Section B

FUNCTIONAL SYSTEMS

INTRODUCTION

This section explains how the nervous system is organized to assess sensory input and execute motor actions. The functioning nervous system has a hierarchical organization to carry out its activities.

Incoming sensory fibers, called *afferents*, have their input into the spinal cord as well as the brainstem, except for the special senses of vision and olfaction (which will be discussed separately). This sensory input is processed by relay nuclei, including the thalamus, before the information is analyzed by the cortex. In the cortex, there are primary areas that receive the information, other cortical association areas that elaborate the sensory information, and still other areas that integrate the various sensory inputs.

On the motor side, the outgoing motor fibers, called *efferents*, originate from motor neurons in the brainstem and the spinal cord. These motor nuclei are under the control of motor centers in the brainstem and cerebral cortex. In turn, these motor areas are influenced by other cortical areas and by the basal ganglia, as well as by the cerebellum.

Simpler motor patterns are organized as reflexes. In all cases, except for the myotatic (muscle) reflex, called the stretch reflex (discussed with Figure 44), there is some processing that occurs in the CNS, involving interneurons in the spinal cord, brainstem, thalamus, or cortex.

The processing of both sensory and motor activities, beyond simple reflexes, therefore involves a series of neuronal connections, creating functional systems. These include nuclei of the CNS at the level of the spinal cord, brainstem, and thalamus. In almost all functional systems in humans, the cerebral cortex is also involved. The axonal connections between the nuclei in a functional system usually run together forming a distinct bundle of fibers, called a **tract or pathway**. These tracts are named according to the direction of the pathway, for example spino-thalamic, means that the pathway is going from the spinal cord to the thalamus; cortico-spinal means the pathway is going from the cortex to the spinal cord. Along their way, these axons may distribute information to several other parts of the CNS by means of **axon collaterals**.

In Part I of this section, we will be concerned with the sensory tracts or pathways and their connections in the CNS. Part II introduces the reticular formation, which has both sensory, motor, and other "integrative" functions. In Part III we will discuss the pathways and brain regions concerned with motor control.

PART I: SENSORY SYSTEMS

Sensory systems, also called modalities (singular **modality**), share many features. All sensory systems begin with **receptors**, sometimes free nerve endings and others that are highly specialized, such as those in the skin for touch and vibration sense, and the hair cells in the cochlea for hearing, as well as the rods and cones in the retina. These receptors activate the peripheral sensory fibers appropriate for that sensory system. The peripheral nerves have their cell bodies in **sensory ganglia**, which belong to the peripheral nervous system (**PNS**). For the body (neck down), these are the dorsal root ganglia, located in the intervertebral spaces (see Figure 1). The trigeminal ganglion inside the skull serves the sensory fibers of the head. The central process of these peripheral neurons enters the CNS and synapses in the nucleus appropriate for that sensory system (this is hard-wired).

Generally speaking, the older systems both peripherally and centrally involve axons of small diameter that are thinly myelinated or unmyelinated, with a slow rate of conduction. In general, these pathways consist of fibers-synapses-fibers, with collaterals, creating a multisynaptic chain with many opportunities for spreading the information, but thereby making transmission slow and quite insecure. The newer pathways that have evolved have larger axons that are more thickly myelinated and therefore conduct more rapidly. These form rather direct connections with few, if any, collaterals. The latter type of pathway transfers information more securely and is more specialized functionally.

Because of the upright posture of humans, the sensory systems go upward or ascend to the cortex — the **ascending systems**. The sensory information is "processed" by various nuclei along the pathway. Three systems are concerned with sensory information from the skin, two from the body region and one (with subparts) from the head:

- The **dorsal column — medial lemniscus** pathway, a newer pathway for the somatosensory sensory modalities of disriminative touch, joint position, and "vibration." **Discriminative touch** is the ability to discriminate whether the skin is being touched by one or two points simultaneously; it is usually tested by asking the patient to identify objects (e.g., a coin) placed in the hand, with the eyes closed; in fact, this act requires interpretation by the cortex. **Joint position** is tested by moving a joint and asking the patient to report the direction of the movement (again with the eyes closed). **Vibration** is tested by placing a tuning fork that has been set into motion onto a bony prominence (e.g., the wrist, the ankle). These sensory receptors in the skin and the joint surfaces are quite specialized; the fibers carrying the afferents to the CNS are large in diameter and thickly myelinated, meaning that the information is carried quickly and with a high degree of fidelity.
- The **anterolateral system**, an older system that carries pain and temperature, and some less discriminative forms of touch sensations, was formerly called the lateral spino-thalamic and ventral (anterior) spino-thalamic tracts, respectively.
- The **trigeminal pathway**, carrying sensations from the face and head area (including discriminative touch, pain, and temperature), involves both newer and older types of sensation.

Some of the special senses will be studied in detail, namely the auditory and visual systems. Each has unique features that will be described. Other sensory pathways, such as vestibular (balance) and taste also will be reviewed. All these pathways, except for olfaction, relay in the thalamus before going on to the cerebral cortex (see Figure 63); the olfactory system (smell) will be considered with the limbic system (see Figure 79).

PART II: RETICULAR FORMATION

Interspersed with the consideration of the functional systems is the reticular formation, located in the core of the brainstem. This group of nuclei comprises a rather old system with multiple functions — some generalized and some involving the sensory or the motor systems. Some sensory pathways have collaterals to the reticular formation, some do not.

The reticular formation is partially responsible for setting the level of activity of motor neurons; in addition, some motor pathways originate in the reticular formation. The explanation of the reticular formation will be presented after the sensory pathways; the motor aspects will be discussed with the motor systems.

Clinical Aspect

Destruction of the nuclei and pathways due to disease or injury leads to a neurological loss of function. How does the physician or neurologist diagnose what is wrong? He or she does so on the basis of a detailed knowledge of the pathways and their position within the central nervous system; this is a prerequisite for the part of the diagnosis that locates *where* the disease is occurring in the nervous system, i.e., **localization**. The disease that is causing the loss of function, the *etiological* diagnosis, can sometimes be recognized by experienced physicians on the basis of the pattern of the disease process; at other times, specialized investigations are needed to make the disease-specific diagnosis.

There is an additional caveat — almost all of the pathways cross the midline, each at a unique and different location; this is called a **decussation**. The important clinical correlate is that destruction of a pathway may affect the opposite side of the body, depending upon the location of the lesion in relation to the level of the decussation.

Note on Use of the CD-ROM: The pathways in this section are presented on the CD-ROM with flash animation demonstrating activation of the pathway. After studying the details of a pathway with the text and illustration, the learner should then view the same figure on the CD for a better understanding of the course of the tract, the synaptic relays, and the decussation of the fibers.

FIGURE 31
PATHWAYS AND X-SECTIONS

ORIENTATION TO DIAGRAMS

The illustrations of the sensory and motor pathways in this section of the atlas are all done in a standard manner:

- On the left side, the CNS is depicted, including spinal cord, brainstem, thalamus, and a coronal section through the hemispheres, with small diagrams of the hemisphere at the top showing the area of the cerebral cortex involved.
- On the right side, cross-sections (X-sections) of the brainstem and spinal cord, at standardized levels are depicted; the exact levels are indicated by arrows on the diagram on the left. In all, there are 10 cross-sections — 8 through the brainstem and 2 through the spinal cord. For each of the pathways, 5 of these will be used.

The diagram of the hemispheres is a coronal section, similar to the one already described in Section A, at the plane of the lenticular nucleus (see Figure 29). Note the basal ganglia, the thalamus, the internal capsule, and the ventricles; these labels will not be repeated in the following diagrams. This diagram will be used to convey the overall course of the tract and, particularly, at what level the fibers cross (i.e., decussate).

The X-sections (cross-sections) of the brainstem and the spinal cord include:

- Two levels through the midbrain — upper and lower
- Three levels through the pons — upper, mid, and lower
- Three levels through the medulla — upper, mid, and lower
- Two levels through the spinal cord — cervical and lumbar

The exact position of the tract under consideration is indicated in these cross-sections. It is important to note that only some of the levels are used in describing each of the pathways.

These brainstem and spinal cord cross-sections are the same as those shown in Section C of this atlas (see Figure 64–Figure 69). In that section, details of the histological anatomy of the spinal cord and brainstem are given. We have titled that section of the atlas Neurological Neuroanatomy because it allows precise location of the tracts, which is necessary for the localization of an injury or disease. The learner may wish to consult these detailed diagrams at this stage.

Learning Plan

Studying pathways in the central nervous system necessitates visualizing the pathways, a challenging task for many. The pathways that are under study extend longitudinally through the CNS, going from spinal cord and brainstem to thalamus and cortex for sensory (ascending) pathways, and from cortex to brainstem and spinal cord for motor (descending) pathways. As is done in other texts and atlases, diagrams are used to facilitate this visualization exercise for the learner; color adds to the ability to visualize these pathways, as does the illustration on a CD-ROM.

Clinical Aspect

This section is a foundation for the student in correlating the anatomy of the pathways with the clinical symptomatology.

Note to the Learner: In this presentation of the pathways, the learner is advised to return to the description of the thalamus and the various specific relay nuclei (see Figure 12 and Figure 63). Likewise, referring to the cortical illustrations (see Figure 13–Figure 17) will inform the learner which areas of the cerebral cortex are involved in the various sensory modalities. This will assist in integrating the anatomical information presented in the previous section.

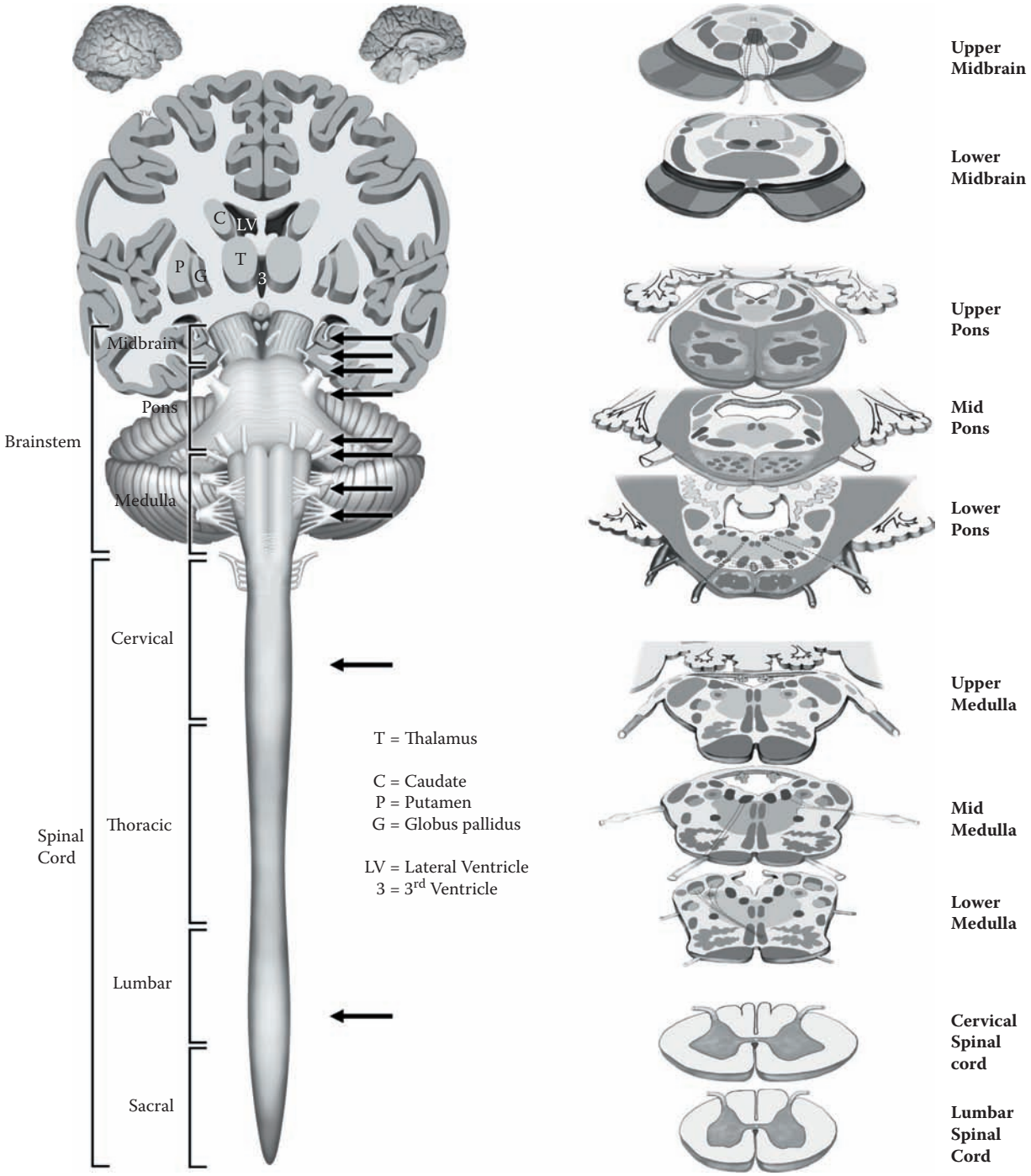


FIGURE 31: Pathways — Orientation to Diagrams

PART I: SENSORY SYSTEMS
FIGURE 32
SPINAL CORD X-SECTION

SENSORY: NUCLEI AND AFFERENTS

This is a representation of a spinal cord cross-section, at the cervical level (see Figure 4), with a focus on the sensory afferent side. All levels of the spinal cord have the same sensory organization, although the size of the nuclei will vary with the number of afferents.

UPPER FIGURE

The dorsal horn of the spinal cord has a number of nuclei related to sensory afferents, particularly pain and temperature, as well as crude touch. The first nucleus encountered is the posteromarginal, where some sensory afferents terminate. The next and most prominent nucleus is the **substantia gelatinosa**, composed of small cells, where many of the pain afferents terminate. Medial to this is the **proper sensory nucleus**, which is a relay site for these fibers; neurons in this nucleus project across the midline and give rise to a tract — the anterolateral tract (see below and Figure 34).

There is a small local tract that carries pain and temperature afferents up and down the spinal cord for a few segments, called the **dorsolateral fasciulus** (of Lissauer).

The other sensory-related nucleus is the **dorsal nucleus** (of Clarke). This is a relay nucleus for muscle afferents that project to the cerebellum. In the lower illustration, the fibers from this nucleus are seen to ascend, on the same side, as the **dorsal spino-cerebellar tract** (see Figure 55 and Figure 68).

LOWER FIGURE

This illustration shows the difference at the entry level between the two sensory pathways — the dorsal column tracts and the anterolateral system. The cell bodies for these peripheral nerves are located in the **dorsal root ganglion**, the **DRG** (see Figure 1).

On the left side, the afferent fibers carrying discriminative touch, position sense, and vibration enter the dorsal horn and immediately turn upward. The fibers may give off local collaterals (e.g., to the intermediate gray), but the information from these rapidly conducting, heavily myelinated fibers is carried upward in the two tracts that lie between the dorsal horns, called collectively the **dorsal columns**. The first synapse in this pathway occurs at the level of the lower medulla (see Figure 33).

On the right side, the afferents carrying the pathways for pain, temperature, and crude touch enter and synapse in the nuclei of the dorsal horn. The nerves conveying this sensory input into the spinal cord are thinly myelinated or unmyelinated, and conduct slowly. After several synapses, these fibers cross the midline in the white matter in front of the commissural gray matter (the gray matter joining the two sides), called the **ventral (anterior) white commissure** (see upper illustration). The fibers then ascend as the spino-thalamic tracts, called collectively the **anterolateral system** (see Figure 34).

Clinical Aspect

The effect of a lesion of one side of the spinal cord will therefore affect the two sensory systems differently because of this arrangement. The sensory modalities of the dorsal column system will be disrupted on the same side. The pain and temperature pathway, having crossed, will lead to a loss of these modalities on the opposite side.

Any lesion that disrupts just the crossing pain and temperature fibers at the segmental level will lead to a loss of pain and temperature of just the levels affected. There is an uncommon disease called **syringomyelia** that involves a pathological cystic enlargement of the central canal. The cause for this is largely unknown but sometimes can be related to a previous traumatic injury. The enlargement of the central canal interrupts the pain and temperature fibers in their crossing anteriorly in the anterior white commissure. Usually this occurs in the cervical region and the patients complain of the loss of these modalities in the upper limbs and hand, in what is called a cape-like distribution. The enlargement can be visualized with MRI.

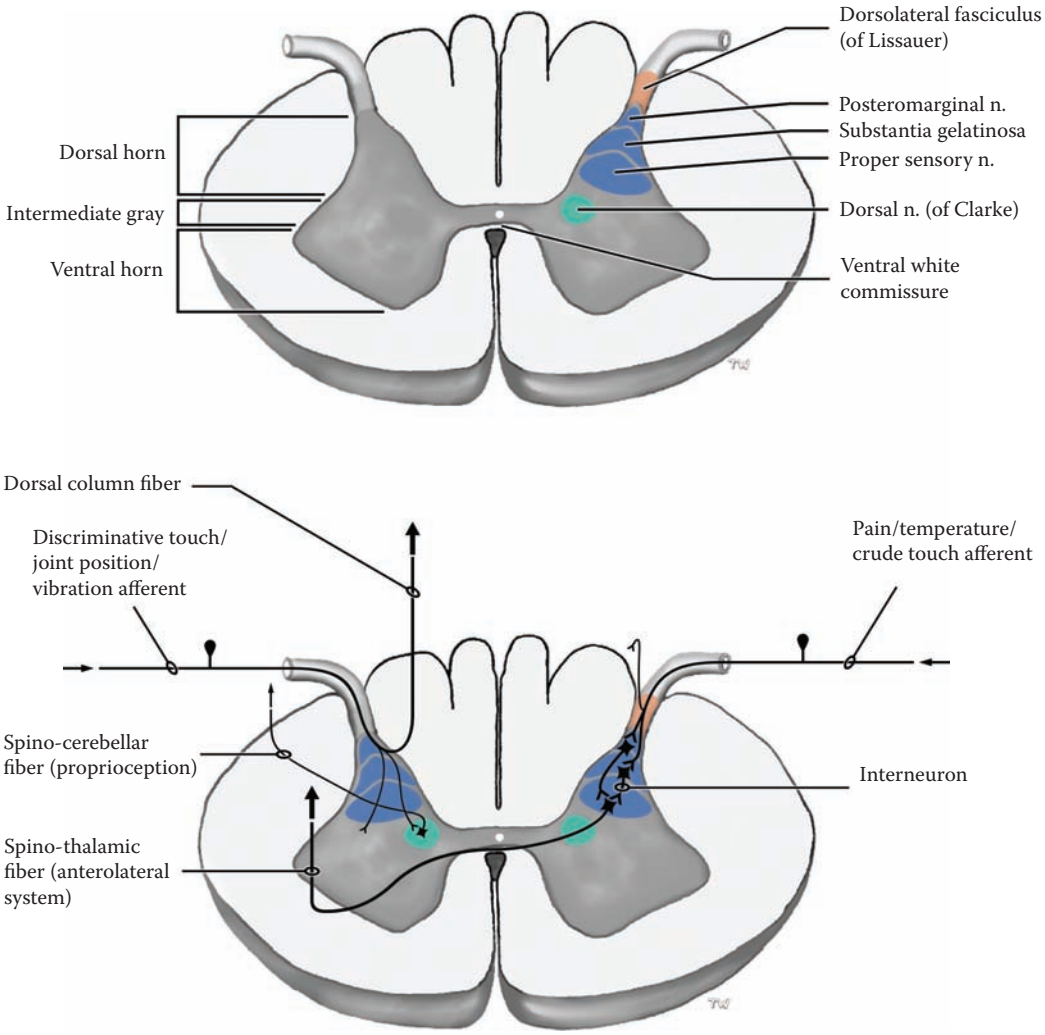


FIGURE 32: Spinal Cord Nuclei — Sensory

FIGURE 33
DORSAL COLUMN — MEDIAL LEMNISCUS PATHWAY

DISCRIMINATIVE TOUCH, JOINT POSITION, VIBRATION

This pathway carries the modalities **discriminative touch**, **joint position**, and the somewhat artificial "sense" of **vibration** from the body. Receptors for these modalities are generally specialized endings in the skin and joint capsule.

The axons enter the spinal cord and turn upward, with no synapse (see Figure 32). Those fibers entering below spinal cord level T6 (sixth thoracic spinal segmental level) form the **fasciculus gracilis**, the gracile tract; those entering above T6, particularly those from the upper limb, form the **fasciculus cuneatus**, the cuneate tract, which is situated more laterally. These tracts ascend the spinal cord between the two dorsal horns, forming the **dorsal column** (see Figure 32, Figure 68, and Figure 69).

The first synapse in this pathway is found in two nuclei located in the lowermost part of the medulla, in the **nuclei gracilis and cuneatus** (see Figure 9B, Figure 40, and Figure 67C). Topographical representation, also called **somatotopic** organization, is maintained in these nuclei, meaning that there are distinct populations of neurons that are activated by areas of the periphery that were stimulated.

After neurophysiological processing, axons emanate from these two nuclei, which will cross the midline. This stream of fibers, called the **internal arcuate fibers,** can be recognized in suitably stained sections of the lower medulla, (see Figure 40 and Figure 67C). The fibers then group together to form the **medial lemniscus,** which ascends through the brainstem. This pathway does not give off collaterals to the reticular formation in the brainstem. This pathway changes orientation and position as it ascends through the pons and midbrain (see Figure 40 and Figure 65–Figure 67).

The medial lemniscus terminates (i.e., synapses) in the **ventral posterolateral nucleus** of the thalamus, the **VPL** (see Figure 12 and Figure 63). The fibers then enter the internal capsule, its posterior limb, and travel to the somatosensory cortex, terminating along the **post-central gyrus**, **areas 1, 2, and 3** (see Figure 14A and Figure 63). The representation of the body on this gyrus is not proportional to the size of the area being represented; for example, the fingers, particularly the thumb, are given a much larger area of cortical representation than the trunk; this is called the **sensory "homunculus."** The lower limb, represented on the medial aspect of the hemisphere (see Figure 17), has little cortical representation.

Neurological Neuroanatomy

The cross-sectional levels for this pathway include the lumbar and cervical spinal cord levels, and the brainstem levels, lower medulla, mid-pons, and upper midbrain.

In the spinal cord, the pathways are found between the two dorsal horns, as a well myelinated bundle of fibers, called the dorsal column(s). The tracts have a topographical organization, with the lower body and lower limb represented in the medially placed gracile tract, and the upper body and upper limb in the laterally placed cuneate tract. After synapsing in their respective nuclei and the crossing of the fibers in the lower medulla (internal arcuate fibers), the medial lemniscus tract is formed. This heavily myelinated tract that is easily seen in myelin-stained sections of the brainstem (e.g., see Figure 67C), is located initially between the inferior olivary nuclei and is oriented in the dorsal-ventral position (see Figure 40 and Figure 67B). The tract moves more posteriorly, shifts laterally, and also changes orientation as it ascends (see Figure 40; also Figure 65A, Figure 66A, and Figure 67A). The fibers are topographically organized, with the leg represented laterally and the upper limb medially. The medial lemniscus is joined by the anterolateral system and trigeminal pathway in the upper pons (see Figure 36 and Figure 40).

Clinical Aspect

Lesions involving this tract will result in the loss of the sensory modalities carried in this pathway. A lesion of the dorsal column in the spinal cord will cause a loss on the same side; after the crossing in the lower brainstem, any lesion of the medial lemniscus will result in the deficit occurring on the opposite side of the body. Lesions occurring in the midbrain and internal capsule will usually involve the fibers of the anterolateral pathway, as well as the modalities carried in the trigeminal pathway (to be discussed with Figure 36 and Figure 40). With cortical lesions, the part of the body affected will be determined by the area of the post-central gyrus involved.

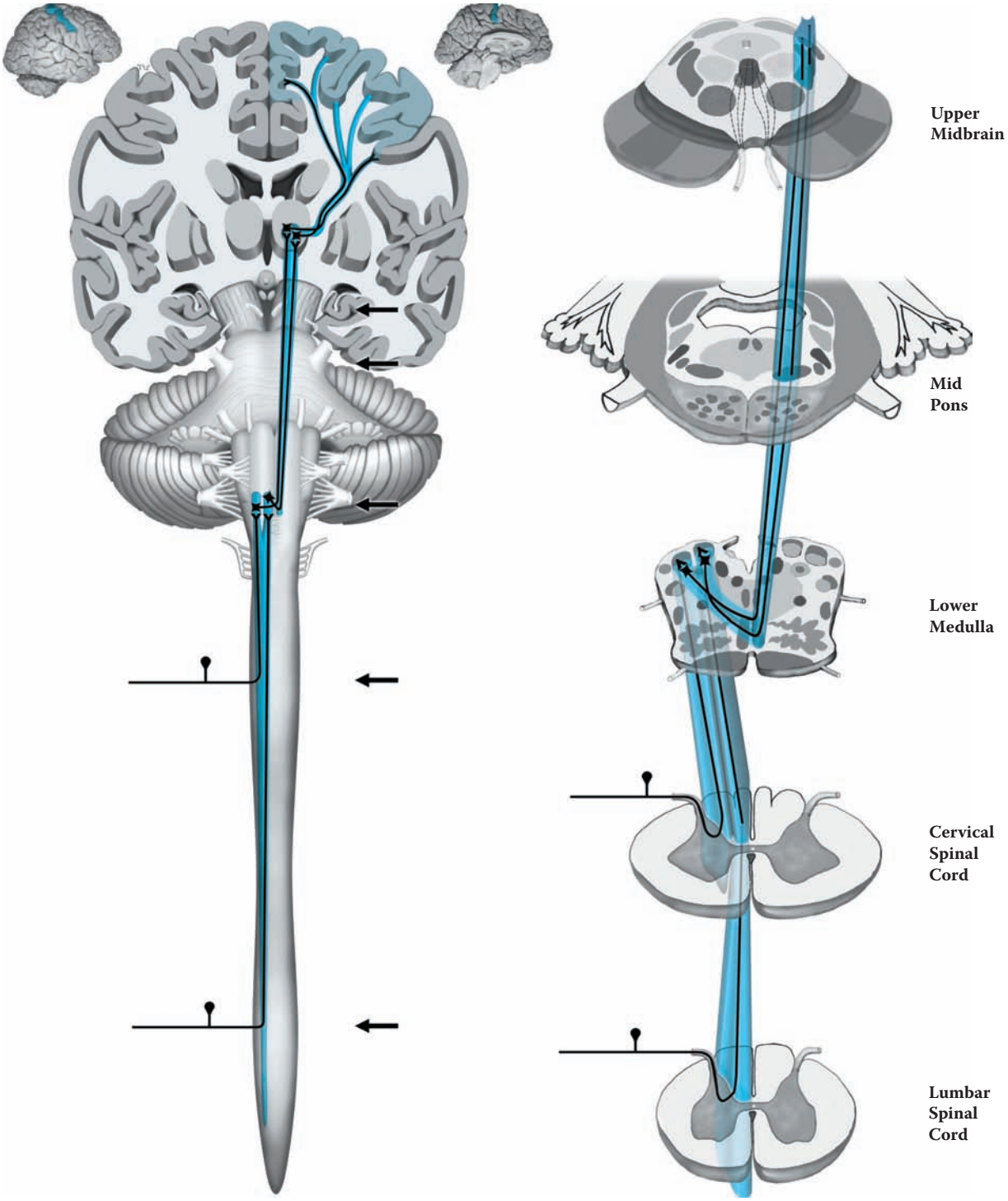


FIGURE 33: Dorsal Column — Medial Lemniscus — Discriminative Touch, Joint Position, and Vibration

FIGURE 34
ANTEROLATERAL SYSTEM

PAIN, TEMPERATURE, CRUDE TOUCH

This pathway carries the modalities of **pain and temperature** and a form of touch sensation called **crude or light touch**. The sensations of itch and tickle, and other forms of sensation (e.g., "sexual") are likely carried in this system. In the periphery the receptors are usually simply free nerve endings, without any specialization.

These incoming fibers (sometimes called the first order neuron) enter the spinal cord and synapse in the dorsal horn (see Figure 4 and Figure 32). There are many collaterals within the spinal cord that are the basis of several protective reflexes (see Figure 44). The number of synapses formed is variable, but eventually a neuron is reached that will project its axon up the spinal cord (sometimes referred to as the second order neuron). This axon will cross the midline, decussate, in the **ventral** (anterior) **white commissure**, usually within two to three segments above the level of entry of the peripheral fibers (see Figure 4 and Figure 32).

These axons now form the **anterolateral** tract, located in that portion of the white matter of the spinal cord. It was traditional to speak of two pathways — one for pain and temperature, the **lateral spino-thalamic tract**, and another for light (crude) touch, the **anterior (ventral) spino-thalamic tract**. Both are now considered together under one name.

The tract ascends in the same position through the spinal cord (see Figure 68 and Figure 69). As fibers are added from the upper regions of the body, they are positioned medially, pushing the fibers from the lower body more laterally. Thus, there is a topographic organization to this pathway in the spinal cord. The axons of this pathway are either unmyelinated or thinly myelinated. In the brainstem, collaterals are given off to the reticular formation, which are thought to be quite significant functionally. Some of the ascending fibers terminate in the **ventral posterolateral (VPL) nucleus** of the thalamus (sometimes referred to as the third order neuron in a sensory pathway), and some in the nonspecific intralaminar nuclei (see Figure 12 and Figure 63).

There is a general consensus that pain sensation has two functional components. The older (also called the **paleospinothalamic**) pathway involves the reported sensation of an ache, or diffuse pain that is poorly localized. The fibers underlying this pain system are likely unmyelinated both peripherally and centrally, and the central connections are probably very diffuse; most likely these fibers terminate in the nonspecific thalamic nuclei and influence the cortex widely. The newer pathway, sometimes called the **neospinothalamic** system, involves thinly myelinated fibers in the PNS and CNS, and likely ascends to the VPL nucleus of the thalamus and from there is relayed to the postcentral (sensory) gyrus. Therefore, the sensory information in this pathway can be well localized. The common example for these different pathways is a paper cut — immediately one knows exactly where the cut has occurred; this is followed several seconds later by a diffuse poorly localized aching sensation.

Neurological Neuroanatomy

The cross-sectional levels for this pathway include the lumbar and cervical spinal cord levels, and the brainstem levels mid-medulla, mid-pons, and upper midbrain.

In the spinal cord, this pathway is found among the various pathways in the anterolateral region of the white matter (see Figure 32, Figure 68, and Figure 69), hence its name. Its two parts cannot be distinguished from each other or from the other pathways in that region. In the brainstem, the tract is small and cannot usually be seen as a distinct bundle of fibers. In the medulla, it is situated dorsal to the inferior olivary nucleus; in the uppermost pons and certainly in the midbrain, the fibers join the medial lemniscus (see Figure 40).

Clinical Aspect

Lesions of the anterolateral pathway from the point of crossing in the spinal cord upward will result in a loss of the modalities of pain and temperature and crude touch on the opposite side of the body. The exact level of the lesion can be quite accurately ascertained, as the sensation of pain can be quite simply tested at the bedside by using the end of a pin. (The tester should be aware that this is quite uncomfortable or unpleasant for the patient being tested.)

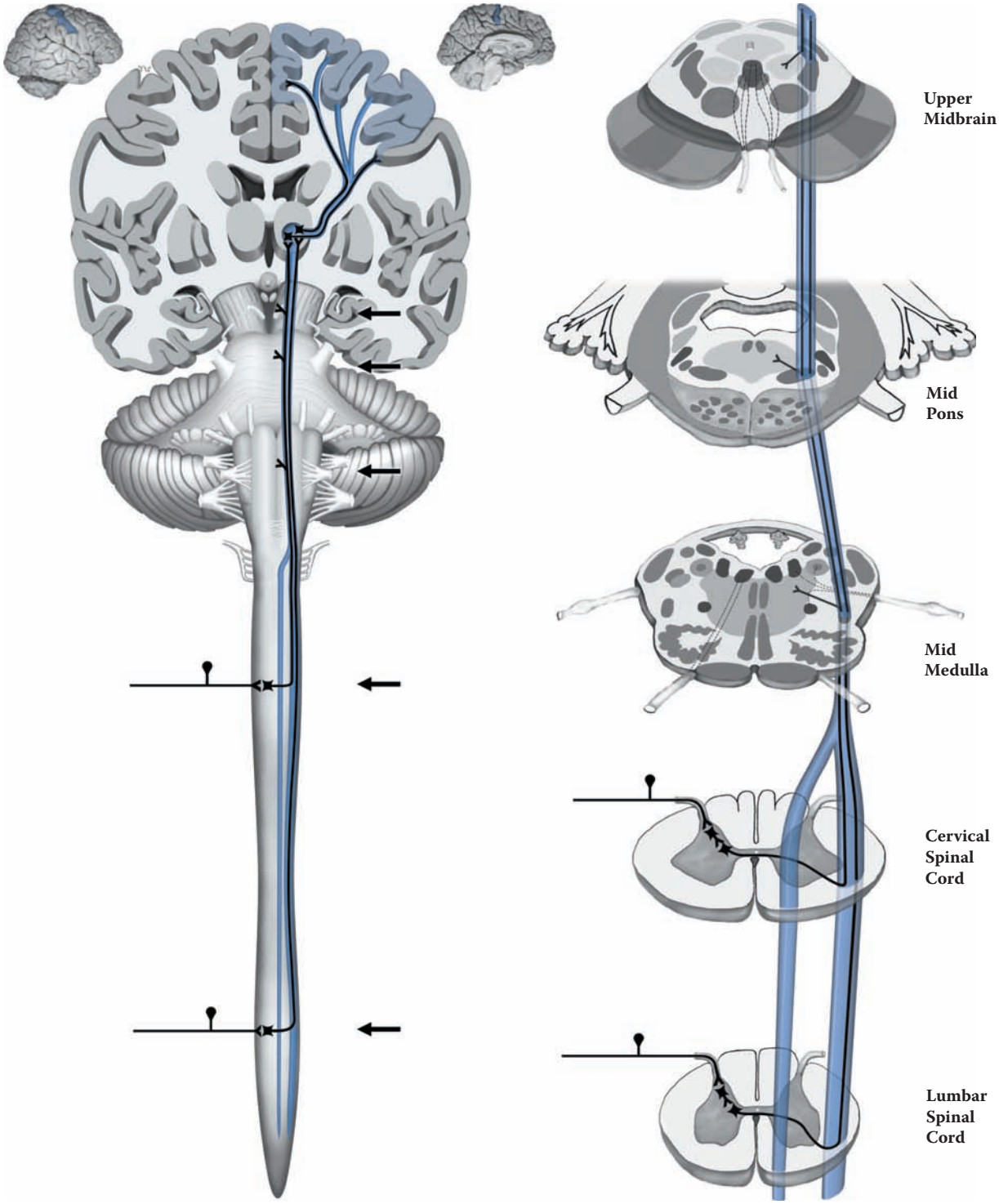


FIGURE 34: Anterolateral System — Pain, Temperature, and Crude Touch

FIGURE 35
TRIGEMINAL PATHWAYS

DISCRIMINATIVE TOUCH, PAIN, TEMPERATURE

The sensory fibers include the modalities discriminative touch as well as pain and temperature. The sensory input comes from the face, particularly from the lips, all the mucous membranes inside the mouth, the conjunctiva of the eye, and the teeth. The fiber sizes and degree of myelination are similar to the sensory inputs below the neck. The cell bodies of these fibers are found in the trigeminal ganglion inside the skull.

The fibers enter the brainstem along the middle cerebellar peduncle (see Figure 6 and Figure 7). Within the CNS there is a differential handling of the modalities, comparable to the previously described pathways in the spinal cord.

Those fibers carrying the sensations of discriminative touch will synapse in the **principal (main) nucleus** of CN V, in the mid-pons, at the level of entry of the nerve (see Figure 8B and Figure 66B). The fibers then cross the midline and join the medial lemniscus, terminating in the **ventral posteromedial** (**VPM**) **nucleus** of the thalamus (see Figure 12 and Figure 63). They are then relayed via the posterior limb of the internal capsule to the postcentral gyrus, where the face area is represented on the dorsolateral surface (see Figure 14A); the lips and tongue are very well represented on the sensory homunculus.

Those fibers carrying the modalities of pain and temperature descend within the brainstem. They form a tract that starts at the mid-pontine level, descends through the medulla, and reaches the upper level of the spinal cord (see Figure 8B) called the **descending or spinal tract of V**, also called the **spinal trigeminal tract**. Immediately medial to this tract is a nucleus with the same name. The fibers terminate in this nucleus and, after synapsing, cross to the other side and ascend (see Figure 40). Therefore, these fibers decussate over a wide region and do not form a compact bundle of crossing fibers; they also send collaterals to the reticular formation. These trigeminal fibers join with those carrying touch, forming the **trigeminal pathway** in the mid-pons. They terminate in the VPM and other thalamic nuclei, similar to those of the anterolateral system (see Figure 34; also Figure 12 and Figure 63). The trigeminal pathway joins the medial lemniscus in the upper pons, as does the anterolateral pathway (see Figure 36 and Figure 40).

Neurological Neuroanatomy

The cross-sectional levels for this pathway include the three medullary levels of the brainstem, the mid-pons, and the lower midbrain.

The principal nucleus of CN V is seen at the mid-pontine level (see also Figure 66B). The descending trigeminal tract is found in the lateral aspect of the medulla, with the nucleus situated immediately medially (see Figure 67A and Figure 67B). The crossing pain and temperature fibers join the medial lemniscus over a wide area and are thought to have completely crossed by the lower pontine region (see Figure 66A). The collaterals of these fibers to the reticular formation are shown.

Clinical Aspect

Trigeminal neuralgia is an affliction of the trigeminal nerve of uncertain origin which causes severe "lightning" pain in one of the branches of CN V; often there is a trigger such as moving the jaw, or an area of skin. The shooting pains may occur in paroxysms lasting several minutes. An older name for this affliction is tic douloureux. Treatment of these cases, which cause enormous pain and suffering, is difficult, and used to involve the possibility of surgery involving the trigeminal ganglion inside the skull, an extremely difficult if not risky treatment; nowadays most cases can be managed with medical therapy.

A vascular lesion in the lateral medulla will disrupt the descending pain and temperature fibers and result in a loss of these sensations on the same side of the face, while leaving the fibers for discriminative touch sensation from the face intact. This lesion, known as the lateral medullary syndrome (of Wallenberg), includes other deficits (see Figure 40 and discussed with Figure 67B). A lesion of the medial lemniscus above the mid-pontine level will involve all trigeminal sensations on the opposite side. Internal capsule and cortical lesions cause a loss of trigeminal sensations from the opposite side, as well as involving other pathways.

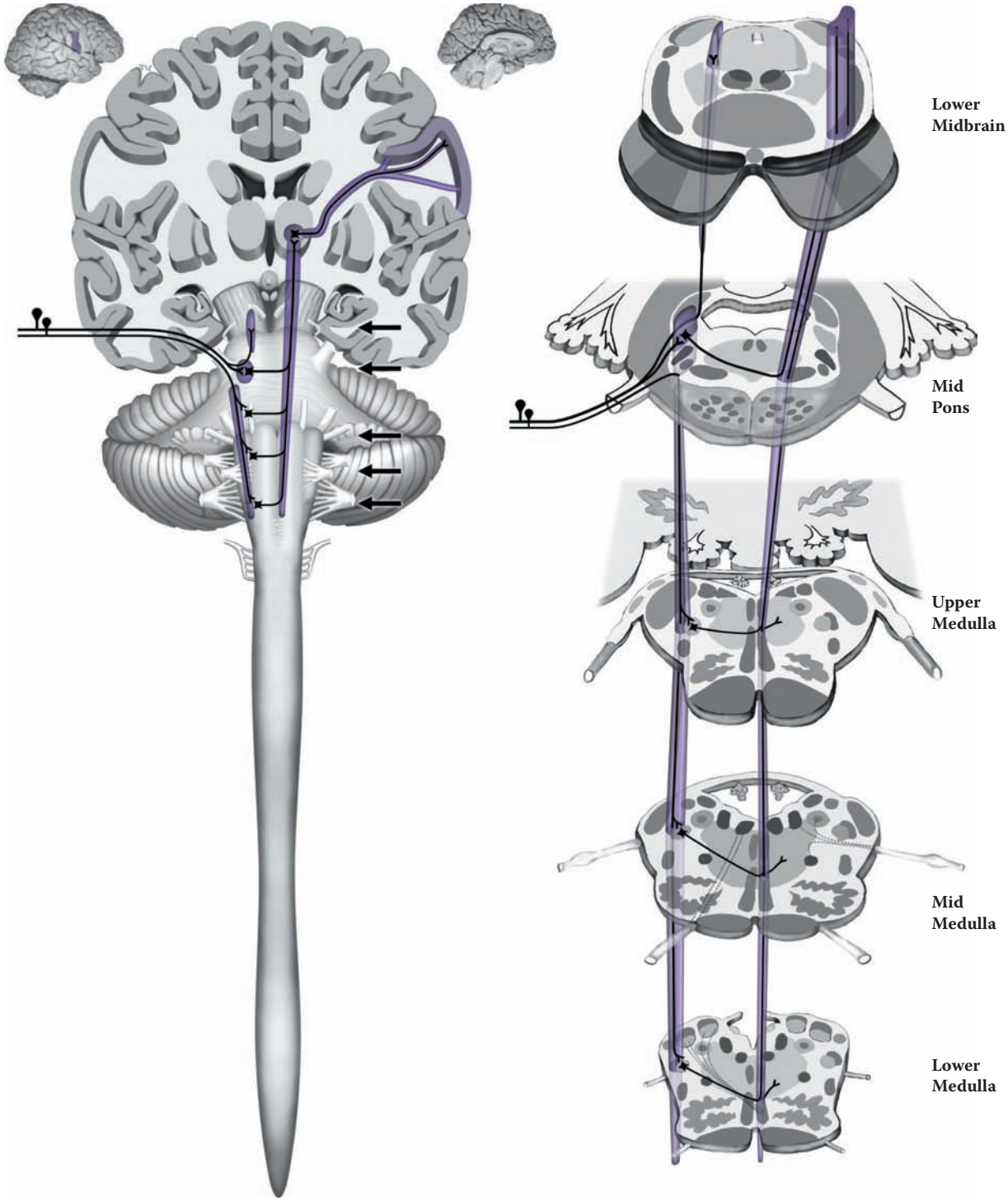


FIGURE 35: Trigeminal Pathways — Discriminative Touch, Pain, and Temperature

FIGURE 36
SENSORY SYSTEMS

SOMATOSENSORY AND TRIGEMINAL PATHWAYS

This diagram presents all the somatosensory pathways, the dorsal column-medial lemniscus, the anterolateral, and the trigeminal pathway as they pass through the midbrain region into the thalamus and onto the cortex. The view is a dorsal perspective (as in Figure 10 and Figure 40).

The pathway that carries discriminative touch sensation and information about joint position (as well as vibration) from the body is the medial lemniscus (see Figure 33). The equivalent pathway for the face comes from the principal nucleus of the trigeminal, which is located at the mid-pontine level (see Figure 8B and Figure 35). The anterolateral pathway conveying pain and temperature from the body has joined up with the medial lemniscus by this level (see Figure 34). The trigeminal pain and temperature fibers have likewise joined up with the other trigeminal fibers (see Figure 35).

The various sensory pathways are all grouped together at the level of the midbrain (see cross-section). At the level of the lower midbrain, these pathways are located near to the surface, dorsal to the substantia nigra; as they ascend they are found deeper within the midbrain, dorsal to the red nucleus (shown in cross-section in Figure 65A and Figure 65B).

The two pathways carrying the modalities of fine touch and position sense (and vibration) terminate in different specific relay nuclei of the thalamus (see Figure 12 and Figure 63):

- The medial lemniscus in the VPL, ventral posterolateral nucleus
- The trigeminal pathway in the VPM, ventral posteromedial nucleus

Sensory modality and topographic information is retained in these nuclei. There is physiologic processing of the sensory information, and some type of sensory "perception" likely occurs at the thalamic level.

After the synaptic relay, the pathways continue as the (superior) thalamo-cortical radiation through the **posterior limb** of the **internal capsule**, between the thalamus and lenticular nucleus (see Figure 26, Figure 27, Figure 28A, and Figure 28B). The fibers are then found within the white matter of the hemispheres. The somatosensory information is distributed to the cortex along the **postcentral gyrus** (see the small diagrams of the brain above the main illustration of Figure 36), also called **S1**. Precise localization and two-point discrimination are cortical functions.

The information from the face and hand is topographically located on the dorsolateral aspect of the hemispheres (see Figure 13 and Figure 14A). The information from the lower limb is localized along the continuation of this gyrus on the medial aspect of the hemispheres (see Figure 17). This cortical representation is called the sensory **"homunculus**," a distorted representation of the body and face with the trunk and lower limbs having very little area, whereas the face and fingers receive considerable representation.

Further elaboration of the sensory information occurs in the **parietal association** areas adjacent to the postcentral gyrus (see Figure 14A and Figure 60). This allows us to learn to recognize objects by tactile sensations (e.g., coins in the hand).

The pathways carrying pain and temperature from the body (the anterolateral system) and the face (spinal trigeminal system) terminate in part in the specific relay nuclei, ventral posterolateral and ventral posteromedial (VPL and VPM), respectively, but mainly in the intralaminar nuclei. These latter terminations may be involved with the emotional correlates that accompany many sensory experiences (e.g., pleasant or unpleasant).

The fibers that have relayed pain information project from these nuclei to several cortical areas, including the post-central gyrus, SI, and area **SII** (a secondary sensory area), which is located in the lower portion of the parietal lobe, as well as other cortical regions. The output from the intralaminar nuclei of the thalamus goes to widespread cortical areas.

Clinical Aspect

Lesions of the thalamus may sometimes give rise to pain syndromes (also discussed with Figure 63).

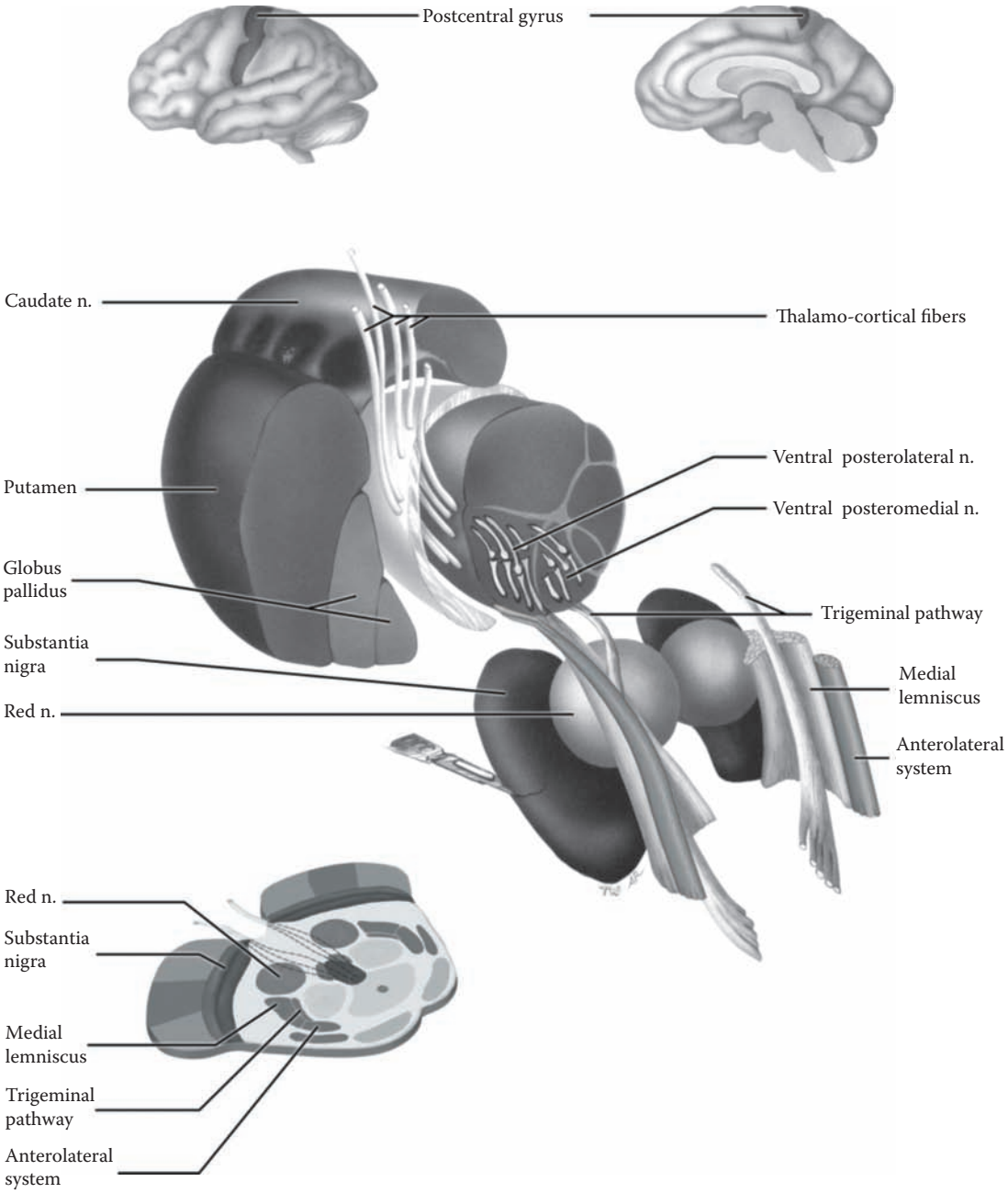


FIGURE 36: Somatosensory and Trigeminal Pathways

FIGURE 37
AUDITION 1

AUDITORY PATHWAY 1

The auditory pathway is somewhat more complex, firstly because it is bilateral, and secondly, because there are more synaptic stations (nuclei) along the way, with numerous connections across the midline. It also has a unique feature — a feedback pathway from the CNS to cells in the receptor organ, the cochlea.

The specialized hair cells in the cochlea respond maximally to certain frequencies (pitch) in a tonotopic manner; tones of a certain pitch cause patches of hair cells to respond maximally, and the distribution of this response is continuous along the cochlea. The peripheral ganglion for these sensory fibers is the **spiral ganglion**. The central fibers from the ganglion project to the first brainstem nuclei, the dorsal and ventral **cochlear nuclei**, at the level of entry of the VIIIth nerve at the uppermedullary level (see Figure 8B, Figure 40, and Figure 67A).

After this, the pathway can follow a number of different routes. In an attempt to make some semblance of order, these will be discussed in sequence, even though an axon may or may not synapse in each of these nuclei.

Most of the fibers leaving the cochlear nuclei will synapse in the **superior olivary complex**, either on the same side or on the opposite side. Crossing fibers are found in a structure known as the **trapezoid body**, a compact bundle of fibers that crosses the midline in the lower pontine region (see Figure 40 and Figure 67C). The main function of the superior olivary complex is sound localization; this is based on the fact that an incoming sound will not reach the two ears at the exact same moment.

Fibers from the superior olivary complex either ascend on the same side or cross (in the trapezoid body) and ascend on the other side. They form a tract, the **lateral lemniscus**, which begins just above the level of these nuclei (see Figure 40). The lateral lemniscus carries the auditory information upward through the pons (see Figure 66B) to the inferior colliculus of the midbrain. There are nuclei scattered along the way, and some fibers may terminate or relay in these nuclei; the lateral lemnisci are interconnected across the midline (not shown).

Almost all the axons of the lateral lemniscus terminate in the **inferior colliculus** (see Figure 9A and Figure 65B). The continuation of this pathway to the medial geniculate nucleus of the thalamus is discussed in the following illustration.

In summary, audition is a complex pathway, with numerous opportunities for synapses. Even though named a "lemniscus," it does not transmit information in the efficient manner seen with the medial lemniscus. It is important to note that although the pathway is predominantly a crossed system, there is also a significant ipsilateral component. There are also numerous interconnections between the two sides.

The auditory pathway has a feedback system, from the higher levels to lower levels (e.g., from the inferior colliculus to the superior olivary complex). The final link in this feedback is somewhat unique in the mammalian CNS, for it influences the cells in the receptor organ itself. This pathway, known as the **olivo-cochlear bundle**, has its cells of origin in the vicinity of the superior olivary complex. It has both a crossed and an uncrossed component. Its axons reach the hair cells of the cochlea by traveling in the VIIIth nerve. This system changes the responsiveness of the peripheral hair cells.

Neurological Neuroanatomy

The auditory system is shown at various levels of the brainstem, including the upper medulla, all three pontine levels, and the lower midbrain (inferior collicular) level.

The cochlear nuclei are the first CNS synaptic relays for the auditory fibers from the peripheral spiral ganglion; these nuclei are found along the incoming VIIIth nerve at the level of the upper medulla (see Figure 67A). The superior olivary complex, consisting of several nuclei, is located at the lower pontine level (see Figure 66C), along with the trapezoid body, containing the crossing auditory fibers. By the mid-pons (see Figure 66B), the lateral lemniscus can be recognized. These fibers move toward the outer margin of the upper pons and terminate in the inferior colliculus (see Figure 65B).

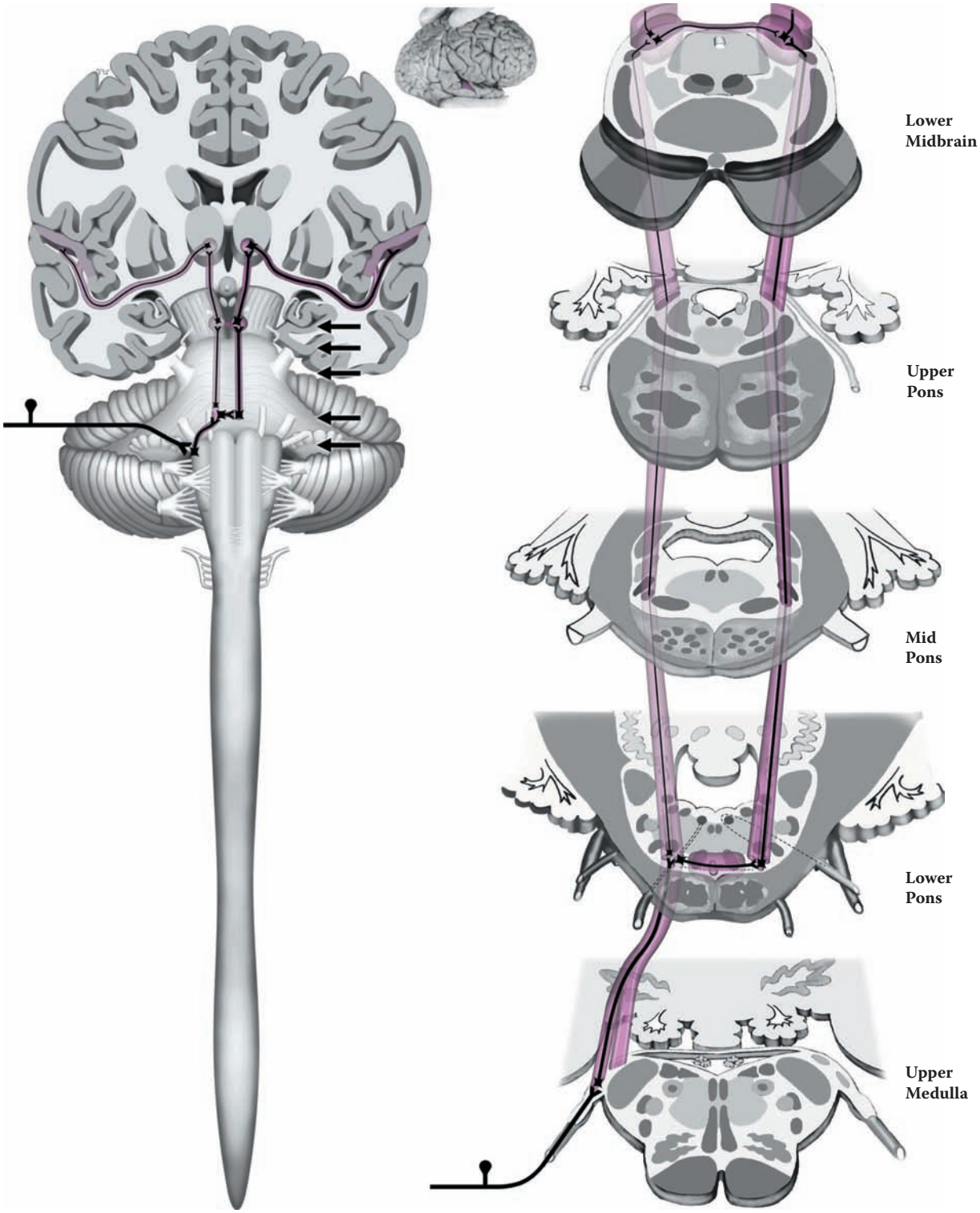


FIGURE 37: **Auditory System 1** — Auditory Pathway 1

FIGURE 38
AUDITION 2

AUDITORY PATHWAY 2

This illustration shows the projection of the auditory system fibers from the level of the inferior colliculus, the lower midbrain, to the thalamus and then to the cortex.

Auditory information is carried via the lateral lemniscus to the inferior colliculus (see Figure 37 and Figure 40), after several synaptic relays. There is another synapse in this nucleus, making the auditory pathway overall somewhat different and more complex than the medial lemniscal and different than the visual pathways (see Figure 41A, Figure 41B, and Figure 41C). The inferior colliculi are connected to each other by a small commissure (not labeled).

The auditory information is next projected to a specific relay nucleus of the thalamus, the **medial geniculate** (nucleus) body (**MGB**, see Figure 12 and Figure 63). The tract that connects the two, the **brachium** of the inferior colliculus, can be seen on the dorsal aspect of the midbrain (see Figure 10; see also Figure 9A, not labeled); this is shown diagrammatically in the present figure.

From the medial geniculate nucleus the auditory pathway continues to the cortex. This projection, which courses beneath the lenticular (lentiform) nucleus of the basal ganglia (see Figure 22), is called the **sublenticular** pathway, the **inferior limb** of the internal capsule, or simply the **auditory radiation**. The cortical areas involved with receiving this information are the **transverse gyri of Heschl**, situated on the superior temporal gyrus, within the lateral fissure. The location of these gyri is shown in the inset as the primary auditory areas (also seen in a photographic view in the next illustration).

The medial geniculate nucleus is likely involved with some analysis and integration of the auditory information. More exact analysis occurs in the cortex. Further elaboration of auditory information is carried out in the adjacent cortical areas. On the dominant side for language, these cortical areas are adjacent to Wernicke's language area (see Figure 14A).

Sound frequency, known as **tonotopic** organization, is maintained all along the auditory pathway, starting in the cochlea. This can be depicted as a musical scale with high and low notes. The auditory system localizes the direction of a sound in the superior olivary complex (discussed with the previous illustration); this is done by analyzing the difference in the timing that sounds reach each ear and by the difference in sound intensity reaching each ear. The loudness of a sound would be represented physiologically by the number of receptors stimulated and by the frequency of impulses, as in other sensory modalities.

Neurological Neuroanatomy

This view of the brain includes the midbrain level and the thalamus, with the lentiform nucleus lateral to it. The lateral ventricle is open (cut through its body) and the thalamus is seen to form the floor of the ventricle; the body of the caudate nucleus lies above the thalamus and on the lateral aspect of the ventricle.

The auditory fibers leave the inferior colliculus and course via the brachium of the inferior colliculus to the medial geniculate nucleus of the thalamus. From here the auditory radiation courses below the lentiform nucleus to the auditory gyri on the superior surface of the temporal lobe within the lateral fissure. The gyri are shown in the diagram above and in the next illustration.

This diagram also includes the lateral geniculate body (nucleus) which subserves the visual system and its projection, the optic radiation (to be discussed with Figure 41A and Figure 41B).

Additional Detail

The temporal lobe structures are also shown, including the inferior horn of the lateral ventricle, the hippocampus proper, and adjoining structures relevant to the limbic system (Section D).

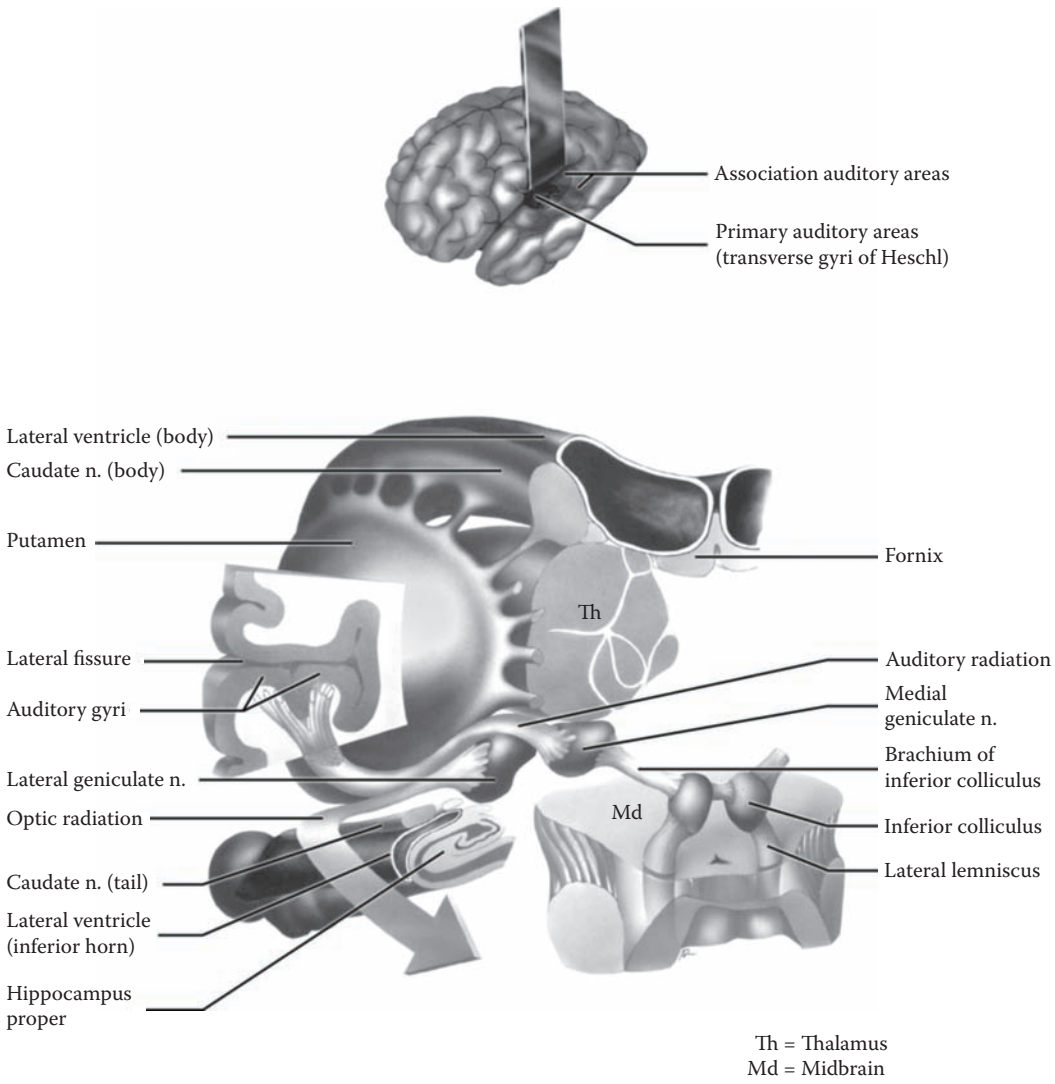


FIGURE 38: **Auditory System 2** — Auditory Pathway 2

FIGURE 39
AUDITION 3

AUDITORY GYRI (PHOTOGRAPHIC VIEW)

This photographic view of the left hemisphere is shown from the lateral perspective (see Figure 14A). The lateral fissure has been opened, and this exposes two gyri, which are oriented transversely. These gyri are the areas of the cortex that receive the incoming auditory sensory information first. They are named the **transverse gyri of Heschl** (as was also shown in the previous illustration), the auditory gyri, areas 41 and 42 (see Figure 60).

The lateral fissure forms a complete separation between this part of the temporal lobe and the frontal and parietal lobes above. Looked at descriptively, the auditory gyri occupy the superior aspect of the temporal lobe, within the lateral fissure.

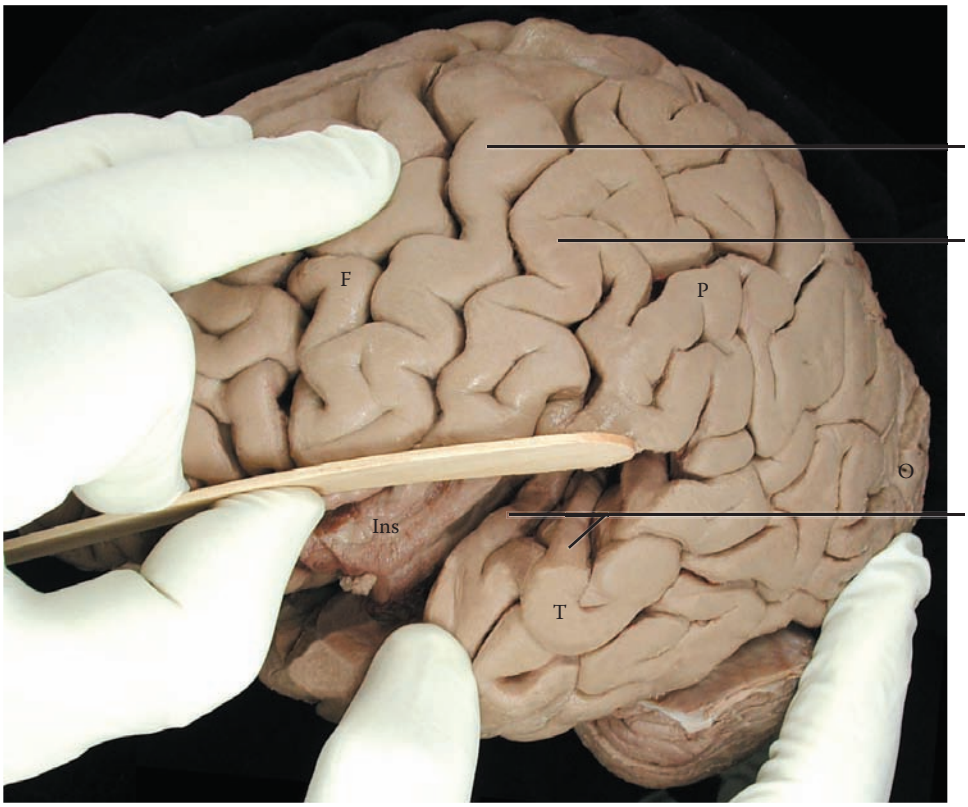
Cortical representation of sensory systems reflects the particular sensation (modality). The auditory gyri are organized according to pitch, giving rise to the term **tonotopic** localization. This is similar to the representation of the somatosensory system on the postcentral gyrus (somatotopic localization; the sensory "homunculus").

Further opening of the lateral fissure reveals some cortical tissue that is normally completely hidden from view. This area is the **insula** or insular cortex (see Figure 14B). The insula typically has five short gyri, and these are seen in the depth of the lateral fissure. It is important not to confuse the two areas, auditory gyri and insula. The position of the insula in the depth of the lateral fissure is also shown in a dissection of white matter bundles (see Figure 19B) and in the coronal slice of the brain (see Figure 29).

It should be noted that the lateral fissure has within it a large number of blood vessels, branches of the middle cerebral artery, which have been removed (see Figure 58). These branches emerge and then become distributed to the cortical tissue of the dorsolateral surface, including the frontal, temporal, parietal, and occipital cortex (discussed with Figure 58 and Figure 60). Other small branches to the internal capsule and basal ganglia are given off within the lateral fissure (discussed with Figure 62).

Clinical Aspect

Since the auditory system has a bilateral pathway to the cortex, a lesion of the auditory pathway or cortex on one side will not lead to a total loss of hearing (deafness) of the opposite ear. Nonetheless, the pathway still has a strong crossed aspect; speech is directed to the dominant hemisphere.



F = Frontal lobe
P = Parietal lobe
T = Temporal lobe
O = Occipital lobe

Ins = Insula

FIGURE 39: **Auditory System 3** — Auditory Gyri (photograph)

FIGURE 40
SENSORY SYSTEMS

SENSORY NUCLEI AND ASCENDING TRACTS

This diagrammatic presentation of the internal structures of the brainstem is shown from the dorsal perspective (as in Figure 10 and Figure 36). The information concerning the various structures will be presented in an abbreviated manner, as most of the major points have been reviewed previously. The orientation of the cervical spinal cord representation should be noted.

The major sensory systems include:

- Dorsal column-medial lemniscus (discriminative touch, joint position, and vibration) and its nuclei
- Anterolateral system (pain and temperature)
- Trigeminal system and its nuclei (discriminative touch, pain, and temperature)
- Lateral lemniscus (audition), with its nuclei

The Dorsal Column-Medial Lemniscus

The dorsal columns (gracile and cuneate tracts) of the spinal cord terminate (synapse) in the nuclei gracilis and cuneatus in the lowermost medulla (see Figure 9B). Axons from these nuclei then cross the midline (decussate) as the internal arcuate fibers (see Figure 67C), forming a new bundle called the medial lemniscus. These fibers ascend through the medulla, change orientation in the pons, and move laterally, occupying a lateral position in the midbrain.

The Anterolateral System

This tract, having already crossed in the spinal cord, ascends and continues through the brainstem. In the medulla it is situated posterior to the inferior olive. At the upper pontine level, this tract becomes associated with the medial lemniscus, and the two lie adjacent to each other in the midbrain region.

The Trigeminal Pathway

The sensory afferents for discriminative touch synapse in the principal nucleus of V; the fibers then cross at the level of the mid-pons and form a tract that joins the medial lemniscus. The pain and temperature fibers descend and form the descending trigeminal tract through the medulla with the nucleus adjacent to it. These fibers synapse and cross, over a wide area of the medulla, eventually joining the other trigeminal tract. The two tracts form the trigeminal pathway, which joins with the medial lemniscus in the uppermost pons (see Figure 36).

The Lateral Lemniscus

The auditory fibers (of CN VIII) enter the brainstem at the uppermost portion of the medulla. After the initial synapse in the cochlear nuclei, many of the fibers cross the midline, forming the trapezoid body. Some of the fibers synapse in the superior olivary complex. From this point, the tract known as the lateral lemniscus is formed. The fibers relay in the inferior colliculus.

Clinical Aspect

This diagram allows the visualization of all the pathways together, which assists in understanding lesions of the brainstem. The cranial nerve nuclei affected help locate the level of the lesion.

One of the classic lesions of the brainstem is an infarct of the lateral medulla (see Figure 67B), known as the Wallenberg syndrome. (The blood supply of the brainstem is reviewed with Figure 58.) This lesion affects the pathways and cranial nerve nuclei located in the lateral area of the medulla, including the anterolateral tract and the lateral lemniscus, but not the medial lemniscus; the descending trigeminal system is also involved, as are the nuclei of CN IX and X. Additional deficits may include vestibular or cerebellar signs, as the vestibular nuclei are nearby and afferents to the cerebellum may be interrupted. Notwithstanding the fact that the lateral lemniscus is most likely involved in this lesion, auditory deficits are not commonly associated with this clinical syndrome, probably due to the fact that this is a bilateral pathway. The lateral meduallary syndrome is discussed with Figure 67B.

Additional Detail

The superior cerebellar peduncles are shown in this diagram, although not part of the sensory systems. These will be described with the cerebellum (see Figure 57). This fiber pathway from the cerebellum to the thalamus decussates in the lower midbrain at the inferior collicular level (shown in cross-section, see Figure 65B).

The red nucleus is one of the prominent structures of the midbrain (see Figure 65A); its contribution to motor function in humans is not yet clear (discussed with Figure 47).

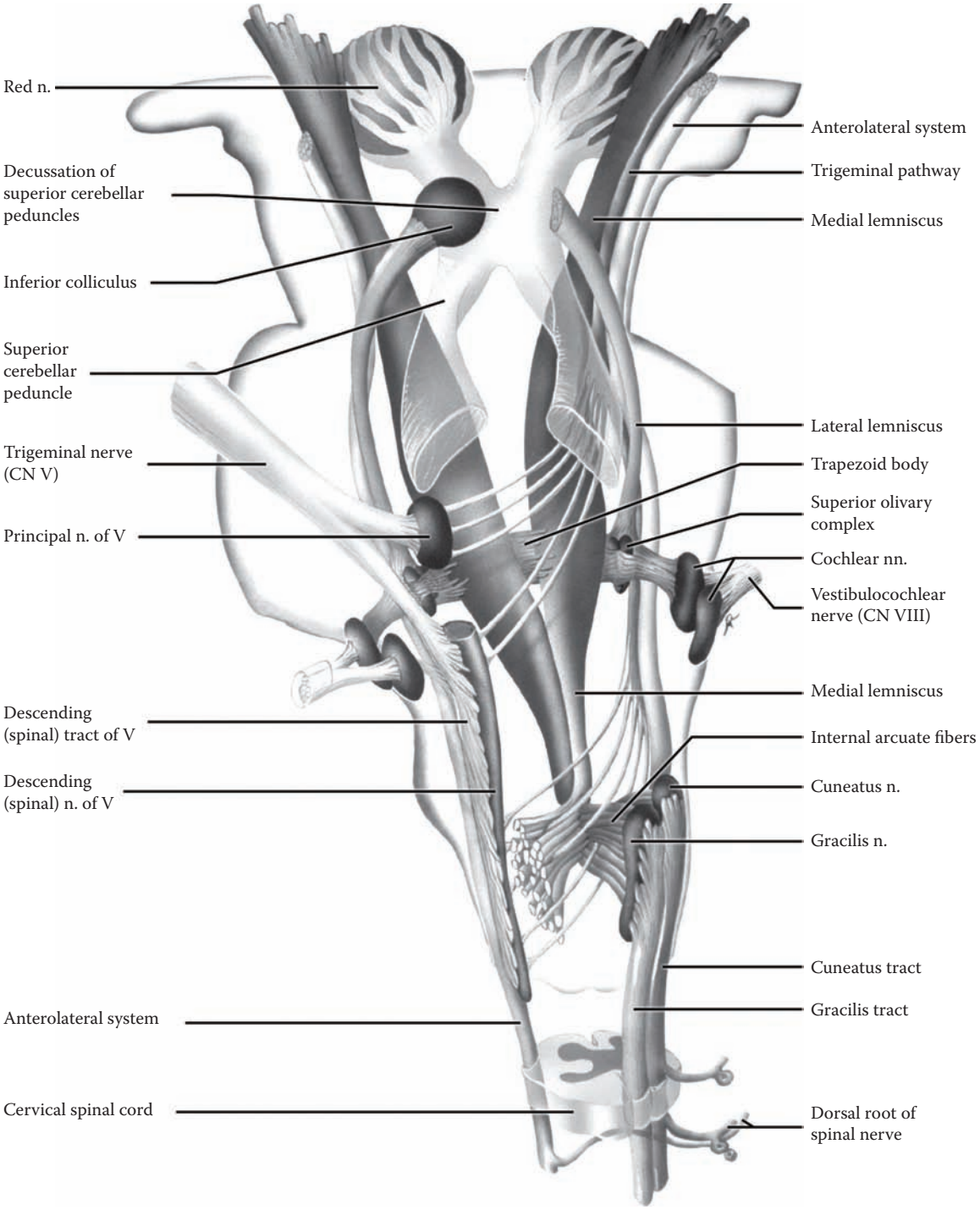


FIGURE 40: **Sensory Systems** — Sensory Nuclei and Ascending Tracts

FIGURE 41A
VISION 1

VISUAL PATHWAY 1

The visual image exists in the outside world, and is designated the **visual field**; there is a visual field for each eye. This image is projected onto the retina, where it is now termed the **retinal field**. Because of the lens of the eye, the visual information from the upper visual field is seen in the lower retina (and likewise for the lower visual field). The visual fields are also divided into temporal (lateral) and nasal (medial) portions. The temporal visual field of one eye is projected onto the nasal part of the retina of the ipsilateral eye, and onto the temporal part of the retina of the contralateral eye. The primary purpose of the visual apparatus (e.g., muscles) is to align the visual image on corresponding points of the retina of both eyes.

Visual processing begins in the retina with the photoreceptors, the highly specialized receptor cells, the **rods and cones**. The central portion of the visual field projects onto the **macular** area of the retina, composed of only cones, which is the area required for discriminative vision (e.g., reading) and color vision. Rods are found in the peripheral areas of the retina and are used for peripheral vision and seeing under conditions of low-level illumination. These receptors synapse with the **bipolar neurons** located in the retina, the first actual neurons in this system (functionally equivalent to DRG neurons). These connect with the **ganglion cells** (still in the retina) whose axons leave the retina at the optic disc to form the **optic nerve** (CN II). The optic nerve is in fact a tract of the CNS, as its myelin is formed by oligodendrocytes (the glial cell that forms and maintains CNS myelin).

After exiting from the orbit, the optic nerves undergo a partial crossing (decussation) in the **optic chiasm**. The fibers from both nasal retinas, representing the temporal visual fields, cross and then continue in the now-named **optic tract** (see Figure 15A and Figure 15B). The result of this rearrangement is to bring together the visual information from the visual field of one eye to the opposite side of the brain.

The visual fibers terminate in the **lateral geniculate nucleus** (**LGB**), a specific relay nucleus of the thalamus (see Figure 12 and Figure 63). The lateral geniculate is a layered nucleus (see Figure 41C); the fibers of the optic nerve synapse in specified layers and, after processing, project to the **primary visual cortex, area 17**. The projection consists of two portions with some of the fibers projecting directly posteriorly, while others sweep forward alongside the inferior horn of the lateral ventricle in the temporal lobe, called **Meyer's loop** (see also Figure 41C); both then project to the visual cortex of the occipital lobe as the **geniculo-calcarine radiation**. The projection from thalamus to cortex eventually becomes situated behind the lenticular nucleus and is called the retro-lenticular portion of the internal capsule, or simply the **visual or optic radiation** (see also Figure 27, Figure 28B, and Figure 38).

The visual information goes to **area 17**, the **primary visual area**, also called the **calcarine cortex** (seen in the upper diagrams and also in the next illustration), and then to adjacent association areas 18 and 19.

Clinical Aspect

The visual pathway is easily testable, even at the bedside. Lesions of the visual pathway are described as a deficit of the visual field, for example, loss of one-half of a field of vision is called **hemianopia** (visual loss is termed anopia). Loss of the visual field in both eyes is termed **homonymous** or **heteronymous**, as defined by the projection to the visual cortex on one side or both sides. Students should be able to draw the visual field defect in both eyes that would follow a lesion of the optic nerve, at the optic chiasm (i.e., bitemporal heteronymous hemianopia), and in the optic tract (i.e., homonymous hemianopia). (**Note to the Learner**: The best way of learning this is to do a sketch drawing of the whole visual pathway using colored pens or pencils.)

Lesions of the optic radiation are somewhat more difficult to understand:

- Loss of the fibers that project from the lower retinal field, those that sweep forward into the temporal lobe (Meyer's loop), results in a loss of vision in the upper visual field of both eyes on the side opposite the lesion, specifically the upper quadrant of both eyes, called superior (right or left) homonymous quadrantanopia.
- Loss of those fibers coming from the upper retinal field, which project directly posteriorly, passing deep within the parietal lobe, results in the loss of the lower visual field of both eyes on the side opposite the lesion, specifically the lower quadrant of both eyes, called inferior (right or left) homonymous quadrantanopia.

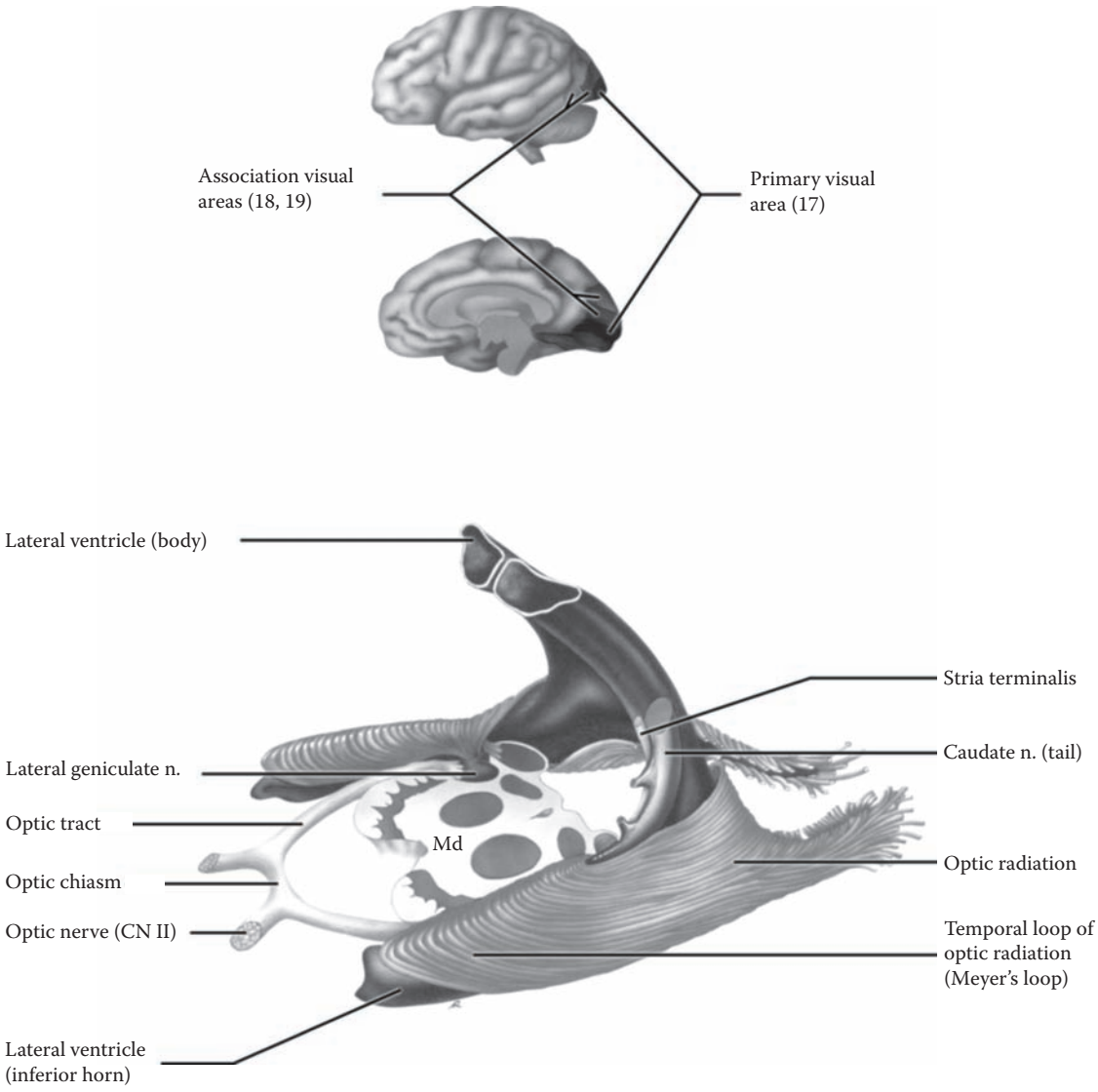


FIGURE 41A: Visual System 1 — Visual Pathway 1

FIGURE 41B
VISION 2

VISUAL PATHWAY 2 AND VISUAL CORTEX (PHOTOGRAPHS)

We humans are visual creatures. We depend on vision for access to information (the written word), the world of images (e.g., photographs, television), and the complex urban landscape. There are many cortical areas devoted to interpreting the visual world.

UPPER ILLUSTRATION (PHOTOGRAPHIC VIEW)

The visual fibers in the optic radiation terminate in **area 17**, the primary visual area, specifically the upper and lower gyri along the calcarine fissure. The posterior portion of area 17, extending to the occipital pole, is where macular vision is represented; the visual cortex in the more anterior portion of area 17 is the cortical region where the peripheral areas of the retina project.

The adjacent cortical areas, **areas 18 and 19**, are visual association areas; fibers are relayed here via the pulvinar of the thalamus (see below and Figure 12 and Figure 63). There are many other cortical areas for elaboration of the visual information, including a region on the inferior aspect of the hemisphere for face recognition.

LOWER ILLUSTRATION (PHOTOGRAPHIC VIEW)

This is a higher magnification of the medial aspect of the brain (shown in Figure 17). The interthalamic adhesion, fibers joining the thalamus of each side across the midline, has been cut (see Figure 6, not labeled). The optic chiasm is seen anteriorly; posteriorly, the tip of the pulvinar can be seen. The midbrain includes areas where fibers of the visual system synapse.

Fibers emerge from the **pulvinar**, the visually related association nucleus of the thalamus (see Figure 12 and Figure 63) and travel in the optic radiations to areas 18 and 19, the visual association areas of the cortex (shown in the previous diagram, alongside area 17). Some optic fibers terminate in the **superior colliculi** (see also Figure 9A and Figure 10), which are involved with coordinating eye movements (discussed with the next illustration). Visual fibers also end in the **pretectal "nucleus**," an area in front of the superior colliculus, for the pupillary light reflex (reviewed with the next illustration). Some other fibers terminate in the **suprachiasmatic** nucleus of the hypothalamus (located above the optic chiasm), which is involved in the control of diurnal (day-night) rhythms.

The additional structures labeled in this illustration have been noted previously (see Figure 17 in Section A), except the superior medullary velum, located in the upper part of the roof of the fourth ventricle (see Figure 10); this band of white matter is associated with the superior cerebellar peduncles (discussed with the cerebellum, see Figure 57).

Clinical Aspect

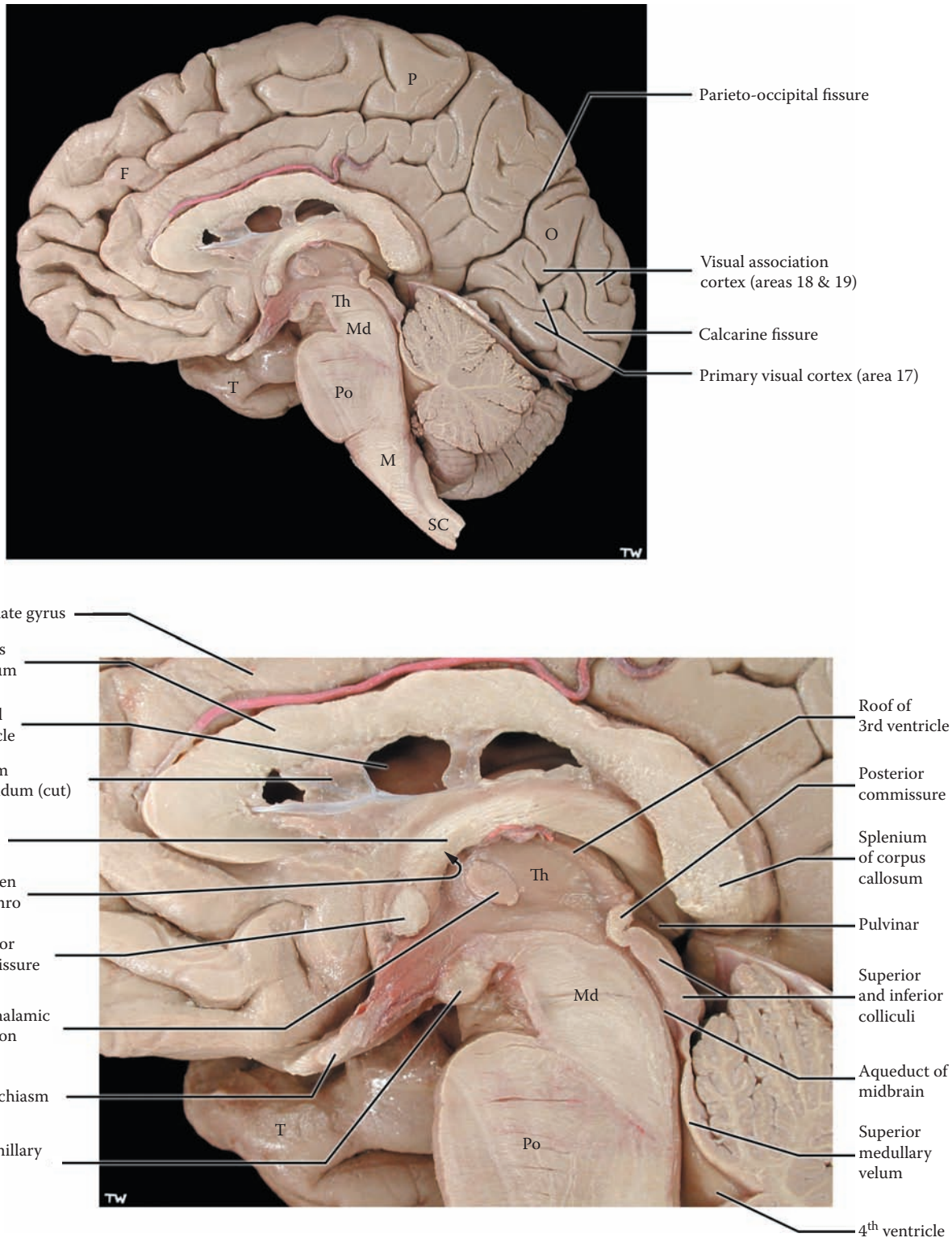
It is very important for the learner to know the visual system. The system traverses the whole brain and cranial fossa, from front to back, and testing the complete visual pathway from retina to cortex is an opportunity to sample the intactness of the brain from frontal pole to occipital pole.

Diseases of CNS myelin, such as multiple sclerosis (MS), affect the optic nerve or optic tract, causing visual loss. Sometimes this is the first manifestation of MS.

Visual loss can occur for many reasons, one of which is the loss of blood supply to the cortical areas. The visual cortex is supplied by the posterior cerebral artery (from the vertebro-basilar system, discussed with Figure 61). Part of the occipital pole, with the representation of the macular area of vision, may be supplied by the middle cerebral artery (from the internal carotid system, see Figure 60). In some cases, macular sparing is found after occlusion of the posterior cerebral artery, presumably because the blood supply to this area was coming from the carotid vascular supply.

Additional Detail

The work on visual processing and its development has offered us remarkable insights into the formation of synaptic connections in the brain, critical periods in development, and the complex way in which sensory information is "processed" in the cerebral cortex. It is now thought that the primate brain has more than a dozen specialized visual association areas, including face recognition, color, and others. Neuroscience texts should be consulted for further details concerning the processing of visual information.



F = Frontal lobe
P = Parietal lobe
T = Temporal lobe
O = Occipital lobe

Th = Thalamus
Md = Midbrain
Po = Pons

M = Medulla
SC = Spinal cord

FIGURE 41B: **Visual System 2** — Visual Pathway 2 and Visual Cortex (photograph)

FIGURE 41C
VISION 3

VISUAL REFLEXES

The upper illustration shows the details of the optic radiation alongside the posterior horn of the lateral ventricle. The fibers end in the visual cortex along both banks of the calcarine fissure, the primary visual area, area 17 (see Figure 41A and Figure 41B).

This illustration also shows some fibers from the optic tract that project to the **superior colliculus** by-passing the lateral geniculate via the **brachium** of the superior colliculus (labeled in the lower illustration). This nucleus serves as an important center for visual reflex behavior, particularly involving eye movements. Fibers project to nuclei of the extra-ocular muscles (see Figure 8A and Figure 51A) and neck muscles via a small pathway, the **tecto-spinal tract**, which is found incorporated with the MLF, the medial longitudinal fasciculus (see Figure 51B).

Reflex adjustments of the visual system are also required for seeing nearby objects, known as the accommodation reflex. A small but extremely important group of fibers from the optic tract (not shown) project to the **pretectal area** for the pupillary light reflex.

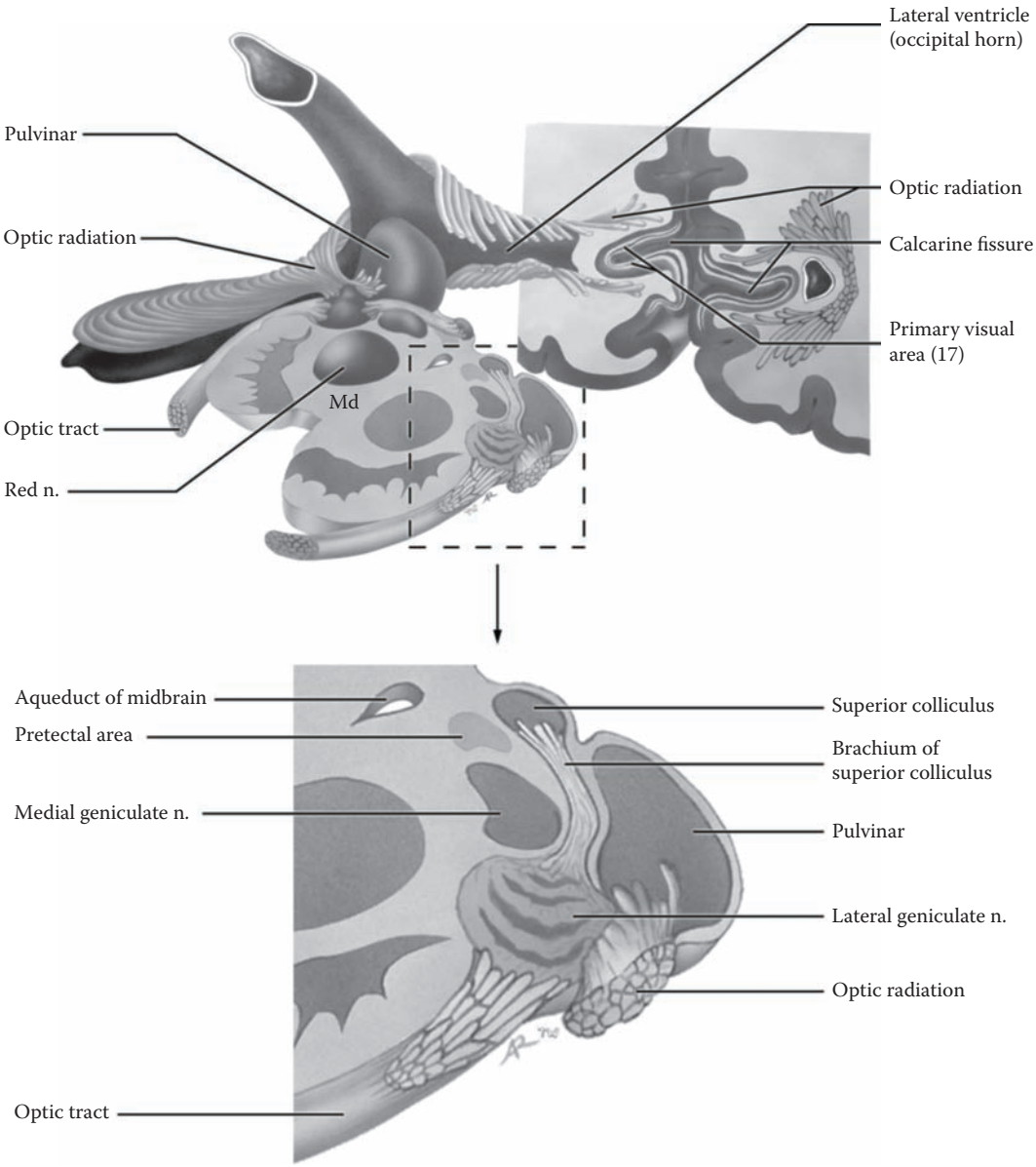
- **Accommodation reflex** The accommodation reflex is activated when looking at a nearby object, as in reading. Three events occur simultaneously — convergence of both eyes (involving both medial recti muscles), a change (rounding) of the curvature of the lens, and pupillary constriction. This reflex requires the visual information to be processed at the cortical level. The descending cortico-bulbar fibers (see Figure 46 and Figure 48) go to the oculomotor nucleus and influence both the motor portion (to the medial recti muscles), and also to the parasympathetic (Edinger-Westphal) portion (to the smooth muscle of the lens and the pupil, via the ciliary ganglion) to effect the reflex.
- **Pupillary light reflex** Some of the visual information (from certain ganglion cells in the retina) is carried in the optic nerve and tract to the midbrain. A nucleus located in the area in front of the colliculi (the other name for the colliculi is the tectal area, see Figure 9A, Figure 10, and Figure 65), called the **pretectal area** (see also Figure 51B), is the site of synapse for the pupillary light reflex. Shining light on the retina causes a constriction of the pupil on the same side; this is the *direct* pupillary light reflex. Fibers also cross to the nucleus on the other side (via a commissure), and the pupil of the other eye reacts as well; this is the *consensual* light reflex. The efferent part of the reflex involves the parasympathetic nucleus (Edinger-Westphal) of the oculomotor nucleus (see Figure 8A and also Figure 65A); the efferent fibers course in CN III, synapsing in the ciliary ganglion (parasympathetic) in the orbit before innervating the smooth muscle of the iris, which controls the diameter of the pupil.

Clinical Aspect

The pupillary light reflex is a critically important clinical sign, particularly in patients who are in a coma, or following a head injury. It is essential to ascertain the status of the reaction of the pupil to light, ipsilaterally and on the opposite side. The learner is encouraged to draw out this pathway and to work out the clinical picture of a lesion involving the afferent visual fibers, the midbrain area, and a lesion affecting the efferent fibers (CN III).

In a disease such as multiple sclerosis, or with diseases of the retina, there can be a reduced sensory input via the optic nerve, and this can cause a condition called a "relative afferent pupillary defect." A specific test for this is the swinging light reflex, which is performed in a dimly lit room. Both pupils will constrict when the light is shone on the normal side. As the light is shone in the affected eye, because of the diminished afferent input from the retina to the pretectal nucleus, the pupil of this eye will dilate in a paradoxical manner.

CN III, the oculomotor nerve, is usually involved in brain herniation syndromes, particularly uncal herniation (discussed with Figure 15B). This results in a fixed dilated pupil on one side, a critical sign when one is concerned about increased intracranial pressure from any cause. The significance and urgency of this situation must be understood by anyone involved in critical care.



Md = Midbrain

FIGURE 41C: Visual System 3 — Visual Reflexes

PART II: RETICULAR FORMATION
FIGURE 42A
RETICULAR FORMATION 1

RETICULAR FORMATION: ORGANIZATION

The reticular formation, **RF**, is the name for a group of neurons found throughout the brainstem. Using the ventral view of the brainstem, the reticular formation occupies the central portion or core area of the brainstem from midbrain to medulla (see also brainstem cross-sections in Figure 65–Figure 67).

This collection of neurons is a phylogenetically old set of neurons that functions like a network or reticulum, from which it derives its name. The RF receives afferents from most of the sensory systems (see next illustration) and projects to virtually all parts of the nervous system.

Functionally, it is possible to localize different subgroups within the reticular formation:

- **Cardiac and respiratory "centers"**: Subsets of neurons within the medullary reticular formation and also in the pontine region are responsible for the control of the vital functions of heart rate and respiration. The importance of this knowledge was discussed in reference to the clinical emergency, tonsillar herniation (with Figure 9B).
- **Motor areas**: Both the pontine and medullary nuclei of the reticular formation contribute to motor control via the cortico-reticulo-spinal system (discussed in Section B, Part III, Introduction; also with Figure 49A and Figure 49B). In addition, these nuclei exert a very significant influence on muscle tone, which is very important clinically (discussed with Figure 49B).
- **Ascending projection system**: Fibers from the reticular formation ascend to the thalamus and project to various nonspecific thalamic nuclei. From these nuclei, there is a diffuse distribution of connections to all parts of the cerebral cortex. This whole system is concerned with consciousness and is known as the **ascending reticular activating system (ARAS)**.
- **Pre-cerebellar nuclei**: There are numerous nuclei in the brainstem that are located within the boundaries of the reticular formation that project to the cerebellum. These are not always included in discussions of the reticular formation.

It is also possible to describe the reticular formation topographically. The neurons appear to be arranged in three longitudinal sets; these are shown in the left-hand side of this illustration:

- The **lateral group** consists of neurons that are small in size. These are the neurons that receive the various inputs to the reticular formation, including those from the anterolateral system (pain and temperature, see Figure 34), the trigeminal pathway (see Figure 35), as well as auditory and visual input.
- The next group is the **medial group**. These neurons are larger in size and project their axons upward and downward. The ascending projection from the midbrain area is particularly involved with the consciousness system. Nuclei within this group, notably the nucleus gigantocellularis of the medulla, and the pontine reticular nuclei, caudal (lower) and oral (upper) portions, give origin to the two reticulo-spinal tracts (discussed with the next illustration, also Figure 49A and Figure 49B).
- Another set of neurons occupy the midline region of the brainstem, the **raphe nuclei**, which use the catecholamine serotonin for neurotransmission. The best-known nucleus of this group is the nucleus raphe magnus, which plays an important role in the descending pain modulation system (to be discussed with Figure 43).

In addition, both the locus ceruleus (shown in the upper pons) and the periaqueductal gray (located in the midbrain, see next illustration and also Figure 65 and Figure 65A) are considered part of the reticular formation (discussed with the next illustration).

In summary, the reticular formation is connected with almost all parts of the CNS. Although it has a generalized influence within the CNS, it also contains subsystems that are directly involved in specific functions. The most clinically significant aspects are:

- Cardiac and respiratory centers in the medulla
- Descending systems in the pons and medulla that participate in motor control and influence muscle tone
- Ascending pathways in the upper pons and midbrain that contribute to the consciousness system

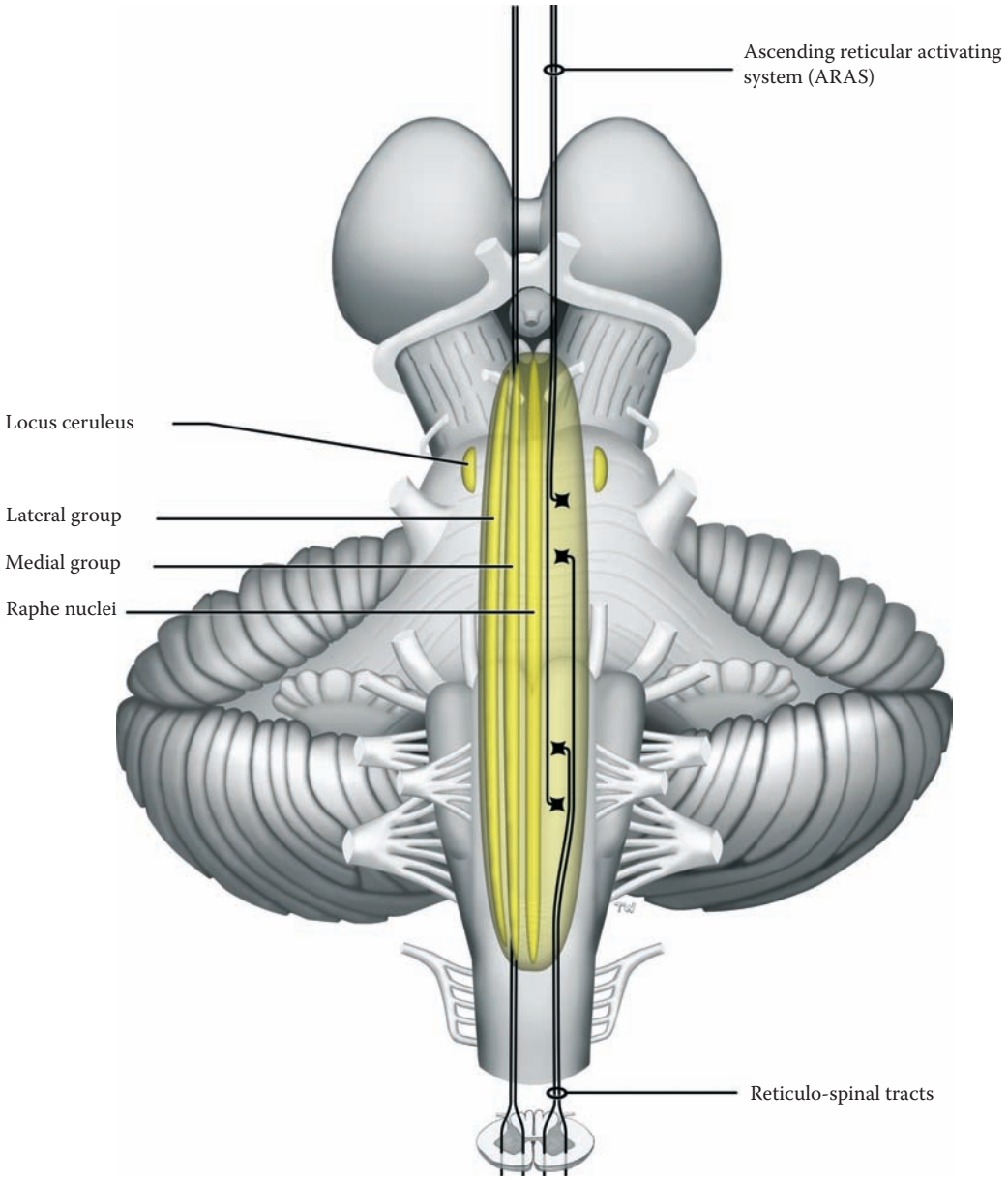


FIGURE 42A: Reticular Formation 1 — Organization

FIGURE 42B
RETICULAR FORMATION 2

RETICULAR FORMATION: NUCLEI

In this diagram, the reticular formation is being viewed from the dorsal (posterior) perspective (see Figure 10 and Figure 40). Various nuclei of the reticular formation, **RF**, which have a significant (known) functional role, are depicted, as well as the descending tracts emanating from some of these nuclei.

Functionally, there are afferent and efferent nuclei in the reticular formation and groups of neurons that are distinct because of the catecholamine neurotransmitter used, either serotonin or noradrenaline. The afferent and efferent nuclei of the RF include:

- Neurons that receive the various inputs to the RF are found in the lateral group (as discussed with the previous illustration). In this diagram, these neurons are shown receiving collaterals (or terminal branches) from the ascending anterolateral system, carrying pain and temperature (see Figure 34; also Figure 35).
- The neurons of the medial group are larger in size, and these are the output neurons of the reticular formation, at various levels. These cells project their axons upward or downward. The **nucleus gigantocellularis** of the medulla, and the **pontine reticular nuclei**, **caudal**, and **oral** portions, give rise to the descending tracts that emanate from these nuclei — the medial and lateral reticulo-spinal pathways, part of the indirect voluntary and nonvoluntary motor system (see Figure 49A and Figure 49B).
- Raphe nuclei use the neurotransmitter serotonin and project to all parts of the CNS. Recent studies indicate that serotonin plays a significant role in emotional equilibrium, as well as in the regulation of sleep. One special nucleus of this group, the **nucleus raphe magnus**, located in the upper part of the medulla, plays a special role in the descending pain modulation pathway (described with the next illustration).

There are other nuclei in the brainstem that appear to functionally belong to the reticular formation yet are not located within the core region. These include the periaqueductal gray and the locus ceruleus.

The **periaqueductal gray** of the midbrain (for its location see Figure 65 and Figure 65A) includes neurons that are found around the aqueduct of the midbrain (see also Figure 20B). This area also receives input (illustrated but not labeled in this diagram) from the ascending sensory systems conveying pain and temperature, the anterolateral pathway; the same occurs with the trigeminal system. This area is part of a descending pathway to the spinal cord, which is concerned with pain modulation (as shown in the next illustration).

The **locus ceruleus** is a small nucleus in the upper pontine region (see Figure 66 and Figure 66A). In some species (including humans), the neurons of this nucleus accumulate a pigment that can be seen when the brain is sectioned (prior to histological processing, see photograph of the pons, Figure 66). Output from this small nucleus is distributed widely throughout the brain to virtually every part of the CNS, including all cortical areas, subcortical structures, the brainstem and cerebellum, and the spinal cord. The neurotransmitter that is used by these neurons is noradrenaline and its electrophysiological effects at various synapses are still not clearly known. Although the functional role of this nucleus is still not completely understood, the locus ceruleus has been thought to act like an "alarm system" in the brain. It has been implicated in a wide variety of CNS activities, such as mood, the reaction to stress, and various autonomic activities.

The cerebral cortex sends fibers to the RF nuclei, including the periaqueductal gray, forming part of the cortico-bulbar system of fibers (see Figure 46). The nuclei that receive this input and then give off the pathways to the spinal cord form part of an indirect voluntary motor system — the cortico-reticulo-spinal pathways (discussed in Section B, Part III, Introduction; see Figure 49A and Figure 49B). In addition, this system is known to play an extremely important role in the control of muscle tone (discussed with Figure 49B).

Clinical Aspect

Lesions of the cortical input to the reticular formation in particular have a very significant impact on muscle tone. In humans, the end result is a state of increased muscle tone, called spasticity, accompanied by hyper-reflexia, an increase in the responsiveness of the deep tendon reflexes (discussed with Figure 49B).

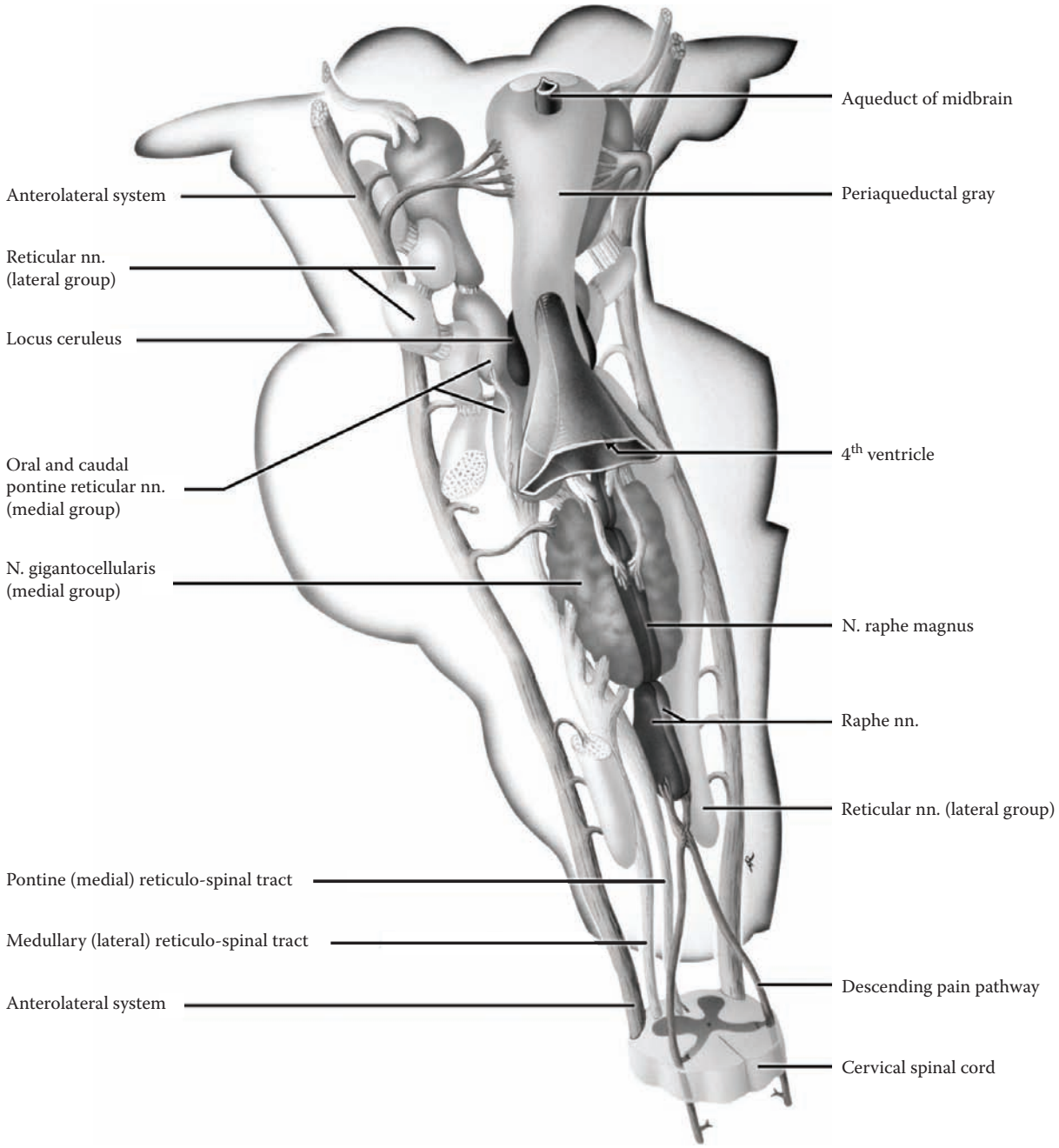


FIGURE 42B: Reticular Formation 2 — Nuclei

FIGURE 43
RETICULAR FORMATION 3

PAIN MODULATION SYSTEM

Pain, both physical and psychic, is recognized by the nervous system at multiple levels. Localization of pain, knowing which parts of the limbs and body wall are involved, requires the cortex of the postcentral gyrus (SI); SII is also likely involved in the perception of pain (discussed with Figure 36). There is good evidence that some "conscious" perception of pain occurs at the thalamic level.

We have a built-in system for dampening the influences of pain from the spinal cord level — the **descending pain modulation pathway**. This system apparently functions in the following way: The neurons of the periaqueductal gray can be activated in a number of ways. It is known that many ascending fibers from the anterolateral system and trigeminal system activate neurons in this area (only the anterolateral fibers are being shown in this illustration), either as collaterals or direct endings of these fibers in the midbrain. This area is also known to be rich in opiate receptors, and it seems that neurons of this region can be activated by circulating endorphins. Experimentally, one can activate these neurons by direct stimulation or by a local injection of morphine. In addition, descending cortical fibers (cortico-bulbar) may activate these neurons (see Figure 46).

The axons of some of the neurons of the periaqueductal gray descend and terminate in one of the serotonin-containing raphe nuclei in the upper medulla, the **nucleus raphe magnus**. From here, there is a descending, crossed, pathway, which is located in the dorsolateral white matter (funiculus) of the spinal cord. The serotonergic fibers terminate in the substantia gelatinosa of the spinal cord, a nuclear area of the dorsal horn of the spinal cord where the pain afferents synapse (see Figure 32). The descending serotonergic fibers are thought to terminate on small interneurons, which contain enkephalin. There is evidence that these enkephalin-containing spinal neurons inhibit the transmission of the pain afferents entering the spinal cord from peripheral pain receptors. Thus, descending influences are thought to modulate a local circuit.

There is a proposed mechanism that these same interneurons in the spinal cord can be activated by stimulation of other sensory afferents, particularly those from the touch receptors in the skin and the mechanoreceptors in the joints; these give rise to anatomically large well-myelinated peripheral nerve fibers, which send collaterals to the dorsal horn (see Figure 32). This is the physiological basis for the **gate theory of pain**. In this model, the same circuit is activated at a segmental level.

It is useful to think about multiple gates for pain transmission. We know that mental states and cognitive processes can affect, positively and negatively, the experience of pain and our reaction to pain. The role of the limbic system and the "emotional reaction" to pain will be discussed in Section D.

Clinical Aspect

In our daily experience with local pain, such as a bump or small cut, the common response is to vigorously rub and/or shake the limb or the affected region. What we may be doing is activating the local segmental circuits via the touch- and mechano-receptors to decrease the pain sensation.

Some of the current treatments for pain are based upon the structures and neurotransmitters being discussed here. The gate theory underlies the use of transcutaneous stimulation, one of the current therapies offered for the relief of pain. More controversial and certainly less certain is the postulated mechanism(s) for the use of acupuncture in the treatment of pain.

Most discussions concerning pain refer to ACUTE pain, or short-term pain caused by an injury or dental procedure. CHRONIC pain should be regarded from a somewhat different perspective. Living with pain on a daily basis, caused, for example, by arthritis, cancer, or diabetic neuropathy, is an unfortunately tragic state of being for many people. Those involved with pain therapy and research on pain have proposed that the CNS actually rewires itself in reaction to chronic pain and may in fact become more sensitized to pain the longer the pain pathways remain active; some of this may occur at the receptor level. Many of these people are now being referred to "pain clinics," where a team of physicians and other health professionals (e.g., anesthetists, neurologists, psychologists) try to assist people, using a variety of therapies, to alleviate their disabling condition.

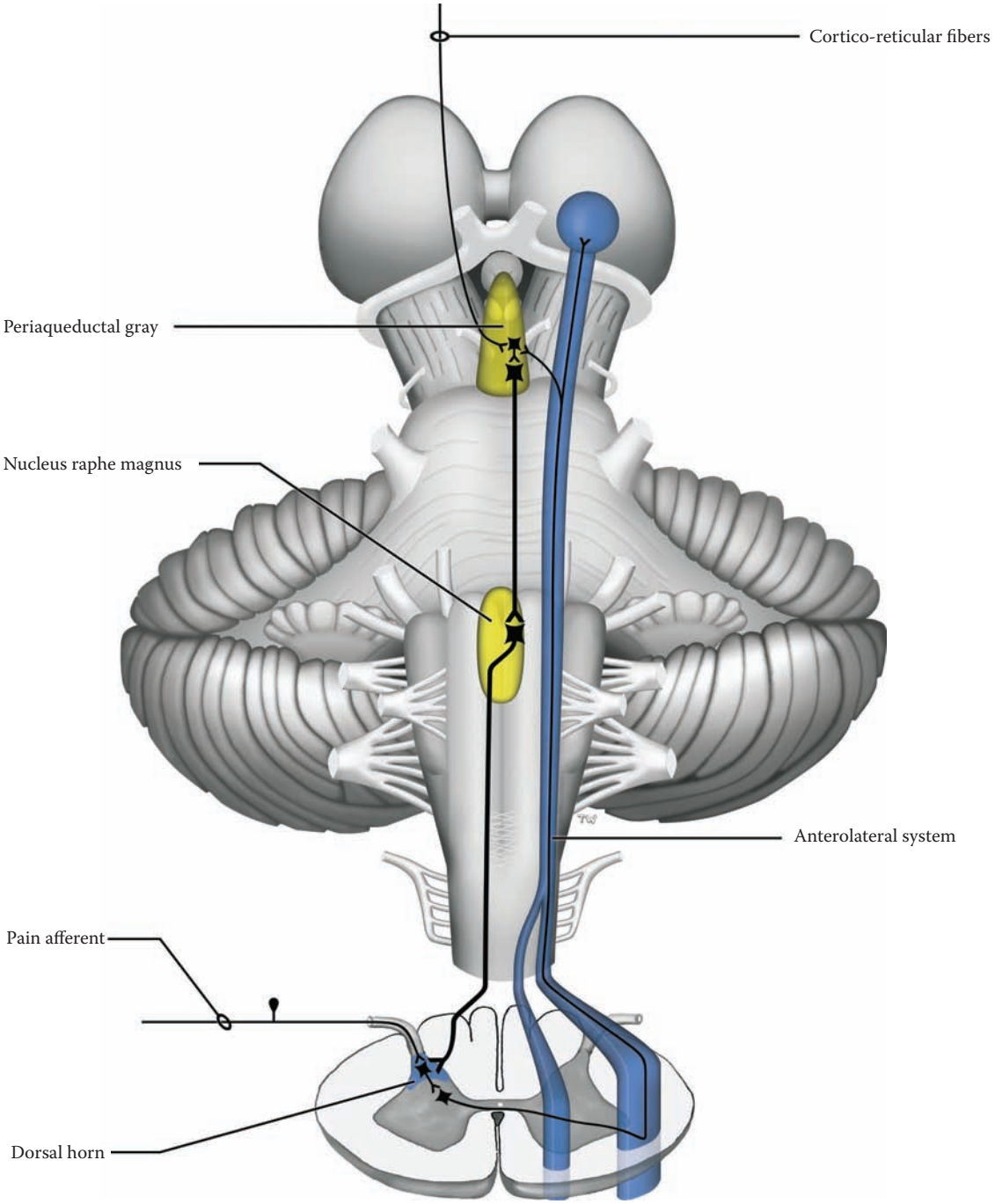


FIGURE 43: Reticular Formation 3 — Pain Modulation System

PART III: MOTOR SYSTEMS INTRODUCTION

There are multiple areas involved in motor control, which is the reason for the title Motor Systems (plural). The parts of the CNS that regulate the movement of our muscles include: motor areas of the cerebral cortex, the basal ganglia (including the substantia nigra and the subthalamic nucleus), the cerebellum (with its functional subdivisions), nuclei of the brainstem including portions of the reticular formation, and finally the output motor neurons of the cranial nerve motor nuclei and the spinal cord (the anterior horn cells, also known as the lower motor neurons).

One way of approaching this complexity is to separate motor activity into a voluntary system and a nonvoluntary system.

- **Voluntary motor control** involves both direct and indirect pathways:
  - The **direct voluntary pathway**, for the control of fine motor movements, includes the cortico-bulbar fibers to cranial nerve nuclei and the cortico-spinal fibers and its pathway continuation in the spinal cord, the lateral cortico-spinal tract.
  - The **indirect voluntary pathway**, an older system for the control of proximal joint movements and axial musculature, involves the motor cortex acting through the reticular formation of the brainstem.
- **Nonvoluntary motor regulation** is an older system for adjustment of the body to vestibular and gravitational changes, as well as visual input. The various nuclei of the brainstem (the red nucleus, the vestibular nuclei, and the reticular formation) are regulated by older functional parts of the cerebellum but may be influenced by the cerebral cortex. This system also controls muscle tone and the deep tendon reflex, the reactivity of the muscle (stretch) reflex.

There are three areas of the cerebral cortex directly involved in motor control (see Figure 14A, Figure 17, Figure 53, and Figure 60):

- The **motor cortex** is the precentral gyrus anatomically, **area 4**, also called the motor strip. The various portions of the body are functionally represented along this gyrus; the fingers and particularly the thumb, as well as the tongue and lips are heavily represented on the dorsolateral surface, with the lower limb on the medial surface of the hemisphere. This motor "homunculus" is not unlike the sensory homunculus. The large neurons of the motor strip (in the deeper cortical layers) send their axons as projection fibers to form the cortico- bulbar and cortico-spinal tracts. It is this cortical strip that contributes most to voluntary movements.
- Anterior to this is another wedge-shaped cortical area, the **premotor cortex**, **area 6**, with a less definite body representation. This cortical area sends its axons to the motor cortex as well as to the cortico-spinal tract, and its function likely has more to do with proximal joint control and postural adjustments needed for movements.
- The **supplementary motor cortex** is located on the dorsolateral surface and mostly on the medial surface of the hemisphere, anterior to the motor areas. This is an organizing area for movements and its axons are sent to the premotor and motor cortex.

These motor areas of the cerebral cortex are regulated by the basal ganglia and certain (newer) parts of the cerebellum. These two important large areas of the brain are "working behind the scenes" to adjust and calibrate the neuronal circuits of the cerebral cortex involved in motor control. All these areas also receive input from other parts of the cerebral cortex, particularly from the sensory postcentral gyrus, as well as from the parietal lobe.

The voluntary and nonvoluntary motor systems act directly or indirectly upon the motor neurons in the spinal cord and the cranial nerve motor nuclei, whose axons innervate the muscles. Therefore, there are several pathways that "descend" through the spinal cord — each with its own crossing (decussation) and each of which may result in a functional loss of the control of movement, with a change in responsiveness of the stretch (deep tendon) reflexes.

The motor pathways (tracts) are called descending because they commence in the cortex or brainstem and influence motor cells lower down in the neuraxis, either in the brainstem or spinal cord. Those neurons in the cortex or brainstem (including the reticular formation) giving rise to these pathways are collectively called the **upper motor neurons**. The motor neurons in the spinal cord or brainstem that give origin to the peripheral efferent fibers (spinal and cranial nerves) are often called collectively the **lower motor neuron** (discussed with Figure 44).

Learning Plan

This section will consider the motor areas of the cerebral cortex, the basal ganglia, the cerebellum, the motor nuclei of the thalamus, and the nuclei of the brainstem and reticular formation involved in motor regulation. The same standardized diagram of the nervous system will be used

as with the sensory systems, as well as the inclusion of select X-sections of the spinal cord and brainstem.

The descending tracts or pathways that will be considered include:

- **Cortico-spinal tract**: This pathway originates in motor areas of the cerebral cortex. The cortico-spinal tract, from cortex to spinal cord, is a relatively new tract and the most important for voluntary movements in humans, particularly of the hand and digits — the direct voluntary motor pathway.
- **Cortico-bulbar fibers**: This is a descriptive term that is poorly defined and includes all fibers that go to the brainstem, both cranial nerve nuclei and other brainstem nuclei. The fibers that go to the reticular formation include those that form part of the indirect voluntary motor pathway. The cortico-pontine fibers are described with the cerebellum.
- **Rubro-spinal tract**: The red nucleus of the midbrain gives rise to the rubro-spinal tract. Its connections are such that it may play a role in voluntary and nonvoluntary motor activity; this may be the case in higher primates, but its precise role in humans is not clear.
- **Reticulo-spinal tracts**: These tracts are involved in the indirect voluntary pathways and in nonvoluntary motor regulation, as well as in the underlying control of muscle tone and reflex responsiveness. Two tracts descend from the reticular formation, one from the pontine region, the medial reticulo-spinal tract, and one from the medulla, the lateral reticulo-spinal tract.
- **Lateral vestibulo-spinal tract**: The lateral vestibular nucleus of the pons gives rise to the lateral vestibulo-spinal tract. This nucleus plays an important role in the regulation of our responses to gravity (vestibular afferents). It is therefore a nonvoluntary pathway. It is under control of the cerebellum, not the cerebral cortex.
- **Medial longitudinal fasciculus (MLF)**: This is a complex pathway of the brainstem and upper spinal cord that serves to coordinate various eye and neck reflexes. There are both ascending and descending fibers within the MLF, from vestibular and other nuclei.

Broca's area for the motor control of speech is situated on the dominant side on the dorsolateral surface, a little anterior to the lower portions of the motor areas (see Figure 14A). The frontal eye field, in front of the premotor area, controls voluntary eye movements (see Figure 14A).

Clinical Aspect

The conceptual approach to the motor system as comprising an upper motor neuron and a lower motor neuron is most important for clinical neurology. A typical human lesion of the brain (e.g., vascular, trauma, tumor) usually affects cortical and subcortical areas, and several of the descending systems, resulting in a mixture of deficits of movement, as well as a change in muscle tone (flaccidity or spasticity) and an alteration of the stretch reflexes (discussed with Figure 49B).

There is one abnormal reflex that indicates, in the human, that there has been a lesion interrupting the cortico-spinal pathway — at any level (cortex, white matter, internal capsule, brainstem, spinal cord). The reflex involves stroking the lateral aspect of the bottom of the foot (a most uncomfortable sensation for most people). Normally, the response involves flexion of the toes, the **plantar reflex**, and oftentimes an attempt to withdraw the limb. Testing this same reflex after a lesion interrupts the cortico-spinal pathway results in an upward movement of the big toe (extension) and a fanning apart of the other toes. The abnormal response is called a **Babinski sign — not reflex —** and it can be elicited almost immediately after any lesion that interrupts any part of the cortico-spinal pathway, from cortex through to spinal cord (except spinal shock, see Figure 5).

Most interestingly, this Babinski sign is normally present in the infant and disappears somewhere in the second year of life, concurrent with the myelination that occurs in this pathway.

FIGURE 44
SPINAL CORD CROSS-SECTION

MOTOR-ASSOCIATED NUCLEI

UPPER ILLUSTRATION

The motor regions of the spinal cord in the ventral horn are shown in this diagram. The lateral motor nuclei supply the distal musculature (e.g., the hand), and as would be expected this area is largest in the region of the limb plexuses (brachial and lumbosacral, see Figure 69). The medial group of neurons supplies the axial musculature.

LOWER ILLUSTRATION

In the spinal cord, the neurons that are located in the ventral or anterior horn, and are (histologically) the anterior horn cells, are usually called the **lower motor neurons**. Physiologists call these neurons the **alpha motor neurons**. In the brainstem, these neurons include the motor neurons of the cranial nerves (see Figure 8A). Since all of the descending influences converge upon the lower motor neurons, these neurons have also been called, in a functional sense, **the final common pathway**. The lower motor neuron and its axon and the muscle fibers that it activates are collectively called the **motor unit**. The intactness of the motor unit determines muscle strength and muscle function.

Motor Reflexes

The **myotatic reflex** is elicited by stretching a muscle (e.g., by tapping on its tendon), and this causes a contraction of the same muscle that was stretched; thus the reflex is also known as the **stretch reflex**, the **deep tendon reflex**, often simply **DTR**. In this reflex arc (shown on the left side), the information from the muscle spindle (afferent) ends directly on the anterior horn cell (efferent); there is only one synapse (i.e., a monosynaptic reflex).

All other reflexes, even a simple withdrawal reflex (e.g., touching a hot surface) involves some central processing (more than one synapse, multisynaptic) in the spinal cord, prior to the response (shown on the right side). All these reflexes involve hard-wired circuits of the spinal cord but are influenced by information descending from higher levels of the nervous system.

Recent studies indicate that complex motor patterns are present in the spinal cord, such as stepping movements with alternating movements of the limbs, and that influences from higher centers provide the organization for these built-in patterns of activity.

Clinical Aspect

The deep tendon reflex is a monosynaptic reflex and perhaps the most important for a neurological examination. The degree of reactivity of the lower motor neuron is influenced by higher centers, also called descending influences, particularly by the reticular formation (to be discussed with Figure 49B). An increase in this reflex responsiveness is called *hyperreflexia*, a decrease *hyporeflexia*. The state of activity of the lower motor neuron also influences **muscle tone** — the "feel" of a muscle at rest and the way in which the muscles react to passive stretch (by the examiner); again, there be may be *hypertonia* or *hypotonia*.

Disease or destruction of the anterior horn cells results in weakness or paralysis of the muscles supplied by those neurons. The extent of the weakness depends upon the extent of the neuronal loss and is rated on a clinical scale, called the MRC (Medical Research Council). There is also a decrease in muscle tone, and a decrease in reflex responsiveness (hyporeflexia) of the affected segments; the plantar response is normal.

The specific disease that affects these neurons is poliomyelitis, a childhood infectious disease carried in fecal-contaminated water. This disease entity has almost been totally eradicated in the industrialized world by immunization of all children.

In adults, the disease that affects these neurons specifically (including cranial nerve motor neurons) is amyotrophic lateral sclerosis, ALS, also known as Lou Gehrig's disease. In this progressive degenerative disease there is also a loss of the motor neurons in the cerebral cortex (the upper motor neurons). The clinical picture depends upon the degree of loss of the neurons at both levels. People afflicted with this devastating disease suffer a continuous march of loss of function, including swallowing and respiratory function, leading to their death. Researchers are actively seeking ways to arrest the destruction of these neurons.

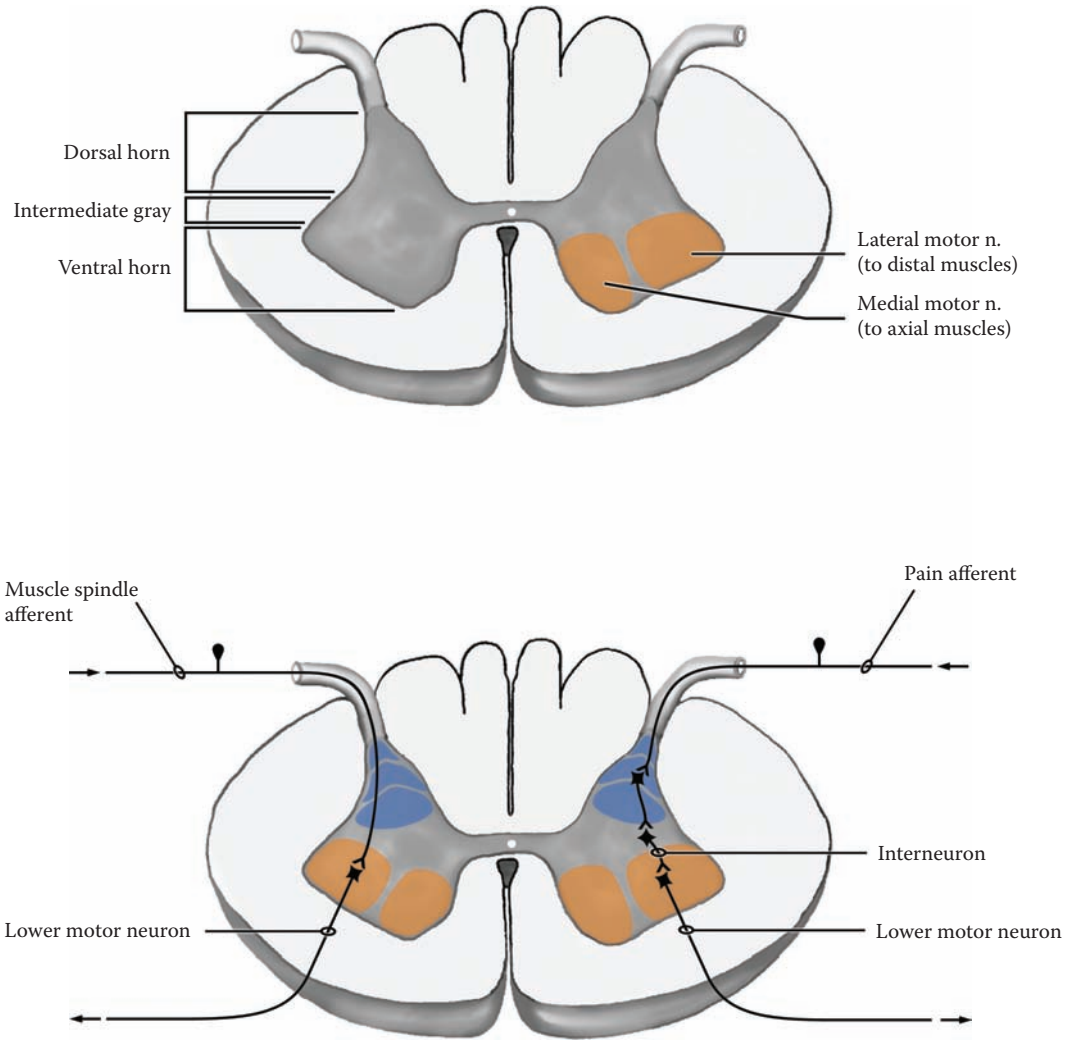


FIGURE 44: Spinal Cord Nuclei — Motor

FIGURE 45
CORTICO-SPINAL TRACT — THE PYRAMIDAL SYSTEM

DIRECT VOLUNTARY PATHWAY

The cortico-spinal tract, a direct pathway linking the cortex with the spinal cord, is the most important one for voluntary motor movements in humans.

This pathway originates mostly from the motor areas of the cerebral cortex, areas 4 and 6 (see Figure 14A, Figure 17, and Figure 60; discussed in Section B, Part III, Introduction and with Figure 48). The well-myelinated axons descend through the white matter of the hemispheres, through the posterior limb of the internal capsule (see Figure 26, Figure 27, Figure 28A, and Figure 28B), continue through the midbrain and pons (see below) and are then found within the medullary pyramids (see Figure 6 and Figure 7). Hence, the cortico-spinal pathway is often called the **pyramidal tract**, and clinicians may sometimes refer to this pathway as the pyramidal system. At the lowermost part of the medulla, most (90%) of the cortico-spinal fibers decussate (cross) in the **pyramidal decussation** (see Figure 7) and form the **lateral cortico-spinal tract** in the spinal cord (see Figure 68).

Many of these fibers end directly on the lower motor neuron, particularly in the cervical spinal cord. This pathway is involved with controlling the individualized movements, particularly of our fingers and hands (i.e., the distal limb musculature). Experimental work with monkeys has shown that, after a lesion is placed in the medullary pyramid, there is muscle weakness and a loss of ability to perform fine movements of the fingers and hand (on the opposite side); the animals were still capable of voluntary gross motor movements of the limb. There was no change in the deep tendon reflexes, and a decrease in muscle tone was reported. The innervation for the lower extremity is similar but clearly involves less voluntary activity.

Those fibers that do not cross in the pyramidal decussation form the **anterior (or ventral) cortico-spinal tract**. Many of the axons in this pathway will cross before terminating, while others supply motor neurons on both sides. The ventral pathway is concerned with movements of the proximal limb joints and axial movements, similar to other pathways of the nonvoluntary motor system.

Other areas of the cortex contribute to the cortico-spinal pathway; these include the sensory cortical areas, the postcentral gyrus (also discussed with the next illustration).

Neurological Neuroanatomy

The cross-sectional levels for following this pathway include the upper midbrain, the mid-pons, the mid-medulla, and cervical and lumbar spinal cord levels.

After emerging from the internal capsule, the cortico-spinal tract is found in the midportion of the cerebral peduncles in the midbrain (see Figure 6, Figure 7, next illustration, and Figure 48). The cortico-spinal fibers are then dispersed in the pontine region and are seen as bundles of axons among the pontine nuclei (see Figure 66B). The fibers collect again in the medulla as a single tract, in the pyramids on each side of the midline (see Figure 6, Figure 7, Figure 67, and Figure 67B). At the lowermost level of the medulla, 90% of the fibers decussate and form the lateral cortico-spinal tract, situated in the lateral aspect of the spinal cord (see Figure 68). The ventral cortico-spinal tract is found in the anterior portion of the white matter of the spinal cord (see Figure 68).

Clinical Aspect

Lesions involving the cortico-spinal tract in humans are quite devastating, as they rob the individual of voluntary motor control, particularly the fine skilled motor movements. This pathway is quite commonly involved in strokes, as a result of vascular lesions of the cerebral arteries or of the deep arteries to the internal capsule (reviewed with Figure 60 and Figure 62). This lesion results in a weakness (paresis) or paralysis of the muscles on the opposite side. The clinical signs in humans will reflect the additional loss of cortical input to the brainstem nuclei, particularly to the reticular formation.

Damage to the tract in the spinal cord is seen after traumatic injuries (e.g., automobile and diving accidents). In this case, other pathways would be involved and the clinical signs will reflect this damage, with the loss of the nonvoluntary tracts (discussed with Figure 68). If one-half of the spinal cord is damaged, the loss of function is ipsilateral to the lesion.

A Babinski sign (discussed in Section B, Part III, Introduction) is seen with all lesions of the cortico-spinal tract (except spinal shock, see Figure 5).

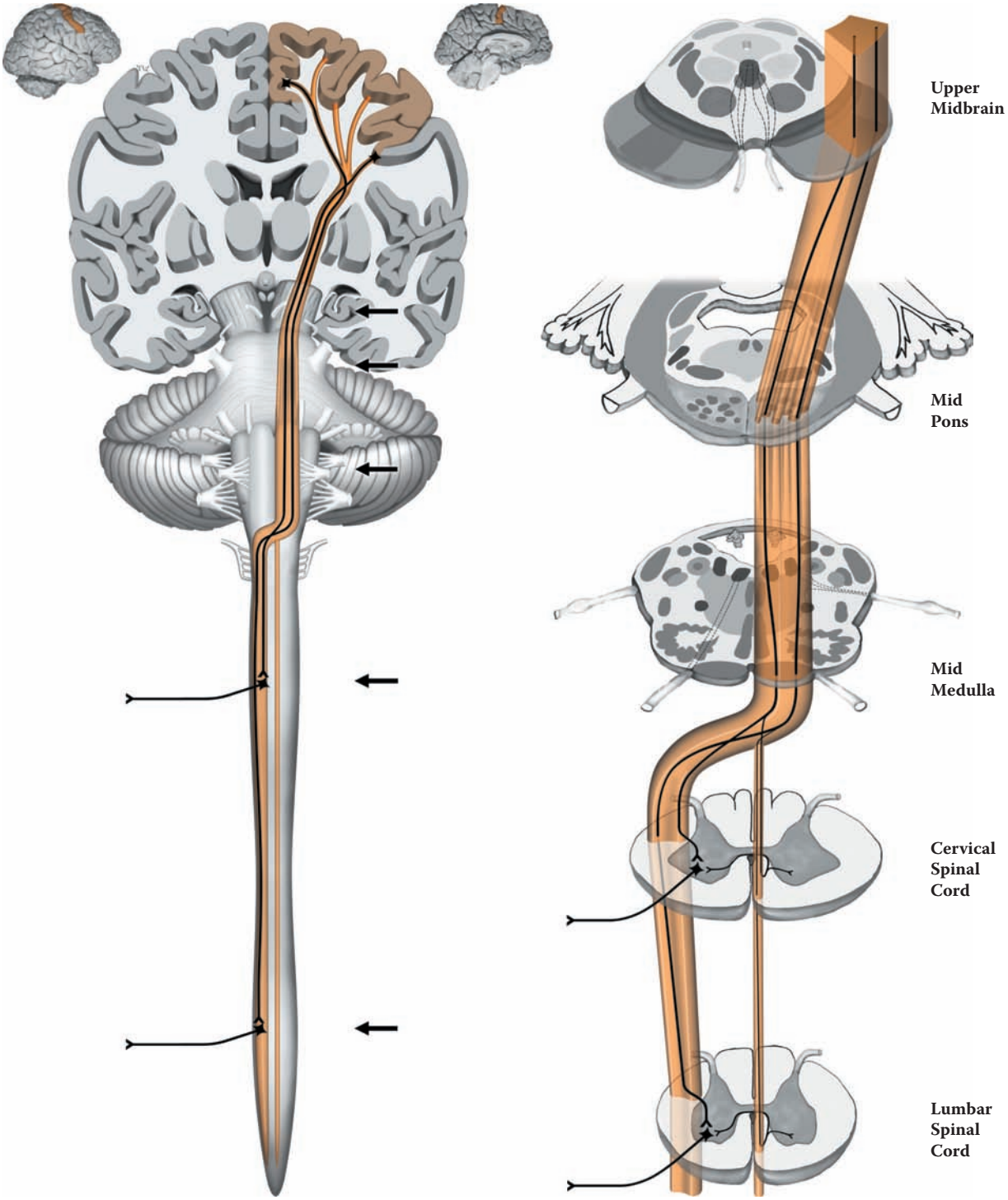


FIGURE 45: Cortico-Spinal Tract — Pyramidal System

FIGURE 46
CORTICO-BULBAR FIBERS

NUCLEI OF THE BRAINSTEM

The word "bulb" (i.e., bulbar) is descriptive and refers to the brainstem. The cortico-bulbar fibers do not form a single pathway. The fibers end in a wide variety of nuclei of the brainstem; those fibers ending in the pontine nuclei are considered separately (see Figure 48).

Wide areas of the cortex send fibers to the brainstem as projection fibers (see Figure 16). These axons course via the internal capsule and continue into the cerebral peduncles of the midbrain (see Figure 26). The fibers involved with motor control occupy the middle third of the cerebral peduncle along with the cortico-spinal tract (described with the previous illustration; see Figure 48), supplying the motor cranial nerve nuclei of the brainstem (see Figure 8A and Figure 48), the reticular formation and other motor-associated nuclei of the brainstem.

- **Cranial Nerve Nuclei**: The motor neurons of the cranial nerves of the brainstem are lower motor neurons (see Figure 8A and Figure 48); the cortical motor cells are the upper motor neurons. These motor nuclei are generally innervated by fibers from both sides, i.e., each nucleus receives input from both hemispheres.

There are two exceptions to this rule, which are very important in the clinical setting:

  - The major exception is the cortical input to the **facial nucleus**. The portion of the facial nucleus supplying the upper facial muscles is supplied from both hemispheres, whereas the part of the nucleus supplying the lower facial muscles is innervated only by the opposite hemisphere (crossed).
  - The cortical innervation to the **hypoglossal** nucleus is not always bilateral. In some individuals, there is a predominantly crossed innervation.

- **Brainstem motor control nuclei**: Cortical fibers influence all the brainstem motor nuclei, particularly the reticular formation, including the red nucleus and the substantia nigra, but not the lateral vestibular nucleus (see Figure 49A, Figure 49B, and Figure 50). The cortico-reticular fibers are extremely important for voluntary movements of the proximal joints (indirect voluntary pathway) and for the regulation of muscle tone.
- **Other brainstem nuclei**: The cortical input to the sensory nuclei of the brainstem is consistent with cortical input to all relay nuclei; this includes the somatosensory nuclei, the nuclei cuneatus and gracilis (see Figure 33). There is also cortical input to the periaqueductal gray, as part of the pain modulation system (see Figure 43).

Clinical Aspect

Loss of cortical innervation to the cranial nerve motor nuclei is usually associated with a weakness, not paralysis, of the muscles supplied. For example, a lesion on one side may result in difficulty in swallowing or phonation, and often these problems dissipate in time.

Facial movements: A lesion of the facial area of the cortex or of the cortico-bulbar fibers affects the muscles of the face differentially. A patient with such a lesion will be able to wrinkle his or her forehead normally on both sides when asked to look up, but will not be able to show the teeth or smile symmetrically on the side opposite the lesion. Because of the marked weakness of the muscles of the lower face, there will be a drooping of the lower face on the side opposite the lesion. This will also affect the muscle of the cheek (the buccinator muscle) and cause some difficulties with drinking and chewing (the food gets stuck in the cheek and oftentimes has to be manually removed); sometimes there is also drooling.

This clinical situation must be distinguished from a lesion of the **facial nerve** itself, a lower motor neuron lesion, most often seen with Bell's palsy (a lesion of the facial nerve as it emerges from the skull); in this case, the movements of the muscles of both the upper and lower face are lost on one (affected) side.

Tongue movements: The fact that the hypoglossal nucleus may or my not receive innervation from the cortex of both sides or only from the opposite side makes interpretation of tongue deviation not a reliable sign in the clinical setting. A lesion affecting the hypoglossal nucleus or nerve is a lower motor lesion of one-half of the tongue (on the same side) and will lead to paralysis and atrophy of the side affected.

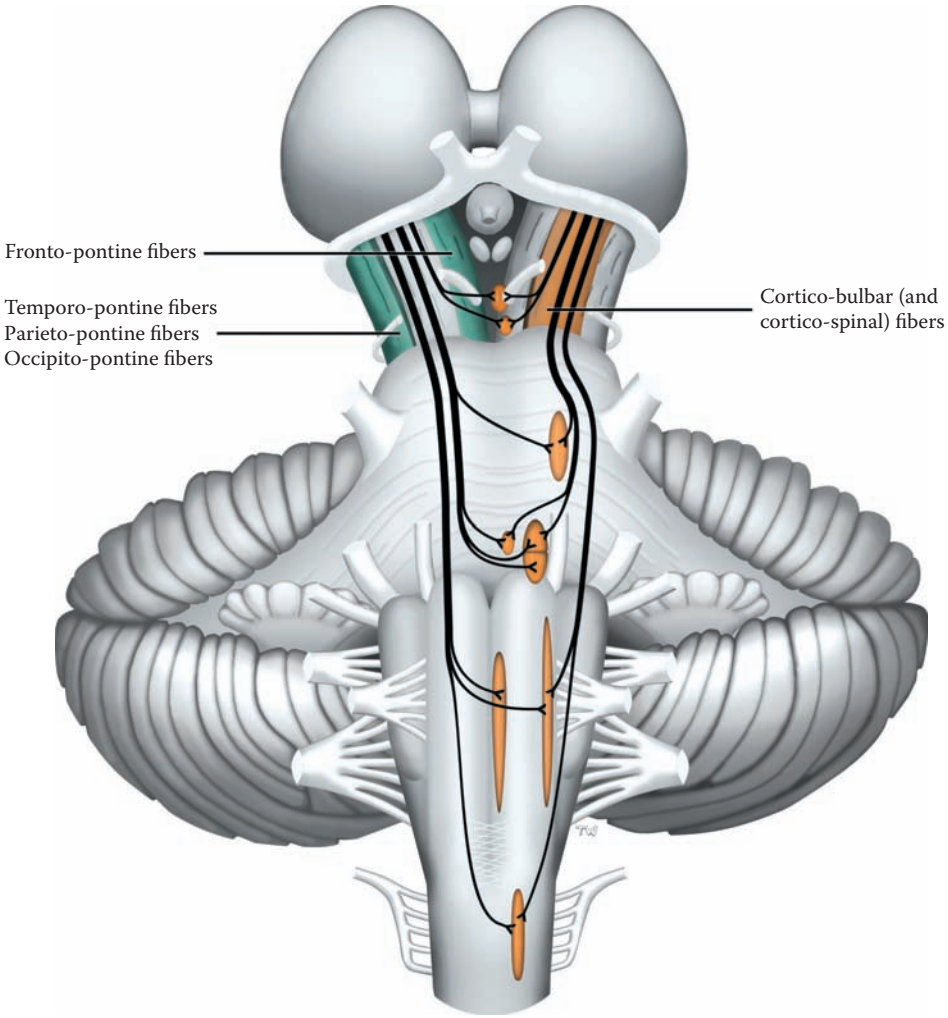


FIGURE 46: Cortico-Bulbar Tracts — Nuclei of the Brainstem

FIGURE 47
RUBRO-SPINAL TRACT

VOLUNTARY/NONVOLUNTARY MOTOR CONTROL

The **red nucleus** is a prominent nucleus of the midbrain. It gets its name from a reddish color seen in fresh dissections of the brain, presumably due to its high vascularity. The nucleus (see Figure 48, Figure 51B, and Figure 65A) has two portions, a small-celled upper division and a portion with large neurons more ventrally located. The rubro-spinal pathway originates, at least in humans, from the larger cells.

The red nucleus receives its input from the motor areas of the cerebral cortex and from the cerebellum (see Figure 53). The cortical input is directly onto the projecting cells, thus forming a potential two-step pathway from motor cortex to spinal cord.

The rubro-spinal tract is also a crossed pathway, with the decussation occurring in the ventral part of the midbrain (see also Figure 48 and Figure 51B). The tract descends within the central part of the brainstem (the tegmentum), and is not clearly distinguishable from other fiber systems. The fibers then course in the lateral portion of the white matter of the spinal cord, just anterior to and intermingled with the lateral cortico-spinal tract (see Figure 68 and Figure 69).

The rubro-spinal tract is a well-developed pathway in some animals. In monkeys, it seems to be involved in flexion movements of the limbs. Stimulation of this tract in cats produces an increase in tone of the flexor muscles.

Neurological Neuroanatomy

The location of this tract within the brainstem is shown at cross-sectional levels of the upper midbrain, the mid-pons, the mid-medulla, and cervical and lumbar spinal cord levels. The tract is said to continue throughout the length of the spinal cord in primates but probably only extends into the cervical spinal cord in humans.

The fibers of CN III (oculomotor) exit through the medial aspect of this nucleus at the level of the upper midbrain (see Figure 65A).

Clinical Aspect

The functional significance of this pathway in humans is not well known. The number of large cells in the red nucleus in humans is significantly less than in monkeys. Motor deficits associated with a lesion involving only the red nucleus or only the rubro-spinal tract have not been adequately described. Although the rubro-spinal pathway may play a role in some flexion movements, it seems that the cortico-spinal tract predominates in the human.

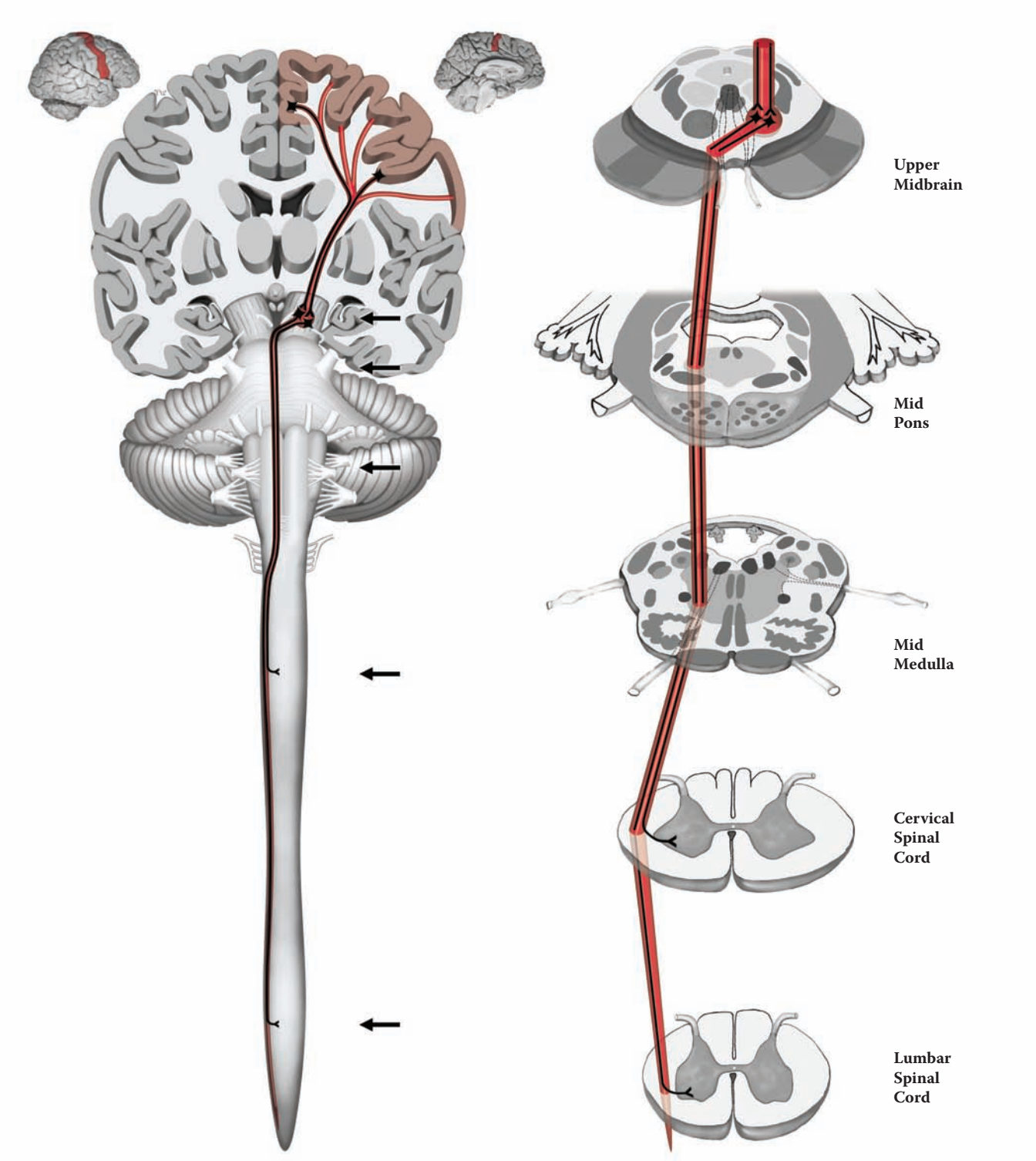


FIGURE 47: Rubro-Spinal Tract

FIGURE 48
MOTOR TRACTS AND CRANIAL NERVE NUCLEI

DESCENDING TRACTS AND CORTICO-PONTINE FIBERS

The descending pathways that have been described are shown, using the somewhat oblique posterior view of the brainstem (see Figure 10 and Figure 40), along with those cranial nerve nuclei that have a motor component. These pathways will be presented in summary form:

- **Cortico-spinal tract** (see Figure 45): These fibers course in the middle third of the cerebral peduncle, are dispersed in the pontine region between the pontine nuclei, and regroup as a compact bundle in the medulla, situated within the pyramids. At the lowermost part of the medulla (Figure 7), most of the fibers decussate to form the lateral cortico-spinal tract of the spinal cord (see Figure 68 and Figure 69). A small portion of the tract continues ipsilaterally, mostly into the cervical spinal cord region, as the anterior (ventral) cortico-spinal tract.
- **Cortico-bulbar fibers** (see Figure 46): The cortical fibers that project to the cranial nerve nuclei of the brainstem are shown in this diagram. The term also includes those cortical fibers that project to the reticular formation and other brainstem nuclei. These are also located in the middle third of the cerebral peduncle and are given off at various levels within the brainstem.
- **Rubro-spinal tract** (see Figure 47): This tract from the lower portion of the red nucleus decussates in the midbrain region and descends through the brainstem. In the spinal cord, the fibers are located anterior to the lateral cortico-spinal tract (see Figure 68).

Cortico-Pontine Fibers

The cortico-pontine fibers are part of a circuit that involves the cerebellum. The cortical fibers arise from the motor areas as well as from widespread parts of the cerebral cortex. The fibers are located in the outer and inner thirds of the cerebral peduncle (see also Figure 46): the fronto-pontine fibers in the inner third, and fibers from the other lobes in the outer third. They terminate in the nuclei of the pons proper (see Figure 6), and the information is then relayed (after crossing) to the cerebellum via the massive middle cerebellar peduncle (discussed with Figure 55; see also Figure 6 and Figure 7). The role of this circuit in motor control will be explained with the cerebellum (see Figure 54–Figure 57).

The motor cranial nerve nuclei and their function have been discussed (see Figure 7 and Figure 8A), and their location within the brainstem will be described (see Figure 64–Figure 67). Only topographical aspects will be described here:

- **CN III — Oculomotor** (to most extra-ocular muscles and parasympathetic): These fibers traverse through the medial portion of the red nucleus, before exiting in the fossa between the cerebral peduncles, the interpeduncular fossa (see Figure 65A).
- **CN IV — Trochlear** (to the superior oblique muscle): The fibers from this nucleus cross in the posterior aspect of the lower midbrain before exiting posteriorly (see Figure 10 and Figure 66A). The slender nerve then wraps around the lower border of the cerebral peduncles in its course anteriorly.
- **CN V — Trigeminal** (to muscles of mastication): The motor fibers pierce the middle cerebellar peduncle in the mid-pontine region, along with the sensory component.
- **CN VI — Abducens** (to the lateral rectus muscle): The anterior course of the exiting fibers could not be depicted from this perspective.
- **CN VII — Facial** (to muscles of facial expression): The fibers to the muscles of facial expression have an internal loop before exiting. The nerve loops over the abducens nucleus, forming a bump called the facial colliculus in the floor of the fourth ventricle (see Figure 10). It should be noted that the nerve of only one side is being shown in this illustration.
- **CN IX — Glossopharyngeal and CN X-Vagus** (motor and parasympathetic): The fibers exit on the lateral aspect of the medulla, behind the inferior olive.
- **CN XI — Spinal Accessory** (to neck muscles): The fibers that supply the large muscles of the neck (sternomastoid and trapezius) originate in the upper spinal cord and ascend into the skull before exiting.
- **CN XII — Hypoglossal** (to muscles of the tongue): These fibers actually course anteriorly, exiting from the medulla between the inferior olive and the cortico-spinal (pyramidal) tract.

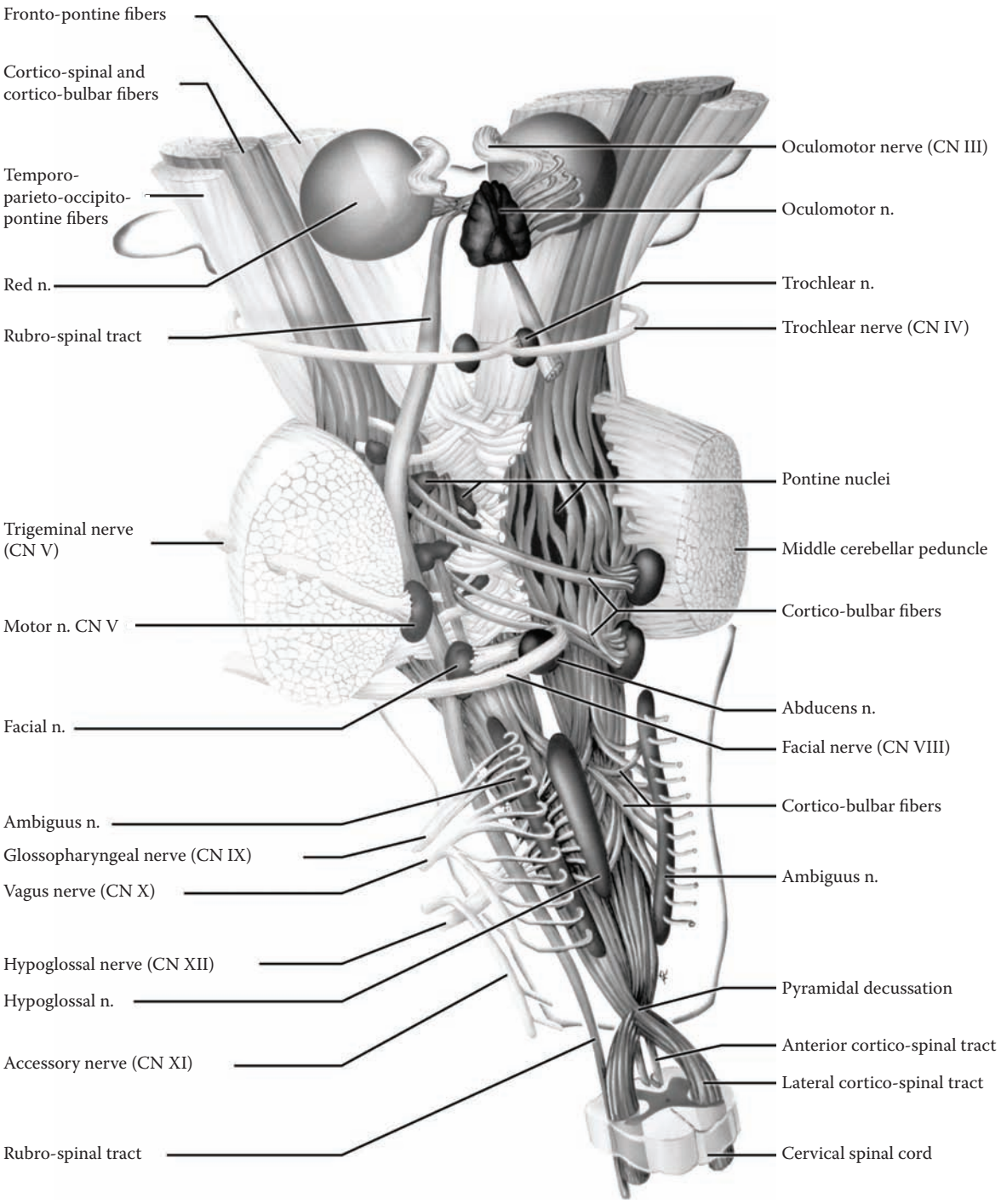


FIGURE 48: Descending Tracts and Cortico-Pontine Fibers

FIGURE 49A AND FIGURE 49B RETICULO-SPINAL TRACTS

INDIRECT VOLUNTARY AND NONVOLUNTARY MOTOR REGULATION

As has been noted (see Figure 42A and Figure 42B), the reticular formation is a collection of nuclei that participates in a number of functions, some quite general (e.g., "arousal") and others more specific (e.g., respiratory control). These nuclei of the reticular formation are also part of the indirect voluntary motor pathway, as well as nonvoluntary motor regulation (see Section B, Part III, Introduction).

The indirect voluntary pathway, the cortico-reticulospinal pathway, is thought to be an older pathway for the control of movements, particularly of proximal joints and the axial musculature. Therefore, some voluntary movements can still be performed after destruction of the cortico-spinal pathway (discussed with Figure 45). Muscle tone and reflex responsiveness are greatly influenced by activity in the reticular formation as part of the nonvoluntary motor system; it is important to note that cortical input to the reticular formation is part of this regulation.

The reticular formation receives input from many sources, including most sensory pathways (anterolateral, trigeminal, auditory, and visual). At this point, the focus is on the input from the cerebral cortex, from both hemispheres. These axons form part of the "cortico-bulbar system of fibers" (discussed with Figure 46).

Note to the Learner: Understanding the complexity of the various parts of the motor system and the role of the reticular formation in particular is not easy. One approach is to start with the basic reflex arc — the reticular formation assumes a significant role in the modification of this response, i.e., hyperreflexia or hyporeflexia, as well as muscle tone. In addition, there is the role of the reticular formation and other motor brainstem nuclei in the nonvoluntary response of the organism to gravitational changes. The next step would be the role of the reticular formation in motor control, particularly for axial musculature, as part of the indirect voluntary motor system. It now becomes important to understand that the cortex has an important role in controlling this system.

There are two pathways from the reticular formation to the spinal cord: one originates in the pontine region (this illustration) and one in the medullary region (next illustration).

FIGURE 49A — PONTINE (MEDIAL) RETICULO-SPINAL TRACT

This tract originates in the pontine reticular formation from two nuclei: the upper one is called the **oral portion** of the pontine reticular nuclei (nucleus reticularis pontis oralis), and the lower part is called the **caudal portion** (see Figure 42B). The tract descends to the spinal cord and is located in the medial region of the white matter (see Figure 68 and Figure 69); this pathway therefore is called the medial reticulo-spinal tract.

Functionally, this pathway exerts its action on the extensor muscles, both movements and tone. The area in the pons is known as the reticular extensor facilitatory area. The fibers terminate on the anterior horn cells controlling the axial muscles, likely via interneurons (see Figure 44). This system is complementary to that from the lateral vestibular nucleus (see Figure 50).

Neurological Neuroanatomy

The location of the tract in the brainstem is shown at cross-sectional levels of the mid-pons, the lower pons, the mid-medulla, and cervical and lumbar spinal cord levels. The tract is intermingled with others in the white matter of the spinal cord.

Clinical Aspect

Lesions involving the cortico-bulbar fibers including the cortico-reticular fibers will be discussed with the medullary reticular formation (next illustration).

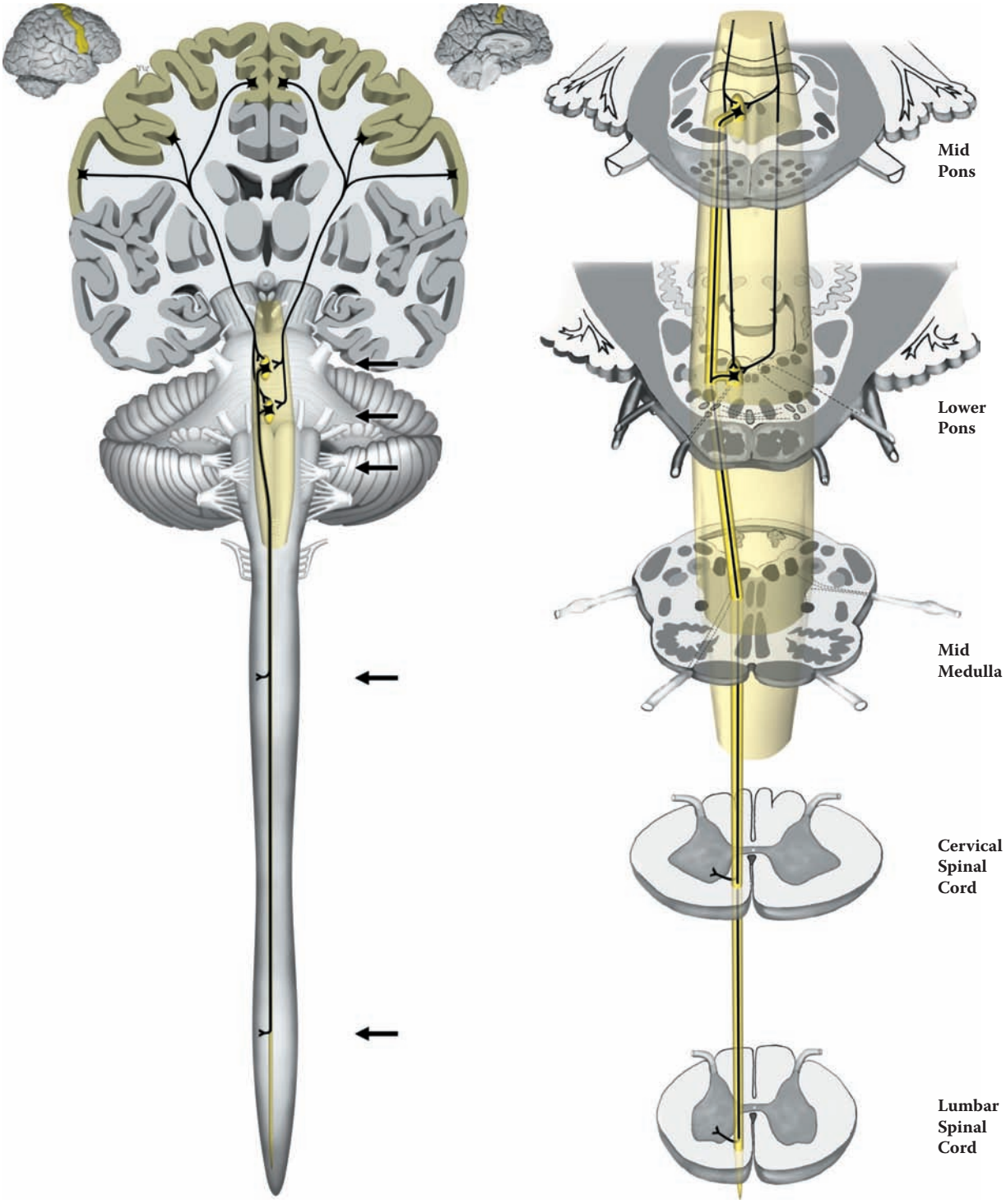


FIGURE 49A: Pontine (Medial) Reticulo-Spinal Tract

FIGURE 49B MEDULLARY (LATERAL) RETICULO-SPINAL TRACT

This tract originates in the medullary reticular formation, mainly from the **nucleus gigantocellularis** (meaning very large cells, see Figure 42A, Figure 42B, and Figure 67C). The tract descends more laterally in the spinal cord than the pontine pathway, and is thus named the lateral reticulo-spinal tract (see Figure 68 and Figure 69); some of the fibers are crossed. The tract lies beside the lateral vestibulo-spinal pathway.

The pathway also has its greatest influence on axial musculature. This part of the reticular formation is functionally the reticular extensor inhibitory area, opposite to that of the pontine reticular formation. This area depends for its normal activity on influences coming from the cerebral cortex.

Neurological Neuroanatomy

The location of the tract in the brainstem is shown at the cross-sectional levels of the mid-pons, the lower pons, the mid-medulla, and cervical and lumbar spinal cord levels, intermingled with other tracts in the white matter of the spinal cord (see Figure 68 and Figure 69).

Clinical Aspect: Spasticity

A lesion destroying the cortico-bulbar fibers, an **upper motor neuron lesion**, results in an increase in the tone of the extensor/anti-gravity muscles, which develops over a period of days. This increase in tone, called **spasticity**, tested by passive flexion and extension of a limb, is velocity dependent, meaning that the joint of the limb has to be moved quickly. It is the anti-gravity muscles that are affected in spasticity; in humans, for reasons that are difficult to explain, these muscles are the flexors of the upper limb and the extensors of the lower limb. There is also an increase in responsiveness of the stretch reflex, called **hyperreflexia**, as tested using the deep tendon reflex, DTR (discussed with Figure 44), which also develops over a period of several days.

There are two hypotheses for the increase in the stretch (monosynaptic) reflex responsiveness:

- **Denervation supersensitivity**: One possibility is a change of the level of responsivity of the neurotransmitter receptors of the motor neurons themselves caused by the loss of the descending input, leading to an increase in excitability.
- **Collateral sprouting**: Another possibility is that axons adjacent to an area that has lost synaptic input will sprout branches and occupy the vacated synaptic sites of the lost descending fibers. In this case, the sprouting is thought to be of the incoming muscle afferents (called 1A afferents, from the muscle spindles).

There is experimental evidence (in animals) for both mechanisms. Spasticity and hyperreflexia usually occur in the same patient. Another feature accompanying hyperreflexia is **clonus**. This can be elicited by grasping the foot and jerking the ankle upward; in a person with hyperreflexia, the response is a short burst of flexion-extension responses of the ankle, which the tester can feel and which also can be seen.

Lesions involving parts of the motor areas of the cerebral cortex, large lesions of the white matter of the hemispheres or of the posterior limb of the internal capsule, and certain lesions of the upper brainstem all may lead to a similar clinical state in which a patient is paralyzed or has marked weakness, with spasticity and hyperreflexia (with or without clonus) on the contralateral side some days after the time of the damage. The cortico-spinal tract would also be involved in most of these lesions, with loss of voluntary motor control, and with the appearance of the Babinski sign in most cases immediately after the lesion (see Introduction to this section).

A similar situation occurs following large lesions of the spinal cord in which all the descending motor pathways are disrupted, both voluntary and nonvoluntary. Destruction of the whole cord would lead to paralysis below the level of the lesion (paraplegia), bilateral spasticity, and hyperreflexia (usually with clonus), a severely debilitating state.

It is most important to distinguish this state from that seen in a Parkinsonian patient who has a change of muscle tone called **rigidity** (discussed with Figure 24), with no change in reflex responsiveness and a normal plantar response.

This state should be contrasted with a **lower motor neuron lesion** of the anterior horn cell, with hypotonia and hyporeflexia as well as weakness (e.g., polio, discussed with Figure 44).

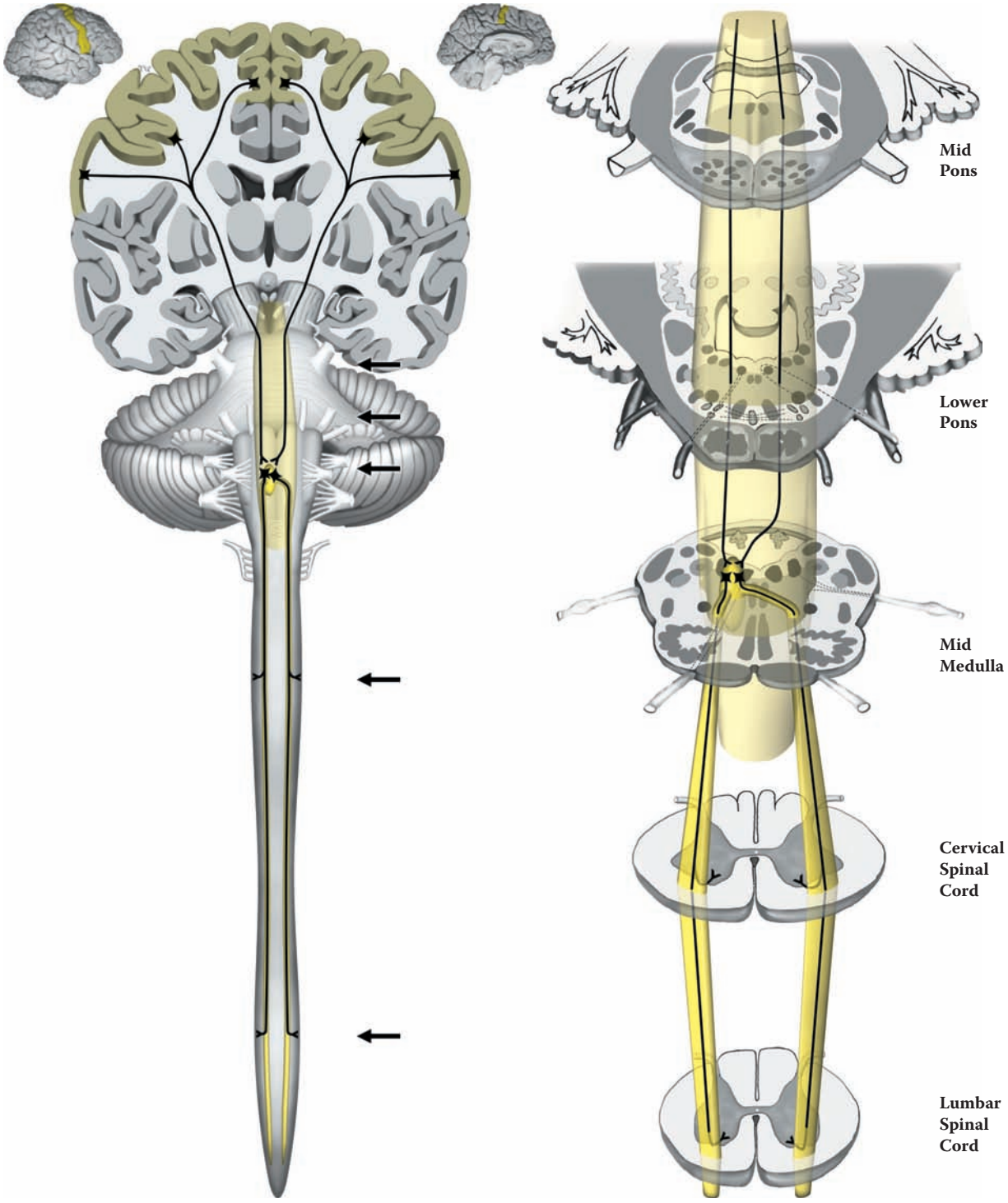


FIGURE 49B: Medullary (Lateral) Reticulo-Spinal Tract

FIGURE 50
LATERAL VESTIBULO-SPINAL TRACT

NONVOLUNTARY MOTOR REGULATION

This pathway is very important in that it provides a link between the vestibular influences (i.e., gravity and balance) and the control of axial musculature, via the spinal cord. The main function is to provide corrective muscle activity when the body (and head) tilt or change orientation in space (activation of the vestibular system, CN VIII, see Figure 8B).

This tract originates in the **lateral vestibular nucleus**, which is located in the lower pontine region (see next illustration and Figure 66C). The nucleus is found at the lateral edge of the fourth ventricle and is characterized by extremely large neurons. (This nucleus is also called Deiter's nucleus in some texts and the large neurons are often called by the same name.)

The lateral vestibular nucleus receives its major inputs from the vestibular system and from the cerebellum; there is no cerebral cortical input. This tract descends through the medulla and traverses the entire spinal cord in the ventral white matter (see Figure 68 and Figure 69). It does not decussate. The fibers terminate in the medial portion of the anterior horn, namely on those motor cells that control the axial musculature (see Figure 44).

Functionally, this pathway increases extensor muscle tone and activates extensor muscles. It is easier to think of these muscles as anti-gravity muscles in a four-legged animal; in humans, one must translate these muscles in functional terms, which are the flexors of the upper extremity and the extensors of the lower extremity.

Neurological Neuroanatomy

The same cross-sectional levels have been used as with the reticular formation, starting at the mid-pons. The vestibular nuclei are found at the lower pontine level and are seen through the mid-medulla; the tract descends throughout the spinal cord, as seen at cervical and lumbar levels. In the spinal cord the tract is positioned anteriorly, just in front of the ventral horn (see Figure 68 and Figure 69) and innervates the medial group of motor nuclei.

Clinical Aspect

A lesion of this pathway would occur with spinal cord injuries and this would be one of the "upper motor neuron" pathways involved, leading to spasticity and hyperreflexia.

Decorticate rigidity: Humans with severe lesions of the cerebral hemispheres but whose brainstem circuitry is intact often exhibit a postural state known as decorticate rigidity. In this condition, there is a state of flexion of the forearm and extension of the legs.

Decerebrate Rigidity: Humans with massive cerebral trauma, anoxic damage, or midbrain destructive lesions exhibit a postural state in which all four limbs are rigidly extended. The back is arched and this may be so severe as to cause a posture known as opisthotonus, in which the person is supported by the back of the neck and the heels.

Physiologically, these conditions are not related to Parkinsonian rigidity but to the abnormal state of spasticity (see discussion with the previous illustration). The postulated mechanism involves the relative influence of the pontine and medullary reticular formations, along with the vestibulo-spinal pathway, with and without the input from the cerebral cortex.

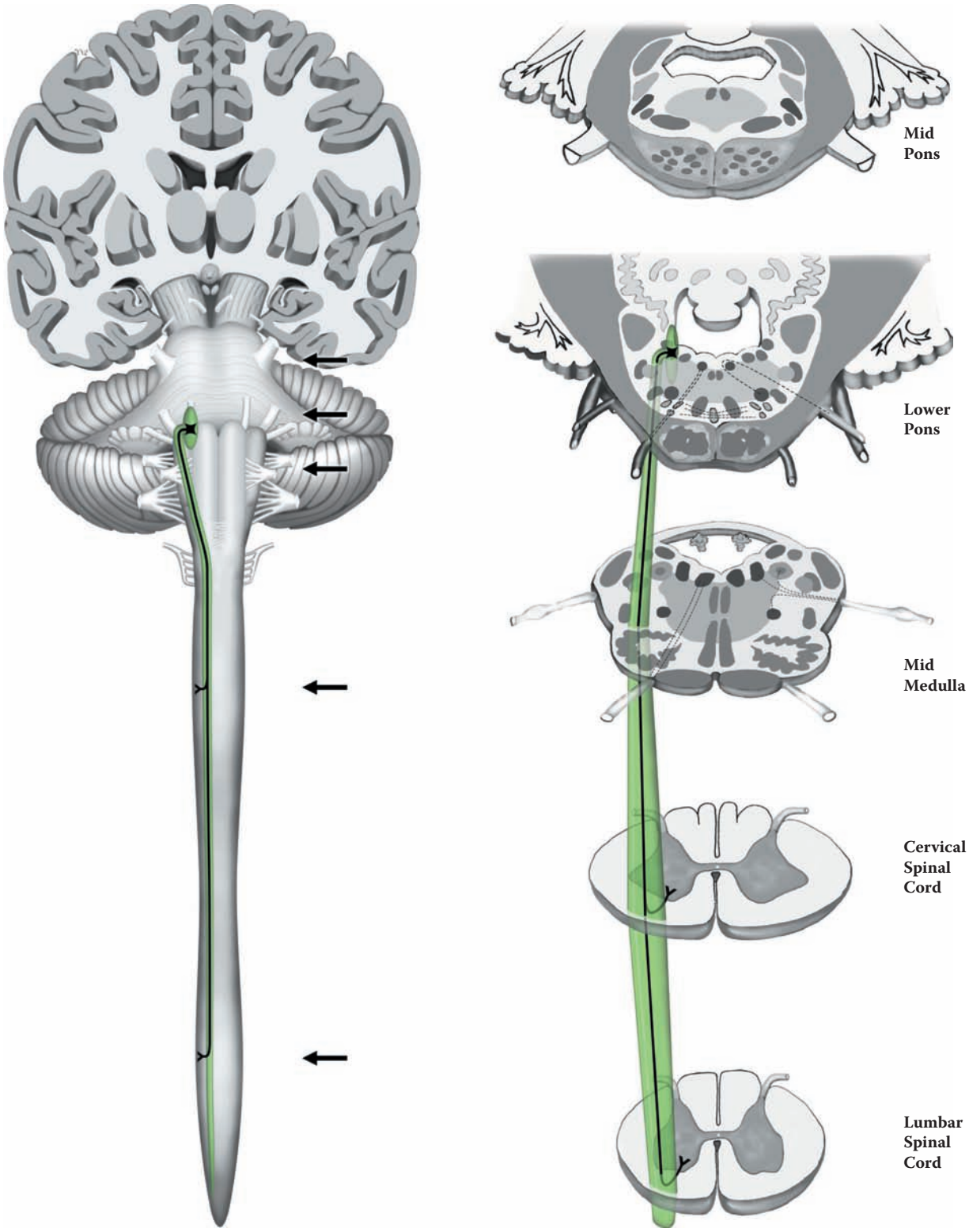


FIGURE 50: Lateral Vestibulo-Spinal Tract

FIGURE 51A
VESTIBULAR SYSTEM

VESTIBULAR NUCLEI AND EYE MOVEMENTS

The vestibular system carries information about our position in relation to gravity and changes in that position. The sensory system is located in the inner ear and consists of three **semicircular canals** and other sensory organs in a bony and membranous labyrinth. There is a peripheral ganglion (the spiral ganglion), and the central processes of these cells, CN VIII, enter the brainstem at the cerebellar-pontine angle, just above the cerebellar flocculus (see Figure 6, Figure 7, and Figure 8B).

The vestibular information is carried to **four vestibular nuclei**, which are located in the upper part of the medulla and lower pons: superior, lateral, medial, and inferior (see Figure 8B; also Figure 66C, Figure 67A, and Figure 67B). The **lateral vestibular nucleus** gives rise to the lateral vestibulo-spinal tract (as described in the previous illustration; see also the following illustration). This is the pathway that serves to adjust the postural musculature to changes in relation to gravity.

The **medial and inferior vestibular nuclei** give rise to both ascending and descending fibers, which join a conglomerate bundle called the **medial longitudinal fasciculus (MLF)** (described more fully with the next illustration). The descending fibers from the medial vestibular nucleus, if considered separately, could be named the **medial vestibulo-spinal tract** (see Figure 68). This system is involved with postural adjustments to positional changes, using the axial musculature.

The ascending fibers adjust the position of the eyes and coordinate eye movements of the two eyes by interconnecting the three cranial nerve nuclei involved in the control of eye movements — CN III (oculomotor) in the upper midbrain, CN IV (trochlear) in the lower midbrain, and CN VI (abducens) in the lower pons (see Figure 8A, Figure 48, and also Figure 51B). If one considers lateral gaze, a movement of the eyes to the side (in the horizontal plane), this requires the coordination of the lateral rectus muscle (abducens nucleus) of one side and the medial rectus (oculomotor nucleus) of the other side; this eye movement is called conjugate. These fibers for coordinating the eye movements are carried in the MLF.

There is a "gaze center" within the pontine reticular formation for **saccadic** eye movements. These are extremely rapid (ballistic) movements of both eyes, yoked together, usually in the horizontal plane so that we can shift our focus extremely rapidly from one object to another. The fibers controlling this movement originate from the cortex, from the frontal eye field (see Figure 14A), and also likely course in the MLF.

Clinical Aspect

A not uncommon tumor, called an acoustic neuroma, can occur along the course of the acoustic nerve, usually at the cerebello-pontine angle. This is a slow-growing benign tumor, composed of Schwann cells, the cell responsible for myelin in the peripheral nervous system. Initially, there will be a complaint of loss of hearing, or perhaps a ringing noise in the ear (called tinnitus). Because of its location, as it grows it will begin to compress the adjacent nerves (including CN VII). Eventually, if left unattended, there would be additional symptoms due to further compression of the brainstem and an increase in intracranial pressure. Modern imaging techniques allow early detection of this tumor. Surgical removal, though, still requires considerable skill so as not to damage CN VIII itself (which would produce a loss of hearing), or CN VII (which would produce a paralysis of facial muscles) and adjacent neural structures.

Additional Detail

There is a small nucleus in the periaqueductal gray region of the midbrain that is associated with the visual system and is involved in the coordination of eye and neck movements. This nucleus is called the interstitial nucleus (of Cajal). It is located near the oculomotor nucleus. This nucleus (see also the next illustration) receives input from various sources and contributes fibers to the MLF. Some have named this pathway the interstitio-spinal "tract."

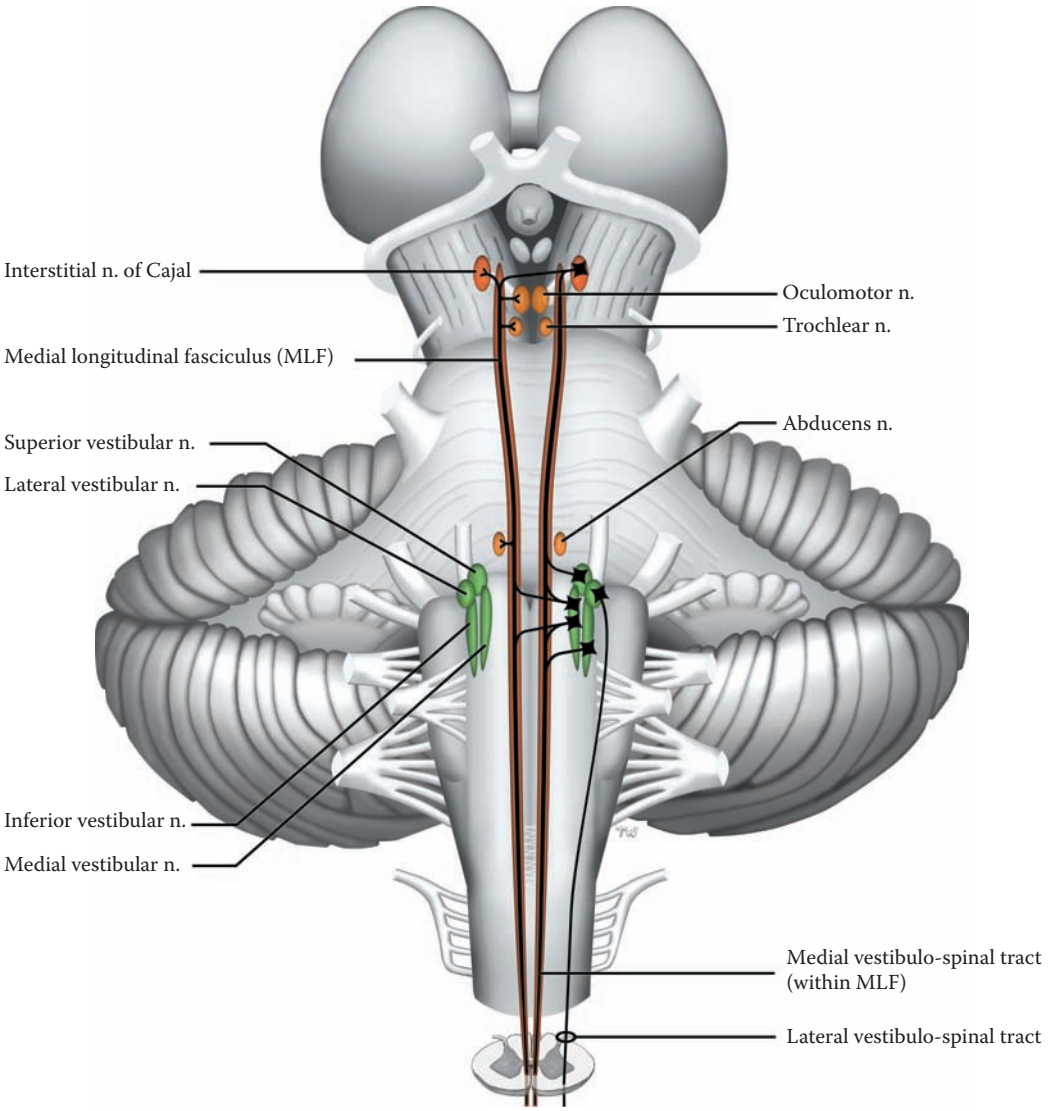


FIGURE 51A: Vestibular Nuclei and Eye Movements

FIGURE 51B MEDIAL LONGITUDINAL FASCICULUS (MLF)

MLF AND ASSOCIATED TRACTS

This diagram shows the brainstem from the posterior perspective (as in Figure 10 and Figure 40). Note the orientation of the spinal cord (with the ventral horn away from the viewer).

The MLF is a tract within the brainstem and upper spinal cord that links the visual world and vestibular events with the movements of the eyes and the neck, as well as linking up the nuclei that are responsible for eye movements. The tract runs from the midbrain level to the upper thoracic level of the spinal cord. It has a rather constant location near the midline, dorsally, just anterior to the aqueduct of the midbrain and the fourth ventricle (see brainstem cross-sections, e.g., Figure 65A, Figure 66A, and Figure 67A).

The MLF is, in fact, composed of several tracts running together:

- **Vestibular fibers**: Of the four vestibular nuclei (see previous illustration), descending fibers originate from the medial vestibular nuclei and become part of the MLF; this can be named separately the medial vestibulo-spinal tract. There are also ascending fibers that come from the medial, inferior, and superior vestibular nuclei that also are carried in the MLF. Therefore, the MLF carries both ascending and descending vestibular fibers.
- **Visuomotor fibers**: The interconnections between the various nuclei concerned with eye movements are carried in the MLF (as described in the previous illustration).
- **Vision-related fibers**: Visual information is received by various brainstem nuclei.
  - The superior colliculus is a nucleus for the coordination of visual-related reflexes, including eye movements (see Figure 9A). The superior colliculus coordinates the movements of the eyes and the turning of the neck in response to visual information. It also receives input from the visual association cortical areas, areas 18 and 19 (see Figure 17 and Figure 41B). The descending fibers from the superior colliculus, called the **tecto-spinal tract**, are closely associated with the MLF and can be considered part of this system (although in most books it is discussed separately). As shown in the upper inset, these fibers cross in the midbrain. (Note that the superior colliculus [SC] of only one side is shown in order not to obscure the crossing fiber systems at that level.)
  - The small interstitial nucleus and its contribution have already been noted and discussed with the previous illustration.

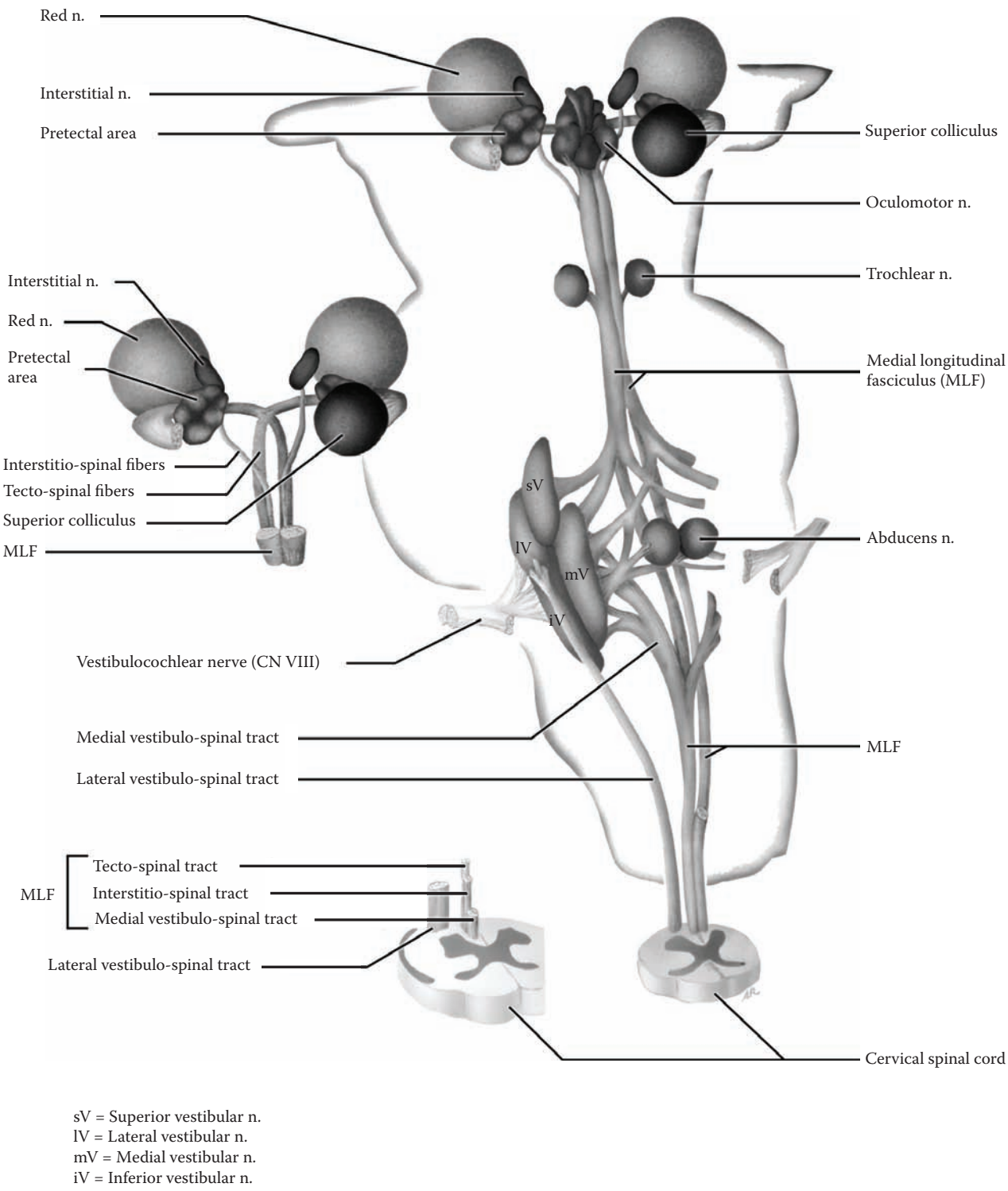
The lower inset shows the MLF in the ventral funiculus (white matter) of the spinal cord, at the cervical level (see Figure 68 and Figure 69). The three components of the tract are identified, those coming from the medial vestibular nucleus, the fibers from the interstitial nucleus, and the tecto-spinal tract. These fibers are mingled together in the MLF.

In summary, the MLF is a complex fiber bundle that is necessary for the proper functioning of the visual apparatus. The MLF interconnects the three cranial nerve nuclei responsible for movements of the eyes, with the motor nuclei controlling the movements of the head and neck. It allows the visual movements to be influenced by vestibular, visual, and other information, and carries fibers (upward and downward) that coordinate the eye movements with the turning of the neck.

The diagram also shows the posterior commissure (not labeled). This small commissure carries fibers connecting the superior colliculi. In addition, it carries the important fibers for the consensual pupillary light reflex coordinated in the pretectal "nucleus"' (discussed with Figure 41C).

Clinical Aspect

A lesion of the MLF interferes with the normal conjugate movements of the eyes. When a person is asked to follow an object (e.g., the tip of a pencil moving to the right) with the head steady, the two eyes move together in the horizontal plane. With a lesion of the MLF (such as demyelination in multiple sclerosis), the abducting eye (the right eye) moves normally but the adducting eye (the left eye) fails to follow; yet, adduction is preserved on convergence. Clearly the nuclei and the nerves are intact; the lesion, then, is in the fibers coordinating the movement. This condition is known as **internuclear ophthalmoplegia**. Sometimes there is also monocular horizontal nystagmus (rapid side-to-side movements) of the abducting eye.



sV = Superior vestibular n.
lV = Lateral vestibular n.
mV = Medial vestibular n.
iV = Inferior vestibular n.

FIGURE 51B: Medial Longitudinal Fasciculus (MLF)

FIGURE 52
MOTOR REGULATORY SYSTEM A

BASAL GANGLIA CIRCUITRY

Upper Illustration

This is the same view of the basal ganglia as shown previously (see Figure 24), with the head of the caudate nucleus removed. The illustration includes the two other parts of the basal ganglia as a functional "system" — the subthalamic nucleus and the substantia nigra.

- **The subthalamic nucleus (S)** is situated in a small region below the level of the thalamus.
- **The substantia nigra (SN)** is a flattened nucleus located in the midbrain region. It is composed of two parts (see Figure 65A).
  - The **pars compacta** has the pigment-containing cells (see Figure 15B and Figure 65). These neurons project their fibers to the caudate and putamen (the striatum or neostriatum). This is called the nigro-striatal "pathway," although the fibers do not form a compact bundle; the neurotransmitter involved is dopamine.
  - The **pars reticulata** is situated more ventrally. It receives fibers from the striatum and is also an output nucleus from the basal ganglia to the thalamus, like the internal segment of the globus pallidus (see below).

Lower Illustration: Basal Ganglia Circuitry

Information flows into the caudate (C) and putamen (P) from all areas of the cerebral cortex (in a topographic manner, see next illustration), from the substantia nigra (dopaminergic from the pars compacta), and from the centromedian nucleus of the thalamus (see below). This information is processed and passed through to the globus pallidus, internal segment (GPi), and the pars reticulata of the substantia nigra; these are the output nuclei of the basal ganglia.

Most of this information is relayed to the specific relay nuclei of the thalamus, the ventral anterior (**VA**) and **ventral lateral** (**VL**) nuclei (see Figure 12 and Figure 63). These project to the premotor and supplementary motor cortical areas (see Figure 14A, Figure 17, and Figure 60). (This is to be contrasted with the projection of the cerebellum to the cortex, discussed with Figure 57.) The circuitry involving the basal ganglia, the thalamus, and the motor cortical areas will be described in detail with the next illustration.

In addition, there is a subcircuit involving the subthalamic nucleus (S): the external segment of the globus pallidus sends fibers to the subthalamic nucleus, and this nucleus sends fibers to the internal segment of the globus pallidus, the output portion.

Another subloop of the basal ganglia involves the centromedian nucleus of the thalamus, a nonspecific nucleus (see Figure 12). The loop starts in the striatum (only the caudate nucleus is shown here), to both segments of the globus pallidus; then fibers from the globus pallidus internal segment are sent to the centromedian nucleus, which then sends its fibers back to the striatum (see Figure 63).

Clinical Aspect (see also Figure 24)

Parkinson's disease: The degeneration of the dopamine-containing neurons of the pars compacta of the substantia nigra, with the consequent loss of their dopamine input to the basal ganglia (the striatum) leads to this clinical entity. Those afflicted with this disease have slowness of movement (bradykinesia), reduced facial expressiveness ("mask-like" face), and a tremor at rest, typically a "pill-rolling" type of tremor. On examination, there is **rigidity**, manifested as an increased resistance to passive movement of both flexors and extensors, which is not velocity-dependent. (This is to be contrasted with spasticity, discussed with Figure 49B.) In addition, there is *no* change in reflexes.

The medical treatment of Parkinson's disease has limitations, although various medications and combinations (as well as newer drugs) can be used for many years. For these patients, as well as in other select clinical cases, a surgical approach for the alleviation of the symptoms of the Parkinson's disease has been advocated, including placing lesions in the circuitry or using stimulating electrodes (with external control devices). To date, the theory has been that these surgical approaches are attempting to restore the balance of excitation and inhibition to the thalamus, thereby restoring the appropriate influence to the cortical areas involved in motor control.

The motor abnormality associated with a lesion of the subthalamic nucleus is called **hemiballismus**. The person is seen to have sudden flinging movements of a limb, on the side of the body opposite to the lesion. The likely cause for this is usually a vascular lesion.

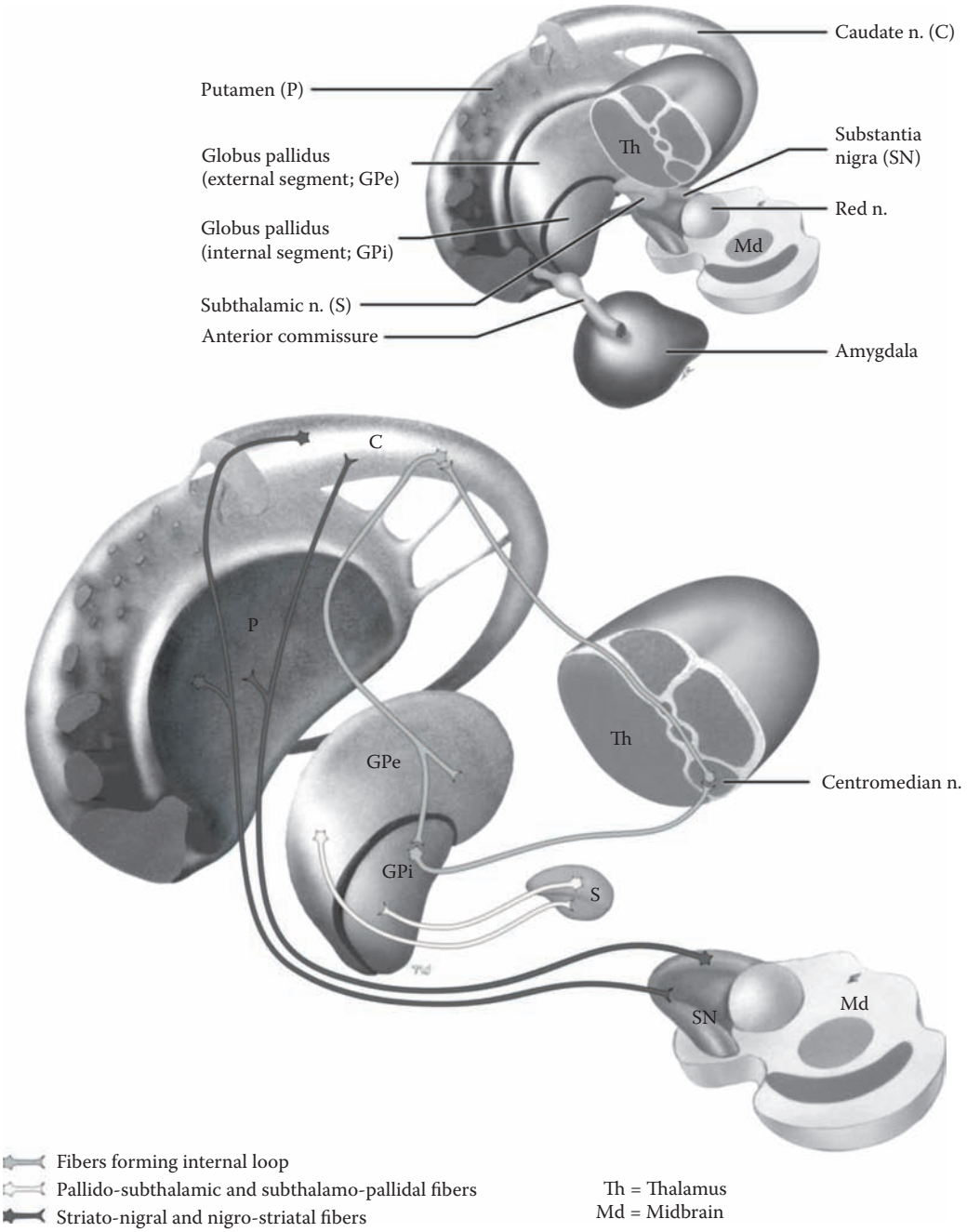


FIGURE 52: Basal Ganglia Circuitry

FIGURE 53
MOTOR REGULATORY SYSTEM B

THALAMUS: MOTOR CIRCUITS

The specific relay nuclei of the thalamus that are linked with the motor systems, the basal ganglia and the cerebellum, are the **ventral lateral (VL) and the ventral anterior (VA)** nuclei (see Figure 12 and Figure 63). These project to the different cortical areas involved in motor control, the motor strip, the premotor area, and the supplementary motor area (as shown in the upper insets). These thalamic nuclei also receive input from these cortical areas, in line with the reciprocal connections of the thalamus and cortex. One of the intralaminar nuclei, the centromedian nucleus, is also linked with the circuitry of the basal ganglia (described in the previous illustration).

Basal Ganglia: The neostriatum receives input from wide areas of the cerebral cortex, as well as from the dopamergic neurons of the substantia nigra. Fibers are then sent to the globus pallidus. The major outflow from the basal ganglia, from the internal (medial) segment of the globus pallidus, follows two slightly different pathways to the thalamus, as pallido-thalamic fibers. One group of fibers passes around, and the other passes through the fibers of the internal capsule (represented on the diagram by large stippled arrows). These merge and end in the ventral anterior (VA) and ventral lateral (VL) nuclei of the thalamus (see Figure 63). (The ventral anterior nucleus is not seen on this section through the thalamus.) The other outflow from the basal ganglia via the pars reticulata of the substantia nigra generally follows the same projection to these thalamic nuclei (not shown). The projection from these thalamic nuclei to the cerebral cortex goes to the premotor and supplementary motor areas, as shown in the small insets (in the upper figures; see Figure 14A and Figure 17; also Figure 60), cortical areas concerned with motor regulation and planning.

The pathway from thalamus to cortex is excitatory. The basal ganglia influence is to modulate the level of excitation of the thalamic nuclei. Too much inhibition leads to a situation that the motor cortex has insufficient activation, and the prototypical syndrome for this is Parkinson's (discussed with Figure 24 and Figure 52). Too little inhibition leads to a situation that the motor cortex receives too much stimulation and the prototypical syndrome for this is Huntington's chorea (discussed with Figure 24). The analogy that has been used to understand these diseases is to a motor vehicle, in which a balance is needed between the brake and the gas pedal for controlled forward motion in traffic.

The MOTOR areas of the cerebral cortex that receive input from these two subsystems of the motor system are shown diagrammatically in the small insets, both on the dorsolateral surface and on the medial surface of the hemispheres (see Figure 14 and Figure 17).

Cerebellum (to be reviewed *after* study of the cerebellum): The other part of the motor regulatory systems, the cerebellum, also projects (via the superior cerebellar peduncles) to the thalamus. The major projection is to the VL nucleus, but to a different portion of it than the part that receives the input from the basal ganglia. From here, the fibers project to the motor areas of the cerebral cortex, predominantly the precentral gyrus as well as the premotor area, areas 4 and 6, respectively (see Figure 57).

Clinical Aspect

Many years ago it was commonplace to refer to the basal ganglia as part of the **extrapyramidal motor system** (in contrast to the pyramidal motor system — discussed with Figure 45, the cortico-spinal tract). It is now known that the basal ganglia exert their influence through the appropriate parts of the cerebral cortex, which then acts either directly, i.e., using the cortico-spinal (pyramidal) tract, or indirectly via certain brainstem nuclei (cortico-bulbar pathways, see Figure 46) to alter motor activity. The term extrapyramidal should probably be abandoned, but it is still frequently encountered in a clinical setting.

Tourette's syndrome is a motor disorder manifested by tics, uncontrolled sudden movements; occasionally, these individuals have bursts of uncontrolled language, which rarely contains vulgar expletives. This disorder starts in childhood and usually has other associated behavioral problems, including problems with attention. There is growing evidence that this disorder is centered in the basal ganglia. The condition may persist into adulthood.

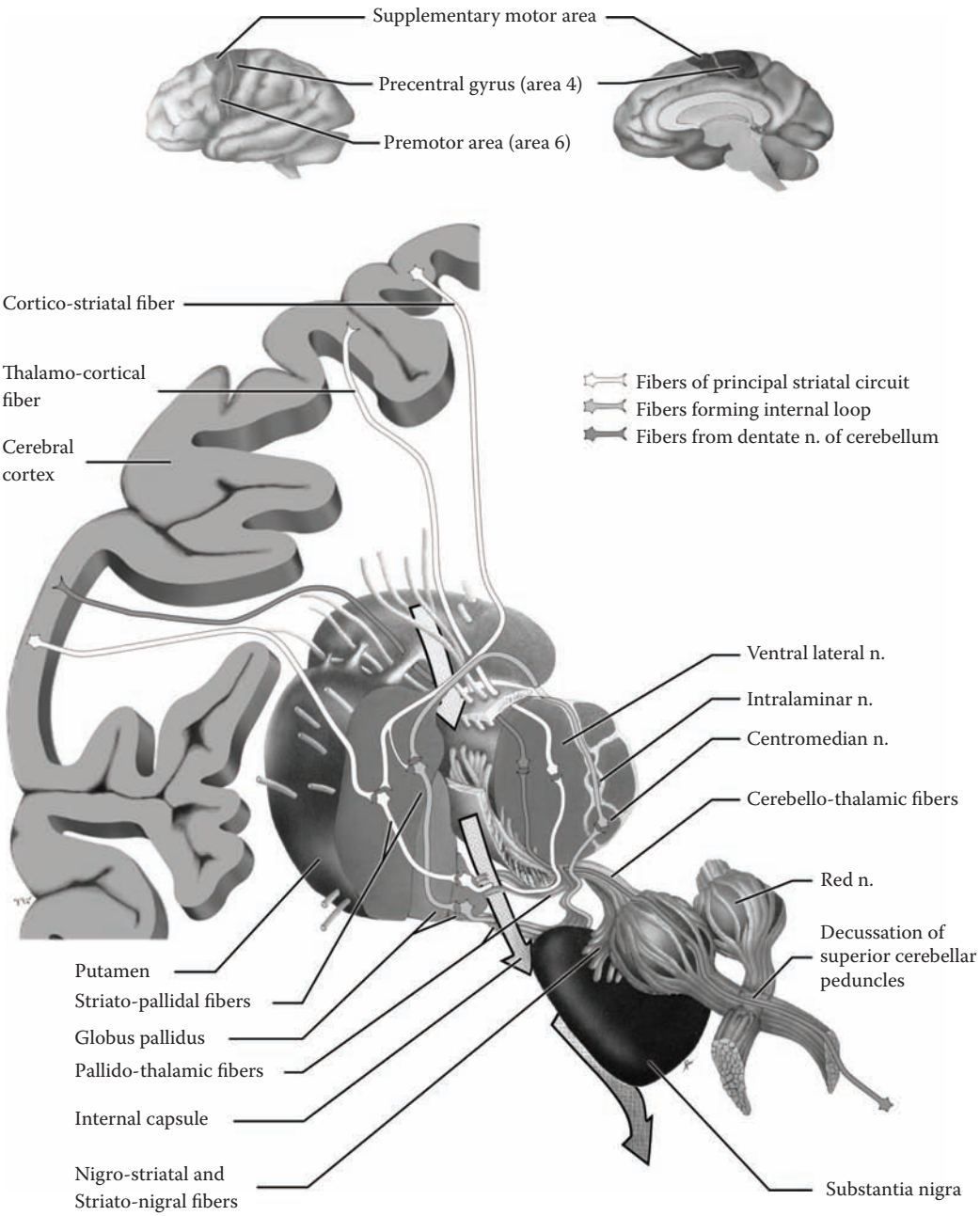


FIGURE 53: Thalamus — Motor Circuits

FIGURE 54
CEREBELLUM 1

FUNCTIONAL LOBES

The cerebellum has been subdivided anatomically according to some constant features and fissures (see Figure 9A and Figure 9B). In the midline, the worm-like portion is the **vermis**; the lateral portions are the **cerebellar hemispheres**. The horizontal fissure lies approximately at the division between the superior and the inferior surfaces. The deep primary fissure is found on the superior surface and the area in front of it is the **anterior lobe** of the cerebellum. The only other parts to be noted are the nodulus and lingula of the vermis, as well as the tonsil.

In order to understand the functional anatomy of the cerebellum and its contribution to the regulation of motor control, it is necessary to subdivide the cerebellum into operational units. The three functional lobes of the cerebellum are

A. Vestibulocerebellum
B. Spinocerebellum
C. Neo- or cerebrocerebellum

These lobes of the cerebellum are defined by the areas of the cerebellar cortex involved, the related deep cerebellar nucleus, and the connections (afferents and efferents) with the rest of the brain.

There is a convention of portraying the functional cerebellum as if it is found in a single plane, using the lingula and the nodulus of the vermis as fixed points (see also Figure 17).

Note to the Learner: The best way to visualize this is to use the analogy of a book, with the binding toward you — representing the horizontal fissure. Place the fingers of your left hand on the edge of the front cover (the superior surface of the cerebellum) and the fingers of your right hand on the edges of the back cover (the inferior surface of the cerebellum), then (gently) open up the book so as to expose both the front and back covers. Both are now laid out in a single plane; now, the lingula is at the "top" of the cerebellum and the nodulus is at the bottom of the diagram. This same "flattening" can be done with an isolated brainstem and attached cerebellum in the laboratory.

Having done this, as is shown in the upper part of this figure, it is now possible to discuss the three functional lobes of the cerebellum.

- The **vestibulocerebellum** is the functional part of the cerebellum responsible for balance and gait. It is composed of two cortical components, the flocculus and the nodulus; hence, it is also called the **flocculonodular lobe**. The flocculus is a small lobule of the cerebellum located on its inferior surface and oriented in a transverse direction, below the middle cerebellar peduncle (see Figure 6 and Figure 7); the nodulus is part of the vermis. The vestibulocerebellum sends its fibers to the **fastigial** nucleus, one of the deep cerebellar nuclei (discussed with Figure 56 and Figure 57).
- The **spinocerebellum** is concerned with coordinating the activities of the limb musculature. Part of its role is to act as a *comparator* between the intended and the actual movements. It is made up of three areas:
  - The **anterior lobe** of the cerebellum, the cerebellar area found on the superior surface, in front of the primary fissure (see Figure 9A)
  - Most of the **vermis** (other than the parts mentioned above, see Figure 9A and Figure 9B)
  - A strip of tissue on either side of the vermis called the **paravermal** or **intermediate zone** — there is no anatomical fissure demarcating this functional area

  The output deep cerebellar nuclei for this functional part of the cerebellum are mostly the **interposed** nuclei, the globose and emboliform nuclei (see Figure 56A and Figure 56B) and, in part, the fastigial nucleus.
- The **neocerebellum** includes the remainder of the cerebellum, the areas behind the primary fissure and the inferior surface of the cerebellum (see Figure 9A and Figure 9B), with the exception of the vermis itself and the adjacent strip, the paravermal zone. This is the largest part of the cerebellum and the newest from an evolutionary point of view. It is also known as the **cerebrocerebellum**, since most if its connections are with the cerebral cortex. The output nucleus of this part of the cerebellum is the **dentate** nucleus (see Figure 56 and Figure 57). The neocerebellum is involved with the overall coordination of voluntary motor activities and is also involved in motor planning.

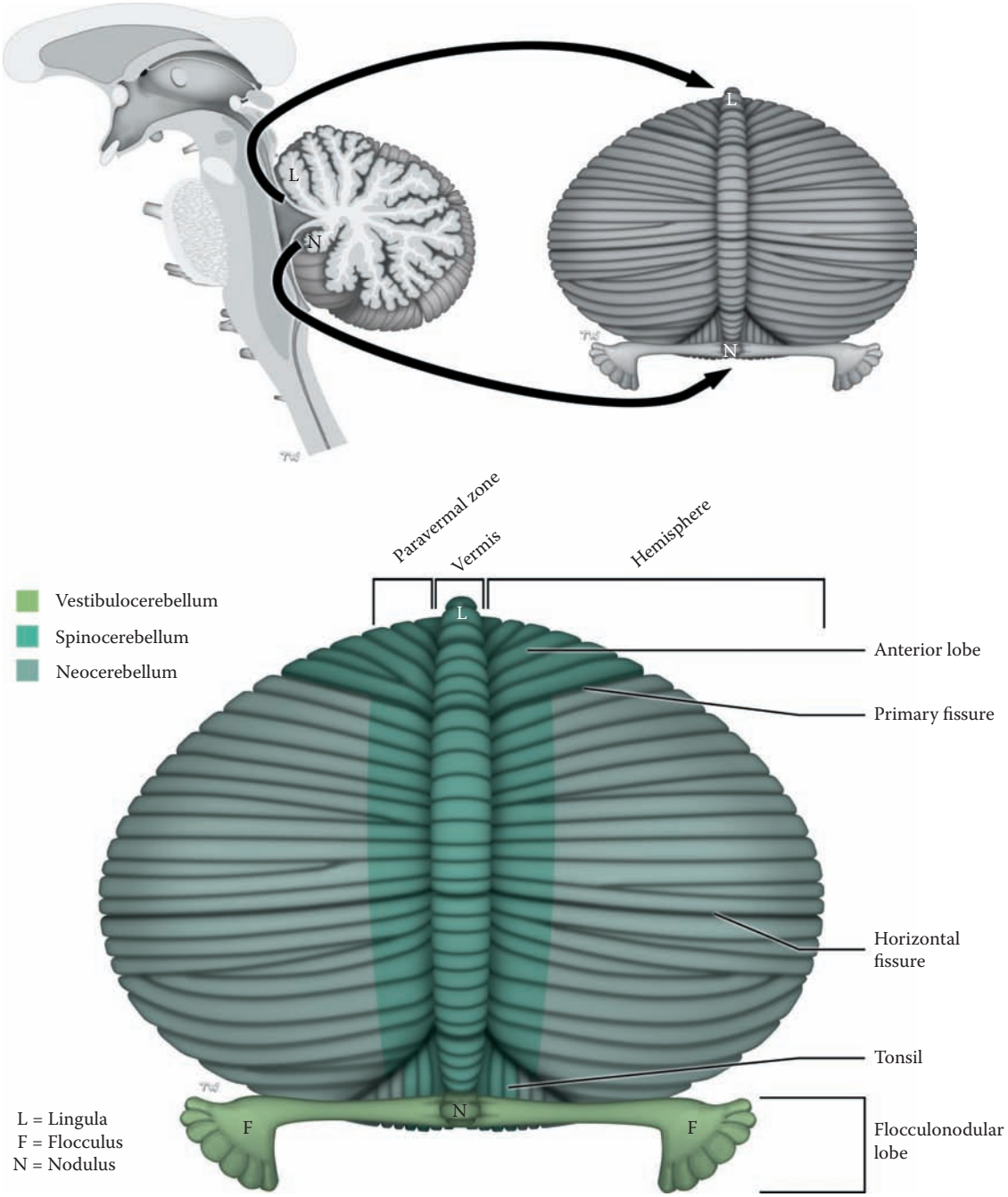


FIGURE 54: Cerebellum 1 — Functional Lobes

FIGURE 55
CEREBELLUM 2

CEREBELLAR AFFERENTS

Information relevant to the role of the cerebellum in motor regulation comes from the cerebral cortex, the brainstem, and from the muscle receptors in the periphery. The information is conveyed to the cerebellum mainly via the middle and inferior cerebellar peduncles.

- **Inferior Cerebellar Peduncle**: The inferior cerebellar peduncle goes from the medulla to the cerebellum. It lies behind the inferior olivary nucleus and can sometimes be seen on the ventral view of the brainstem (as in Figure 7). This peduncle conveys a number of fiber systems to the cerebellum. These are shown schematically in this diagram of the ventral view of the brainstem and cerebellum. They include the following:
  - **The posterior (dorsal) spino-cerebellar** pathway conveys proprioceptive information from most of the body. This is one of the major tracts of the inferior peduncle. These fibers, carrying information from the muscle spindles, relay in the dorsal nucleus of Clarke in the spinal cord (see Figure 32). They ascend ipsilaterally in a tract that is found at the edge of the spinal cord (see Figure 68). The dorsal spino-cerebellar fibers terminate ipsilaterally; these fibers are distributed to the spino-cerebellar areas of the cerebellum.
  - The homologous tract for the upper limb is the **cuneo-cerebellar** tract. These fibers relay in the accessory (external) cuneate nucleus, located in the lower medulla (see Figure 67B and Figure 67C). This pathway is not shown in the diagram.
  - The **olivo-cerebellar** tract is also carried in this peduncle. The fibers originate from the inferior olivary nucleus (see Figure 6, Figure 7, Figure 67, and Figure 67B), cross in the medulla, and are distributed to all parts of the cerebellum. These axons have been shown to be the climbing fibers to the main dendritic branches of the Purkinje neurons.
  - Other cerebellar afferents from other nuclei of the brainstem, including the reticular formation, are conveyed to the cerebellum via this peduncle. Most important are those from the medial (and inferior) vestibular nuclei to the vestibulocerebellum. Afferents from the visual and auditory system are also known to be conveyed to the cerebellum.
- **Middle Cerebellar Peduncle**: All parts of the cerebral cortex contribute to the massive **cortico-pontine** system of fibers (also described with Figure 48). These fibers descend via the anterior and posterior limbs of the internal capsule, then the inner and outer parts of the cerebral peduncle, and terminate in the pontine nuclei. The fibers synapse and cross, and go to all parts of the cerebellum via the middle cerebellar peduncle (see Figure 6 and Figure 7). This input provides the cerebellum with the cortical information relevant to motor commands and the planned (intended) motor activities.
- **Superior Cerebellar Peduncle**: Only one afferent tract enters via the superior cerebellar peduncle (see below). This peduncle carries the major efferent pathway from the cerebellum (discussed with Figure 57).

Additional Detail

One group of cerebellar afferents, those carried in the **ventral (anterior) spino-cerebellar tract**, enters the cerebellum via the superior cerebellar peduncle. These fibers cross in the spinal cord, ascend (see Figure 68), enter the cerebellum, and cross again, thus terminating on the same side from which they originated.

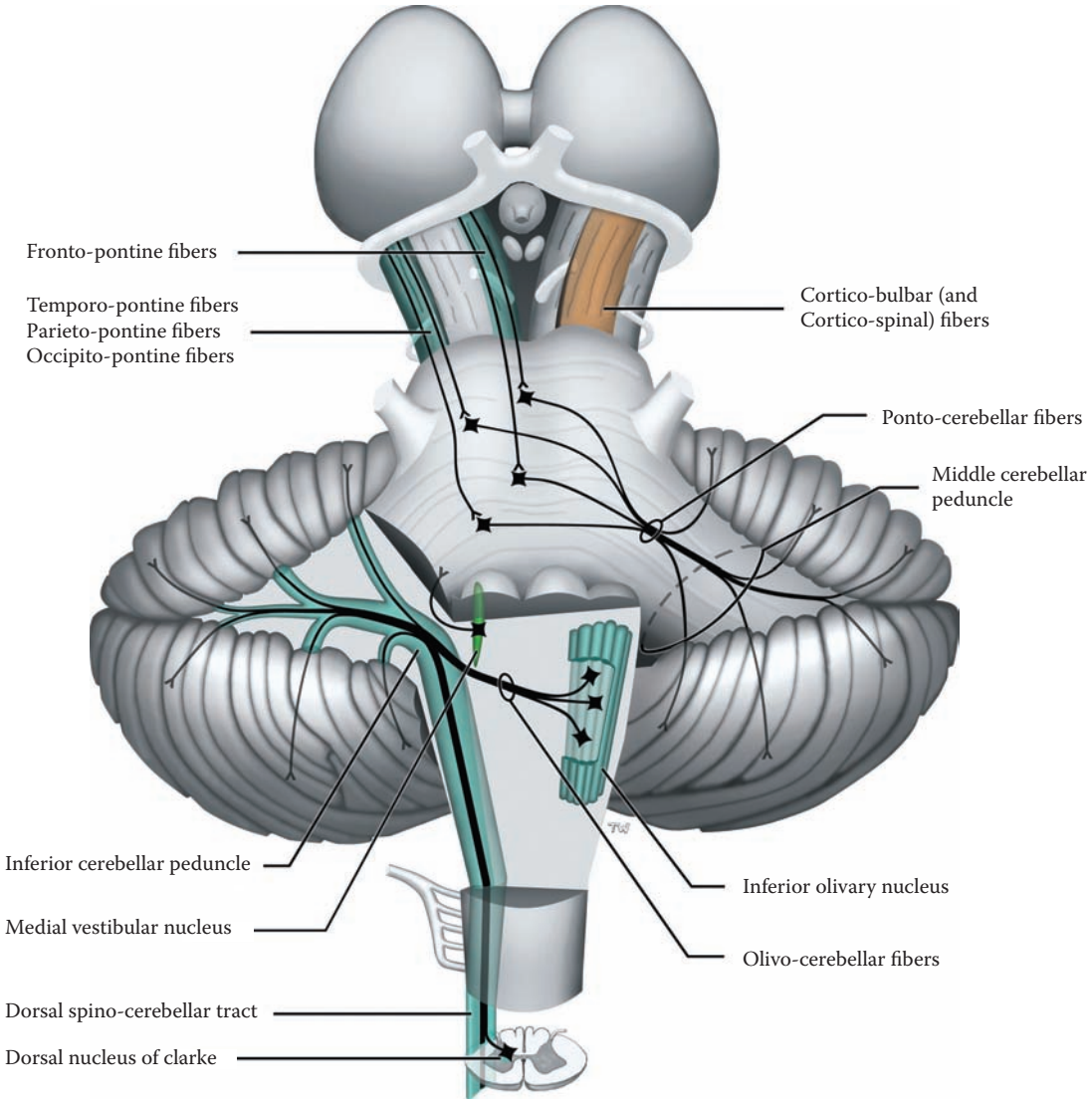


FIGURE 55: Cerebellum 2 — Cerebellar Afferents

FIGURE 56A
CEREBELLUM 3

INTRACEREBELLAR (DEEP CEREBELLAR) NUCLEI

The brainstem is presented from the anterior perspective, with the cerebellum attached (as in Figure 6, Figure 7, Figure 8A, and Figure 8B). This diagram shows the **intracerebellar** nuclei — also called the **deep cerebellar nuclei** — within the cerebellum.

There are four pairs of deep cerebellar nuclei — the **fastigial** nucleus, the **globose** and **emboliform** nuclei (together called the intermediate or interposed nucleus), and the lateral or **dentate** nucleus. Each belongs to a different functional part of the cerebellum. These nuclei are the output nuclei of the cerebellum to other parts of the central nervous system.

- The fastigial (medial) nucleus is located next to the midline.
- The globose and emboliform nuclei are slightly more lateral; often these are grouped together and called the intermediate or interposed nucleus.
- The dentate nucleus, with its irregular margin, is most lateral. This nucleus is sometimes called the lateral nucleus and is by far the largest.

The nuclei are located within the cerebellum at the level of the junction of the medulla and the pons. Therefore, the cross-sections shown at this level (see Figure 66C) may include these deep cerebellar nuclei. Usually, only the dentate nucleus can be identified in sections of the gross brainstem and cerebellum done at this level (see Figure 67).

Two of the afferent fiber systems are shown on the left side — representing cortico-ponto-cerebellar fibers and spino-cerebellar fibers. All afferent fibers send collaterals to the deep cerebellar nuclei en route to the cerebellar cortex, and these are excitatory. Therefore, these neurons are maintained in a chronic state of activity.

The lateral vestibular nucleus functions as an additional deep cerebellar nucleus, because its main input is from the vestibulocerebellum (shown in the next illustration); its output is to the spinal cord (see Figure 50).

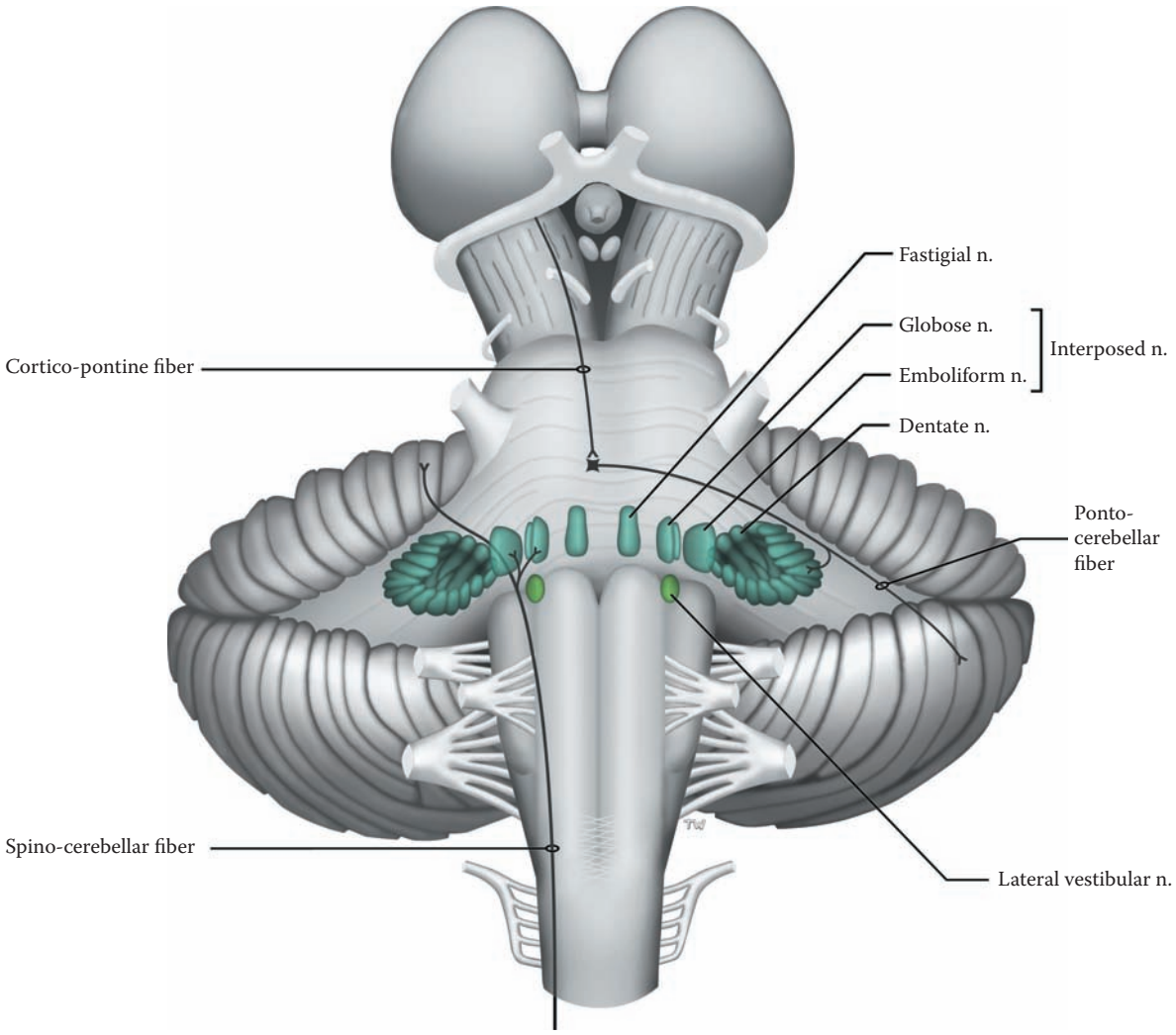


FIGURE 56A: Cerebellum 3 — Intracerebellar (Deep Cerebellar) Nuclei

FIGURE 56B
CEREBELLUM 4

INTRACEREBELLAR CIRCUITRY

The cerebellum is being presented from the dorsal perspective (as in Figure 9A). The third ventricle is situated between the two diencephala; the pineal gland is seen attached to the posterior aspect of the thalamus. Below are the colliculi, superior and inferior. On the right side of the illustration, the cerebellar hemisphere has been cut away, revealing the "interior" on this side.

The cerebellum is organized with cortical tissue on the outside, the **cerebellar cortex**. The cortex consists of three layers, and all areas of the cerebellum are histologically alike. The most important cell of the cortex is the **Purkinje neuron**, which forms a layer of cells; their massive dendrites receive the input to the cerebellum. Various interneurons are also located in the cortex. The axon of the Purkinje neuron is the only axonal system to leave the cerebellar cortex.

Deep within the cerebellum are the intracerebellar nuclei or the deep cerebellar nuclei, now shown from the posterior view (see Figure 56A).

Overall, the circuitry is as follows: All (excitatory) afferents to the cerebellum go to both the deep cerebellar nuclei (via collaterals) and the cerebellar cortex. After processing in the cortex, the Purkinje neuron sends its axon on to the neurons of the deep cerebellar nuclei — all Purkinje neurons are inhibitory. Their influence modulates the activity of the deep cerebellar neurons, which are tonically active (described in more detail below). The output of the deep cerebellar neurons, which is excitatory, influences neurons in the brainstem and cerebral cotex via the thalamus (discussed with the next illustration).

The connections of the cortical areas with the intracerebellar nuclei follow the functional divisions of the cerebellum:

- The vestibulocerebellum is connected to the fastigial nucleus, as well as to the lateral vestibular nucleus.
- The spinocerebellum connects with the interposed nucleus (the globose and emboliform).
- The neocerebellum connects to the dentate nucleus.

Axons from the deep nuclei neurons project from the cerebellum to many areas of the CNS, including brainstem motor nuclei (e.g., vestibular, reticular formation) and thalamus (to motor cortex). In this way, the cerebellum exerts its influence on motor performance. This will be discussed with the next illustration.

Details of Cerebellar Circuitry

The cerebellum receives information from many parts of the nervous system, including the spinal cord, the vestibular system, the brainstem, and the cerebral cortex. Most of this input is related to motor function, but some is also sensory. These afferents are excitatory in nature and influence the ongoing activity of the neurons in the intracerebellar nuclei, as well as projecting to the cerebellar cortex.

The incoming information to the cerebellar cortex is processed by various interneurons of the cerebellar cortex and eventually influences the Purkinje neuron. This will lead to either increased or decreased firing of this neuron. Its axon is the only one to leave the cerebellar cortex, and these axons project, in an organized manner, to the deep cerebellar nuclei.

The Purkinje neurons are inhibitory, and their influence modulates the activity of the deep cerebellar nuclei. Increased firing of the Purkinje neuron increases the ongoing inhibition onto these deep cerebellar nuclei, while decreased Purkinje cell firing results in a decrease in the inhibitory effect on the deep cerebellar cells, i.e., this results in the increased firing of the deep cerebellar neurons (called disinhibition).

It is interesting to note that the cerebellar cortex projects fibers directly to the lateral vestibular nucleus (see Figure 50, not illustrated). As would be anticipated, these are inhibitory. The lateral vestibular nucleus could therefore, in some sense, be considered one of the intracerebellar nuclei. This nucleus also receives input from the vestibular system, and then projects to the spinal cord (see Figure 50 and Figure 51A).

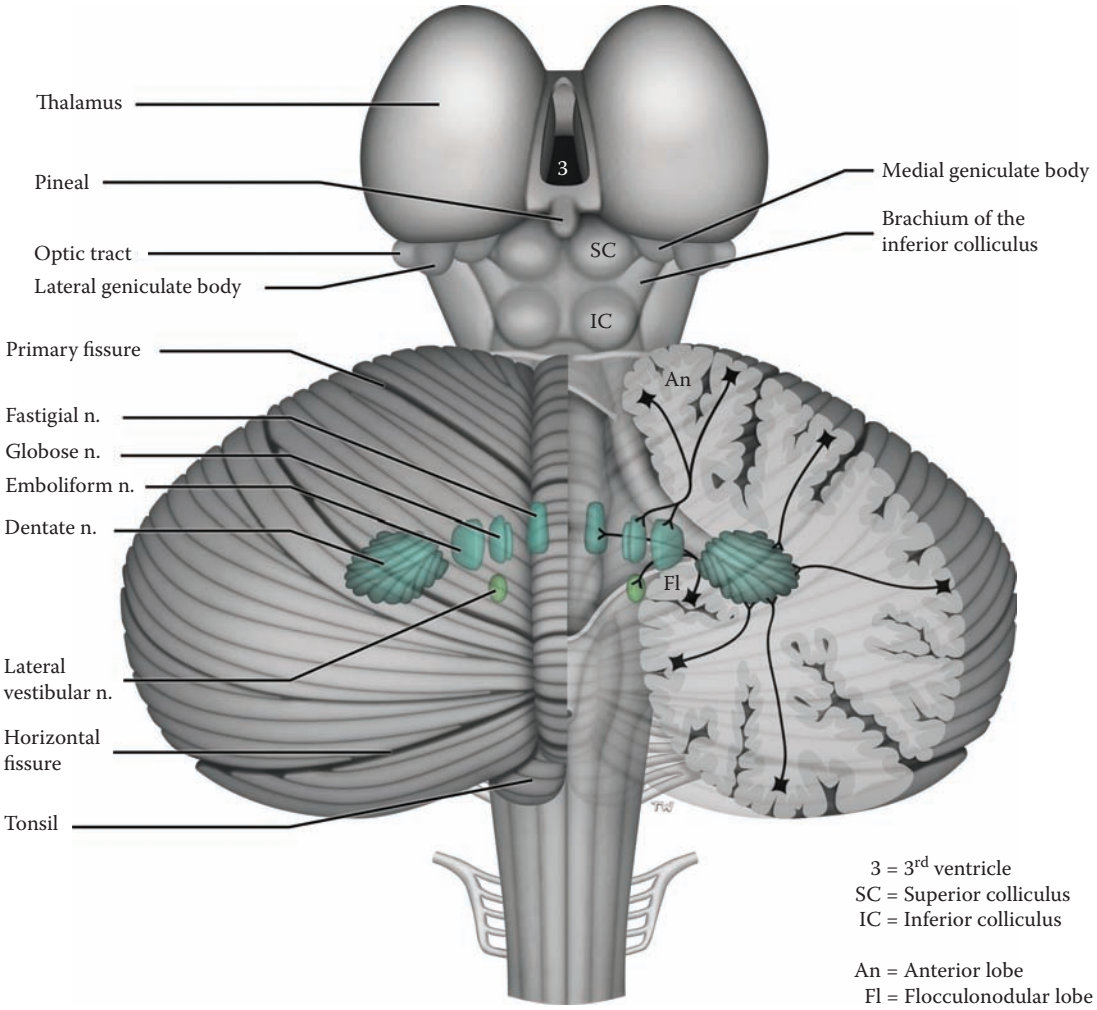


FIGURE 56B: Cerebellum 4 — Intracerebellar Circuitry

FIGURE 57
CEREBELLUM 5

CEREBELLAR EFFERENTS

This is again a dorsal view of the diencephalon, brainstem, and cerebellum, with the deep cerebellar (intracerebellar) nuclei. The cerebellar tissue has been removed in the midline, revealing the fourth ventricle (as in Figure 10); the three cerebellar peduncles are also visualized from this posterior perspective (see Figure 10).

The output from the cerebellum will be described, following the functional divisions of the cerebellum:

- **Vestibulocerebellum**: Efferents from the fastigial nuclei go to brainstem motor nuclei (e.g., vestibular nuclei and reticular formation), influencing balance and gait. They exit in a bundle that is found adjacent to the inferior cerebellar peduncle (named the juxtarestiform body).
- **Spinocerebellum**: The emboliform and globose, the interposed nucleus, also project to brainstem nuclei, including the red nucleus of the midbrain. They also project to the appropriate limb areas of the motor cortex via the thalamus (see below); these are the fibers involved in the comparator function of this part of the cerebellum.
- **Neocerebellum**: The dentate nucleus is the major outflow from the cerebellum via the superior cerebellar peduncle (see Figure 10 and Figure 40). This peduncle connects the cerebellar efferents, through the midbrain, to the thalamus on their way to the motor cortex. Some of the fibers terminate in the red nucleus of the midbrain, particularly those from the interposed nucleus. The majority of the fibers, those from the dentate nucleus, terminate in the ventral lateral (VL) nucleus of the thalamus (see Figure 53 and Figure 63). From here they are relayed to the motor cortex, predominantly area 4, and also to the premotor cortex, area 6. The neocerebellum is involved in motor coordination and planning. (This is to be compared with the influence of the basal ganglia on motor activity, see Figure 53.)

DETAILED PATHWAY

The outflow fibers of the superior cerebellar peduncles originate mainly from the dentate nucleus, with some from the interposed nucleus (as shown). The axons start laterally and converge toward the midline (see Figure 10 and Figure 40), passing in the roof of the upper half of the fourth ventricle (see Figure 21 and Figure 41B). The fibers continue to "ascend" through the upper part of the pons (see the cross-sections in Figure 66 and Figure 66A). In the lower midbrain there is a complete decussation of the peduncles (see Figure 65B).

CORTICAL LOOP

The cerebral cortex is linked to the neocerebellum by a circuit that forms a loop. Fibers are relayed from the cerebral cortex via the pontine nuclei to the cerebellum. The ponto-cerebellar fibers cross and go to the neocerebellum of the opposite side. After cortical processing in the cerebellar cortex, the fibers project to the dentate nucleus. These efferents project to the thalamus, after crossing (decussating) in the lower midbrain. From the thalamus, fibers are relayed mainly to the motor areas of the cerebral cortex. Because of the two crossings, the messages are returned to the same side of the cerebral cortex from which the circuit began.

CLINICAL ASPECT

Lesions of the neocerebellum (of one side) cause motor deficits to occur on the same side of the body, that is, ipsilaterally for the cerebellum. The explanation for this lies in the fact that the cortico-spinal tract is also a crossed pathway (see Figure 45). For example, the errant messages from the left cerebellum that are delivered to the right cerebral cortex cause the symptoms to appear on the left side — contralaterally for the cerebral cortex but ipsilaterally from the point of view of the cerebellum.

The cerebellar symptoms associated with lesions of the neocerebellum are collectively called **dyssynergia**, in which the range, direction, and amplitude of voluntary muscle activity are disturbed. The specific symptoms include the following:

- Distances are improperly gauged when pointing, called dysmetria, and include pastpointing.
- Rapid alternating movements are poorly performed, called dysdiadochokinesis.
- Complex movements are performed as a series of successive movements, which is called a decomposition of movement.
- There is a tremor seen during voluntary movement, an **intention tremor**. (This is in contrast to the Parkinsonian tremor, which is present at rest.)
- Disturbances also occur in the normally smooth production of words, resulting in slurred and explosive speech.

In addition, cerebellar lesions in humans are often associated with hypotonia and sluggish deep tendon reflexes.

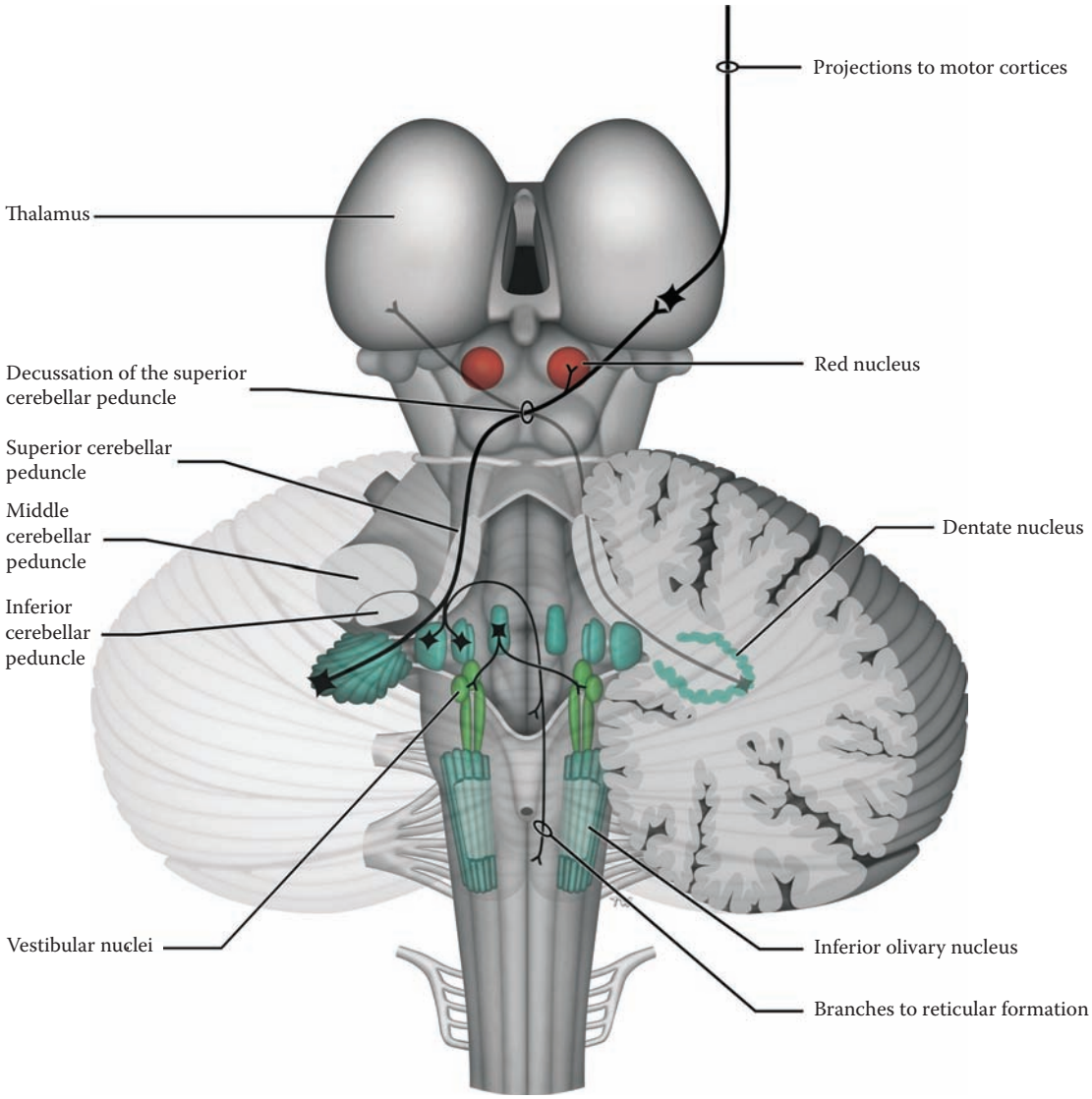


FIGURE 57: Cerebellum 5 — Cerebellar Efferents