trauma, presumably due to functional impairment (without structural lesion) of the ARAS.
**Syncope.** This is a transient loss of consciousness due to insufficient brain perfusion as seen in arterial hypotension, hypovolemia, and cardiac arrhythmias.

**Vegetative state.** This is characterized by preservation of arousal mechanisms (alertness) but complete lack of awareness. These patients do not follow commands, do not move purposefully, but may open their eyes spontaneously, albeit without evidence of tracking or seeing objects. Their arousal may vary throughout the day in a “sleep-wake”-like cycle. Persistent vegetative state (PVS) is defined arbitrarily as the prolongation of the vegetative state for more than a month (1994). The pathological substrate of the vegetative state is widespread injury of both cerebral hemispheres with sparing of the brainstem, a situation commonly seen as consequence of hypoxic-ischemic injury of the brain.

**Akinetic mutism.** In this state there is wakefulness with limited objective evidence of awareness (Ackermann and Ziegler, 1995). Patients with akinetic mutism are unable to move or to speak, but have periods of increased awareness with eye opening and suggestion of visual pursuit. In this condition, there is injury or dysfunction of the mesial aspect of the frontal lobes or cingulate gyri, leading to impairment of motivation and other executive functions.

**Delirium.** In delirium, the main abnormality resides in the content of consciousness; it is characterized by fluctuating changes in level of consciousness, disorganized thinking, hallucinations, and memory impairment, also known as confusional state. Delirium is most frequently the consequence of acute toxic, infectious, metabolic, or endocrine disorders, but may also result from frontal lobe lesions or postictal states (Burns et al., 2004). A common cause of delirium in forensic histories is alcohol withdrawal.

**Locked-in syndrome.** This is not truly a disorder of consciousness; rather, it is a tragic situation in which the patient is fully conscious, or at times confused, but deprived of motor output, i.e., tetraplegic and anarthric. This syndrome is usually caused by lesions of the ventral pons, such as hemorrhages, infarcts, and trauma (Smith and Delargy, 2005). The sparing of the midbrain, and of the III and IV cranial nerves, spares pupillary responses and vertical eye movements, the latter sometimes allowing the patient to establish a communicating code. A similar syndrome with
de-efferentation and preserved awareness may be seen in acute polyneuropathies, Guillain-Barré syndrome, and botulism (Smith and Delargy, 2005),(Vargas et al., 2000).

**Brain death.** This is the irreversible loss of all cerebral and brainstem function. These patients are unconscious, have no motor responses to pain, and lack brainstem reflexes and respiratory drive. Importantly, these deficits should exist in the absence of toxic, metabolic, or physiologic causes of coma (Wijdicks, 2001).

**Motor function**
The performance of motor tasks requires the integrity and coordination of many structures and neuronal circuits throughout the central and peripheral nervous system and their connections with skeletal muscles, which are beyond the scope of this chapter. Nevertheless, we present a few practical concepts that we believe will help the forensic neuropathologist to delineate clinical-pathological correlations. In very general terms, the cornerstone of voluntary movements is the corticospinal pathway, modulated by the basal ganglia and cerebellum.

**The corticospinal pathway** originates with the projection neurons of the motor cortex, also known as upper motor neurons. Axons from these nerve cells descend through the centrum semiovale, internal capsule, cerebral peduncles, basis pontis, and pyramids of the medulla (thus the name pyramidal tract). At the level of the cervicomedullary junction, the axons cross to the opposite side to travel downwards in the lateral columns of the spinal cord (lateral corticospinal tract). These axons form synapses with the lower motor neurons of the spinal cord, which provide innervation to the muscles of the extremities, respiration, trunk, and abdominal wall. Lesions of the motor cortex or of the axons of upper motor neurons above the cervicomedullary junction, where they decussate, produce a contralateral motor deficit, which could be partial (hemiparesis) or complete (hemiplegia). This paralysis is usually accompanied by spasticity, which in time may result in flexion contracture of the upper extremity and extension contracture of the lower extremity. Lesions of the corticospinal tract below the cervicomedullary junction, i.e., in the spinal cord, lead to an ipsilateral motor deficit below the level of the lesion. Unilateral cord lesions, as seen in vascular lesions or stab wounds are rather uncommon in forensic autopsies, however, we more frequently encounter bilateral cord injuries due to trauma sustained
in diving accidents, vehicular accidents, or gunshot wounds. These bilateral injuries produce devastating motor deficits. Injuries below the cervical enlargement cause paralysis of the lower extremities (paraplegia), whereas injuries that involve the cervical cord will lead to paralysis of lower and upper extremities (quadriplegia or tetraplegia). Notably, lesions at the C4 level or above will also interfere with the innervation and function of the diaphragm, thus impairing respiration.

The basal ganglia encompass the caudate and putamen nuclei (collectively known as striatum), globus pallidum, subthalamic nucleus, and substantia nigra. These nuclei, in connection with thalamic and motor cortex circuits, are critical modulators of motor function and contribute to setting muscle tone, initiation of movement, and postural reflexes. Lesions of the nigrostriatal system as seen in Parkinson’s disease are characterized clinically by resting tremor, rigidity, akinesia, gait impairment, and loss of postural reflexes. Because of the impairment of gait and stance, patients with diseases of the basal ganglia are prone to fall, and because of their poor postural reflexes, they tend to have traumatic brain lesions that are frequently larger than those suffered by normal subjects. Degeneration of the striatum, typical of Huntington’s disease, manifests as chorea.

The cerebellum and its projections are important for the coordination and accuracy of voluntary movements. Lesions of the cerebellar hemispheres, as seen in vascular lesions, abscesses, or tumors, cause ipsilateral loss of motor coordination, whereas lesions or degeneration of the vermis (midline), frequently seen in alcoholics, cause truncal instability and gait ataxia (prone to fall).

Common motor syndromes

Hemiplegia and hemiparesis
This is the unilateral paralysis or weakness of one side of the body resulting from a lesion on the opposite side of the brain. These lesions are most frequently vascular in nature, but may also be traumatic. Frequently, a hemiplegia is associated with spasticity, leading to flexion contracture of
the upper extremity and extension contracture of the lower extremity. When the brain injury occurs in a young child, atrophy of the involved limbs is common.

Tetraplegia and paraplegia.
Tetraplegia is the paralysis of the four limbs and it is usually the result of a lesion of the cervical cord. When the lesion is at or above the C4 level, where the roots of the phrenic nerve emerge, there is also paralysis of the diaphragm and impairment of respiration. Most of the cervical lesions seen at a forensic institution are traumatic in nature, the consequence of diving accidents, falls, or gunshot wounds, but they could also result from vascular lesions, stab wounds, or chiropractic manipulations.

Paraplegia is the paralysis of the lower extremities resulting from lesions of the thoracic or lumbosacral spinal cord. The most common cause of tetraplegia is trauma due to falls or vehicular accidents. Also of note, the thoracic cord is susceptible to ischemia as a result of lesions or surgery of the descending aorta. The forensic pathologist should be aware that in very exceptional circumstances, paraplegia may result not from a cord injury but from a lesion of the mesial aspect of the frontal lobes involving the motor cortices bilaterally. This situation may occur if a lesion, such as a parasagittal meningioma, involves the lower extremity representation of the motor umunculus, located in the mesial aspect of the cerebral hemisphere, but spares the representation of the upper extremity, which is in the lateral convexity of the hemisphere.

Parkinsonism
This is a syndrome that includes paucity of movements (akinesia), resting tremor, muscle rigidity, gait abnormalities such as shuffling or difficulty with initiation, and postural instability. As the name suggests, the Parkinsonian syndrome is characteristic of a specific entity known as idiopathic Parkinson’s disease, but it is also present in other neurodegenerative diseases such as progressive supranuclear palsy (PSP), multiple system atrophy (MSA), and it also could be vascular or traumatic in nature, or induced by the administration of neuroleptic drugs.

Gait and Station
Abnormalities of gait and station predispose patients to fall; thus, they are important for forensic analyses. Gait, station, and balance are subserved by the integrated activity of multiple structures of the motor and sensory systems. Among the disorders that interfere with gait and postural reflexes, we should emphasize those that involve the basal ganglia, such as idiopathic Parkinson’s disease or progressive supranuclear palsy. Sensory disorders that interfere with proprioception, such as peripheral neuropathy or lesions of the posterior columns, may also contribute to abnormal gait, poor balance, and falls. In a forensic setting, we frequently deal with the consequences of falls in the elderly and in alcoholics. In the first group, subjects are prone to fall as a result of multifactorial deficits of balance, sensory input, and vision. Alcoholics fall due to the acute effects of alcohol on the cerebellum and vestibular system, which result in poor balance and coordination.

**Vision**

The visual pathway originates in the ganglion cells of the retina which project via their axons to the lateral geniculate bodies. These axons travel first in the optic nerves, then in the optic chiasm, and finally in the optic tracts to reach the lateral geniculate bodies. The axons that originate in the nasal half of the retina decussate at the chiasm and project to the contralateral lateral geniculate body, whereas the axons originating in the temporal half of the retina do not cross at the chiasm and project to the ipsilateral geniculate body. The neurons of the lateral geniculate body send their axons via the optic radiation to the calcarine cortices in the occipital lobes. Lesions of the eye or optic nerve produce partial or complete monocular blindness. Lesions of the optic tracts, geniculate bodies, optic radiations, or calcarine cortices/occipital lobes result in partial or total contralateral visual field defects (hemianopsia). Sellar, pituitary, or hypothalamic lesions can compress the optic chiasm and cause various types of visual field defects; the most classical one is bilateral temporal hemianopsia. Arguably, the most common lesion of the visual system encountered by the forensic pathologist is the unilateral or bilateral hemorrhagic infarct of the calcarine cortex/occipital lobe secondary to compression of the posterior cerebral artery in uncal herniation.

**General References**

*Neuroanatomy*
Carpenter MB and Sutin J. Human Neuroanatomy, eight edition 1983 Williams & Wilkins, Baltimore, Maryland.

Clinical Pathological Correlations


Cited References