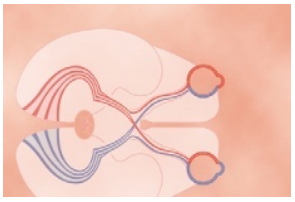
The Eye: III. Central Neurophysiology of Vision



Visual Pathways

Figure 51-1 shows the principal visual pathways from the two retinas to the *visual cortex*. The visual nerve signals leave the retinas through the *optic nerves*. At the *optic chiasm*, the optic nerve fibers from the nasal halves of the retinas cross to the opposite sides, where they join the fibers from the opposite temporal retinas to form the *optic tracts*. The fibers of each optic tract then synapse in the *dorsal lateral geniculate nucleus* of the thalamus, and from there, *geniculocalcarine fibers* pass by way of the *optic radiation* (also called the *geniculocalcarine tract*) to the *primary visual cortex* in the *calcarine fissure* area of the medial occipital lobe.

Visual fibers also pass to several older areas of the brain: (1) from the optic tracts to the *suprachiasmatic nucleus of the hypothalamus*, presumably to control circadian rhythms that synchronize various physiologic changes of the body with night and day; (2) into the *pretectal nuclei* in the midbrain, to elicit reflex movements of the eyes to focus on objects of importance and to activate the pupillary light reflex; (3) into the *superior colliculus*, to control rapid directional movements of the two eyes; and (4) into the *ventral lateral geniculate nucleus* of the thalamus and surrounding basal regions of the brain, presumably to help control some of the body's behavioral functions.

Thus, the visual pathways can be divided roughly into an *old system* to the midbrain and base of the forebrain and a *new system* for direct transmission of visual signals into the visual cortex located in the occipital lobes. In humans, the new system is responsible for perception of virtually all aspects of visual form, colors, and other conscious vision. Conversely, in many primitive animals, even visual form is detected by the older system, using the superior colliculus in the same manner that the visual cortex is used in mammals.

Function of the Dorsal Lateral Geniculate Nucleus of the Thalamus

The optic nerve fibers of the new visual system terminate in the *dorsal lateral geniculate nucleus*, located at the dorsal end of the thalamus and also called the *lateral geniculate body*, as shown in Figure 51-1. The dorsal lateral geniculate nucleus serves two principal functions: First, it relays visual information from the optic tract to the *visual cortex* by way of the *optic radiation* (also called the *geniculocalcarine tract*). This relay function is so accurate that there is exact point-to-point transmission with a high degree of spatial fidelity all the way from the retina to the visual cortex.

Half the fibers in each optic tract after passing the optic chiasm are derived from one eye and half from the other eye, representing corresponding points on the two retinas. However, the signals from the two eyes are kept apart in the dorsal lateral geniculate nucleus. This nucleus is composed of six nuclear layers. Layers II, III, and V (from ventral to dorsal) receive signals from the lateral half of the ipsilateral retina, whereas layers I, IV, and VI receive signals from the medial half of the retina of the opposite eye. The respective retinal areas of the two eyes connect with neurons that are superimposed over one another in

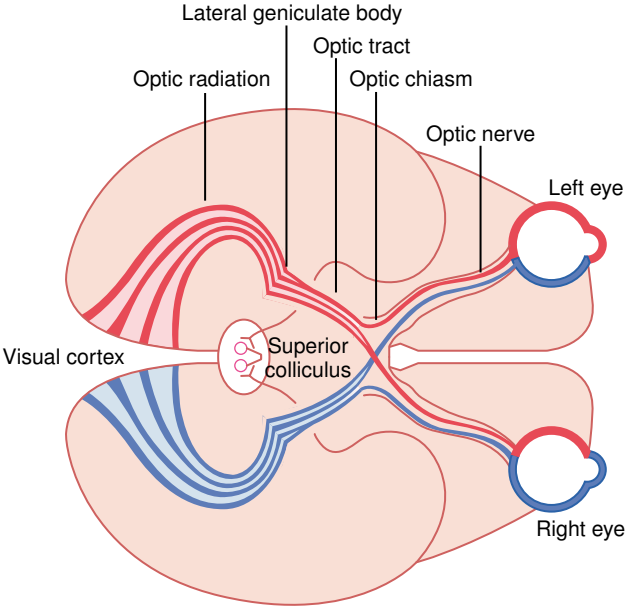


Figure 51-1 Principal visual pathways from the eyes to the visual cortex. (Modified from Polyak SL: The Retina. Chicago: University of Chicago, 1941.)

the paired layers, and similar parallel transmission is preserved all the way to the visual cortex.

The second major function of the dorsal lateral geniculate nucleus is to "gate" the transmission of signals to the visual cortex—that is, to control how much of the signal is allowed to pass to the cortex. The nucleus receives gating control signals from two major sources: (1) *corticofugal fibers* returning in a backward direction from the primary visual cortex to the lateral geniculate nucleus, and (2) *reticular areas of the mesencephalon*. Both of these are inhibitory and, when stimulated, can turn off transmission through selected portions of the dorsal lateral geniculate nucleus. Both of these gating circuits help highlight the visual information that is allowed to pass.

Finally, the dorsal lateral geniculate nucleus is divided in another way: (1) Layers I and II are called *magnocellular layers* because they contain large neurons. These receive their input almost entirely from the large *type Y retinal ganglion cells*. This magnocellular system provides a *rapidly conducting* pathway to the visual cortex. However, this system is color blind, transmitting only black-and-white information. Also, its point-to-point transmission is poor because there are not many Y ganglion cells, and their dendrites spread widely in the retina. (2) Layers III through VI are called *parvocellular layers* because they contain large numbers of small to medium-sized neurons. These neurons receive their input almost entirely from the *type X retinal ganglion cells* that transmit color and convey accurate point-to-point spatial information, but at only a moderate velocity of conduction rather than at high velocity.

Organization and Function of the Visual Cortex

Figures 51-2 and 51-3 show the *visual cortex* located primarily on the medial aspect of the occipital lobes. Like the cortical representations of the other sensory systems, the visual cortex is divided into a *primary visual cortex* and *secondary visual areas*.

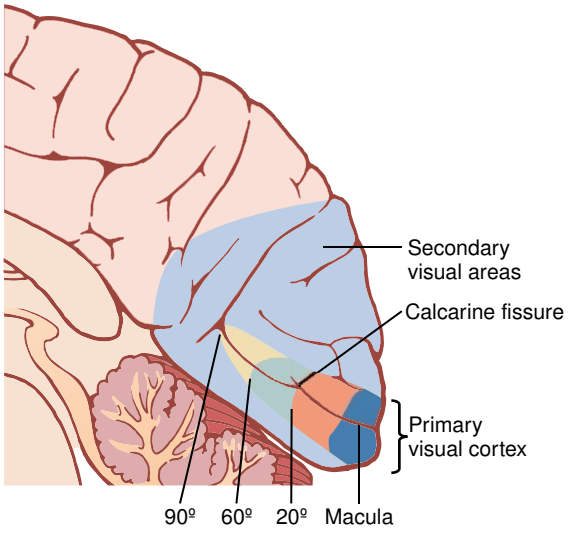


Figure 51-2 Visual cortex in the *calcarine fissure area* of the *medial* occipital cortex.

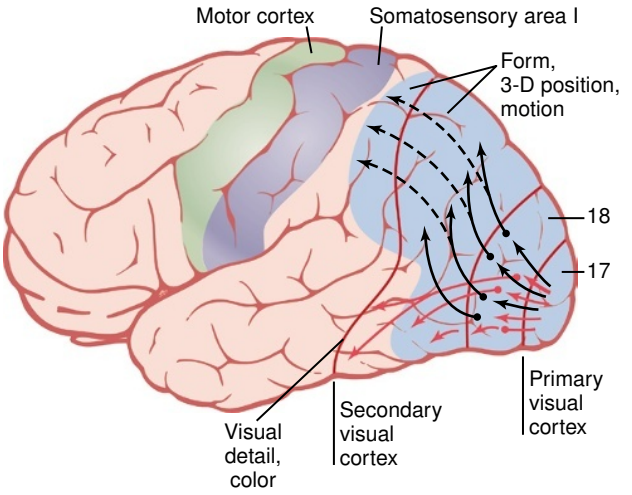


Figure 51-3 Transmission of visual signals from the primary visual cortex into secondary visual areas on the lateral surfaces of the occipital and parietal cortices. Note that the signals representing form, third-dimensional position, and motion are transmitted mainly into the superior portions of the occipital lobe and posterior portions of the parietal lobe. By contrast, the signals for visual detail and color are transmitted mainly into the anteroventral portion of the occipital lobe and the ventral portion of the posterior temporal lobe.

Primary Visual Cortex. The primary visual cortex (see Figure 51-2) lies in the *calcarine fissure area*, extending forward from the *occipital pole* on the *medial* aspect of each occipital cortex. This area is the terminus of direct visual signals from the eyes. Signals from the macular area of the retina terminate near the occipital pole, as shown in Figure 51-2, whereas signals from the more peripheral retina terminate at or in concentric half circles anterior to the pole but still along the calcarine fissure on the medial occipital lobe. The upper portion of the retina is represented superiorly and the lower portion inferiorly.

Note in the figure the large area that represents the macula. It is to this region that the retinal fovea transmits its signals. The fovea is responsible for the highest degree of visual acuity. Based on retinal area, the fovea has several hundred times as much representation in the primary visual cortex as do the most peripheral portions of the retina.

The primary visual cortex is also called *visual area I*. Still another name is the *striate cortex* because this area has a grossly striated appearance.

Secondary Visual Areas of the Cortex. The secondary visual areas, also called *visual association areas*, lie lateral, anterior, superior, and inferior to the primary visual cortex. Most of these areas also fold outward over the lateral surfaces of the occipital and parietal cortex, as shown in Figure 51-3. Secondary signals are transmitted to these areas for analysis of visual meanings. For instance,

on all sides of the primary visual cortex is *Brodmann's area 18* (see Figure 51-3), which is where virtually all signals from the primary visual cortex pass next. Therefore, Brodmann's area 18 is called *visual area II*, or simply V-2. The other, more distant secondary visual areas have specific designations—V-3, V-4, and so forth—up to more than a dozen areas. The importance of all these areas is that various aspects of the visual image are progressively dissected and analyzed.

The Primary Visual Cortex Has Six Major Layers

Like almost all other portions of the cerebral cortex, the primary visual cortex has six distinct layers, as shown in Figure 51-4. Also, as is true for the other sensory systems, the geniculocalcarine fibers terminate mainly in layer IV. But this layer, too, is organized into subdivisions. The rapidly conducted signals from the Y retinal ganglion cells terminate in layer IVcα, and from there they are relayed vertically both outward toward the cortical surface and inward toward deeper levels.

The visual signals from the medium-sized optic nerve fibers, derived from the X ganglion cells in the retina, also terminate in layer IV, but at points different from the Y signals. They terminate in layers IVa and IVcβ, the shallowest and deepest portions of layer IV, shown to the right in Figure 51-4. From there, these signals are transmitted vertically both toward the surface of the cortex and to deeper layers. It is these X ganglion pathways that transmit the accurate point-to-point type of vision, as well as color vision.

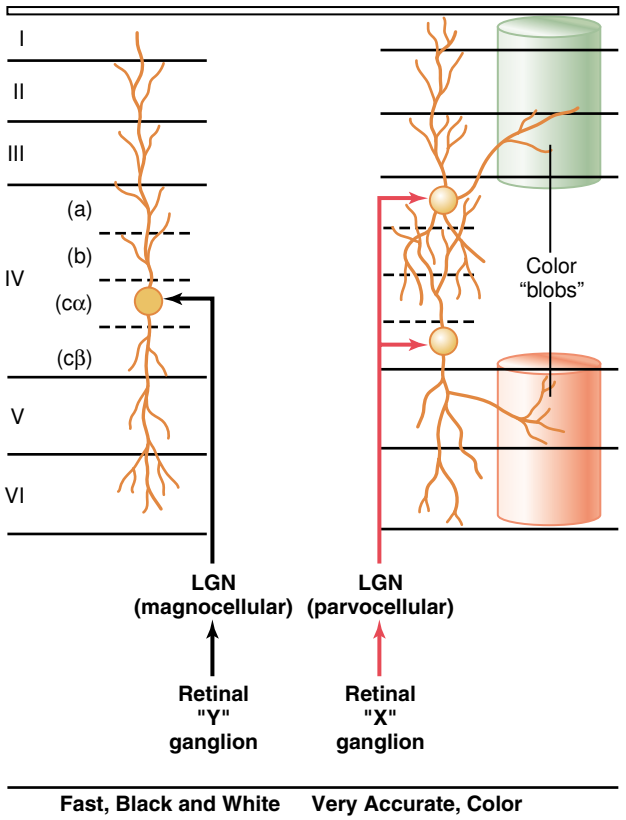


Figure 51-4 Six layers of the primary visual cortex. The connections shown on the left side of the figure originate in the magnocellular layers of the lateral geniculate nucleus (LGN) and transmit rapidly changing black-and-white visual signals. The pathways to the right originate in the parvocellular layers (layers III through VI) of the LGN; they transmit signals that depict accurate spatial detail, as well as color. Note especially the areas of the visual cortex called "color blobs," which are necessary for detection of color.

Vertical Neuronal Columns in the Visual Cortex. The visual cortex is organized structurally into several million vertical columns of neuronal cells, each column having a diameter of 30 to 50 micrometers. The same vertical columnar organization is found throughout the cerebral cortex for the other senses as well (and also in the motor and analytical cortical regions). Each column represents a functional unit. One can roughly calculate that each of the visual vertical columns has perhaps 1000 or more neurons.

After the optic signals terminate in layer IV, they are further processed as they spread both outward and inward along each vertical column unit. This processing is believed to decipher separate bits of visual information at successive stations along the pathway. The signals that pass outward to layers I, II, and III eventually transmit signals for short distances laterally in the cortex. Conversely, the signals that pass inward to layers V and VI excite neurons that transmit signals much greater distances.

"Color Blobs" in the Visual Cortex. Interspersed among the primary visual columns, as well as among the columns of some of the secondary visual areas, are special column-like areas called *color blobs*. They receive lateral signals from adjacent visual columns and are activated specifically by color signals. Therefore, these blobs are presumably the primary areas for deciphering color.

Interaction of Visual Signals from the Two Separate Eyes. Recall that visual signals from the two separate eyes are relayed through separate neuronal layers in the lateral geniculate nucleus. These signals still remain separated from each other when they arrive in layer IV of the primary visual cortex. In fact, layer IV is interlaced with stripes of neuronal columns, each stripe about 0.5 millimeter wide; the signals from one eye enter the columns of every other stripe, alternating with signals from the second eye. This cortical area deciphers whether the respective areas of the two visual images from the two separate eyes are "in register" with each other—that is, whether corresponding points from the two retinas fit with each other. In turn, the deciphered information is used to adjust the directional gaze of the separate eyes so that they will fuse with each other (be brought into "register"). The information observed about degree of register of images from the two eyes also allows a person to distinguish the distance of objects by the mechanism of *stereopsis*.

Two Major Pathways for Analysis of Visual Information—(1) The Fast "Position" and "Motion" Pathway; (2) The Accurate Color Pathway

Figure 51-3 shows that after leaving the primary visual cortex, the visual information is analyzed in two major pathways in the secondary visual areas.

1. **Analysis of Third-Dimensional Position, Gross Form, and Motion of Objects.** One of the analytical pathways, demonstrated in Figure 51-3 by the black arrows, analyzes the third-dimensional positions of visual objects in the space around the body. This pathway also analyzes the gross physical form of the visual scene, as well as motion in the scene. In other words, this pathway tells where every object is during each instant and whether it is moving. After leaving the primary visual cortex, the signals flow generally into the *posterior midtemporal area* and upward into the broad *occipitoparietal cortex*. At the anterior border of the parietal cortex, the signals overlap with signals from the posterior somatic association areas that analyze three-dimensional aspects of somatosensory signals. The signals transmitted in this *position-form-motion* pathway are mainly from the large Y optic nerve fibers of the retinal Y ganglion cells, transmitting rapid signals but depicting only black and white with no color.
2. **Analysis of Visual Detail and Color.** The red arrows in Figure 51-3, passing from the primary visual cortex into secondary visual areas of the *inferior, ventral*, and *medial regions* of the *occipital* and *temporal cortex*, show the principal pathway for analysis of visual detail. Separate portions of this pathway specifically dissect out color as well. Therefore, this pathway is concerned with such visual feats as recognizing letters, reading, determining the texture of surfaces, determining detailed colors of objects, and deciphering from all this information what the object is and what it means.

Neuronal Patterns of Stimulation During Analysis of the Visual Image

Analysis of Contrasts in the Visual Image. If a person looks at a blank wall, only a few neurons in the primary visual cortex will be stimulated, regardless of whether the illumination of the wall is bright or weak. Therefore, what does the primary visual cortex detect? To answer this, let us now place on the wall a large solid cross, as shown to the left in Figure 51-5. To the right is shown the spatial pattern of the most excited neurons in the visual cortex. *Note that the areas of maximum excitation occur along the sharp borders of the visual pattern*. Thus, the visual signal in the primary visual cortex is concerned mainly with *contrasts* in the visual scene, rather than with noncontrasting areas. We noted in Chapter 50 that this is also true of most of the retinal ganglion because equally

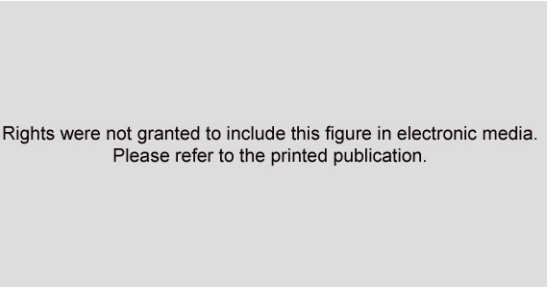


Figure 51-5 Pattern of excitation that occurs in the visual cortex in response to a retinal image of a dark cross.

stimulated adjacent retinal receptors mutually inhibit one another. But at any border in the visual scene where there is a change from dark to light or light to dark, mutual inhibition does not occur, and the intensity of stimulation of most neurons is proportional to the *gradient of contrast*—that is, the greater the sharpness of contrast and the greater the intensity difference between light and dark areas, the greater the degree of stimulation.

Visual Cortex Also Detects Orientation of Lines and Borders—"Simple" Cells. The visual cortex detects not only the existence of lines and borders in the different areas of the retinal image but also the direction of orientation of each line or border—that is, whether it is vertical or horizontal or lies at some degree of inclination. This is believed to result from linear organizations of mutually inhibiting cells that excite second-order neurons when inhibition occurs all along a line of cells where there is a contrast edge. Thus, for each such orientation of a line, specific neuronal cells are stimulated. A line oriented in a different direction excites a different set of cells. These neuronal cells are called *simple cells*. They are found mainly in layer IV of the primary visual cortex.

Detection of Line Orientation When a Line Is Displaced Laterally or Vertically in the Visual Field—"Complex" Cells. As the visual signal progresses farther away from layer IV, some neurons respond to lines that are oriented in the same direction but are not position specific. That is, even if a line is displaced moderate distances laterally or vertically in the field, the same few neurons will still be stimulated if the line has the same direction. These cells are called *complex cells*.

Detection of Lines of Specific Lengths, Angles, or Other Shapes. Some neurons in the outer layers of the primary visual columns, as well as neurons in some secondary visual areas, are stimulated only by lines or borders of specific lengths, by specific angulated shapes, or by images that have other characteristics. That is, these neurons detect still higher orders of information from the visual scene. Thus, as one goes farther into the analytical pathway of the visual cortex, progressively more characteristics of each visual scene are deciphered.

Detection of Color

Color is detected in much the same way that lines are detected: by means of color contrast. For instance, a red area is often contrasted against a green area, a blue area against a red area, or a green area against a yellow area. All these colors can also be contrasted against a white area within the visual scene. In fact, this contrasting against white is believed to be mainly responsible for the phenomenon called "color constancy"; that is, when the color of an illuminating light changes, the color of the "white" changes with the light, and appropriate computation in the brain allows red to be interpreted as red even though the illuminating light has changed the color entering the eyes.

The mechanism of color contrast analysis depends on the fact that contrasting colors, called "opponent colors," excite specific neuronal cells. It is presumed that the initial details of color contrast are detected by simple cells, whereas more complex contrasts are detected by complex and hypercomplex cells.

Effect of Removing the Primary Visual Cortex

Removal of the primary visual cortex in the human being causes loss of conscious vision, that is, blindness. However, psychological studies demonstrate that such "blind" people can still, at times, react subconsciously to changes in light intensity, to movement in the visual scene, or, rarely, even to some gross patterns of vision. These reactions include turning the eyes, turning the head, and avoidance. This vision is believed to be subserved by neuronal pathways that pass from the optic tracts mainly into the superior colliculi and other portions of the older visual system.

Fields of Vision; Perimetry

The *field of vision* is the visual area seen by an eye at a given instant. The area seen to the nasal side is called the *nasal field of vision*, and the area seen to the lateral side is called the *temporal field of vision*.

To diagnose blindness in specific portions of the retina, one charts the field of vision for each eye by a process called *perimetry*. This is done by having the subject look with one eye closed and the other eye looking toward a central spot directly in front of the eye. Then a small dot of light or a small object is moved back and forth in all areas of the field of vision, and the subject indicates when the spot of light or object can be seen and when it cannot. Thus, the field of vision for the left eye is plotted as shown in Figure 51-6. In all perimetry charts, a *blind spot* caused by lack of rods and cones in the retina over the *optic disc* is found about 15 degrees lateral to the central point of vision, as shown in the figure.

Abnormalities in the Fields of Vision. Occasionally, blind spots are found in portions of the field of vision other than the optic disc area. Such blind spots are called *scotomata*; they frequently are caused by damage to the optic nerve resulting from glaucoma (too much fluid pressure in the eyeball), from allergic reactions in the retina, or from toxic conditions such as lead poisoning or excessive use of tobacco.

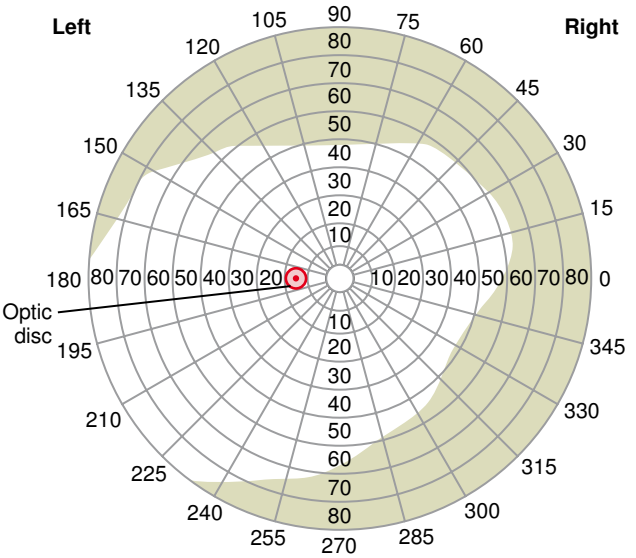


Figure 51-6 Perimetry chart, showing the field of vision for the left eye.

Another condition that can be diagnosed by perimetry is *retinitis pigmentosa*. In this disease, portions of the retina degenerate, and excessive melanin pigment deposits in the degenerated areas. Retinitis pigmentosa usually causes blindness in the peripheral field of vision first and then gradually encroaches on the central areas.

Effect of Lesions in the Optic Pathway on the Fields of Vision. Destruction of an entire *optic nerve* causes blindness of the affected eye.

Destruction of the *optic chiasm* prevents the crossing of impulses from the nasal half of each retina to the opposite optic tract. Therefore, the nasal half of each retina is blinded, which means that the person is blind in the temporal field of vision for each eye *because the image of the field of vision is inverted on the retina* by the optical system of the eye; this condition is called *bitemporal hemianopsia*. Such lesions frequently result from tumors of the pituitary gland pressing upward from the sella turcica on the bottom of the optic chiasm.

Interruption of an *optic tract* denervates the corresponding half of each retina on the same side as the lesion; as a result, neither eye can see objects to the opposite side of the head. This condition is known as *homonymous hemianopsia*.

Eye Movements and Their Control

To make full use of the visual abilities of the eyes, almost equally as important as interpretation of the visual signals from the eyes is the cerebral control system for directing the eyes toward the object to be viewed.

Muscular Control of Eye Movements. The eye movements are controlled by three pairs of muscles, shown in Figure 51-7: (1) the *medial* and *lateral recti*, (2) the *superior* and *inferior recti*, and (3) the *superior* and

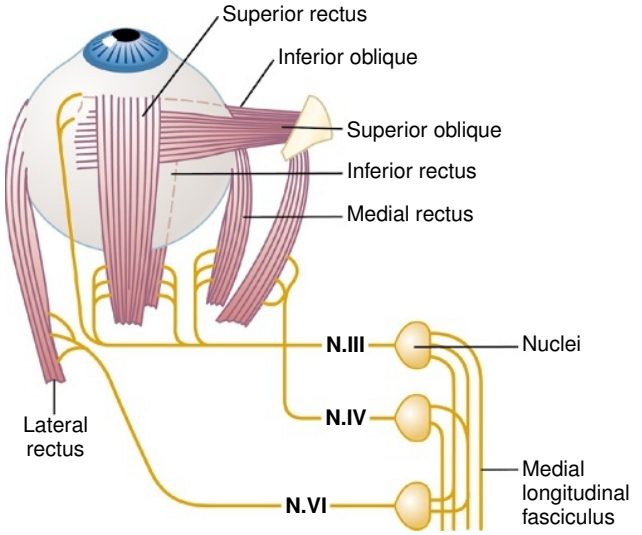


Figure 51-7 Extraocular muscles of the eye and their innervation.

inferior obliques. The medial and lateral recti contract to move the eyes from side to side. The superior and inferior recti contract to move the eyes upward or downward. The oblique muscles function mainly to rotate the eyeballs to keep the visual fields in the upright position.

Neural Pathways for Control of Eye Movements. Figure 51-7 also shows brain stem nuclei for the third, fourth, and sixth cranial nerves and their connections with the peripheral nerves to the ocular muscles. Shown, too, are interconnections among the brain stem nuclei by way of the nerve tract called the *medial longitudinal fasciculus*. Each of the three sets of muscles to each eye is *reciprocally* innervated so that one muscle of the pair relaxes while the other contracts.

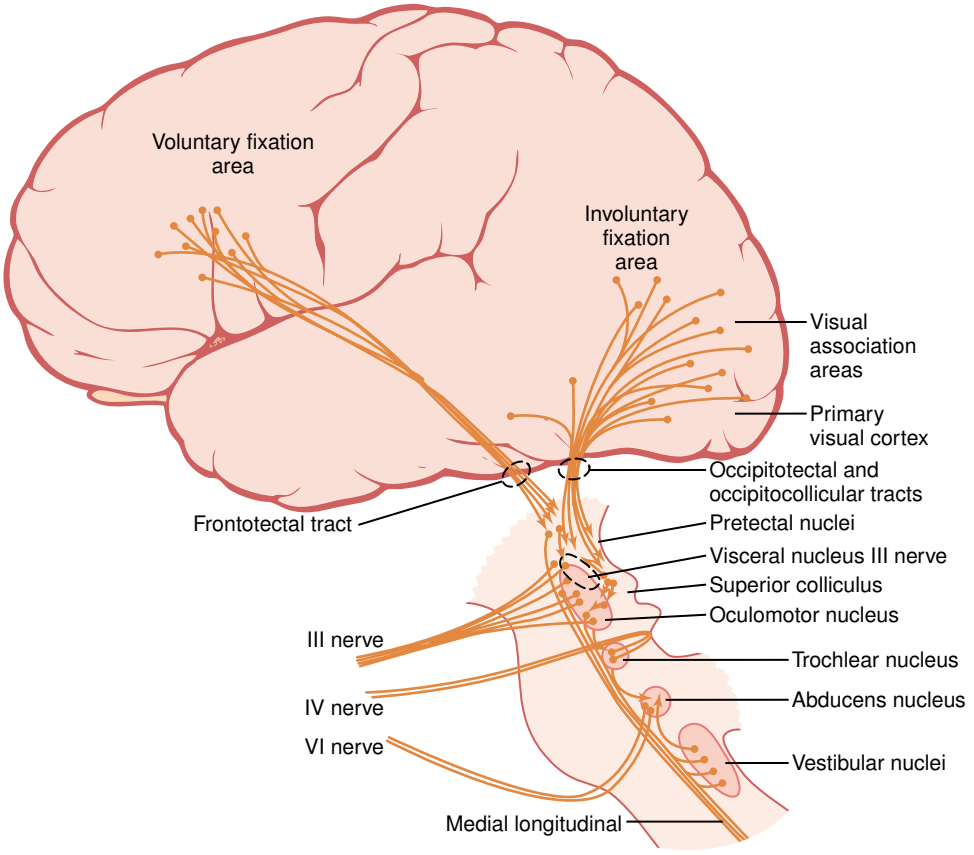
Figure 51-8 demonstrates cortical control of the oculomotor apparatus, showing spread of signals from visual areas in the occipital cortex through occipitotectal and occipitocollicular tracts to the pretectal and superior colliculus areas of the brain stem. From both the pretectal and the superior colliculus areas, the oculomotor control signals pass to the brain stem nuclei of the oculomotor nerves. Strong signals are also transmitted from the body's equilibrium control centers in the brain stem into the oculomotor system (from the vestibular nuclei by way of the medial longitudinal fasciculus).

Fixation Movements of the Eyes

Perhaps the most important movements of the eyes are those that cause the eyes to "fix" on a discrete portion of the field of vision. Fixation movements are controlled by two neuronal mechanisms. The first of these allows a person to move the eyes voluntarily to find the object on which he or she wants to fix the vision; this is called the *voluntary fixation mechanism*. The second is an involuntary mechanism that holds the eyes firmly on the object once it has been found; this is called the *involuntary fixation mechanism*.

The voluntary fixation movements are controlled by a cortical field located bilaterally in the premotor

Figure 51-8 Neural pathways for control of conjugate movement of the eyes.



cortical regions of the frontal lobes, as shown in Figure 51-8. Bilateral dysfunction or destruction of these areas makes it difficult for a person to "unlock" the eyes from one point of fixation and move them to another point. It is usually necessary to blink the eyes or put a hand over the eyes for a short time, which then allows the eyes to be moved.

Conversely, the fixation mechanism that causes the eyes to "lock" on the object of attention once it is found is controlled by *secondary visual areas in the occipital cortex*, located mainly anterior to the primary visual cortex. When this fixation area is destroyed bilaterally in an animal, the animal has difficulty keeping its eyes directed toward a given fixation point or may become totally unable to do so.

To summarize, posterior "involuntary" occipital cortical eye fields automatically "lock" the eyes on a given spot of the visual field and thereby prevent movement of the image across the retinas. To unlock this visual fixation, voluntary signals must be transmitted from cortical "voluntary" eye fields located in the frontal cortices.

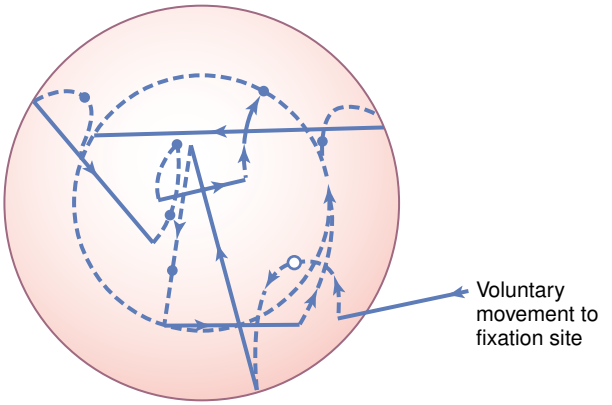


Figure 51-9 Movements of a spot of light on the fovea, showing sudden "flicking" eye movements that move the spot back toward the center of the fovea whenever it drifts to the foveal edge. (The *dashed lines* represent slow drifting movements, and the *solid lines* represent sudden flicking movements.) (Modified from Whitteridge D: Central control of the eye movements. In Field J, Magoun HW, Hall VE (eds): Handbook of Physiology. vol. 2, sec. 1. Washington, DC: American Physiological Society, 1960.)

Mechanism of Involuntary Locking Fixation—Role of the Superior Colliculi. The involuntary locking type of fixation discussed in the previous section results from a negative feedback mechanism that prevents the object of attention from leaving the foveal portion of the retina. The eyes normally have three types of continuous but almost imperceptible movements: (1) a *continuous tremor* at a rate of 30 to 80 cycles per second caused by successive contractions of the motor units in the ocular muscles, (2) a *slow drift* of the eyeballs in one direction or another, and (3) sudden *flicking movements* that are controlled by the involuntary fixation mechanism.

When a spot of light has become fixed on the foveal region of the retina, the tremulous movements cause the spot to move back and forth at a rapid rate across the cones, and the drifting movements cause the spot to drift slowly across the cones. Each time the spot drifts as far as the edge of the fovea, a sudden reflex reaction occurs, producing a flicking movement that moves the spot away from this edge back toward the center of the fovea. Thus, an automatic response moves the image back toward the central point of vision.

These drifting and flicking motions are demonstrated in Figure 51-9, which shows by the dashed lines the slow drifting across the fovea and by the solid lines the flicks that keep the image from leaving the foveal region. This involuntary fixation capability is mostly lost when the superior colliculi are destroyed.

Saccadic Movement of the Eyes—A Mechanism of Successive Fixation Points. When a visual scene is moving continually before the eyes, such as when a person is riding in a car, the eyes fix on one highlight after another in the visual field, jumping from one to the next at a rate of two to three jumps per second. The jumps are called *saccades*, and the movements are called *opticokinetic movements*. The saccades occur so rapidly that no more than 10 percent of the total time is spent in moving the eyes, with 90 percent of the time being allocated to the fixation sites. Also, the brain suppresses the visual image during saccades, so the person is not conscious of the movements from point to point.

Saccadic Movements During Reading. During the process of reading, a person usually makes several saccadic movements of the eyes for each line. In this case, the visual scene is not moving past the eyes, but the eyes are trained to move by means of several successive saccades across the visual scene to extract the important information. Similar saccades occur when a person observes a painting, except that the saccades occur in upward, sideways, downward, and angulated directions one after another from one highlight of the painting to another, and so forth.

Fixation on Moving Objects—"Pursuit Movement." The eyes can also remain fixed on a moving object, which is called *pursuit movement*. A highly developed cortical mechanism automatically detects the course of movement of an object and then rapidly develops a similar course of movement for the eyes. For instance, if an object is moving up and down in a wavelike form at a rate of several times per second, the eyes at first may be unable to fixate on it. However, after a second or so, the eyes begin to jump by means of saccades in approximately the same wavelike pattern of movement as that of the object. Then, after another few seconds, the eyes develop progressively smoother movements and finally follow the wave movement almost exactly. This represents a high degree of automatic subconscious computational ability by the pursuit system for controlling eye movements.

Superior Colliculi Are Mainly Responsible for Turning the Eyes and Head Toward a Visual Disturbance

Even after the visual cortex has been destroyed, a sudden visual disturbance in a lateral area of the visual field often causes immediate turning of the eyes in that direction. This does not occur if the superior colliculi have also been destroyed. To support this function, the various points of the retina are represented topographically in the superior colliculi in the same way as in the primary visual cortex, although with less accuracy. Even so, the principal direction of a flash of light in a peripheral retinal field is mapped by the colliculi, and secondary signals are transmitted to the oculomotor nuclei to turn the eyes. To help in this directional movement of the eyes, the superior colliculi also have topological maps of somatic sensations from the body and acoustic signals from the ears.

The optic nerve fibers from the eyes to the colliculi, which are responsible for these rapid turning movements, are branches from the rapidly conducting Y fibers, with one branch going to the visual cortex and the other going to the superior colliculi. (The superior colliculi and other regions of the brain stem are also strongly supplied with visual signals transmitted in type W optic nerve fibers. These represent the oldest visual pathway, but their function is unclear.)

In addition to causing the eyes to turn toward a visual disturbance, signals are relayed from the superior colliculi through the *medial longitudinal fasciculus* to other levels of the brain stem to cause turning of the whole head and even of the whole body toward the direction of the disturbance. Other types of nonvisual disturbances, such as strong sounds or even stroking of the side of the body, cause similar turning of the eyes, head, and body, but only if the superior colliculi are intact. Therefore, the superior colliculi play a global role in orienting the eyes, head, and body with respect to external disturbances, whether they are visual, auditory, or somatic.

"Fusion" of the Visual Images from the Two Eyes

To make the visual perceptions more meaningful, the visual images in the two eyes normally *fuse* with each other on "corresponding points" of the two retinas. The visual cortex plays an important role in fusion. It was pointed out earlier in the chapter that corresponding points of the two retinas transmit visual signals to different neuronal layers of the lateral geniculate body, and these signals in turn are relayed to parallel neurons in the visual cortex. Interactions occur between these cortical neurons to cause *interference excitation* in specific neurons when the two visual images are not "in register"—that is, are not precisely "fused." This excitation presumably provides the signal that is transmitted to the oculomotor apparatus to cause convergence or divergence or rotation of the eyes so that fusion can be re-established. Once the corresponding points of the two retinas are in register, excitation of the specific "interference" neurons in the visual cortex disappears.

Neural Mechanism of Stereopsis for Judging Distances of Visual Objects

In Chapter 49, it is pointed out that because the two eyes are more than 2 inches apart, the images on the two retinas are not exactly the same. That is, the right eye sees a little more of the right-hand side of the object, and the left eye a little more of the left-hand side, and the closer the object, the greater the disparity. Therefore, even when the two eyes are fused with each other, it is still impossible for all corresponding points in the two visual images to be exactly in register at the same time. Furthermore, the nearer the object is to the eyes, the less the degree of register. This degree of nonregister provides the neural mechanism for *stereopsis*, an important mechanism for judging the distances of visual objects up to about 200 feet (60 meters).

The neuronal cellular mechanism for stereopsis is based on the fact that some of the fiber pathways from the retinas to the visual cortex stray 1 to 2 degrees on each side of the central pathway. Therefore, some optic pathways from the two eyes are exactly in register for objects 2 meters away; still another set of pathways is in register for objects 25 meters away. Thus, the distance is determined by which set or sets of pathways are excited by nonregister or register. This phenomenon is called *depth perception*, which is another name for stereopsis.

Strabismus—Lack of Fusion of the Eyes

Strabismus, also called *squint* or *cross-eye*, means lack of fusion of the eyes in one or more of the visual coordinates: horizontal, vertical, or rotational. The basic types of strabismus are shown in Figure 51-10: (1) *horizontal strabismus*, (2) *torsional strabismus*, and (3) *vertical strabismus*. Combinations of two or even all three of the different types of strabismus often occur.

Strabismus is often caused by abnormal "set" of the fusion mechanism of the visual system. That is, in a young child's early efforts to fixate the two eyes on the same object, one of the eyes fixates satisfactorily while the other fails do so, or they both fixate satisfactorily but never simultaneously. Soon the patterns of conjugate movements of the eyes become abnormally "set" in the neuronal control pathways themselves, so the eyes never fuse.

Suppression of the Visual Image from a Repressed Eye. In a few patients with strabismus, the eyes alternate in fixing on the object of attention. In other patients, one eye alone is used all the time, and the other eye becomes repressed and is never used for precise vision. The visual acuity of the repressed eye develops only slightly, sometimes remaining 20/400 or less. If the dominant eye then becomes blinded,

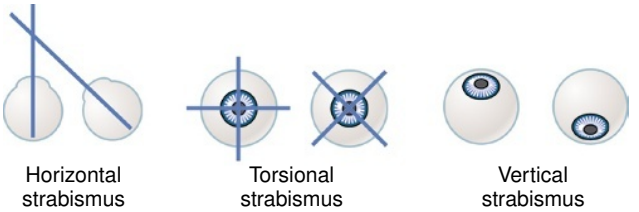


Figure 51-10 Basic types of strabismus.

vision in the repressed eye can develop only to a slight extent in adults but far more in young children. This demonstrates that visual acuity is highly dependent on proper development of central nervous system synaptic connections from the eyes. In fact, even anatomically, the numbers of neuronal connections diminish in the visual cortex areas that would normally receive signals from the repressed eye.

Autonomic Control of Accommodation and Pupillary Aperture

Autonomic Nerves to the Eyes. The eye is innervated by both parasympathetic and sympathetic nerve fibers, as shown in Figure 51-11. The parasympathetic preganglionic fibers arise in the *Edinger-Westphal nucleus* (the visceral nucleus portion of the third cranial nerve) and then pass in the *third nerve* to the *ciliary ganglion*, which lies immediately behind the eye. There, the preganglionic fibers synapse with postganglionic parasympathetic neurons, which in turn send fibers through *ciliary nerves* into the eyeball. These nerves excite (1) the ciliary muscle that controls focusing of the eye lens and (2) the sphincter of the iris that constricts the pupil.

The sympathetic innervation of the eye originates in the *intermediolateral horn cells* of the first thoracic segment of the spinal cord. From there, sympathetic fibers enter the sympathetic chain and pass upward to the *superior cervical ganglion*, where they synapse with postganglionic neurons. Postganglionic sympathetic fibers from these then spread along the surfaces of the carotid artery and successively smaller arteries until they reach the eye. There, the sympathetic fibers innervate the radial fibers of the iris (which open the pupil), as well as several extraocular muscles of the eye, which are discussed subsequently in relation to Horner's syndrome.

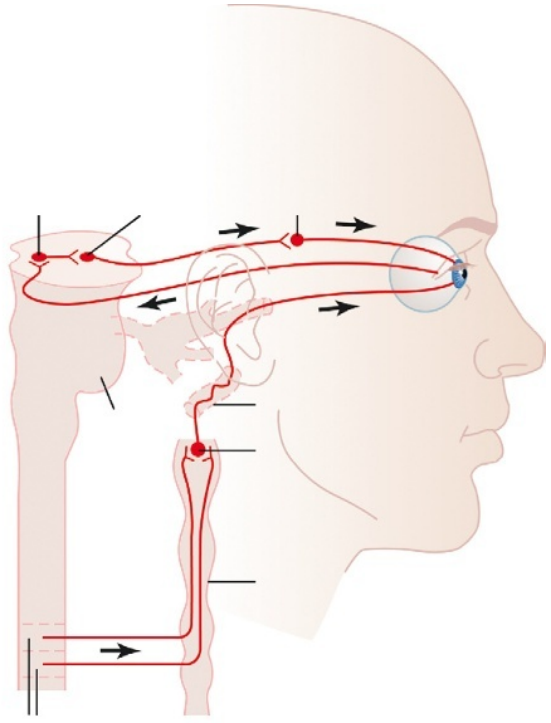


Figure 51-11 Autonomic innervation of the eye, showing also the reflex arc of the light reflex. (Modified from Ranson SW, Clark SL: Anatomy of the Nervous System: Its Development and Function, 10th ed. Philadelphia: WB Saunders, 1959.)

Control of Accommodation (Focusing the Eyes)

The accommodation mechanism—that is, the mechanism that focuses the lens system of the eye—is essential for a high degree of visual acuity. Accommodation results from contraction or relaxation of the eye ciliary muscle. Contraction causes increased refractive power of the lens, as explained in Chapter 49, and relaxation causes decreased power. How does a person adjust accommodation to keep the eyes in focus all the time?

Accommodation of the lens is regulated by a negative feedback mechanism that automatically adjusts the refractive power of the lens to achieve the highest degree of visual acuity. When the eyes have been focused on some far object and must then suddenly focus on a near object, the lens usually accommodates for best acuity of vision within less than 1 second. Although the precise control mechanism that causes this rapid and accurate focusing of the eye is unclear, some of the known features are the following.

First, when the eyes suddenly change distance of the fixation point, the lens changes its strength in the proper direction to achieve a new state of focus within a fraction of a second. Second, different types of clues help to change the lens strength in the proper direction:

1. *Chromatic aberration* appears to be important. That is, red light rays focus slightly posteriorly to blue light rays because the lens bends blue rays more than red rays. The eyes appear to be able to detect which of these two types of rays is in better focus, and this clue relays information to the accommodation mechanism whether to make the lens stronger or weaker.
2. When the eyes fixate on a near object, the eyes must converge. The neural mechanisms for *convergence cause a simultaneous signal to strengthen the lens of the eye.*
3. *Because the fovea lies in a hollowed-out depression that is slightly deeper than the remainder of the retina, the clarity of focus in the depth of the fovea is different from the clarity of focus on the edges*. This may also give clues about which way the strength of the lens needs to be changed.
4. *The degree of accommodation of the lens oscillates slightly* all the time at a frequency up to twice per second. The visual image becomes clearer when the oscillation of the lens strength is changing in the appropriate direction and becomes poorer when the lens strength is changing in the wrong direction. This could give a rapid clue as to which way the strength of the lens needs to change to provide appropriate focus.

The brain cortical areas that control accommodation closely parallel those that control fixation movements of the eyes, with analysis of the visual signals in Brodmann's cortical areas 18 and 19 and transmission of motor signals to the ciliary muscle through the pretectal area in the brain stem, then through the *Edinger-Westphal nucleus*, and finally by way of parasympathetic nerve fibers to the eyes.

Control of Pupillary Diameter

Stimulation of the parasympathetic nerves also excites the pupillary sphincter muscle, thereby decreasing the pupillary aperture; this is called *miosis*. Conversely, stimulation of the sympathetic nerves excites the radial fibers of the iris and causes pupillary dilation, called *mydriasis*.

Pupillary Light Reflex. When light is shone into the eyes, the pupils constrict, a reaction called the *pupillary light reflex*. The neuronal pathway for this reflex is demonstrated by the upper two black arrows in Figure 51-11. When light impinges on the retina, a few of the resulting impulses pass from the optic nerves to the pretectal nuclei. From here, secondary impulses pass to the *Edinger-Westphal nucleus* and, finally, back through *parasympathetic nerves* to constrict the sphincter of the iris. Conversely, in darkness, the reflex becomes inhibited, which results in dilation of the pupil.

The function of the light reflex is to help the eye adapt extremely rapidly to changing light conditions, as explained in Chapter 50. The limits of pupillary diameter are about 1.5 millimeters on the small side and 8 millimeters on the large side. Therefore, because light brightness on the retina increases with the square of pupillary diameter, the range of light and dark adaptation that can be brought about by the pupillary reflex is about 30 to 1—that is, up to as much as 30 times change in the amount of light entering the eye.

Pupillary Reflexes or Reactions in Central Nervous System Disease. A few central nervous system diseases damage nerve transmission of visual signals from the retinas to the Edinger-Westphal nucleus, thus sometimes blocking the pupillary reflexes. Such blocks may occur as a result of *central nervous system syphilis, alcoholism, encephalitis*, and so forth. The block usually occurs in the pretectal region of the brain stem, although it can result from destruction of some small fibers in the optic nerves.

The final nerve fibers in the pathway through the pretectal area to the Edinger-Westphal nucleus are mostly of the inhibitory type. When their inhibitory effect is lost, the nucleus becomes chronically active, causing the pupils to remain mostly constricted, in addition to their failure to respond to light.

Yet the pupils can constrict a little more if the Edinger-Westphal nucleus is stimulated through some other pathway. For instance, when the eyes fixate on a near object, the signals that cause accommodation of the lens and those that cause convergence of the two eyes cause a mild degree of pupillary constriction at the same time. This is called the *pupillary reaction to accommodation*. A pupil that fails to respond to light but does respond to accommodation and is also very small (an *Argyll Robertson pupil*) is an important diagnostic sign of central nervous system disease such as syphilis.

Horner's Syndrome. The sympathetic nerves to the eye are occasionally interrupted. Interruption frequently occurs in the cervical sympathetic chain. This causes the clinical condition called *Horner's syndrome*, which consists of the following effects: First, because of interruption of sympathetic nerve fibers to the pupillary dilator muscle, the pupil remains persistently constricted to a smaller diameter than the pupil of the opposite eye. Second, the superior eyelid droops because it is normally maintained in an open position during waking hours partly by contraction of smooth muscle fibers embedded in the superior eyelid and innervated by the sympathetics. Therefore, destruction of the sympathetic nerves makes it impossible to open the superior eyelid as widely as normally. Third, the blood vessels on the corresponding side of the face and head become persistently dilated. Fourth, sweating (which requires sympathetic nerve signals) cannot occur on the side of the face and head affected by Horner's syndrome.

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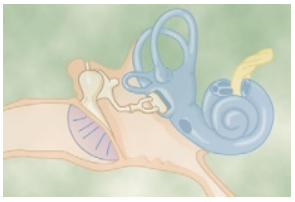
The Sense of Hearing



This chapter describes the mechanisms by which the ear receives sound waves, discriminates their frequencies, and transmits auditory information into the central nervous system, where its meaning is deciphered.

Tympanic Membrane and the Ossicular System

Conduction of Sound from the Tympanic Membrane to the Cochlea

Figure 52-1 shows the *tympanic membrane* (commonly called the *eardrum*) and the *ossicles*, which conduct sound from the tympanic membrane through the middle ear to the *cochlea* (the inner ear). Attached to the tympanic membrane is the *handle* of the *malleus*. The malleus is bound to the *incus* by minute ligaments, so whenever the malleus moves, the incus moves with it. The opposite end of the incus articulates with the stem of the *stapes*, and the *faceplate* of the stapes lies against the *membranous labyrinth* of the cochlea in the opening of the *oval window*.

The tip end of the handle of the malleus is attached to the center of the tympanic membrane, and this point of attachment is constantly pulled by the *tensor tympani muscle*, which keeps the tympanic membrane tensed. This allows sound vibrations on *any* portion of the tympanic membrane to be transmitted to the ossicles, which would not be true if the membrane were lax.

The ossicles of the middle ear are suspended by ligaments in such a way that the combined malleus and incus act as a single lever, having its fulcrum approximately at the border of the tympanic membrane.

The articulation of the incus with the stapes causes the stapes to push forward on the oval window and on the cochlear fluid on the other side of window every time the tympanic membrane moves inward, and to pull backward on the fluid every time the malleus moves outward.

"Impedance Matching" by the Ossicular System. The amplitude of movement of the stapes faceplate with each sound vibration is only three fourths as much as the amplitude of the handle of the malleus. Therefore, the ossicular lever system does not increase the movement distance of the stapes, as is commonly believed. Instead, the system actually reduces the distance but increases the *force* of movement about 1.3 times. In addition, the surface area of the tympanic membrane is about 55 square millimeters, whereas the surface area of the stapes averages 3.2 square millimeters. This 17-fold difference times the 1.3-fold ratio of the lever system causes about 22 times as much *total force* to be exerted on the fluid of the cochlea as is exerted by the sound waves against the tympanic membrane. Because fluid has far greater inertia than air does, increased amounts of force are necessary to cause vibration in the fluid. Therefore, the tympanic membrane and ossicular system provide *impedance matching* between the sound waves in air and the sound vibrations in the fluid of the cochlea. Indeed, the impedance matching is about 50 to 75 percent of perfect for sound frequencies between 300 and 3000 cycles per second, which allows utilization of most of the energy in the incoming sound waves.

In the absence of the ossicular system and tympanic membrane, sound waves can still travel directly through the air of the middle ear and enter the cochlea at the oval window. However, the sensitivity for hearing is then

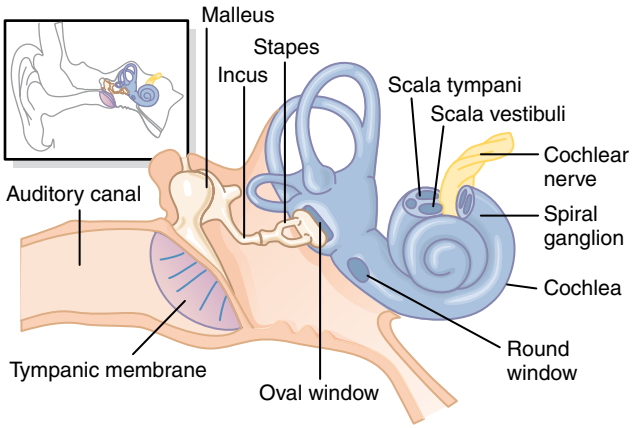


Figure 52-1 Tympanic membrane, ossicular system of the middle ear, and inner ear.

15 to 20 decibels less than for ossicular transmission—equivalent to a decrease from a medium to a barely perceptible voice level.

Attenuation of Sound by Contraction of the Tensor Tympani and Stapedius Muscles. When loud sounds are transmitted through the ossicular system and from there into the central nervous system, a reflex occurs after a latent period of only 40 to 80 milliseconds to cause contraction of the *stapedius muscle* and, to a lesser extent, the *tensor tympani muscle*. The tensor tympani muscle pulls the handle of the malleus inward while the stapedius muscle pulls the stapes outward. These two forces oppose each other and thereby cause the entire ossicular system to develop increased rigidity, thus greatly reducing the ossicular conduction of low-frequency sound, mainly frequencies below 1000 cycles per second.

This *attenuation reflex* can reduce the intensity of lower-frequency sound transmission by 30 to 40 decibels, which is about the same difference as that between a loud voice and a whisper. The function of this mechanism is believed to be twofold:

1. To *protect* the cochlea from damaging vibrations caused by excessively loud sound.
2. To *mask* low-frequency sounds in loud environments. This usually removes a major share of the background noise and allows a person to concentrate on sounds above 1000 cycles per second, where most of the pertinent information in voice communication is transmitted.

Another function of the tensor tympani and stapedius muscles is to decrease a person's hearing sensitivity to his or her own speech. This effect is activated by collateral nerve signals transmitted to these muscles at the same time that the brain activates the voice mechanism.

Transmission of Sound Through Bone

Because the inner ear, the *cochlea*, is embedded in a bony cavity in the temporal bone, called the *bony labyrinth*, vibrations of the entire skull can cause fluid vibrations in the cochlea itself. Therefore, under appropriate conditions, a tuning fork or an electronic vibrator placed on any bony protuberance of the skull, but especially on the mastoid process near the ear, causes the person to hear the sound. However, the energy available even in loud sound in the air is not sufficient to cause hearing via bone conduction unless a special electromechanical sound-amplifying device is applied to the bone.

Cochlea

Functional Anatomy of the Cochlea

The cochlea is a system of coiled tubes, shown in Figure 52-1 and in cross section in Figures 52-2 and 52-3. It consists of three tubes coiled side by side: (1) the *scala vestibuli*, (2) the *scala media*, and (3) the *scala tympani*. The scala vestibuli and scala media are separated from each

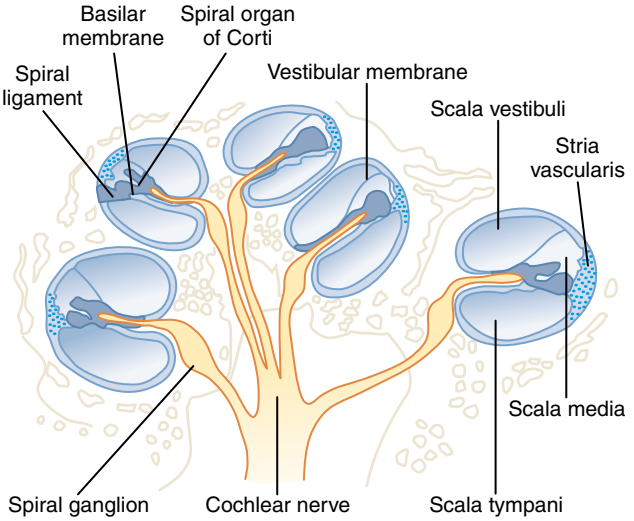


Figure 52-2 Cochlea. (Redrawn from Gray H, Goss CM [eds]: Gray's Anatomy of the Human Body. Philadelphia: Lea & Febiger, 1948.)

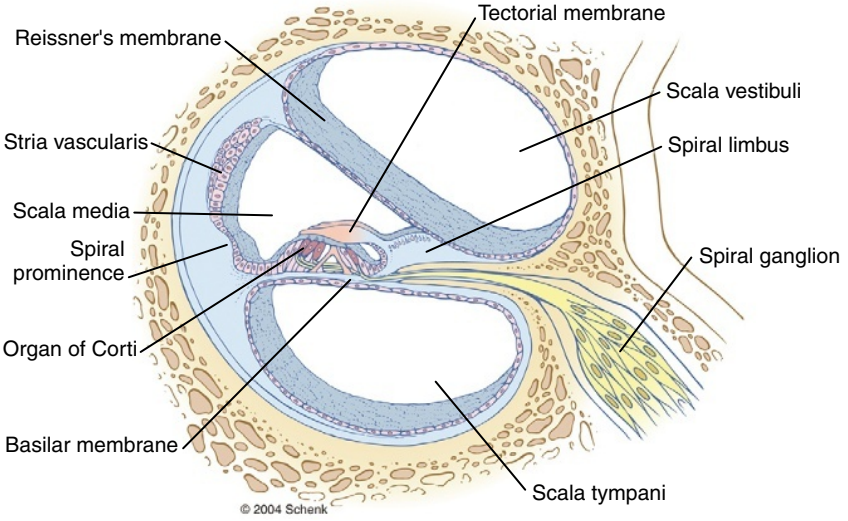


Figure 52-3 Section through one of the turns of the cochlea.

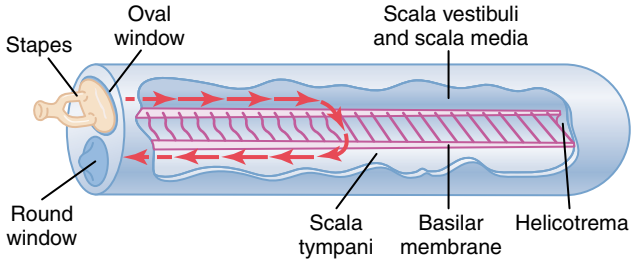


Figure 52-4 Movement of fluid in the cochlea after forward thrust of the stapes.

other by *Reissner's membrane* (also called the *vestibular membrane*), shown in Figure 52-3; the scala tympani and scala media are separated from each other by the *basilar membrane*. On the surface of the basilar membrane lies the *organ of Corti*, which contains a series of electromechanically sensitive cells, the *hair cells*. They are the receptive end organs that generate nerve impulses in response to sound vibrations.

Figure 52-4 diagrams the functional parts of the uncoiled cochlea for conduction of sound vibrations. First, note that Reissner's membrane is missing from this figure. This membrane is so thin and so easily moved that it does not obstruct the passage of sound vibrations from the scala vestibuli into the scala media. Therefore, as far as fluid conduction of sound is concerned, the scala vestibuli and scala media are considered to be a single chamber. (The importance of Reissner's membrane is to maintain a special kind of fluid in the scala media that is required for normal function of the sound-receptive hair cells, as discussed later in the chapter.)

Sound vibrations enter the scala vestibuli from the faceplate of the stapes at the oval window. The faceplate covers this window and is connected with the window's edges by a loose annular ligament so that it can move inward and outward with the sound vibrations. Inward movement causes the fluid to move forward in the scala vestibuli and scala media, and outward movement causes the fluid to move backward.

Basilar Membrane and Resonance in the Cochlea. The basilar membrane is a fibrous membrane that separates the scala media from the scala tympani. It contains 20,000 to 30,000 *basilar fibers* that project from the bony center of the cochlea, the *modiolus*, toward the outer wall. These fibers are stiff, elastic, reedlike structures that are fixed at their basal ends in the central bony structure of the cochlea (the modiolus) but are not fixed at their distal ends, except that the distal ends are embedded in the loose basilar membrane. Because the fibers are stiff and free at one end, they can vibrate like the reeds of a harmonica.

The *lengths* of the basilar fibers *increase* progressively beginning at the oval window and going from the base of the cochlea to the apex, increasing from a length of about 0.04 millimeter near the oval and round windows to 0.5 millimeter at the tip of the cochlea (the "helicotrema"), a 12-fold increase in length.

The *diameters* of the fibers, however, *decrease* from the oval window to the helicotrema, so their overall stiffness decreases more than 100-fold. As a result, the stiff, short fibers near the oval window of the cochlea vibrate best at a very high frequency, whereas the long, limber fibers near the tip of the cochlea vibrate best at a low frequency.

Thus, *high-frequency resonance* of the basilar membrane occurs near the base, where the sound waves enter the cochlea through the oval window. But *low-frequency resonance* occurs near the helicotrema, mainly because of the less stiff fibers but also because of increased "loading" with extra masses of fluid that must vibrate along the cochlear tubules.

Transmission of Sound Waves in the Cochlea—"Traveling Wave"

When the foot of the stapes moves inward against the *oval* window, the *round* window must bulge outward because the cochlea is bounded on all sides by bony walls. The initial effect of a sound wave entering at the oval window is to cause the basilar membrane at the base of the cochlea to bend in the direction of the round window. However, the elastic tension that is built up in the basilar fibers as they bend toward the round window initiates a fluid wave that "travels" along the basilar membrane toward the helicotrema, as shown in Figure 52-5. Figure 52-5*A* shows movement of a high-frequency wave down the basilar membrane; Figure 52-5*B*, a medium-frequency wave; and Figure 52-5*C*, a very low frequency wave. Movement of the wave along the basilar membrane is comparable to the movement of a pressure wave along the arterial walls, which is discussed in Chapter 15; it is also comparable to a wave that travels along the surface of a pond.

Pattern of Vibration of the Basilar Membrane for Different Sound Frequencies. Note in Figure 52-5 the different patterns of transmission for sound waves of different frequencies. Each wave is relatively weak at the

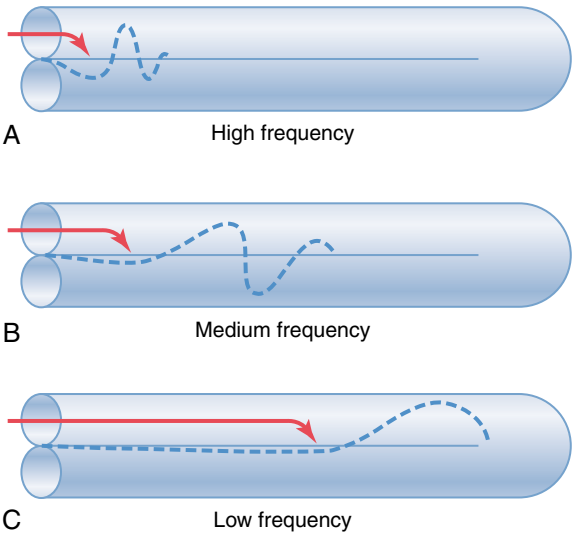


Figure 52-5 "Traveling waves" along the basilar membrane for high-, medium-, and low-frequency sounds.

outset but becomes strong when it reaches that portion of the basilar membrane that has a natural resonant frequency equal to the respective sound frequency. At this point, the basilar membrane can vibrate back and forth with such ease that the energy in the wave is dissipated. Consequently, the wave dies at this point and fails to travel the remaining distance along the basilar membrane. Thus, a high-frequency sound wave travels only a short distance along the basilar membrane before it reaches its resonant point and dies, a medium-frequency sound wave travels about halfway and then dies, and a very low frequency sound wave travels the entire distance along the membrane.

Another feature of the traveling wave is that it travels fast along the initial portion of the basilar membrane but becomes progressively slower as it goes farther into the cochlea. The cause of this is the high coefficient of elasticity of the basilar fibers near the oval window and a progressively decreasing coefficient farther along the membrane. This rapid initial transmission of the wave allows the high-frequency sounds to travel far enough into the cochlea to spread out and separate from one another on the basilar membrane. Without this, all the high-frequency waves would be bunched together within the first millimeter or so of the basilar membrane, and their frequencies could not be discriminated from one another.

Amplitude Pattern of Vibration of the Basilar Membrane. The dashed curves of Figure 52-6*A* show the position of a sound wave on the basilar membrane when the stapes (a) is all the way inward, (b) has moved back to the neutral point, (c) is all the way outward, and (d) has moved back again to the neutral point but is moving inward. The shaded area around these different waves shows the extent of vibration of the basilar membrane during a complete vibratory cycle. This is the *amplitude pattern of vibration* of the basilar membrane for this particular sound frequency.

Figure 52-6*B* shows the amplitude patterns of vibration for different frequencies, demonstrating that the maximum amplitude for sound at 8000 cycles per second occurs near the base of the cochlea, whereas that for frequencies less than 200 cycles per second is all the way at the tip of the basilar membrane near the helicotrema, where the scala vestibuli opens into the scala tympani.

The principal method by which sound frequencies are discriminated from one another is based on the "place" of maximum stimulation of the nerve fibers from the organ of Corti lying on the basilar membrane, as explained in the next section.

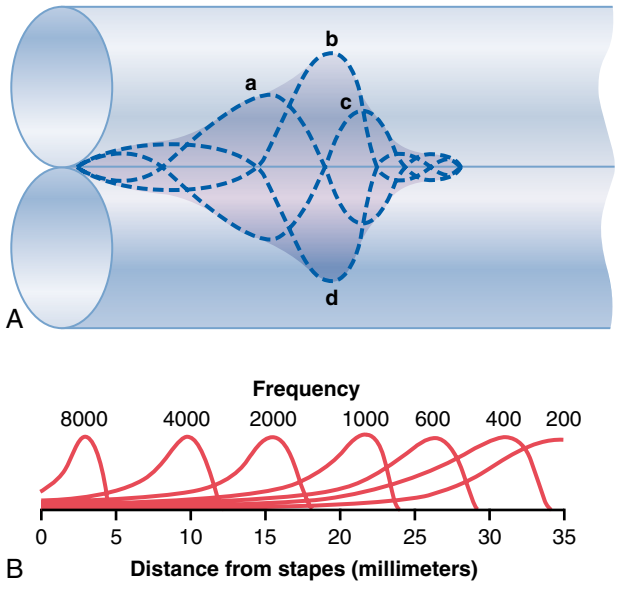


Figure 52-6 *A*, Amplitude pattern of vibration of the basilar membrane for a medium-frequency sound. *B*, Amplitude patterns for sounds of frequencies between 200 and 8000 cycles per second, showing the points of maximum amplitude on the basilar membrane for the different frequencies.

Function of the Organ of Corti

The organ of Corti, shown in Figures 52-3, and 52-7, is the receptor organ that generates nerve impulses in response to vibration of the basilar membrane. Note that the organ of Corti lies on the surface of the basilar fibers and basilar membrane. The actual sensory receptors in the organ of Corti are two specialized types of nerve cells called *hair cells*—a single row of *internal* (or "inner") *hair cells*, numbering about 3500 and measuring about 12 micrometers in diameter, and three or four rows of *external* (or "outer") *hair cells*, numbering about 12,000 and having diameters of only about 8 micrometers. The bases and sides of the hair cells synapse with a network of cochlea nerve endings. Between 90 and 95 percent of these endings terminate on the inner hair cells, which emphasizes their special importance for the detection of sound.

The nerve fibers stimulated by the hair cells lead to the *spiral ganglion of Corti*, which lies in the modiolus (center) of the cochlea. The spiral ganglion neuronal cells send axons—a total of about 30,000—into the *cochlear nerve* and then into the central nervous system at the level of

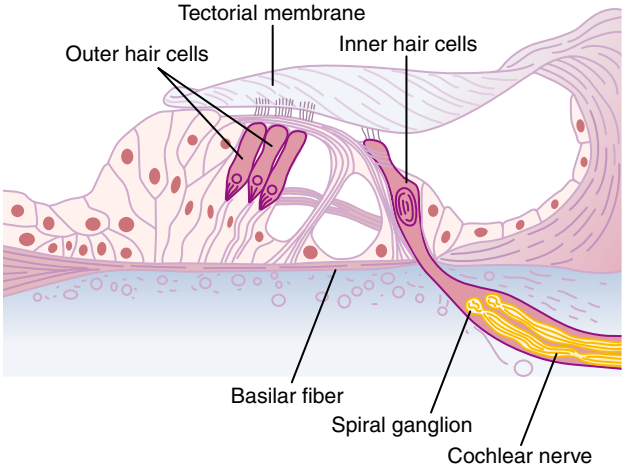


Figure 52-7 Organ of Corti, showing especially the hair cells and the tectorial membrane pressing against the projecting hairs.

the upper medulla. The relation of the organ of Corti to the spiral ganglion and to the cochlear nerve is shown in Figure 52-2.

Excitation of the Hair Cells. Note in Figure 52-7 that minute hairs, or *stereocilia*, project upward from the hair cells and either touch or are embedded in the surface gel coating of the *tectorial membrane*, which lies above the stereocilia in the scala media. These hair cells are similar to the hair cells found in the macula and cristae ampullaris of the vestibular apparatus, which are discussed in Chapter 55. Bending of the hairs in one direction depolarizes the hair cells, and bending in the opposite direction hyperpolarizes them. This in turn excites the auditory nerve fibers synapsing with their bases.

Figure 52-8 shows the mechanism by which vibration of the basilar membrane excites the hair endings. The outer ends of the hair cells are fixed tightly in a rigid structure composed of a flat plate, called the *reticular lamina*, supported by triangular *rods of Corti*, which are attached tightly to the basilar fibers. The basilar fibers, the rods of Corti, and the reticular lamina move as a rigid unit.

Upward movement of the basilar fiber rocks the reticular lamina upward and *inward* toward the modiolus. Then, when the basilar membrane moves downward, the reticular lamina rocks downward and *outward*. The inward and outward motion causes the hairs on the hair cells to shear back and forth against the tectorial membrane. Thus, the hair cells are excited whenever the basilar membrane vibrates.

Auditory Signals Are Transmitted Mainly by the Inner Hair Cells. Even though there are three to four times as many outer hair cells as inner hair cells, about 90 percent of the auditory nerve fibers are stimulated by the inner cells rather than by the outer cells. Yet, despite this, if the outer cells are damaged while the inner cells remain fully functional, a large amount of hearing loss occurs. Therefore, it has been proposed that the outer hair cells in some way control the sensitivity of the inner hair cells at different sound pitches, a phenomenon called "tuning" of the receptor system. In support of this concept, a large number of retrograde nerve fibers pass from the brain stem to the vicinity of the outer hair cells. Stimulating these nerve fibers can actually cause shortening of the outer hair cells and possibly also change their degree of stiffness. These effects suggest a retrograde nervous mechanism for control of the ear's sensitivity to different sound pitches, activated through the outer hair cells.

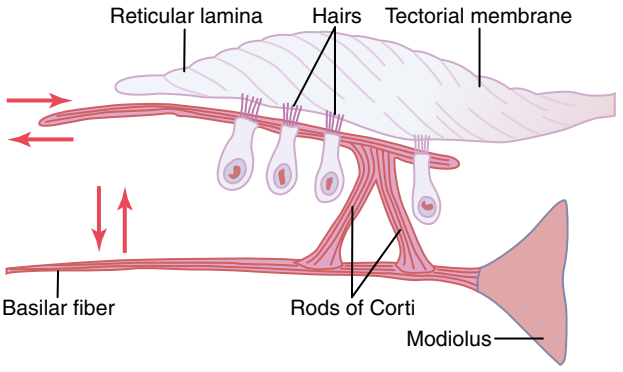


Figure 52-8 Stimulation of the hair cells by to-and-fro movement of the hairs projecting into the gel coating of the tectorial membrane.

Hair Cell Receptor Potentials and Excitation of Auditory Nerve Fibers. The stereocilia (the "hairs" protruding from the ends of the hair cells) are stiff structures because each has a rigid protein framework. Each hair cell has about 100 stereocilia on its apical border. These become progressively longer on the side of the hair cell away from the modiolus, and the tops of the shorter stereocilia are attached by thin filaments to the back sides of their adjacent longer stereocilia. Therefore, whenever the cilia are bent in the direction of the longer ones, the tips of the smaller stereocilia are tugged outward from the surface of the hair cell. This causes a mechanical transduction that opens 200 to 300 cation-conducting channels, allowing rapid movement of positively charged potassium ions from the surrounding scala media fluid into the stereocilia, which causes depolarization of the hair cell membrane.

Thus, when the basilar fibers bend toward the scala vestibuli, the hair cells depolarize, and in the opposite direction they hyperpolarize, thereby generating an alternating hair cell receptor potential. This, in turn, stimulates the cochlear nerve endings that synapse with the bases of the hair cells. It is believed that a rapidly acting neurotransmitter is released by the hair cells at these synapses during depolarization. It is possible that the transmitter substance is glutamate, but this is not certain.

Endocochlear Potential. To explain even more fully the electrical potentials generated by the hair cells, we need to explain another electrical phenomenon called the *endocochlear potential*: The scala media is filled with a fluid called *endolymph*, in contradistinction to the *perilymph* present in the scala vestibuli and scala tympani. The scala vestibuli and scala tympani communicate directly with the subarachnoid space around the brain, so the perilymph is almost identical to cerebrospinal fluid. Conversely, the endolymph that fills the scala media is an entirely different fluid secreted by the *stria vascularis*, a highly vascular area on the outer wall of the scala media. Endolymph contains a high concentration of potassium and a low concentration of sodium, which is exactly opposite to the contents of perilymph.

An electrical potential of about +80 millivolts exists all the time between endolymph and perilymph, with positivity inside the scala media and negativity outside. This is called the *endocochlear potential*, and it is generated by continual secretion of positive potassium ions into the scala media by the stria vascularis.

The importance of the endocochlear potential is that the tops of the hair cells project through the reticular lamina and are bathed by the endolymph of the scala media, whereas perilymph bathes the lower bodies of the hair cells. Furthermore, the hair cells have a negative intracellular potential of –70 millivolts with respect to the perilymph but –150 millivolts with respect to the endolymph at their upper

surfaces where the hairs project through the reticular lamina and into the endolymph. It is believed that this high electrical potential at the tips of the stereocilia sensitizes the cell an extra amount, thereby increasing its ability to respond to the slightest sound.

Determination of Sound Frequency—The "Place" Principle

From earlier discussions in this chapter, it is apparent that low-frequency sounds cause maximal activation of the basilar membrane near the apex of the cochlea, and high-frequency sounds activate the basilar membrane near the base of the cochlea. Intermediate-frequency sounds activate the membrane at intermediate distances between the two extremes. Furthermore, there is spatial organization of the nerve fibers in the cochlear pathway, all the way from the cochlea to the cerebral cortex. Recording of signals in the auditory tracts of the brain stem and in the auditory receptive fields of the cerebral cortex shows that specific brain neurons are activated by specific sound frequencies. Therefore, the *major* method used by the nervous system to detect different sound frequencies is to determine the positions along the basilar membrane that are most stimulated. This is called the *place principle* for the determination of sound frequency.

Yet, referring again to Figure 52-6, one can see that the distal end of the basilar membrane at the helicotrema is stimulated by all sound frequencies below 200 cycles per second. Therefore, it has been difficult to understand from the place principle how one can differentiate between low sound frequencies in the range of 200 down to 20. These low frequencies have been postulated to be discriminated mainly by the so-called *volley* or *frequency principle*. That is, low-frequency sounds, from 20 to 1500 to 2000 cycles per second, can cause volleys of nerve impulses synchronized at the same frequencies, and these volleys are transmitted by the cochlear nerve into the cochlear nuclei of the brain. It is further suggested that the cochlear nuclei can distinguish the different frequencies of the volleys. In fact, destruction of the entire apical half of the cochlea, which destroys the basilar membrane where all lower-frequency sounds are normally detected, does not totally eliminate discrimination of the lower-frequency sounds.

Determination of Loudness

Loudness is determined by the auditory system in at least three ways.

First, as the sound becomes louder, the amplitude of vibration of the basilar membrane and hair cells also increases so that the hair cells excite the nerve endings at more rapid rates.

Second, as the amplitude of vibration increases, it causes more and more of the hair cells on the fringes of the resonating portion of the basilar membrane to become stimulated, thus causing *spatial summation* of impulses—that is, transmission through many nerve fibers rather than through only a few.

Third, the outer hair cells do not become stimulated significantly until vibration of the basilar membrane reaches high intensity, and stimulation of these cells presumably apprises the nervous system that the sound is loud.

Detection of Changes in Loudness—The Power Law. As pointed out in Chapter 46, a person interprets changes in intensity of sensory stimuli approximately in proportion to an inverse power function of the actual intensity. In the case of sound, the interpreted sensation changes approximately in proportion to the cube root of the actual sound intensity. To express this in another way, the ear can discriminate differences in sound intensity from the softest whisper to the loudest possible noise, representing an *approximately 1 trillion times* increase in sound energy or 1 million times increase in amplitude of movement of the basilar membrane. Yet the ear interprets this much difference in sound level as approximately a 10,000-fold change. Thus, the scale of intensity is greatly "compressed" by the sound perception mechanisms of the auditory system. This allows a person to interpret differences in sound intensities over a far wider range than would be possible were it not for compression of the intensity scale.

Decibel Unit. Because of the extreme changes in sound intensities that the ear can detect and discriminate, sound intensities are usually expressed in terms of the logarithm of their actual intensities. A 10-fold increase in sound energy is called 1 *bel*, and 0.1 bel is called 1 *decibel*. One decibel represents an actual increase in sound energy of 1.26 times.

Another reason for using the decibel system to express changes in loudness is that, in the usual sound intensity range for communication, the ears can barely distinguish an approximately 1-decibel *change* in sound intensity.

Threshold for Hearing Sound at Different Frequencies. Figure 52-9 shows the pressure thresholds at which sounds of different frequencies can barely be heard by the ear. This figure demonstrates that a 3000-cycle-per-second sound can be heard even when its intensity is as low as 70 decibels below

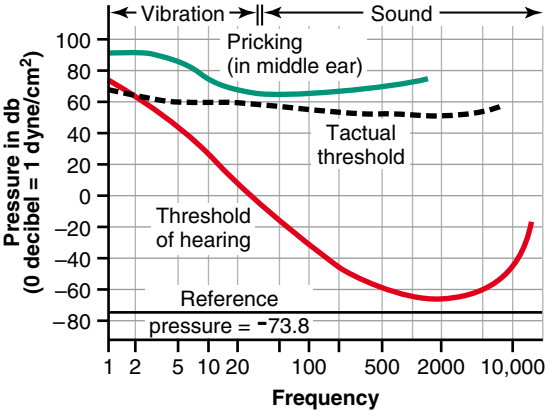


Figure 52-9 Relation of the threshold of hearing and of somesthetic perception (pricking and tactual threshold) to the sound energy level at each sound frequency.

1 dyne/cm^2 sound pressure level, which is one ten-millionth microwatt per square centimeter. Conversely, a 100-cycle-per-second sound can be detected only if its intensity is 10,000 times as great as this.

Frequency Range of Hearing. The frequencies of sound that a young person can hear are between 20 and 20,000 cycles per second. However, referring again to Figure 52-9, we see that the sound range depends to a great extent on loudness. If the loudness is 60 decibels below 1 dyne/cm^2 sound pressure level, the sound range is 500 to 5000 cycles per second; only with intense sounds can the complete range of 20 to 20,000 cycles be achieved. In old age, this frequency range is usually shortened to 50 to 8000 cycles per second or less, as discussed later in the chapter.

Central Auditory Mechanisms

Auditory Nervous Pathways

Figure 52-10 shows the major auditory pathways. It shows that nerve fibers from the *spiral ganglion of Corti* enter the *dorsal* and *ventral cochlear nuclei* located in the upper part of the medulla. At this point, all the fibers synapse, and second-order neurons pass mainly to the opposite side of the brain stem to terminate in the *superior olivary nucleus*. A few second-order fibers also pass to the superior olivary nucleus on the same side.

From the superior olivary nucleus, the auditory pathway passes upward through the *lateral lemniscus*. Some of the fibers terminate in the *nucleus of the lateral lemniscus*, but many bypass this nucleus and travel on to the inferior colliculus, where all or almost all the auditory fibers synapse. From there, the pathway passes to the *medial geniculate nucleus*, where all the fibers do synapse. Finally, the pathway proceeds by way of the *auditory radiation* to the *auditory cortex*, located mainly in the superior gyrus of the temporal lobe.

Several important points should be noted. First, signals from both ears are transmitted through the pathways of both sides of the brain, with a preponderance of transmission in the contralateral pathway. In at least three places in the brain stem, crossing over occurs between the two pathways: (1) in the trapezoid body, (2) in the commissure between the two nuclei of the lateral lemnisci, and (3) in the commissure connecting the two inferior colliculi.

Second, many collateral fibers from the auditory tracts pass directly into the *reticular activating system of the brain stem*. This system projects diffusely upward in the brain stem and downward into the spinal cord and activates the entire nervous system in response to loud sounds. Other collaterals go to the *vermis of the cerebellum*, which is also activated instantaneously in the event of a sudden noise.

Third, a high degree of spatial orientation is maintained in the fiber tracts from the cochlea all the way to the cortex. In fact, there are *three spatial patterns* for termination of the different sound frequencies in the cochlear nuclei, *two patterns* in the inferior colliculi, *one precise pattern* for discrete sound frequencies in the auditory cortex, and *at least five other less precise patterns* in the auditory cortex and auditory association areas.

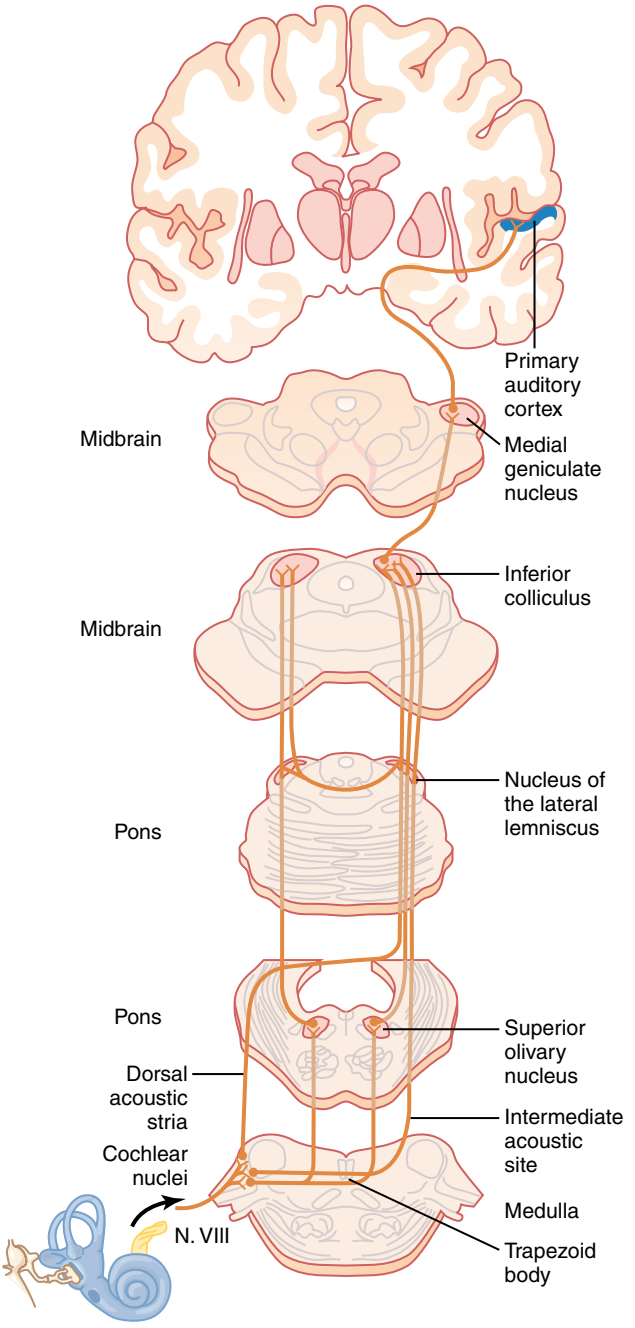


Figure 52-10 Auditory nervous pathways. (Modified from Brodal A: The auditory system. In Neurological Anatomy in Relation to Clinical Medicine, 3rd ed. New York: Oxford University Press, 1981.)

Firing Rates at Different Levels of the Auditory Pathways. Single nerve fibers entering the cochlear nuclei from the auditory nerve can fire at rates up to at least 1000 per second, the rate being determined mainly by the loudness of the sound. At sound frequencies up to 2000 to 4000 cycles per second, the auditory nerve impulses are often synchronized with the sound waves, but they do not necessarily occur with every wave.

In the auditory tracts of the brain stem, the firing is usually no longer synchronized with the sound frequency, except at sound frequencies below 200 cycles per second. Above the

level of the inferior colliculi, even this synchronization is mainly lost. These findings demonstrate that the sound signals are not transmitted unchanged directly from the ear to the higher levels of the brain; instead, information from the sound signals begins to be dissected from the impulse traffic at levels as low as the cochlear nuclei. We will have more to say about this later, especially in relation to perception of direction from which sound comes.

Function of the Cerebral Cortex in Hearing

The projection area of auditory signals to the cerebral cortex is shown in Figure 52-11, which demonstrates that the auditory cortex lies principally on the *supratemporal plane of the superior temporal gyrus* but also extends onto the *lateral side of the temporal lobe*, over much of the *insular cortex*, and even onto the lateral portion of the *parietal operculum*.

Two separate subdivisions are shown in Figure 52-11: the *primary auditory cortex* and the *auditory association cortex* (also called the *secondary auditory cortex*). The primary auditory cortex is directly excited by projections from the medial geniculate body, whereas the auditory association areas are excited secondarily by impulses from the primary auditory cortex, as well as by some projections from thalamic association areas adjacent to the medial geniculate body.

Sound Frequency Perception in the Primary Auditory Cortex. At least six *tonotopic maps* have been found in the primary auditory cortex and auditory association areas. In each of these maps, high-frequency sounds excite neurons at one end of the map, whereas low-frequency sounds excite neurons at the opposite end. In most, the low-frequency sounds are located anteriorly, as shown in Figure 52-11, and the high-frequency sounds are located posteriorly. This is not true for all the maps.

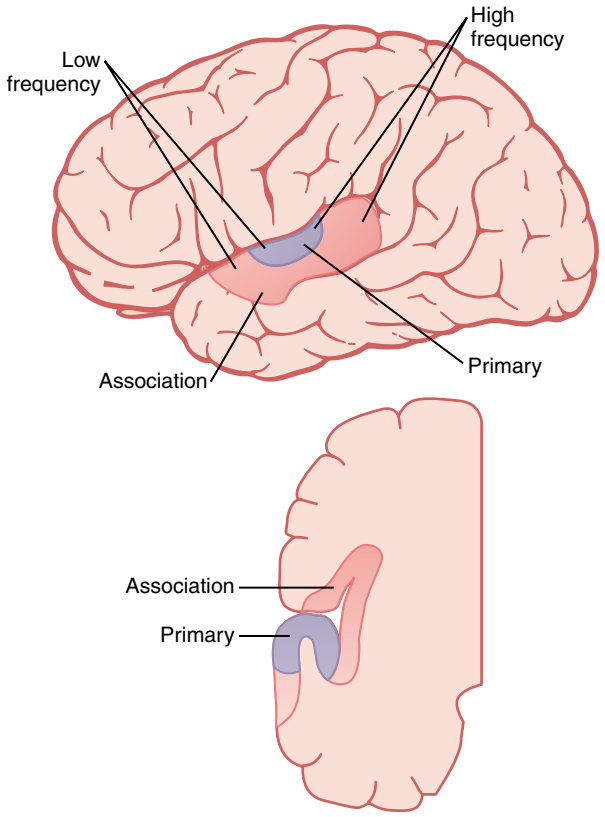


Figure 52-11 Auditory cortex.

Why does the auditory cortex have so many different tonotopic maps? The answer, presumably, is that each of the separate areas dissects out some specific feature of the sounds. For instance, one of the large maps in the primary auditory cortex almost certainly discriminates the sound frequencies themselves and gives the person the psychic sensation of sound pitches. Another map is probably used to detect the direction from which the sound comes. Other auditory cortex areas detect special qualities, such as the sudden onset of sounds, or perhaps special modulations, such as noise versus pure frequency sounds.

The frequency range to which each individual neuron in the auditory cortex responds is much narrower than that in the cochlear and brain stem relay nuclei. Referring to Figure 52-6*B*, note that the basilar membrane near the base of the cochlea is stimulated by sounds of all frequencies, and in the cochlear nuclei, this same breadth of sound representation is found. Yet, by the time the excitation has reached the cerebral cortex, most sound-responsive neurons respond to only a narrow range of frequencies rather than to a broad range. Therefore, somewhere along the pathway, processing mechanisms "sharpen" the frequency response. It is believed that this sharpening effect is caused mainly by the phenomenon of lateral inhibition, which is discussed in Chapter 46 in relation to mechanisms for transmitting information in nerves. That is, stimulation of the cochlea at one frequency inhibits sound frequencies on both sides of this primary frequency; this is caused by collateral fibers angling off the primary signal pathway and exerting inhibitory influences on adjacent pathways. The same effect has been demonstrated to be important in sharpening patterns of somesthetic images, visual images, and other types of sensations.

Many of the neurons in the auditory cortex, *especially in the auditory association cortex*, do not respond only to specific sound frequencies in the ear. It is believed that these neurons "associate" different sound frequencies with one another or associate sound information with information from other sensory areas of the cortex. Indeed, the parietal portion of the auditory association cortex partly overlaps somatosensory area II, which could provide an easy opportunity for the association of auditory information with somatosensory information.

Discrimination of Sound "Patterns" by the Auditory Cortex. Complete bilateral removal of the auditory cortex does not prevent a cat or monkey from detecting sounds or reacting in a crude manner to sounds. However, it does greatly reduce or sometimes even abolish the animal's ability to discriminate different sound pitches and especially *patterns of sound*. For instance, an animal that has been trained to recognize a combination or sequence of tones, one following the other in a particular pattern,

loses this ability when the auditory cortex is destroyed; furthermore, the animal cannot relearn this type of response. Therefore, the auditory cortex is especially important in the discrimination of *tonal* and *sequential sound patterns*.

Destruction of both primary auditory cortices in the human being greatly reduces one's sensitivity for hearing. Destruction of one side only slightly reduces hearing in the opposite ear; it does not cause deafness in the ear because of many crossover connections from side to side in the auditory neural pathway. However, it does affect one's ability to localize the source of a sound, because comparative signals in both cortices are required for the localization function.

Lesions that affect the auditory association areas but not the primary auditory cortex do not decrease a person's ability to hear and differentiate sound tones, or even to interpret at least simple patterns of sound. However, the person is often unable to interpret the *meaning* of the sound heard. For instance, lesions in the posterior portion of the superior temporal gyrus, which is called Wernicke's area and is part of the auditory association cortex, often make it impossible for a person to interpret the meanings of words even though he or she hears them perfectly well and can even repeat them. These functions of the auditory association areas and their relation to the overall intellectual functions of the brain are discussed in more detail in Chapter 57.

Determination of the Direction from Which Sound Comes

A person determines the horizontal direction from which sound comes by two principal means: (1) the time lag between the entry of sound into one ear and its entry into the opposite ear, and (2) the difference between the intensities of the sounds in the two ears.

The first mechanism functions best at frequencies below 3000 cycles per second, and the second mechanism operates best at higher frequencies because the head is a greater sound barrier at these frequencies. The time lag mechanism discriminates direction much more exactly than the intensity mechanism because it does not depend on extraneous factors but only on the exact interval of time between two acoustical signals. If a person is looking straight toward the source of the sound, the sound reaches both ears at exactly the same instant, whereas if the right ear is closer to the sound than the left ear is, the sound signals from the right ear enter the brain ahead of those from the left ear.

The two aforementioned mechanisms cannot tell whether the sound is emanating from in front of or behind the person or from above or below. This discrimination is achieved mainly by the *pinnae* of the two ears. The shape of the pinna changes the *quality* of the sound entering the ear, depending on the direction from which the sound comes. It does this by emphasizing specific sound frequencies from the different directions.

Neural Mechanisms for Detecting Sound Direction.

Destruction of the auditory cortex on both sides of the brain, whether in human beings or in lower mammals, causes loss of almost all ability to detect the direction from which sound comes. Yet, the neural analyses for this detection process begin in the *superior olivary nuclei* in the brain stem, even though the neural pathways all the way from these nuclei to the cortex are required for interpretation of the signals. The mechanism is believed to be the following.

The superior olivary nucleus is divided into two sections: (1) the *medial superior olivary nucleus* and (2) the *lateral superior olivary nucleus*. The lateral nucleus is concerned with detecting the direction from which the sound is coming, presumably by simply comparing the *difference in intensities of the sound* reaching the two ears and sending an appropriate signal to the auditory cortex to estimate the direction.

The *medial superior olivary nucleus*, however, has a specific mechanism for *detecting the time lag between acoustical signals entering the two ears*. This nucleus contains large numbers of neurons that have two major dendrites, one projecting to the right and the other to the left. The acoustical signal from the right ear impinges on the right dendrite, and the signal from the left ear impinges on the left dendrite. The intensity of excitation of each neuron is highly sensitive to a specific time lag between the two acoustical signals from the two ears. The neurons near one border of the nucleus respond maximally to a short time lag, whereas those near the opposite border respond to a long time lag; those in between respond to intermediate time lags. Thus, a spatial pattern of neuronal stimulation develops in the medial superior olivary nucleus, with sound from directly in front of the head stimulating one set of olivary neurons maximally and sounds from different side angles stimulating other sets of neurons on opposite sides. This spatial orientation of signals is then transmitted to the auditory cortex, where sound direction is determined by the locus of the maximally stimulated neurons. It is believed that all these signals for determining sound direction are transmitted through a different pathway and excite a different locus in the cerebral cortex from the transmission pathway and termination locus for tonal patterns of sound.

This mechanism for detection of sound direction indicates again how specific information in sensory signals is dissected out as the signals pass through different levels of neuronal activity. In this case, the "quality" of sound direction is separated from the "quality" of sound tones at the level of the superior olivary nuclei.

Centrifugal Signals from the Central Nervous System to Lower Auditory Centers

Retrograde pathways have been demonstrated at each level of the auditory nervous system from the cortex to the cochlea in the ear itself. The final pathway is mainly from the superior olivary nucleus to the sound-receptor hair cells in the organ of Corti.

These retrograde fibers are inhibitory. Indeed, direct stimulation of discrete points in the olivary nucleus has been shown to inhibit specific areas of the organ of Corti, reducing their sound sensitivities 15 to 20 decibels. One can readily understand how this could allow a person to direct his or her attention to sounds of particular qualities while rejecting sounds of other qualities. This is readily demonstrated when one listens to a single instrument in a symphony orchestra.

Hearing Abnormalities

Types of Deafness

Deafness is usually divided into two types: (1) that caused by impairment of the cochlea, the auditory nerve, or the central nervous system circuits from the ear, which is usually classified as "nerve deafness," and (2) that caused by impairment of the physical structures of the ear that conduct sound itself to the cochlea, which is usually called "conduction deafness."

If either the cochlea or the auditory nerve is destroyed, the person becomes permanently deaf. However, if the cochlea and nerve are still intact but the tympanum-ossicular system has been destroyed or ankylosed ("frozen" in place by fibrosis or calcification), sound waves can still be conducted into the cochlea by means of bone conduction from a sound generator applied to the skull over the ear.

Audiometer. To determine the nature of hearing disabilities, the "audiometer" is used. Simply an earphone connected to an electronic oscillator capable of emitting pure tones ranging from low frequencies to high frequencies, the instrument is calibrated so that zero-intensity-level sound at each frequency is the loudness that can barely be heard by the normal ear. A calibrated volume control can increase the loudness above the zero level. If the loudness must be increased to 30 decibels above normal before it can be heard, the person is said to have a *hearing loss* of 30 decibels at that particular frequency.

In performing a hearing test using an audiometer, one tests about 8 to 10 frequencies covering the auditory spectrum, and the hearing loss is determined for each of these frequencies. Then the so-called *audiogram* is plotted, as shown in Figures 52-12 and 52-13, depicting hearing loss at each of the frequencies in the auditory spectrum. The audiometer, in addition to being equipped with an earphone for testing air conduction by the ear, is equipped with a mechanical vibrator for testing bone conduction from the mastoid process of the skull into the cochlea.

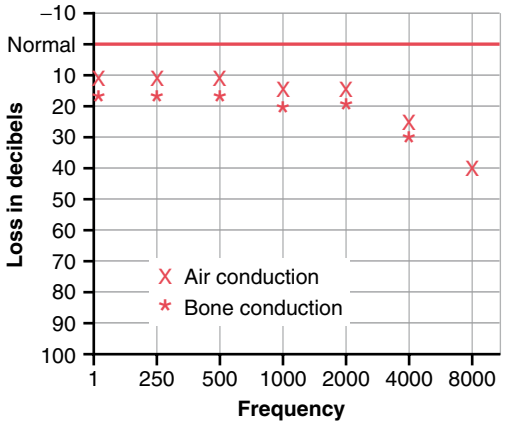


Figure 52-12 Audiogram of the old-age type of nerve deafness.

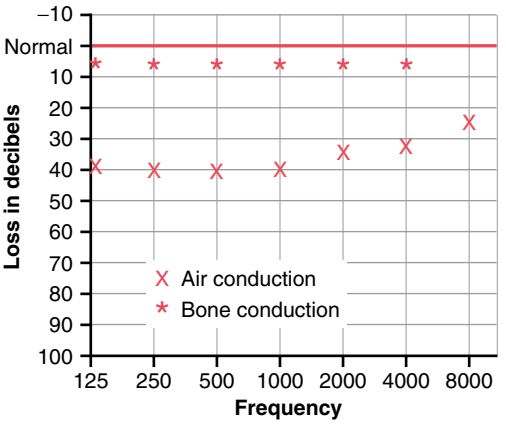


Figure 52-13 Audiogram of air conduction deafness resulting from middle ear sclerosis.

Audiogram in Nerve Deafness. In nerve deafness, which includes damage to the cochlea, the auditory nerve, or the central nervous system circuits from the ear, the person has decreased or total loss of ability to hear sound as tested by both air conduction and bone conduction. An audiogram depicting partial nerve deafness is shown in Figure 52-12. In this figure, the deafness is mainly for high-frequency sound. Such deafness could be caused by damage to the base of the cochlea. This type of deafness occurs to some extent in almost all older people.

Other patterns of nerve deafness frequently occur as follows: (1) deafness for low-frequency sounds caused by excessive and prolonged exposure to very loud sounds (a rock band or a jet airplane engine), because low-frequency sounds are usually louder and more damaging to the organ of Corti, and (2) deafness for all frequencies caused by drug sensitivity of the organ of Corti—in particular, sensitivity to some antibiotics such as streptomycin, kanamycin, and chloramphenicol.

Audiogram for Middle Ear Conduction Deafness. A common type of deafness is caused by fibrosis in the middle ear following repeated infection or by fibrosis that occurs in the hereditary disease called *otosclerosis*. In either case, the sound waves cannot be transmitted easily through the ossicles from the tympanic membrane to the oval window. Figure 52-13 shows an audiogram from a person with "middle ear air conduction deafness." In this case, bone conduction is essentially normal, but conduction through the ossicular system is greatly depressed at all frequencies, but more so at low frequencies. In some instances of conduction deafness, the faceplate of the stapes becomes "ankylosed" by bone overgrowth to the edges of the oval window. In this case, the person becomes totally deaf for ossicular conduction but can regain almost normal hearing by the surgical removal of the stapes and its replacement with a minute Teflon or metal prosthesis that transmits the sound from the incus to the oval window.

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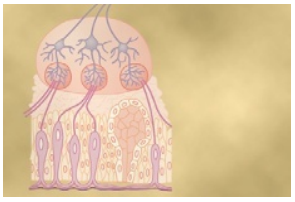
The Chemical Senses—Taste and Smell



The senses of taste and smell allow us to separate undesirable or even lethal foods from those that are pleasant to eat and nutritious. They also elicit physiological responses that are involved in digestion and utilization of foods. The sense of smell also allows animals to recognize the proximity of other animals or even individuals among animals. Finally, both senses are strongly tied to primitive emotional and behavioral functions of our nervous systems. In this chapter, we discuss how taste and smell stimuli are detected and how they are encoded in neural signals transmitted to the brain.

Sense of Taste

Taste is mainly a function of the *taste buds* in the mouth, but it is common experience that one's sense of smell also contributes strongly to taste perception. In addition, the texture of food, as detected by tactual senses of the mouth, and the presence of substances in the food that stimulate pain endings, such as pepper, greatly alter the taste experience. The importance of taste lies in the fact that it allows a person to select food in accord with desires and often in accord with the body tissues' metabolic need for specific substances.

Primary Sensations of Taste

The identities of the specific chemicals that excite different taste receptors are not all known. Even so, psychophysiologic and neurophysiologic studies have identified at least 13 possible or probable chemical receptors in the taste cells, as follows: 2 sodium receptors, 2 potassium receptors, 1 chloride receptor, 1 adenosine receptor, 1 inosine receptor, 2 sweet receptors, 2 bitter receptors, 1 glutamate receptor, and 1 hydrogen ion receptor.

For practical analysis of taste, the aforementioned receptor capabilities have also been grouped into five general categories called the *primary sensations of taste*. They are *sour, salty, sweet, bitter*, and "*umami*."

A person can perceive hundreds of different tastes. They are all supposed to be combinations of the elementary taste sensations, just as all the colors we can see are combinations of the three primary colors, as described in Chapter 50.

Sour Taste. The sour taste is caused by acids, that is, by the hydrogen ion concentration, and the intensity of this taste sensation is approximately proportional to the *logarithm of the hydrogen ion concentration*. That is, the more acidic the food, the stronger the sour sensation becomes.

Salty Taste. The salty taste is elicited by ionized salts, mainly by the sodium ion concentration. The quality of the taste varies somewhat from one salt to another because some salts elicit other taste sensations in addition to saltiness. The cations of the salts, especially sodium cations, are mainly responsible for the salty taste, but the anions also contribute to a lesser extent.

Sweet Taste. The sweet taste is not caused by any single class of chemicals. Some of the types of chemicals that cause this taste include sugars, glycols, alcohols, aldehydes, ketones, amides, esters, some amino acids, some small proteins, sulfonic acids, halogenated acids, and inorganic salts of lead and beryllium. Note specifically that most of the substances that cause a sweet taste are organic chemicals. It is especially interesting that slight changes in the chemical structure, such as addition of a simple radical, can often change the substance from sweet to bitter.

Bitter Taste. The bitter taste, like the sweet taste, is not caused by any single type of chemical agent. Here again, the substances that give the bitter taste are almost entirely organic substances. Two particular classes of substances are especially likely to cause bitter taste sensations: (1) long-chain organic substances that contain nitrogen and (2) alkaloids. The alkaloids include many of the drugs used in medicines, such as quinine, caffeine, strychnine, and nicotine.

Some substances that at first taste sweet have a bitter aftertaste. This is true of saccharin, which makes this substance objectionable to some people.

The bitter taste, when it occurs in high intensity, usually causes the person or animal to reject the food. This is undoubtedly an important function of the bitter taste sensation because many deadly toxins found in poisonous plants are alkaloids, and virtually all of these cause intensely bitter taste, usually followed by rejection of the food.

Umami Taste. *Umami* is a Japanese word (meaning "delicious") designating a pleasant taste sensation that is qualitatively different from sour, salty, sweet, or bitter. Umami is the dominant taste of food containing *L-glutamate,* such as meat extracts and aging cheese, and some physiologists consider it to be a separate, fifth category of primary taste stimuli.

A taste receptor for L-glutamate may be related to one of the glutamate receptors that are also expressed in neuronal synapses of the brain. However, the precise molecular mechanisms responsible for umami taste are still unclear.

Threshold for Taste

The threshold for stimulation of the sour taste by hydrochloric acid averages 0.0009 N; for stimulation of the salty taste by sodium chloride, 0.01 M; for the sweet taste by sucrose, 0.01 M; and for the bitter taste by quinine, 0.000008 M. Note especially how much more sensitive is the bitter taste sense than all the others, which would be expected, because this sensation provides an important protective function against many dangerous toxins in food.

Table 53-1 gives the relative taste indices (the reciprocals of the taste thresholds) of different substances. In this table, the intensities of four of the primary sensations of taste are referred, respectively, to the intensities of the taste of hydrochloric acid, quinine, sucrose, and sodium chloride, each of which is arbitrarily chosen to have a taste index of 1.

Taste Blindness. Some people are taste blind for certain substances, especially for different types of thiourea compounds. A substance used frequently by psychologists for demonstrating taste blindness is *phenylthiocarbamide*, for which about 15 to 30 percent of all people exhibit taste blindness; the exact percentage depends on the method of testing and the concentration of the substance.

Taste Bud and Its Function

Figure 53-1 shows a taste bud, which has a diameter of about $^{1}/_{30}$ millimeter and a length of about $^{1}/_{16}$ millimeter. The taste bud is composed of about 50 modified epithelial cells, some of which are supporting cells called *sustentacular cells* and others of which are *taste cells*. The taste cells are continually being replaced by mitotic division of surrounding epithelial cells, so some taste cells are young cells. Others are mature cells that lie toward the center of the bud; these soon break up and dissolve. The life span of each taste cell is about 10 days in lower mammals but is unknown for humans.

The outer tips of the taste cells are arranged around a minute *taste pore*, shown in Figure 53-1. From the tip of each taste cell, several *microvilli*, or *taste hairs*, protrude outward into the taste pore to approach the cavity of the mouth. These microvilli provide the receptor surface for taste.

Table 53-1 Relative Taste Indices of Different Substances

Sour Substances	Index	Bitter Substances	Index	Sweet Substances	Index	Salty Substances	Index
Hydrochloric acid	1	Quinine	1	Sucrose	1	NaCl	1
Formic acid	1.1	Brucine	11	1-Propoxy-2-amino-4-nitrobenzene	5000	NaF	2
Chloracetic acid	0.9	Strychnine	3.1	Saccharin	675	$CaCl_2$	1
Acetylacetic acid	0.85	Nicotine	1.3	Chloroform	40	NaBr	0.4
Lactic acid	0.85	Phenylthiourea	0.9	Fructose	1.7	NaI	0.35
Tartaric acid	0.7	Caffeine	0.4	Alanine	1.3	LiCl	0.4
Malic acid	0.6	Veratrine	0.2	Glucose	0.8	NH_4Cl	2.5
Potassium H tartrate	0.58	Pilocarpine	0.16	Maltose	0.45	KCl	0.6
Acetic acid	0.55	Atropine	0.13	Galactose	0.32		
Citric acid	0.46	Cocaine	0.02	Lactose	0.3		
Carbonic acid	0.06	Morphine	0.02				

Data from Pfaffman C: Handbook of Physiology, vol 1. Baltimore: Williams & Wilkins, 1959, p 507.

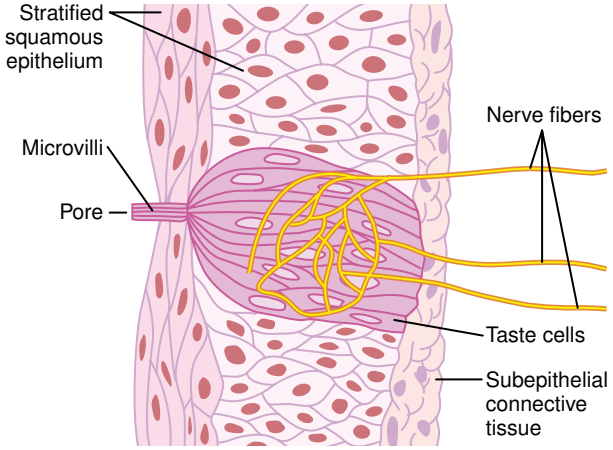


Figure 53-1 Taste bud.

Interwoven around the bodies of the taste cells is a branching terminal network of *taste nerve fibers* that are stimulated by the taste receptor cells. Some of these fibers invaginate into folds of the taste cell membranes. Many vesicles form beneath the cell membrane near the fibers. It is believed that these vesicles contain a neurotransmitter substance that is released through the cell membrane to excite the nerve fiber endings in response to taste stimulation.

Location of the Taste Buds. The taste buds are found on three types of papillae of the tongue, as follows: (1) A large number of taste buds are on the walls of the troughs that surround the circumvallate papillae, which form a V line on the surface of the posterior tongue. (2) Moderate numbers of taste buds are on the fungiform papillae over the flat anterior surface of the tongue. (3) Moderate numbers are on the foliate papillae located in the folds along the lateral surfaces of the tongue. Additional taste buds are located on the palate, and a few are found on the tonsillar pillars, on the epiglottis, and even in the proximal esophagus. Adults have 3000 to 10,000 taste buds, and children have a few more. Beyond the age of 45 years, many taste buds degenerate, causing taste sensitivity to decrease in old age.

Specificity of Taste Buds for a Primary Taste Stimulus. Microelectrode studies from single taste buds show that each taste bud usually *responds mostly to one of the five primary taste stimuli when the taste substance is in low concentration*. But at high concentration, most buds can be excited by two or more of the primary taste stimuli, as well as by a few other taste stimuli that do not fit into the "primary" categories.

Mechanism of Stimulation of Taste Buds

Receptor Potential. The membrane of the taste cell, like that of most other sensory receptor cells, is negatively charged on the inside with respect to the outside. Application of a taste substance to the taste hairs causes partial loss of this negative potential—that is, the taste cell becomes *depolarized*. In most instances, the decrease in potential, within a wide range, is approximately proportional to the logarithm of concentration of the stimulating substance. This *change in electrical potential* in the taste cell is called the *receptor potential* for taste.

The mechanism by which most stimulating substances react with the taste villi to initiate the receptor potential is by binding of the taste chemical to a protein receptor molecule that lies on the outer surface of the taste receptor cell near to or protruding through a villus membrane. This, in turn, opens ion channels, which allows positively charged sodium ions or hydrogen ions to enter and depolarize the normal negativity of the cell. Then the taste chemical itself is gradually washed away from the taste villus by the saliva, which removes the stimulus.

The type of receptor protein in each taste villus determines the type of taste that will be perceived. For sodium ions and hydrogen ions, which elicit salty and sour taste sensations, respectively, the receptor proteins open specific ion channels in the apical membranes of the taste cells, thereby activating the receptors. However, for the sweet and bitter taste sensations, the portions of the receptor protein molecules that protrude through the apical membranes activate *second-messenger transmitter substances* inside the taste cells, and these second messengers cause intracellular chemical changes that elicit the taste signals.

Generation of Nerve Impulses by the Taste Bud. On first application of the taste stimulus, the rate of discharge of the nerve fibers from taste buds rises to a peak in a small fraction of a second but then adapts within the next few seconds back to a lower, steady level as long as the taste stimulus remains. Thus, a strong immediate signal is transmitted by the taste nerve, and a weaker continuous signal is transmitted as long as the taste bud is exposed to the taste stimulus.

Transmission of Taste Signals into the Central Nervous System

Figure 53-2 shows the neuronal pathways for transmission of taste signals from the tongue and pharyngeal region into the central nervous system. Taste impulses from the anterior two thirds of the tongue pass first into the *lingual nerve*, then through the *chorda tympani* into the *facial nerve*, and finally into the *tractus solitarius* in the brain stem. Taste sensations from the circumvallate papillae on the back of the tongue and from other posterior regions of the mouth and throat are transmitted through the *glossopharyngeal nerve* also into the *tractus solitarius*, but at a slightly more posterior level. Finally, a few taste signals are transmitted into the *tractus solitarius* from the base of the tongue and other parts of the pharyngeal region by way of the *vagus nerve*.

All taste fibers synapse in the posterior brain stem in the *nuclei of the tractus solitarius*. These nuclei send second-order neurons to a small area of the *ventral posterior medial nucleus of the thalamus*, located slightly medial

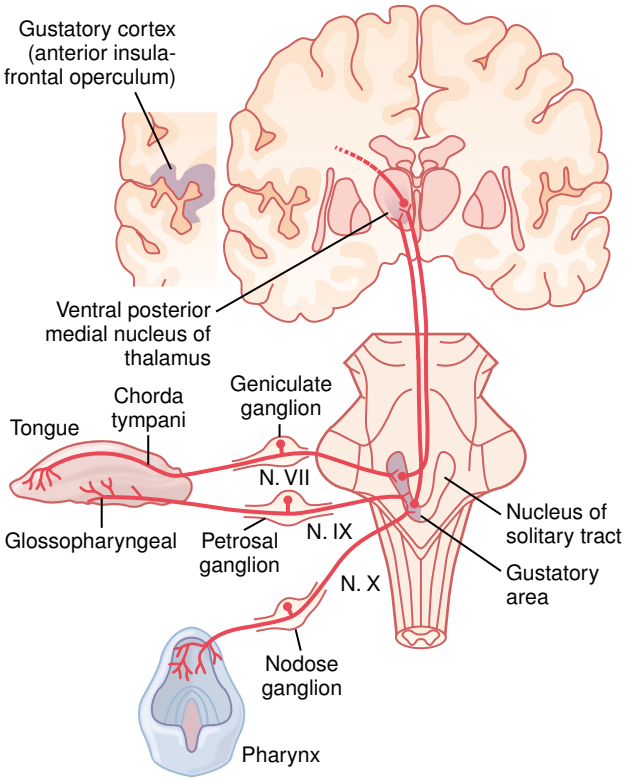


Figure 53-2 Transmission of taste signals into the central nervous system.

to the thalamic terminations of the facial regions of the dorsal column-medial lemniscal system. From the thalamus, third-order neurons are transmitted to the *lower tip of the postcentral gyrus in the parietal cerebral cortex*, where it curls *deep into the sylvian fissure*, and into the adjacent *opercular insular area*. This lies slightly lateral, ventral, and rostral to the area for tongue tactile signals in cerebral somatic area I. From this description of the taste pathways, it is evident that they closely parallel the somatosensory pathways from the tongue.

Taste Reflexes Are Integrated in the Brain Stem. From the tractus solitarius, many taste signals are transmitted within the brain stem itself directly into the *superior* and *inferior salivatory nuclei*, and these areas transmit signals to the submandibular, sublingual, and parotid glands to help control the secretion of saliva during the ingestion and digestion of food.

Rapid Adaptation of Taste. Everyone is familiar with the fact that taste sensations adapt rapidly, often almost completely within a minute or so of continuous stimulation. Yet from electrophysiologic studies of taste nerve fibers, it is clear that adaptation of the taste buds themselves usually accounts for no more than about half of this. Therefore, the final extreme degree of adaptation that occurs in the sensation of taste almost certainly occurs in the central nervous system itself, although the mechanism and site of this are not known. At any rate, it is a mechanism different from that of most other sensory systems, which adapt almost entirely at the receptors.

Taste Preference and Control of the Diet

Taste preference simply means that an animal will choose certain types of food in preference to others, and the animal automatically uses this to help control the diet it eats. Furthermore, its taste preferences often change in accord with the body's need for certain specific substances.

The following experiments demonstrate this ability of animals to choose food in accord with the needs of their bodies. First, adrenalectomized, *salt-depleted* animals automatically select drinking water with a high concentration of sodium chloride in preference to pure water, and this is often sufficient to supply the needs of the body and prevent salt-depletion death. Second, an animal given injections of excessive amounts of insulin develops a depleted blood sugar, and the animal automatically chooses the sweetest food from among many samples. Third, calcium-depleted parathyroidectomized animals automatically choose drinking water with a high concentration of calcium chloride.

The same phenomena are also observed in everyday life. For instance, the "salt licks" of desert regions are known to attract animals from far and wide. Also, human beings reject any food that has an unpleasant affective sensation, which in many instances protects our bodies from undesirable substances.

The phenomenon of taste preference almost certainly results from some mechanism located in the central nervous system and not from a mechanism in the taste receptors themselves, although the receptors often become sensitized in favor of a needed nutrient. An important reason for believing that taste preference is mainly a central nervous system phenomenon is that previous experience with unpleasant or pleasant tastes plays a major role in determining one's taste preferences. For instance, if a person becomes sick soon after eating a particular type of food, the person generally develops a negative taste preference, or *taste aversion*, for that particular food thereafter; the same effect can be demonstrated in lower animals.

Sense of Smell

Smell is the least understood of our senses. This results partly from the fact that the sense of smell is a subjective phenomenon that cannot be studied with ease in lower animals. Another complicating problem is that the sense of smell is poorly developed in human beings in comparison with the sense of smell in many lower animals.

Olfactory Membrane

The olfactory membrane, the histology of which is shown in Figure 53-3, lies in the superior part of each nostril. Medially, the olfactory membrane folds downward along the surface of the superior septum; laterally, it folds over the superior turbinate and even over a small portion of the upper surface of the middle turbinate. In each nostril, the olfactory membrane has a surface area of about 2.4 square centimeters.

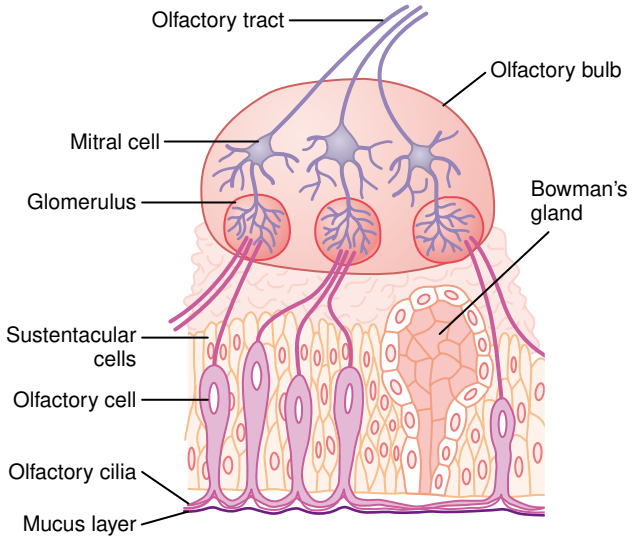


Figure 53-3 Organization of the olfactory membrane and olfactory bulb, and connections to the olfactory tract.

Olfactory Cells. The receptor cells for the smell sensation are the *olfactory cells* (see Figure 53-3), which are actually bipolar nerve cells derived originally from the central nervous system itself. There are about 100 million of these cells in the olfactory epithelium interspersed among *sustentacular cells*, as shown in Figure 53-3. The mucosal end of the olfactory cell forms a knob from which 4 to 25 *olfactory hairs* (also called *olfactory cilia*), measuring 0.3 micrometer in diameter and up to 200 micrometers in length, project into the mucus that coats the inner surface of the nasal cavity. These projecting olfactory cilia form a dense mat in the mucus, and it is these cilia that react to odors in the air and stimulate the olfactory cells, as discussed later. Spaced among the olfactory cells in the olfactory membrane are many small *Bowman's glands* that secrete mucus onto the surface of the olfactory membrane.

Stimulation of the Olfactory Cells

Mechanism of Excitation of the Olfactory Cells. The portion of each olfactory cell that responds to the olfactory chemical stimuli is the *olfactory cilia*. The odorant substance, on coming in contact with the olfactory membrane surface, first diffuses into the mucus that covers the cilia. Then it binds with *receptor proteins* in the membrane of each cilium (Figure 53-4). Each receptor protein is actually a long molecule that threads its way through the membrane about seven times, folding inward and outward. The odorant binds with the portion of the receptor protein that folds to the outside. The inside of the folding protein, however, is coupled to a *G-protein*, itself a combination of three subunits. On excitation of the receptor protein, an *alpha* subunit breaks away from the G-protein and immediately activates *adenylyl cyclase*, which is attached to the inside of the ciliary membrane near the receptor cell body. The activated cyclase, in turn, converts many molecules of intracellular *adenosine triphosphate*

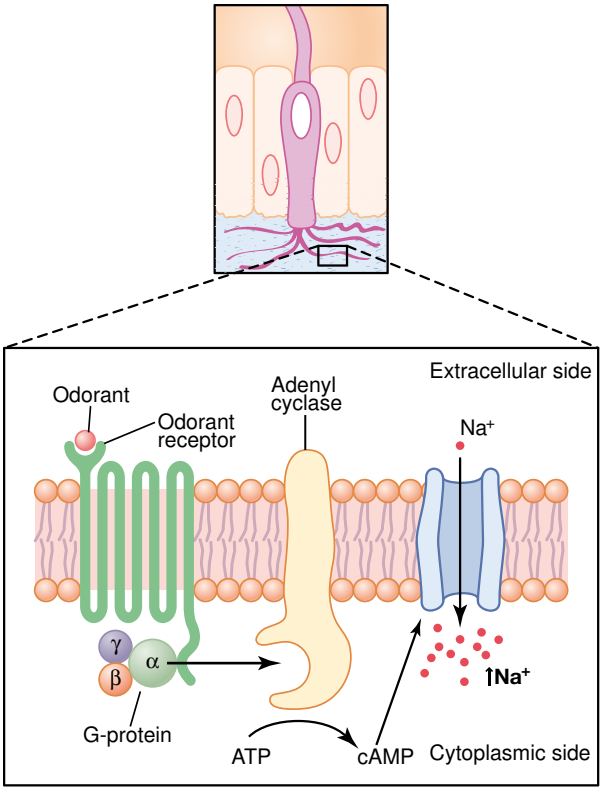


Figure 53-4 Summary of olfactory signal transduction. Binding of the odorant to a G-coupled protein receptor causes activation of adenylate cyclase, which converts adenosine triphosphate (ATP) to cyclic adenosine monophosphate (cAMP). The cAMP activates a gated sodium channel that increases sodium influx and depolarizes the cell, exciting the olfactory neuron and transmitting action potentials to the central nervous system.

into *cyclic adenosine monophosphate* (cAMP). Finally, this cAMP activates another nearby membrane protein, a *gated sodium ion channel*, that opens its "gate" and allows large numbers of sodium ions to pour through the membrane into the receptor cell cytoplasm. The sodium ions increase the electrical potential in the positive direction inside the cell membrane, thus exciting the olfactory neuron and transmitting action potentials into the central nervous system by way of the *olfactory nerve*.

The importance of this mechanism for activating olfactory nerves is that it greatly multiplies the excitatory effect of even the weakest odorant. To summarize: (1) Activation of the receptor protein by the odorant substance activates the G-protein complex. (2) This, in turn, activates multiple molecules of adenylyl cyclase inside the olfactory cell membrane. (3) This causes the formation of many times more molecules of cAMP. (4) Finally, the cAMP opens still many times more sodium ion channels. Therefore, even the most minute concentration of a specific odorant initiates a cascading effect that opens extremely large numbers of sodium channels. This accounts for the exquisite sensitivity of the olfactory neurons to even the slightest amount of odorant.

In addition to the basic chemical mechanism by which the olfactory cells are stimulated, several

physical factors affect the degree of stimulation. First, only volatile substances that can be sniffed into the nostrils can be smelled. Second, the stimulating substance must be at least slightly water soluble so that it can pass through the mucus to reach the olfactory cilia. Third, it is helpful for the substance to be at least slightly lipid soluble, presumably because lipid constituents of the cilium itself are a weak barrier to non-lipid-soluble odorants.

Membrane Potentials and Action Potentials in Olfactory Cells. The membrane potential inside unstimulated olfactory cells, as measured by microelectrodes, averages about –55 millivolts. At this potential, most of the cells generate continuous action potentials at a very slow rate, varying from once every 20 seconds up to two or three per second.

Most odorants cause *depolarization* of the olfactory cell membrane, decreasing the negative potential in the cell from the normal level of –55 millivolts to –30 millivolts or less—that is, changing the voltage in the positive direction. Along with this, the number of action potentials increases to 20 to 30 per second, which is a high rate for the minute olfactory nerve fibers.

Over a wide range, the rate of olfactory nerve impulses changes approximately in proportion to the logarithm of the stimulus strength, which demonstrates that the olfactory receptors obey principles of transduction similar to those of other sensory receptors.

Rapid Adaptation of Olfactory Sensations. The olfactory receptors adapt about 50 percent in the first second or so after stimulation. Thereafter, they adapt very little and very slowly. Yet we all know from our own experience that smell sensations adapt almost to extinction within a minute or so after entering a strongly odorous atmosphere. Because this psychological adaptation is far greater than the degree of adaptation of the receptors themselves, it is almost certain that most of the additional adaptation occurs within the central nervous system. This seems to be true for the adaptation of taste sensations as well.

A postulated neuronal mechanism for the adaptation is the following: Large numbers of centrifugal nerve fibers pass from the olfactory regions of the brain backward along the olfactory tract and terminate on special inhibitory cells in the olfactory bulb, the *granule cells*. It has been postulated that after the onset of an olfactory stimulus, the central nervous system quickly develops strong feedback inhibition to suppress relay of the smell signals through the olfactory bulb.

Search for the Primary Sensations of Smell

In the past, most physiologists were convinced that the many smell sensations are subserved by a few rather discrete primary sensations, in the same way that vision and taste are subserved by a few select primary sensations. On the basis of psychological studies, one attempt to classify these sensations is the following:

1. Camphoraceous
2. Musky
3. Floral
4. Pepperminty
5. Ethereal
6. Pungent
7. Putrid

It is certain that this list does not represent the true primary sensations of smell. In recent years, multiple clues, including specific studies of the genes that encode for the receptor proteins, suggest the existence of at least 100 primary sensations of smell—a marked contrast to only three primary sensations of color detected by the eyes and only four or five primary sensations of taste detected by the tongue. Some studies suggest that there may be as many as 1000 different types of odorant receptors. Further support for the many primary sensations of smell is that people have been found who have *odor blindness* for single substances; such discrete odor blindness has been identified for more than 50 different substances. It is presumed that odor blindness for each substance represents lack of the appropriate receptor protein in olfactory cells for that particular substance.

"Affective Nature of Smell." Smell, even more so than taste, has the affective quality of either *pleasantness* or *unpleasantness*. Because of this, smell is probably even more important than taste for the selection of food. Indeed, a person who has previously eaten food that disagreed with him or her is often nauseated by the smell of that same food on a second occasion. Conversely, perfume of the right quality can be a powerful stimulant of human emotions. In addition, in some lower animals, odors are the primary excitant of sexual drive.

Threshold for Smell. One of the principal characteristics of smell is the minute quantity of stimulating agent in the air that can elicit a smell sensation. For instance, the substance *methylmercaptan* can be smelled when only one 25 trillionth of a gram is present in each milliliter of air. Because of this very low threshold, this substance is mixed with natural gas to give the gas an odor that can be detected when even small amounts of gas leak from a pipeline.

Gradations of Smell Intensities. Although the threshold concentrations of substances that evoke smell are extremely slight, for many (if not most) odorants, concentrations only 10 to 50 times above the threshold evoke maximum intensity of smell. This is in contrast to most other sensory systems of the body, in which the ranges of intensity discrimination are tremendous—for example, 500,000 to 1 in the case of the eyes and 1 trillion to 1 in the case of the ears. This difference might be explained by the fact that smell is concerned more with detecting the presence or absence of odors rather than with quantitative detection of their intensities.

Transmission of Smell Signals into the Central Nervous System

The olfactory portions of the brain were among the first brain structures developed in primitive animals, and much of the remainder of the brain developed around these olfactory beginnings. In fact, part of the brain that originally subserved olfaction later evolved into the basal brain structures that control emotions and other aspects of human behavior; this is the system we call the *limbic system*, discussed in Chapter 58.

Transmission of Olfactory Signals into the Olfactory Bulb. The *olfactory bulb* is shown in Figure 53-5. The olfactory nerve fibers leading backward from the bulb are called *cranial nerve I*, or the *olfactory tract*. However, in reality, both the tract and the bulb are an anterior outgrowth of brain tissue from the base of the brain; the bulbous enlargement at its end, the *olfactory bulb*, lies over the *cribriform plate*, separating the brain cavity from the upper reaches of the nasal cavity. The cribriform plate has multiple small perforations through which an equal number of small nerves pass upward from the olfactory membrane in the nasal cavity to enter the olfactory bulb in the cranial cavity. Figure 53-3 demonstrates the close relation between the *olfactory cells* in the olfactory membrane and the olfactory bulb, showing short axons from the olfactory cells terminating in multiple globular structures within the olfactory bulb called *glomeruli*. Each bulb has several thousand such glomeruli, each of which is the terminus for about 25,000 axons from olfactory cells. Each glomerulus also is the terminus for dendrites from about 25 large *mitral cells* and about 60 smaller *tufted cells*, the cell bodies of which lie in the olfactory bulb superior to the glomeruli. These dendrites receive synapses from the olfactory cell neurons, and the mitral and tufted cells send axons through the olfactory tract to transmit olfactory signals to higher levels in the central nervous system.

Some research has suggested that different glomeruli respond to different odors. It is possible that specific glomeruli are the real clue to the analysis of different odor signals transmitted into the central nervous system.

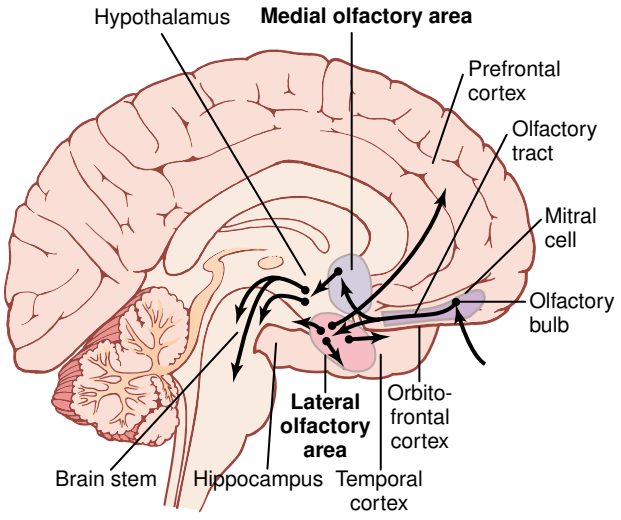


Figure 53-5 Neural connections of the olfactory system.

The Very Old, the Less Old, and the Newer Olfactory Pathways into the Central Nervous System

The olfactory tract enters the brain at the anterior junction between the mesencephalon and cerebrum; there, the tract divides into two pathways, as shown in Figure 53-5, one passing medially into the *medial olfactory area* of the brain stem, and the other passing laterally into the *lateral olfactory area*. The medial olfactory area represents a very old olfactory system, whereas the lateral olfactory area is the input to (1) a less old olfactory system and (2) a newer system.

The Very Old Olfactory System—The Medial Olfactory Area. The medial olfactory area consists of a group of nuclei located in the midbasal portions of the brain immediately anterior to the hypothalamus. Most conspicuous are the *septal nuclei*, which are midline nuclei that feed into the hypothalamus and other primitive portions of the brain's limbic system. This is the brain area most concerned with basic behavior (described in Chapter 58).

The importance of this medial olfactory area is best understood by considering what happens in animals when the lateral olfactory areas on both sides of the brain are removed and only the medial system remains. The answer is that this hardly affects the more primitive responses to olfaction, such as licking the lips, salivation, and other feeding responses caused by the smell of food or by primitive emotional drives associated with smell. Conversely, removal of the lateral areas abolishes the more complicated olfactory conditioned reflexes.

The Less Old Olfactory System—The Lateral Olfactory Area. The lateral olfactory area is composed mainly of the *prepyriform* and *pyriform cortex* plus the *cortical portion of the amygdaloid nuclei*. From these areas, signal pathways pass into almost all portions of the limbic system, especially into less primitive portions such as the hippocampus, which seem to be most important for learning to like or dislike certain foods depending on one's experiences with them. For instance, it is believed that this lateral olfactory area and its many connections with the limbic behavioral system cause a person to develop an absolute aversion to foods that have caused nausea and vomiting.

An important feature of the lateral olfactory area is that many signal pathways from this area also feed directly into an *older part of the cerebral cortex* called the *paleocortex* in the *anteromedial portion of the temporal lobe*. This is the only area of the entire cerebral cortex where sensory signals pass directly to the cortex without passing first through the thalamus.

The Newer Pathway. A newer olfactory pathway that passes through the thalamus, passing to the dorsomedial thalamic nucleus and then to the lateroposterior quadrant of the orbitofrontale cortex, has been found. On the basis of studies in monkeys, this newer system probably helps in the conscious analysis of odor.

Summary. Thus, there appear to be a *very old* olfactory system that subserves the basic olfactory reflexes, a *less old* system that provides automatic but partially learned control of food intake and aversion to toxic and unhealthy foods, and a *newer* system that is comparable to most of the other cortical sensory systems and is used for conscious perception and analysis of olfaction.

Centrifugal Control of Activity in the Olfactory Bulb by the Central Nervous System. Many nerve fibers that originate in the olfactory portions of the brain pass from the brain in the outward direction into the olfactory tract to the olfactory bulb (i.e., "centrifugally" from the brain to the periphery). These terminate on a large number of small *granule cells* located among the mitral and tufted cells in the olfactory bulb. The granule cells send inhibitory signals to the mitral and tufted cells. It is believed that this inhibitory feedback might be a means for sharpening one's specific ability to distinguish one odor from another.

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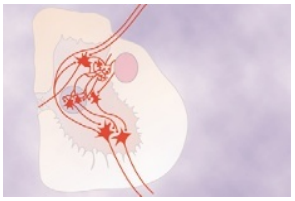
CHAPTER 54

Motor Functions of the Spinal Cord; the Cord Reflexes



Sensory information is integrated at all levels of the nervous system and causes appropriate motor responses that begin in the spinal cord with relatively simple muscle reflexes, extend into the brain stem with more complicated responses, and finally extend to the cerebrum, where the most complicated muscle skills are controlled.

In this chapter, we discuss the control of muscle function by the spinal cord. Without the special neuronal circuits of the cord, even the most complex motor control systems in the brain could not cause any purposeful muscle movement. For example, there is no neuronal circuit anywhere in the brain that causes the specific to-and-fro movements of the legs that are required in walking. Instead, the circuits for these movements are in the cord and the brain simply sends *command* signals to the spinal cord to set into motion the walking process.

Let us not belittle the role of the brain, however, because the brain gives directions that control the sequential cord activities—to promote turning movements when they are required, to lean the body forward during acceleration, to change the movements from walking to jumping as needed, and to monitor continuously and control equilibrium. All this is done through "analytical" and "command" signals generated in the brain. But it also requires the many neuronal circuits of the spinal cord that are the objects of the commands. These circuits provide all but a small fraction of the direct control of the muscles.

Organization of the Spinal Cord for Motor Functions

The cord gray matter is the integrative area for the cord reflexes. Figure 54-1 shows the typical organization of the cord gray matter in a single cord segment. Sensory signals enter the cord almost entirely through the sensory (posterior) roots. After entering the cord, every sensory signal travels to two separate destinations: (1) One branch of the sensory nerve terminates almost immediately in the gray matter of the cord and elicits local segmental cord reflexes and other local effects. (2) Another branch transmits signals to higher levels of the nervous system—to higher levels in the cord itself, to the brain stem, or even to the cerebral cortex, as described in earlier chapters.

Each segment of the spinal cord (at the level of each spinal nerve) has several million neurons in its gray matter. Aside from the sensory relay neurons discussed in Chapters 47 and 48, the other neurons are of two types: (1) *anterior motor neurons* and (2) *interneurons.*

Anterior Motor Neurons. Located in each segment of the anterior horns of the cord gray matter are several thousand neurons that are 50 to 100 percent larger than most of the others and are called *anterior motor neurons* (Figure 54-2). They give rise to the nerve fibers that leave the cord by way of the anterior roots and directly innervate the skeletal muscle fibers. The neurons are of two types, *alpha motor neurons* and *gamma motor neurons.*

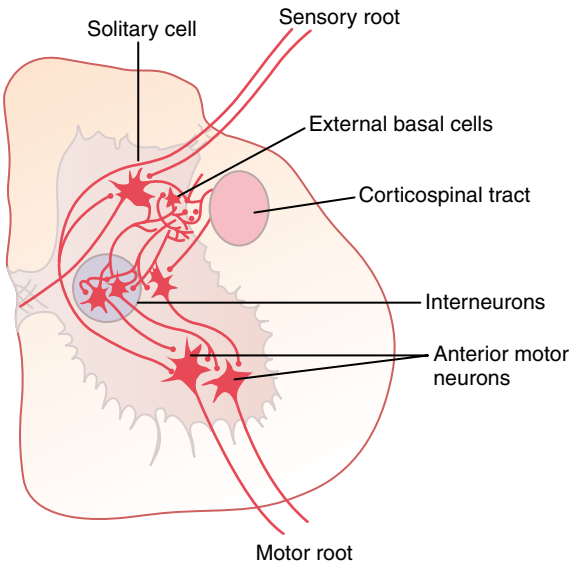


Figure 54-1 Connections of peripheral sensory fibers and corticospinal fibers with the interneurons and anterior motor neurons of the spinal cord.

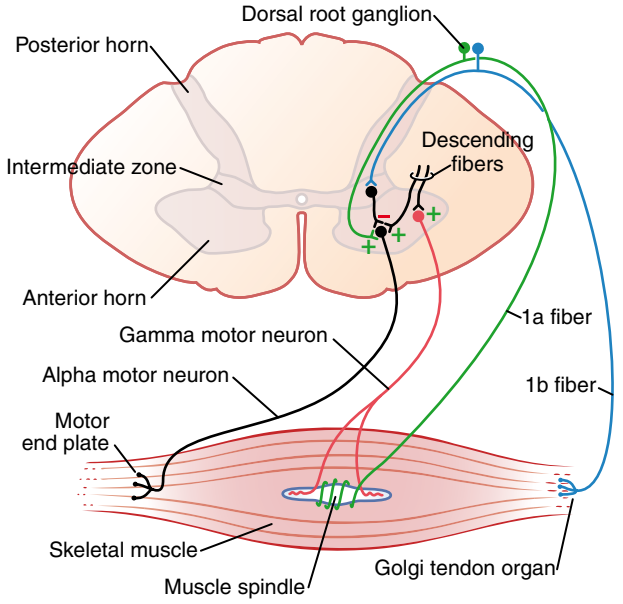


Figure 54-2 Peripheral sensory fibers and anterior motor neurons innervating skeletal muscle.

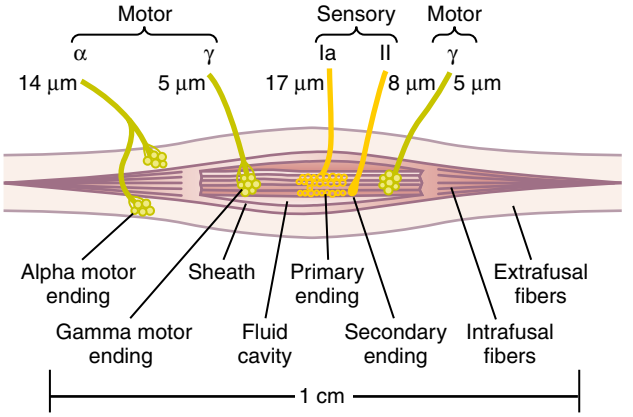


Figure 54-3 Muscle spindle, showing its relation to the large extrafusal skeletal muscle fibers. Note also both motor and sensory innervation of the muscle spindle.

Alpha Motor Neurons. The alpha motor neurons give rise to large type A alpha (Aα) motor nerve fibers, averaging 14 micrometers in diameter; these fibers branch many times after they enter the muscle and innervate the large skeletal muscle fibers. Stimulation of a single alpha nerve fiber excites anywhere from three to several hundred skeletal muscle fibers, which are collectively called the *motor unit.* Transmission of nerve impulses into skeletal muscles and their stimulation of the muscle motor units are discussed in Chapters 6 and 7.

Gamma Motor Neurons. Along with the alpha motor neurons, which excite contraction of the skeletal muscle fibers, about one half as many much smaller *gamma motor neurons* are located in the spinal cord anterior horns. These gamma motor neurons transmit impulses through much smaller type A gamma (Aγ) motor nerve fibers, averaging 5 micrometers in diameter, which go to small, special skeletal muscle fibers called *intrafusal fibers,* shown in Figures 54-2 and 54-3. These fibers constitute the middle of the *muscle spindle,* which helps control basic muscle "tone," as discussed later in this chapter.

Interneurons. Interneurons are present in all areas of the cord gray matter—in the dorsal horns, the anterior horns, and the intermediate areas between them, as shown in Figure 54-1. These cells are about 30 times as numerous as the anterior motor neurons. They are small and highly excitable, often exhibiting spontaneous activity and capable of firing as rapidly as 1500 times per second. They have many interconnections with one another, and many of them also synapse directly with the anterior motor neurons, as shown in Figure 54-1. The interconnections among the interneurons and anterior motor neurons are responsible for most of the integrative functions of the spinal cord that are discussed in the remainder of this chapter.

Essentially all the different types of neuronal circuits described in Chapter 46 are found in the interneuron pool of cells of the spinal cord, including *diverging, converging, repetitive-discharge,* and other types of circuits. In this chapter, we examine many applications of these different circuits in the performance of specific reflex acts by the spinal cord.

Only a few incoming sensory signals from the spinal nerves or signals from the brain terminate directly on the anterior motor neurons. Instead, almost all these signals are transmitted first through interneurons, where they are appropriately processed. Thus, in Figure 54-1, the corticospinal tract from the brain is shown to terminate almost entirely on spinal interneurons, where the signals from this tract are combined with signals from other spinal tracts or spinal nerves before finally converging on the anterior motor neurons to control muscle function.

Renshaw Cells Transmit Inhibitory Signals to Surrounding Motor Neurons. Also located in the anterior horns of the spinal cord, in close association with the motor neurons, are a large number of small neurons called *Renshaw cells.* Almost immediately after the anterior motor neuron axon leaves the body of the neuron, collateral branches from the axon pass to adjacent Renshaw cells. These are *inhibitory cells* that transmit inhibitory signals to the surrounding motor neurons. Thus, stimulation of each motor neuron tends to inhibit adjacent motor neurons, an effect called *lateral inhibition.* This effect is important for the following major reason: The motor system uses this lateral inhibition to focus, or sharpen, its signals in the same way that the sensory system uses the same principle to allow unabated transmission of the primary signal in the desired direction while suppressing the tendency for signals to spread laterally.

Multisegmental Connections from One Spinal Cord Level to Other Levels—Propriospinal Fibers

More than half of all the nerve fibers that ascend and descend in the spinal cord are *propriospinal fibers.* These fibers run from one segment of the cord to another. In addition, as the

sensory fibers enter the cord from the posterior cord roots, they bifurcate and branch both up and down the spinal cord; some of the branches transmit signals to only a segment or two, while others transmit signals to many segments. These ascending and descending propriospinal fibers of the cord provide pathways for the multisegmental reflexes described later in this chapter, including reflexes that coordinate simultaneous movements in the forelimbs and hindlimbs.

Muscle Sensory Receptors—Muscle Spindles and Golgi Tendon Organs—and Their Roles in Muscle Control

Proper control of muscle function requires not only excitation of the muscle by spinal cord anterior motor neurons but also continuous feedback of sensory information from each muscle to the spinal cord, indicating the functional status of each muscle at each instant. That is, what is the length of the muscle, what is its instantaneous tension, and how rapidly is its length or tension changing? To provide this information, the muscles and their tendons are supplied abundantly with two special types of sensory receptors: (1) *muscle spindles* (see Figure 54-2), which are distributed throughout the belly of the muscle and send information to the nervous system about muscle length or rate of change of length, and (2) *Golgi tendon organs* (see Figures 54-2 and 54-8), which are located in the muscle tendons and transmit information about tendon tension or rate of change of tension.

The signals from these two receptors are either entirely or almost entirely for the purpose of intrinsic muscle control. They operate almost completely at a subconscious level. Even so, they transmit tremendous amounts of information not only to the spinal cord but also to the cerebellum and even to the cerebral cortex, helping each of these portions of the nervous system function to control muscle contraction.

Receptor Function of the Muscle Spindle

Structure and Motor Innervation of the Muscle Spindle. The organization of the muscle spindle is shown in Figure 54-3. Each spindle is 3 to 10 millimeters long. It is built around 3 to 12 tiny *intrafusal muscle fibers* that are pointed at their ends and attached to the glycocalyx of the surrounding large *extrafusal* skeletal muscle fibers.

Each intrafusal muscle fiber is a tiny skeletal muscle fiber. However, the central region of each of these fibers—that is, the area midway between its two ends—has few or no actin and myosin filaments. Therefore, this central portion does not contract when the ends do. Instead, it functions as a sensory receptor, as described later. The end portions that do contract are excited by small *gamma motor nerve fibers* that originate from small type A gamma motor neurons in the anterior horns of the spinal cord, as described earlier. These gamma motor nerve fibers are also called *gamma efferent fibers,* in contradistinction to the large *alpha efferent fibers* (type A alpha nerve fibers) that innervate the extrafusal skeletal muscle.

Sensory Innervation of the Muscle Spindle. The receptor portion of the muscle spindle is its central portion. In this area, the intrafusal muscle fibers do not have myosin and actin contractile elements. As shown in Figure 54-3 and in more detail in Figure 54-4, sensory fibers originate in this area. They are stimulated by stretching of this midportion of the spindle. One can readily see that the muscle spindle receptor can be excited in two ways:

1. Lengthening the whole muscle stretches the midportion of the spindle and, therefore, excites the receptor.
2. Even if the length of the entire muscle does not change, contraction of the end portions of the spindle's intrafusal fibers stretches the midportion of the spindle and therefore excites the receptor.

Two types of sensory endings are found in this central receptor area of the muscle spindle. They are the *primary ending* and the *secondary ending.*

Primary Ending. In the center of the receptor area, a large sensory nerve fiber encircles the central portion of each intrafusal fiber, forming the so-called *primary ending* or *annulospiral ending.* This nerve fiber is a type Ia fiber averaging 17 micrometers in diameter, and it transmits sensory signals to the spinal cord at a velocity of 70 to 120 m/sec, as rapidly as any type of nerve fiber in the entire body.

Secondary Ending. Usually one but sometimes two smaller sensory nerve fibers—type II fibers with an average diameter of 8 micrometers—innervate the receptor region on one or both sides of the primary ending, as shown in Figures 54-3 and 54-4. This sensory ending is called the *secondary ending;* sometimes it encircles the intrafusal fibers in the same way that the type Ia fiber does, but often it spreads like branches on a bush.

Division of the Intrafusal Fibers into Nuclear Bag and Nuclear Chain Fibers—Dynamic and Static Responses of the Muscle Spindle. There are also two types of muscle spindle intrafusal fibers: (1) *nuclear bag muscle fibers* (one to three in each spindle), in which several

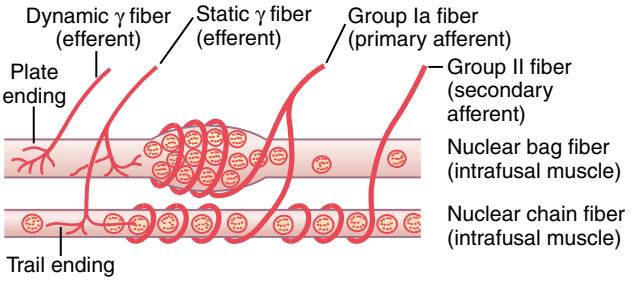


Figure 54-4 Details of nerve connections from the nuclear bag and nuclear chain muscle spindle fibers. (Modified from Stein RB: Peripheral control of movement. Physiol Rev 54:225, 1974.)

muscle fiber nuclei are congregated in expanded "bags" in the central portion of the receptor area, as shown by the top fiber in Figure 54-4, and (2) *nuclear chain fibers* (three to nine), which are about half as large in diameter and half as long as the nuclear bag fibers and have nuclei aligned in a chain throughout the receptor area, as shown by the bottom fiber in the figure. The primary sensory nerve ending (the 17-micrometer sensory fiber) is excited by both the nuclear bag intrafusal fibers *and* the nuclear chain fibers. Conversely, the secondary ending (the 8-micrometer sensory fiber) is usually excited only by nuclear chain fibers. These relations are shown in Figure 54-4.

Response of Both the Primary and the Secondary Endings to the Length of the Receptor—"Static" Response. When the receptor portion of the muscle spindle is stretched *slowly,* the number of impulses transmitted from both the primary and the secondary endings increases almost directly in proportion to the degree of stretching and the endings continue to transmit these impulses for several minutes. This effect is called the *static response* of the spindle receptor, meaning simply that both the primary and secondary endings continue to transmit their signals for at least several minutes if the muscle spindle itself remains stretched.

Response of the Primary Ending (but Not the Secondary Ending) to Rate of Change of Receptor Length—"Dynamic" Response. When the length of the spindle receptor increases suddenly, the primary ending (but not the secondary ending) is stimulated powerfully. This excess stimulus of the primary ending is called the *dynamic response,* which means that the primary ending responds extremely actively to a rapid *rate of change* in spindle length. Even when the length of a spindle receptor increases only a fraction of a micrometer for only a fraction of a second, the primary receptor transmits tremendous numbers of excess impulses to the large 17-micrometer sensory nerve fiber, *but only while the length is actually increasing.* As soon as the length stops increasing, this extra rate of impulse discharge returns to the level of the much smaller static response that is still present in the signal.

Conversely, when the spindle receptor shortens, exactly opposite sensory signals occur. Thus, the primary ending sends extremely strong, either positive or negative, signals to the spinal cord to apprise it of any change in length of the spindle receptor.

Control of Intensity of the Static and Dynamic Responses by the Gamma Motor Nerves. The gamma motor nerves to the muscle spindle can be divided into two types: *gamma-dynamic (gamma-d)* and *gamma-static (gamma-s).* The first of these excites mainly the nuclear bag intrafusal fibers, and the second excites mainly the nuclear chain intrafusal fibers. When the gamma-d fibers excite the nuclear bag fibers, the dynamic response of the muscle spindle becomes tremendously enhanced, whereas the static response is hardly affected. Conversely, stimulation of the gamma-s fibers, which excite the nuclear chain fibers, enhances the static response while having little influence on the dynamic response. Subsequent paragraphs illustrate that these two types of muscle spindle responses are important in different types of muscle control.

Continuous Discharge of the Muscle Spindles Under Normal Conditions. Normally, particularly when there is some degree of gamma nerve excitation, the muscle spindles emit sensory nerve impulses continuously. Stretching the muscle spindles increases the rate of firing, whereas shortening the spindle decreases the rate of firing. Thus, the spindles can send to the spinal cord either *positive signals*—that is, increased numbers of impulses to indicate stretch of a muscle—or *negative signals*—below-normal numbers of impulses to indicate that the muscle is unstretched.

Muscle Stretch Reflex

The simplest manifestation of muscle spindle function is the *muscle stretch reflex.* Whenever a muscle is stretched suddenly, excitation of the spindles causes reflex contraction of the large skeletal muscle fibers of the stretched muscle and also of closely allied synergistic muscles.

Neuronal Circuitry of the Stretch Reflex. Figure 54-5 demonstrates the basic circuit of the muscle spindle stretch reflex, showing a type Ia proprioceptor nerve fiber originating in a muscle spindle and entering a dorsal root of the spinal cord. A branch of this fiber then goes directly to the anterior horn of the cord gray matter and synapses with anterior motor neurons that send motor nerve fibers back to the same muscle from which the muscle spindle fiber originated. Thus, this is a *monosynaptic pathway* that allows a reflex signal to return with the shortest possible time delay back to the muscle after excitation of

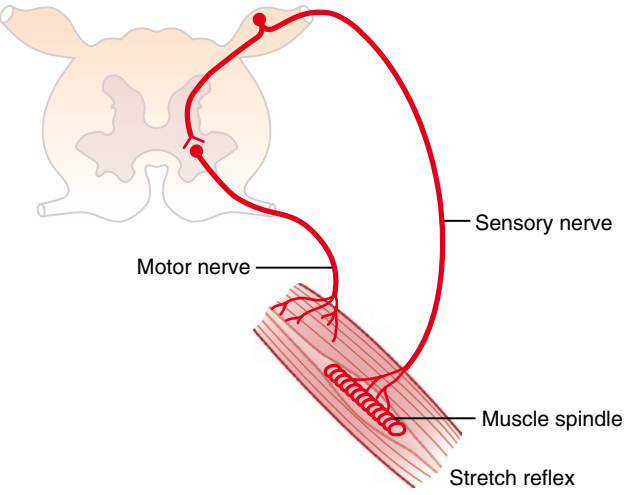


Figure 54-5 Neuronal circuit of the stretch reflex.

the spindle. Most type II fibers from the muscle spindle terminate on multiple interneurons in the cord gray matter, and these transmit delayed signals to the anterior motor neurons or serve other functions.

Dynamic Stretch Reflex and Static Stretch Reflexes. The stretch reflex can be divided into two components: the dynamic stretch reflex and the static stretch reflex. The *dynamic stretch reflex* is elicited by the potent dynamic signal transmitted from the primary sensory endings of the muscle spindles, caused by rapid stretch or unstretch. That is, when a muscle is suddenly stretched or unstretched, a strong signal is transmitted to the spinal cord; this causes an instantaneous strong reflex contraction (or decrease in contraction) of the same muscle from which the signal originated. Thus, *the reflex functions to oppose sudden changes in muscle length.*

The dynamic stretch reflex is over within a fraction of a second after the muscle has been stretched (or unstretched) to its new length, but then a weaker *static stretch reflex* continues for a prolonged period thereafter. This reflex is elicited by the continuous static receptor signals transmitted by both primary and secondary endings. The importance of the static stretch reflex is that it causes the degree of muscle contraction to remain reasonably constant, except when the person's nervous system specifically wills otherwise.

"Damping" Function of the Dynamic and Static Stretch Reflexes

An especially important function of the stretch reflex is its ability to prevent oscillation or jerkiness of body movements. This is a *damping,* or smoothing, function, as explained in the following paragraph.

Damping Mechanism in Smoothing Muscle Contraction. Signals from the spinal cord are often transmitted to a muscle in an unsmooth form, increasing in intensity for a few milliseconds, then decreasing in intensity, then changing to another intensity level, and so forth. When the muscle spindle apparatus is not functioning satisfactorily, the muscle contraction is jerky during the course of such a signal. This effect is demonstrated in Figure 54-6. In curve A, the muscle spindle reflex of the excited muscle is intact. Note that the contraction is relatively smooth, even though the motor nerve to the muscle is excited at a slow frequency of only eight signals per second. Curve B illustrates the same experiment in an animal whose muscle spindle sensory nerves had been sectioned 3 months earlier. Note the unsmooth muscle contraction. Thus, curve A graphically demonstrates the damping mechanism's ability to smooth muscle contractions, even though the primary input signals to the muscle motor system may themselves be jerky. This effect can also be called a *signal averaging* function of the muscle spindle reflex.

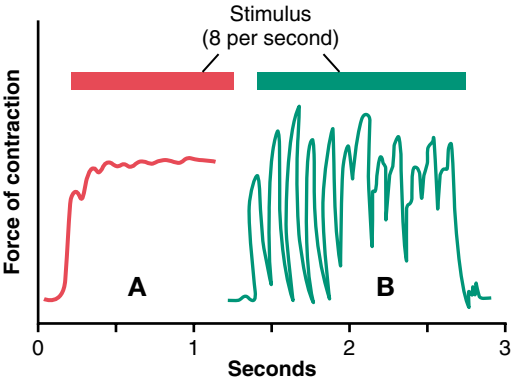


Figure 54-6 Muscle contraction caused by a spinal cord signal under two conditions: *curve A,* in a normal muscle, and *curve B,* in a muscle whose muscle spindles were denervated by section of the posterior roots of the cord 82 days previously. Note the smoothing effect of the muscle spindle reflex in *curve A.* (Modified from Creed RS et al: Reflex Activity of the Spinal Cord. New York: Oxford University Press, 1932.)

Role of the Muscle Spindle in Voluntary Motor Activity

To understand the importance of the gamma efferent system, one should recognize that 31 percent of all the motor nerve fibers to the muscle are the small type A gamma efferent fibers rather than large type A alpha motor fibers. Whenever signals are transmitted from the motor cortex or from any other area of the brain to the alpha motor neurons, in most instances the gamma motor neurons are stimulated simultaneously, an effect called *coactivation* of the alpha and gamma motor neurons. This causes both the extrafusal skeletal muscle fibers and the muscle spindle intrafusal muscle fibers to contract at the same time.

The purpose of contracting the muscle spindle intrafusal fibers at the same time that the large skeletal muscle fibers contract is twofold: First, it keeps the length of the receptor portion of the muscle spindle from changing during the course of the whole muscle contraction. Therefore, coactivation keeps the muscle spindle reflex from opposing the muscle contraction. Second, it maintains the proper damping function of the muscle spindle, regardless of any change in muscle length. For instance, if the muscle spindle did not contract and relax along with the large muscle fibers, the receptor portion of the spindle would sometimes be flail and sometimes be overstretched, in neither instance operating under optimal conditions for spindle function.

Brain Areas for Control of the Gamma Motor System

The gamma efferent system is excited specifically by signals from the *bulboreticular facilitatory* region of the brain stem and, secondarily, by impulses transmitted into the bulboreticular area from (1) the *cerebellum,* (2) the *basal ganglia,* and (3) the *cerebral cortex.*

Little is known about the precise mechanisms of control of the gamma efferent system. However, because the bulboreticular facilitatory area is particularly concerned with antigravity contractions, and because the antigravity muscles have an especially high density of muscle spindles, emphasis is given to the importance of the gamma efferent mechanism for damping the movements of the different body parts during walking and running.

Muscle Spindle System Stabilizes Body Position During Tense Action

One of the most important functions of the muscle spindle system is to stabilize body position during tense motor action. To do this, the bulboreticular facilitatory region and its allied areas of the brain stem transmit excitatory signals through the gamma nerve fibers to the intrafusal muscle fibers of the muscle spindles. This shortens the ends of the spindles and stretches the central receptor regions, thus increasing their signal output. However, if the spindles on both sides of each joint are activated at the same time, reflex excitation of the skeletal muscles on both sides of the joint also increases, producing tight, tense muscles opposing each other at the joint. The net effect is that the position of the joint becomes strongly stabilized, and any force that tends to move the joint from its current position is opposed by highly sensitized stretch reflexes operating on both sides of the joint.

Any time a person must perform a muscle function that requires a high degree of delicate and exact positioning, excitation of the appropriate muscle spindles by signals from the bulboreticular facilitatory region of the brain stem stabilizes the positions of the major joints. This aids tremendously in performing the additional detailed voluntary movements (of fingers or other body parts) required for intricate motor procedures.

Clinical Applications of the Stretch Reflex

Almost every time a clinician performs a physical examination on a patient, he or she elicits multiple stretch reflexes. The purpose is to determine how much background excitation, or "tone," the brain is sending to the spinal cord. This reflex is elicited as follows.

Knee Jerk and Other Muscle Jerks Can Be Used to Assess Sensitivity of Stretch Reflexes. Clinically, a method used to determine the sensitivity of the stretch reflexes is to elicit the knee jerk and other muscle jerks. The knee jerk can be elicited by simply striking the patellar tendon with a reflex hammer; this instantaneously stretches the quadriceps muscle and excites a *dynamic stretch reflex* that causes the lower leg to "jerk" forward. The upper part of Figure 54-7 shows a myogram from the quadriceps muscle recorded during a knee jerk.

Similar reflexes can be obtained from almost any muscle of the body either by striking the tendon of the muscle or by striking the belly of the muscle itself. In other words, sudden stretch of muscle spindles is all that is required to elicit a dynamic stretch reflex.

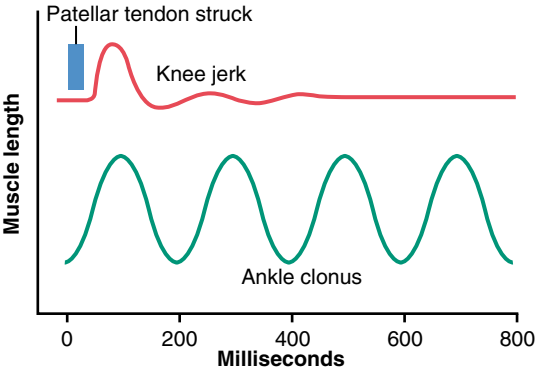


Figure 54-7 Myograms recorded from the quadriceps muscle during elicitation of the knee jerk *(above)* and from the gastrocnemius muscle during ankle clonus *(below)*.

The muscle jerks are used by neurologists to assess the degree of facilitation of spinal cord centers. When large numbers of facilitatory impulses are being transmitted from the upper regions of the central nervous system into the cord, the muscle jerks are greatly exaggerated. Conversely, if the facilitatory impulses are depressed or abrogated, the muscle jerks are considerably weakened or absent. These reflexes are used most frequently in determining the presence or absence of muscle spasticity caused by lesions in the motor areas of the brain or diseases that excite the bulboreticular facilitatory area of the brain stem. Ordinarily, large *lesions in the motor areas of the cerebral cortex* but not in the lower motor control areas (especially lesions caused by strokes or brain tumors) cause greatly exaggerated muscle jerks in the muscles on the opposite side of the body.

Clonus—Oscillation of Muscle Jerks. Under some conditions, the muscle jerks can oscillate, a phenomenon called *clonus* (see lower myogram, Figure 54-7). Oscillation can be explained particularly well in relation to ankle clonus, as follows.

If a person standing on the tip ends of the feet suddenly drops his or her body downward and stretches the gastrocnemius muscles, stretch reflex impulses are transmitted from the muscle spindles into the spinal cord. These impulses reflexively excite the stretched muscle, which lifts the body up again. After a fraction of a second, the reflex contraction of the muscle dies out and the body falls again, thus stretching the spindles a second time. Again, a dynamic stretch reflex lifts the body, but this too dies out after a fraction of a second, and the body falls once more to begin a new cycle. In this way, the stretch reflex of the gastrocnemius muscle continues to oscillate, often for long periods; this is clonus.

Clonus ordinarily occurs only when the stretch reflex is highly sensitized by facilitatory impulses from the brain. For instance, in a decerebrate animal, in which the stretch reflexes are highly facilitated, clonus develops readily. To determine the degree of facilitation of the spinal cord, neurologists test patients for clonus by suddenly stretching a muscle and applying a steady stretching force to it. If clonus occurs, the degree of facilitation is certain to be high.

Golgi Tendon Reflex

Golgi Tendon Organ Helps Control Muscle Tension. The Golgi tendon organ, shown in Figure 54-8, is an encapsulated sensory receptor through which muscle tendon fibers pass. About 10 to 15 muscle fibers are usually connected to each Golgi tendon organ, and the organ is stimulated when this small bundle of muscle fibers is "tensed" by contracting or stretching the muscle. Thus, the major difference in excitation of the Golgi tendon organ versus the muscle spindle is that *the spindle detects muscle length and changes in muscle length,* whereas *the tendon organ detects muscle tension* as reflected by the tension in itself.

The tendon organ, like the primary receptor of the muscle spindle, has both a *dynamic response* and a *static response,* reacting intensely when the muscle tension suddenly increases (the dynamic response) but settling down within a fraction of a second to a lower level of steady-state firing that is almost directly proportional to the muscle tension (the static response). Thus, Golgi tendon organs provide the nervous system with instantaneous information on the degree of tension in each small segment of each muscle.

Transmission of Impulses from the Tendon Organ into the Central Nervous System. Signals from the tendon organ are transmitted through large, rapidly conducting type Ib nerve fibers that average 16 micrometers in diameter, only slightly smaller than those from the primary endings of the muscle spindle. These fibers, like those from the primary spindle endings, transmit signals both into local areas of the cord and, after synapsing in a dorsal horn of the cord, through long fiber pathways such as the spinocerebellar tracts into the cerebellum and through still other tracts to the cerebral cortex. The local cord signal excites a single *inhibitory* interneuron that inhibits the anterior motor neuron. This local circuit directly inhibits the individual muscle without affecting adjacent muscles. The relation between signals to the brain and function of the cerebellum and other parts of the brain for muscle control is discussed in Chapter 56.

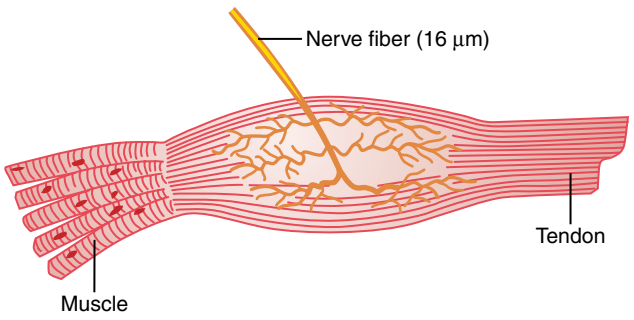


Figure 54-8 Golgi tendon organ.

Inhibitory Nature of the Tendon Reflex and Its Importance

When the Golgi tendon organs of a muscle tendon are stimulated by increased tension in the connecting muscle, signals are transmitted to the spinal cord to cause reflex effects in the respective muscle. This reflex is entirely *inhibitory.* Thus, this reflex provides a *negative feedback* mechanism that prevents the development of too much tension on the muscle.

When tension on the muscle and, therefore, on the tendon becomes extreme, the inhibitory effect from the tendon organ can be so great that it leads to a sudden reaction in the spinal cord that causes instantaneous relaxation of the entire muscle. This effect is called the *lengthening reaction;* it is probably a protective mechanism to prevent tearing of the muscle or avulsion of the tendon from its attachments to the bone. We know, for instance, that direct electrical stimulation of muscles in the laboratory, which cannot be opposed by this negative reflex, can occasionally cause such destructive effects.

Possible Role of the Tendon Reflex to Equalize Contractile Force Among the Muscle Fibers. Another likely function of the Golgi tendon reflex is to equalize contractile forces of the separate muscle fibers. That is, those fibers that exert excess tension become inhibited by the reflex, whereas those that exert too little tension become more excited because of absence of reflex inhibition. This spreads the muscle load over all the fibers and prevents damage in isolated areas of a muscle where small numbers of fibers might be overloaded.

Function of the Muscle Spindles and Golgi Tendon Organs in Conjunction with Motor Control from Higher Levels of the Brain

Although we have emphasized the function of the muscle spindles and Golgi tendon organs in spinal cord control of motor function, these two sensory organs also apprise the higher motor control centers of instantaneous changes taking place in the muscles. For instance, the dorsal spinocerebellar tracts carry instantaneous information from both the muscle spindles and the Golgi tendon organs directly to the cerebellum at conduction velocities approaching 120 m/sec, the most rapid conduction anywhere in the brain or spinal cord. Additional pathways transmit similar information into the reticular regions of the brain stem and, to a lesser extent, all the way to the motor areas of the cerebral cortex. As discussed in Chapters 55 and 56, the information from these receptors is crucial for feedback control of motor signals that originate in all these areas.

Flexor Reflex and the Withdrawal Reflexes

In the spinal or decerebrate animal, almost any type of cutaneous sensory stimulus from a limb is likely to cause the flexor muscles of the limb to contract, thereby withdrawing the limb from the stimulating object. This is called the *flexor reflex.*

In its classic form, the flexor reflex is elicited most powerfully by stimulation of pain endings, such as by a pinprick, heat, or a wound, for which reason it is also called a *nociceptive reflex,* or simply a *pain reflex.* Stimulation of touch receptors can also elicit a weaker and less prolonged flexor reflex.

If some part of the body other than one of the limbs is painfully stimulated, that part will similarly be *withdrawn from the stimulus,* but the reflex may not be confined to flexor muscles, even though it is basically the same type of reflex. Therefore, the many patterns of these reflexes in the different areas of the body are called *withdrawal reflexes.*

Neuronal Mechanism of the Flexor Reflex. The left-hand portion of Figure 54-9 shows the neuronal pathways for the flexor reflex. In this instance, a painful stimulus is applied to the hand; as a result, the flexor muscles of the upper arm become excited, thus withdrawing the hand from the painful stimulus.

The pathways for eliciting the flexor reflex do not pass directly to the anterior motor neurons but instead pass first into the spinal cord interneuron pool of neurons and only secondarily to the motor neurons. The shortest possible circuit is a three- or four-neuron pathway; however, most of the signals of the reflex traverse many more neurons and involve the following basic types of circuits: (1) diverging circuits to spread the reflex to the necessary muscles for withdrawal; (2) circuits to inhibit the antagonist muscles, called *reciprocal inhibition circuits;* and (3) circuits to cause *afterdischarge* lasting many fractions of a second after the stimulus is over.

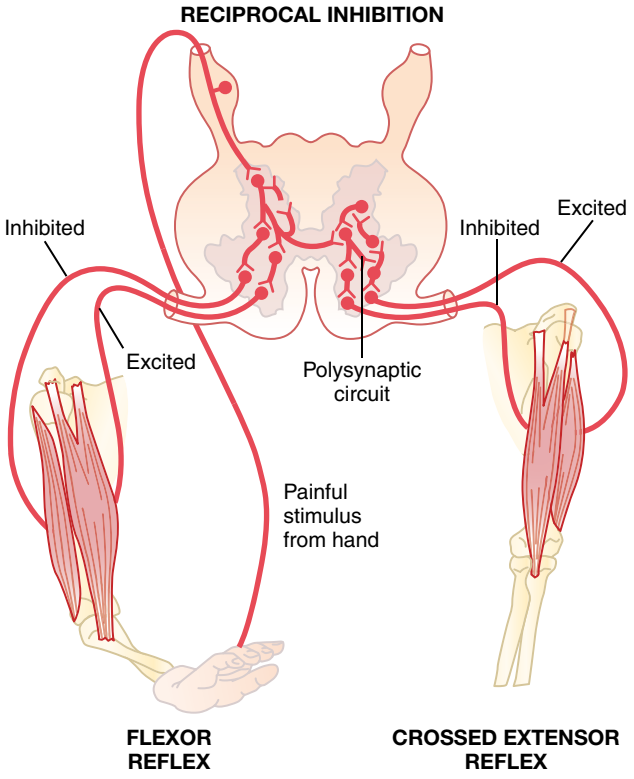


Figure 54-9 Flexor reflex, crossed extensor reflex, and reciprocal inhibition.

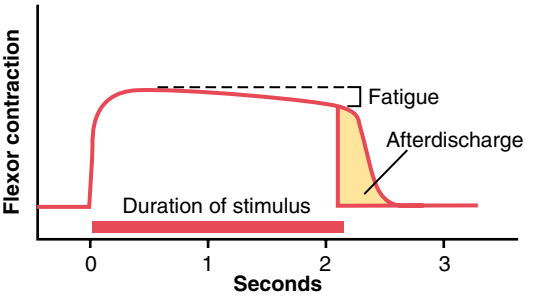


Figure 54-10 Myogram of the flexor reflex showing rapid onset of the reflex, an interval of fatigue, and, finally, afterdischarge after the input stimulus is over.

Figure 54-10 shows a typical myogram from a flexor muscle during a flexor reflex. Within a few milliseconds after a pain nerve begins to be stimulated, the flexor response appears. Then, in the next few seconds, the reflex begins to *fatigue,* which is characteristic of essentially all complex integrative reflexes of the spinal cord. Finally, after the stimulus is over, the contraction of the muscle returns toward the baseline, but because of afterdischarge, it takes many milliseconds for this to occur. The duration of afterdischarge depends on the intensity of the sensory stimulus that elicited the reflex; a weak tactile stimulus causes almost no afterdischarge, but after a strong pain stimulus, the afterdischarge may last for a second or more.

The afterdischarge that occurs in the flexor reflex almost certainly results from both types of repetitive discharge circuits discussed in Chapter 46. Electrophysiologic studies indicate that immediate afterdischarge, lasting for about 6 to 8 milliseconds, results from repetitive firing of the excited interneurons themselves. Also, prolonged afterdischarge occurs after strong pain stimuli, almost certainly resulting from recurrent pathways that initiate oscillation in reverberating interneuron circuits. These, in turn, transmit impulses to the anterior motor neurons, sometimes for several seconds after the incoming sensory signal is over.

Thus, the flexor reflex is appropriately organized to withdraw a pained or otherwise irritated part of the body from a stimulus. Further, because of afterdischarge, the reflex can hold the irritated part away from the stimulus for 0.1 to 3 seconds after the irritation is over. During this time, other reflexes and actions of the central nervous system can move the entire body away from the painful stimulus.

Pattern of Withdrawal. The pattern of withdrawal that results when the flexor reflex is elicited depends on which sensory nerve is stimulated. Thus, a pain stimulus on the inward side of the arm elicits not only contraction of the flexor muscles of the arm but also contraction of abductor muscles to pull the arm

outward. In other words, the integrative centers of the cord cause those muscles to contract that can most effectively remove the paired part of the body away from the object causing the pain. Although this principle, called the principle of "local sign," applies to any part of the body, it is especially applicable to the limbs because of their highly developed flexor reflexes.

Crossed Extensor Reflex

About 0.2 to 0.5 second after a stimulus elicits a flexor reflex in one limb, the opposite limb begins to extend. This is called the *crossed extensor reflex.* Extension of the opposite limb can push the entire body away from the object causing the painful stimulus in the withdrawn limb.

Neuronal Mechanism of the Crossed Extensor Reflex. The right-hand portion of Figure 54-9 shows the neuronal circuit responsible for the crossed extensor reflex, demonstrating that signals from sensory nerves cross to the opposite side of the cord to excite extensor muscles. Because the crossed extensor reflex usually does not begin until 200 to 500 milliseconds after onset of the initial pain stimulus, it is certain that many interneurons are involved in the circuit between the incoming sensory neuron and the motor neurons of the opposite side of the cord responsible for the crossed extension. After the painful stimulus is removed, the crossed extensor reflex has an even longer period of afterdischarge than does the flexor reflex. Again, it is presumed that this prolonged afterdischarge results from reverberating circuits among the interneuronal cells.

Figure 54-11 shows a typical myogram recorded from a muscle involved in a crossed extensor reflex. This demonstrates the relatively long latency before the reflex begins and the long afterdischarge at the end of the stimulus. The prolonged afterdischarge is of benefit in holding the pained area of the body away from the painful object until other nervous reactions cause the entire body to move away.

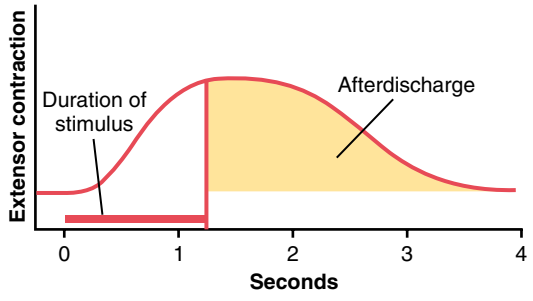


Figure 54-11 Myogram of a crossed extensor reflex showing slow onset but prolonged afterdischarge.

Reciprocal Inhibition and Reciprocal Innervation

We previously pointed out several times that excitation of one group of muscles is often associated with inhibition of another group. For instance, when a stretch reflex excites one muscle, it often simultaneously inhibits the antagonist muscles. This is the phenomenon of *reciprocal inhibition,* and the neuronal circuit that causes this reciprocal relation is called *reciprocal innervation.* Likewise, reciprocal relations often exist between the muscles on the two sides of the body, as exemplified by the flexor and extensor muscle reflexes described earlier.

Figure 54-12 shows a typical example of reciprocal inhibition. In this instance, a moderate but prolonged flexor reflex is elicited from one limb of the body; while this reflex is still being elicited, a stronger flexor reflex is elicited in the limb on the opposite side of the body. This stronger reflex sends reciprocal inhibitory signals to the first limb and depresses its degree of flexion. Finally, removal of the stronger reflex allows the original reflex to reassume its previous intensity.

Reflexes of Posture and Locomotion

Postural and Locomotive Reflexes of the Cord

Positive Supportive Reaction. Pressure on the footpad of a decerebrate animal causes the limb to extend against the pressure applied to the foot. Indeed, this reflex is so strong that if an animal whose spinal cord has been transected for several months—that is, after the reflexes have become exaggerated—is placed on its feet, the reflex often stiffens the limbs sufficiently to support the weight of the body. This reflex is called the *positive supportive reaction.*

The positive supportive reaction involves a complex circuit in the interneurons similar to the circuits responsible for the flexor and cross extensor reflexes. The locus of the pressure on the pad of the foot determines the direction in which the limb will extend; pressure on one side causes extension in that direction, an effect called the *magnet reaction.* This helps keep an animal from falling to that side.

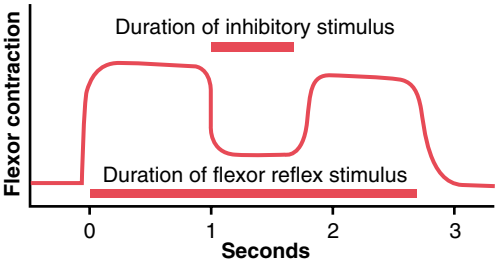


Figure 54-12 Myogram of a flexor reflex showing reciprocal inhibition caused by an inhibitory stimulus from a stronger flexor reflex on the opposite side of the body.

Cord "Righting" Reflexes. When a spinal animal is laid on its side, it will make uncoordinated movements trying to raise itself to the standing position. This is called the *cord righting reflex.* Such a reflex demonstrates that some relatively complex reflexes associated with posture are integrated in the spinal cord. Indeed, an animal with a well-healed transected thoracic cord between the levels for forelimb and hindlimb innervation can right itself from the lying position and even walk using its hindlimbs in addition to its forelimbs. In the case of an opossum with a similar transection of the thoracic cord, the walking movements of the hindlimbs are hardly different from those in a normal opossum—except that the hindlimb walking movements are not synchronized with those of the forelimbs.

Stepping and Walking Movements

Rhythmical Stepping Movements of a Single Limb. Rhythmical stepping movements are frequently observed in the limbs of spinal animals. Indeed, even when the lumbar portion of the spinal cord is separated from the remainder of the cord and a longitudinal section is made down the center of the cord to block neuronal connections between the two sides of the cord and between the two limbs, each hindlimb can still perform individual stepping functions. Forward flexion of the limb is followed a second or so later by backward extension. Then flexion occurs again, and the cycle is repeated over and over.

This oscillation back and forth between flexor and extensor muscles can occur even after the sensory nerves have been cut, and it seems to result mainly from mutually reciprocal inhibition circuits within the matrix of the cord itself, oscillating between the neurons controlling agonist and antagonist muscles.

The sensory signals from the footpads and from the position sensors around the joints play a strong role in controlling foot pressure and frequency of stepping when the foot is allowed to walk along a surface. In fact, the cord mechanism for control of stepping can be even more complex. For instance, if the top of the foot encounters an obstruction during forward thrust, the forward thrust will stop temporarily; then, in rapid sequence, the foot will be lifted higher and proceed forward to be placed over the obstruction. This is the *stumble reflex.* Thus, the cord is an intelligent walking controller.

Reciprocal Stepping of Opposite Limbs. If the lumbar spinal cord is not split down its center, every time stepping occurs in the forward direction in one limb, the opposite limb ordinarily moves backward. This effect results from reciprocal innervation between the two limbs.

Diagonal Stepping of All Four Limbs—"Mark Time" Reflex. If a well-healed spinal animal (with spinal transection in the neck above the forelimb area of the cord) is held up from the floor and its legs are allowed to dangle, the stretch on the limbs occasionally elicits stepping reflexes that involve all four limbs. In general, stepping occurs diagonally between the forelimbs and hindlimbs. This diagonal response is another manifestation of reciprocal innervation, this time occurring the entire distance up and down the cord between the forelimbs and hindlimbs. Such a walking pattern is called a *mark time reflex.*

Galloping Reflex. Another type of reflex that occasionally develops in a spinal animal is the galloping reflex, in which both forelimbs move backward in unison while both hindlimbs move forward. This often occurs when almost equal stretch or pressure stimuli are applied to the limbs on both sides of the body at the same time; unequal stimulation elicits the diagonal walking reflex. This is in keeping with the normal patterns of walking and galloping because in walking, only one forelimb and one hindlimb at a time are stimulated, which would predispose the animal to continue walking. Conversely, when the animal strikes the ground during galloping, both forelimbs and both hindlimbs are stimulated about equally; this predisposes the animal to keep galloping and, therefore, continues this pattern of motion.

Scratch Reflex

An especially important cord reflex in some animals is the scratch reflex, which is initiated by *itch* or *tickle sensation.* It involves two functions: (1) a *position sense* that allows the paw to find the exact point of irritation on the surface of the body and (2) a *to-and-fro scratching movement.*

The *position sense* of the scratch reflex is a highly developed function. If a flea is crawling as far forward as the shoulder of a spinal animal, the hind paw can still find its position, even though 19 muscles in the limb must be contracted simultaneously in a precise pattern to bring the paw to the position of the crawling flea. To make the reflex even more complicated, when the flea crosses the midline, the first paw stops scratching and the opposite paw begins the to-and-fro motion and eventually finds the flea.

The *to-and-fro movement,* like the stepping movements of locomotion, involves reciprocal innervation circuits that cause oscillation.

Spinal Cord Reflexes That Cause Muscle Spasm

In human beings, local muscle spasm is often observed. In many, if not most, instances, localized pain is the cause of the local spasm.

Muscle Spasm Resulting from a Broken Bone. One type of clinically important spasm occurs in muscles that surround a broken bone. The spasm results from pain impulses initiated from the broken edges of the bone, which cause the muscles that surround the area to contract tonically. Pain relief obtained by injecting a local anesthetic at the broken edges

of the bone relieves the spasm; a deep general anesthetic of the entire body, such as ether anesthesia, also relieves the spasm. One of these two anesthetic procedures is often necessary before the spasm can be overcome sufficiently for the two ends of the bone to be set back into their appropriate positions.

Abdominal Muscle Spasm in Peritonitis. Another type of local spasm caused by cord reflexes is abdominal spasm resulting from irritation of the parietal peritoneum by peritonitis. Here again, relief of the pain caused by the peritonitis allows the spastic muscle to relax. The same type of spasm often occurs during surgical operations; for instance, during abdominal operations, pain impulses from the parietal peritoneum often cause the abdominal muscles to contract extensively, sometimes extruding the intestines through the surgical wound. For this reason, deep anesthesia is usually required for intra-abdominal operations.

Muscle Cramps. Still another type of local spasm is the typical muscle cramp. Electromyographic studies indicate that the cause of at least some muscle cramps is as follows: Any local irritating factor or metabolic abnormality of a muscle, such as severe cold, lack of blood flow, or overexercise, can elicit pain or other sensory signals transmitted from the muscle to the spinal cord, which in turn cause reflex feedback muscle contraction. The contraction is believed to stimulate the same sensory receptors even more, which causes the spinal cord to increase the intensity of contraction. Thus, positive feedback develops, so a small amount of initial irritation causes more and more contraction until a full-blown muscle cramp ensues.

Autonomic Reflexes in the Spinal Cord

Many types of segmental autonomic reflexes are integrated in the spinal cord, most of which are discussed in other chapters. Briefly, these include (1) changes in vascular tone resulting from changes in local skin heat (see Chapter 73); (2) sweating, which results from localized heat on the surface of the body (see Chapter 73); (3) intestinointestinal reflexes that control some motor functions of the gut (see Chapter 62); (4) peritoneointestinal reflexes that inhibit gastrointestinal motility in response to peritoneal irritation (see Chapter 66); and (5) evacuation reflexes for emptying the full bladder (see Chapter 31) or the colon (see Chapter 63). In addition, all the segmental reflexes can at times be elicited simultaneously in the form of the so-called *mass reflex,* described next.

Mass Reflex. In a spinal animal or human being, sometimes the spinal cord suddenly becomes excessively active, causing massive discharge in large portions of the cord. The usual stimulus that causes this is a strong pain stimulus to the skin or excessive filling of a viscus, such as overdistention of the bladder or the gut. Regardless of the type of stimulus, the resulting reflex, called the *mass reflex,* involves large portions or even all of the cord. The effects are (1) a major portion of the body's skeletal muscles goes into strong flexor spasm; (2) the colon and bladder are likely to evacuate; (3) the arterial pressure often rises to maximal values, sometimes to a systolic pressure well over 200 mm Hg; and (4) large areas of the body break out into profuse sweating.

Because the mass reflex can last for minutes, it presumably results from activation of great numbers of reverberating circuits that excite large areas of the cord at once. This is similar to the mechanism of epileptic seizures, which involve reverberating circuits that occur in the brain instead of in the cord.

Spinal Cord Transection and Spinal Shock

When the spinal cord is suddenly transected in the upper neck, at first, essentially all cord functions, including the cord reflexes, immediately become depressed to the point of total silence, a reaction called *spinal shock.* The reason for this is that normal activity of the cord neurons depends to a great extent on continual tonic excitation by the discharge of nerve fibers entering the cord from higher centers, particularly discharge transmitted through the reticulospinal tracts, vestibulospinal tracts, and corticospinal tracts.

After a few hours to a few weeks, the spinal neurons gradually regain their excitability. This seems to be a natural characteristic of neurons everywhere in the nervous system—that is, after they lose their source of facilitatory impulses, they increase their own natural degree of excitability to make up at least partially for the loss. In most nonprimates, excitability of the cord centers returns essentially to normal within a few hours to a day or so, but in human beings, the return is often delayed for several weeks and occasionally is never complete; conversely, sometimes recovery is excessive, with resultant hyperexcitability of some or all cord functions.

Some of the spinal functions specifically affected during or after spinal shock are the following:

1. At onset of spinal shock, the arterial blood pressure falls instantly and drastically—sometimes to as low as 40 mm Hg—thus demonstrating that sympathetic nervous system activity becomes blocked almost to extinction. The pressure ordinarily returns to normal within a few days, even in human beings.
2. All skeletal muscle reflexes integrated in the spinal cord are blocked during the initial stages of shock. In lower animals, a few hours to a few days are required for these reflexes to return to normal; in human beings, 2 weeks to several months are sometimes required. In both animals and humans, some reflexes may eventually become hyperexcitable, particularly if a few facilitatory pathways remain intact between the brain and the cord while the remainder of the spinal cord is transected. The first reflexes to return are the stretch reflexes, followed in order by the progressively more complex reflexes: flexor reflexes, postural antigravity reflexes, and remnants of stepping reflexes.
3. The sacral reflexes for control of bladder and colon evacuation are suppressed in human beings for the first few weeks after cord transection, but in most cases they eventually return. These effects are discussed in Chapters 31 and 66.

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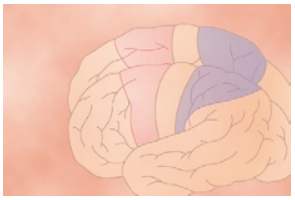
CHAPTER 55

Cortical and Brain Stem Control of Motor Function



Most "voluntary" movements initiated by the cerebral cortex are achieved when the cortex activates "patterns" of function stored in lower brain areas—the cord, brain stem, basal ganglia, and cerebellum. These lower centers, in turn, send specific control signals to the muscles.

For a few types of movements, however, the cortex has almost a direct pathway to the anterior motor neurons of the cord, bypassing some motor centers on the way. This is especially true for control of the fine dexterous movements of the fingers and hands. This chapter and Chapter 56 explain the interplay among the different motor areas of the brain and spinal cord to provide overall synthesis of voluntary motor function.

Motor Cortex and Corticospinal Tract

Figure 55-1 shows the functional areas of the cerebral cortex. Anterior to the central cortical sulcus, occupying approximately the posterior one third of the frontal lobes, is the *motor cortex.* Posterior to the central sulcus is the *somatosensory cortex* (an area discussed in detail in earlier chapters), which feeds the motor cortex many of the signals that initiate motor activities.

The motor cortex itself is divided into three subareas, each of which has its own topographical representation of muscle groups and specific motor functions: (1) the *primary motor cortex,* (2) the *premotor area,* and (3) the *supplementary motor area.*

Primary Motor Cortex

The primary motor cortex, shown in Figure 55-1, lies in the first convolution of the frontal lobes anterior to the central sulcus. It begins laterally in the sylvian fissure, spreads superiorly to the uppermost portion of the brain, and then dips deep into the longitudinal fissure. (This area is the same as area 4 in Brodmann's classification of the brain cortical areas, shown in Figure 47-5.)

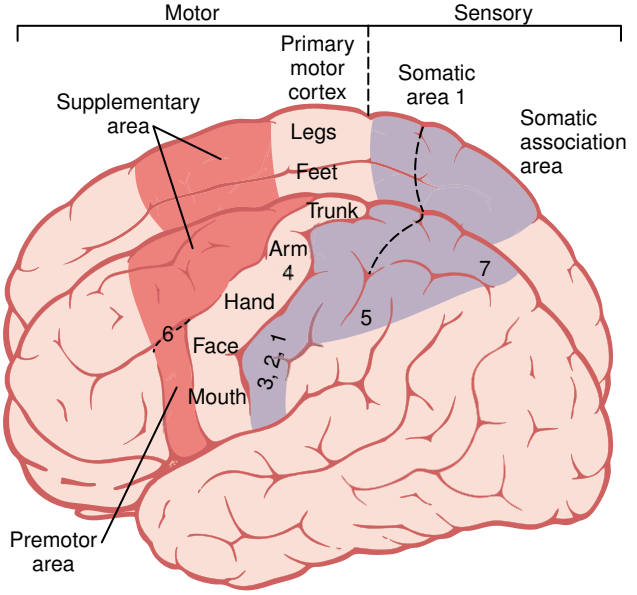


Figure 55-1 Motor and somatosensory functional areas of the cerebral cortex. The numbers *4, 5, 6,* and *7* are Brodmann's cortical areas, as explained in Chapter 47.

Figure 55-1 lists the approximate topographical representations of the different muscle areas of the body in the primary motor cortex, beginning with the face and mouth region near the sylvian fissure; the arm and hand area, in the midportion of the primary motor cortex; the trunk, near the apex of the brain; and the leg and foot areas, in the part of the primary motor cortex that dips into the longitudinal fissure. This topographical organization is demonstrated even more graphically in Figure 55-2, which shows the degrees of representation of the different muscle areas as mapped by Penfield and Rasmussen. This mapping was done by electrically stimulating the different areas of the motor cortex in human beings who were undergoing neurosurgical operations. Note that more than one half of the entire primary motor cortex is concerned with controlling the muscles of the hands and the muscles of speech. Point stimulation in these hand and speech motor areas on rare occasion causes contraction of a single muscle; most often, stimulation contracts a group of muscles instead. To express this in another way, excitation of a single motor

cortex neuron usually excites a specific movement rather than one specific muscle. To do this, it excites a "pattern" of separate muscles, each of which contributes its own direction and strength of muscle movement.

Premotor Area

The premotor area, also shown in Figure 55-1, lies 1 to 3 centimeters anterior to the primary motor cortex, extending inferiorly into the sylvian fissure and superiorly into the longitudinal fissure, where it abuts the supplementary motor area, which has functions similar to those of the premotor area. The topographical organization of the premotor cortex is roughly the same as that of the primary motor cortex, with the mouth and face areas located most laterally; as one moves upward, the hand, arm, trunk, and leg areas are encountered.

Nerve signals generated in the premotor area cause much more complex "patterns" of movement than the discrete patterns generated in the primary motor cortex. For instance, the pattern may be to position the shoulders and arms so that the hands are properly oriented to perform specific tasks. To achieve these results, the most anterior part of the premotor area first develops a "motor image" of the total muscle movement that is to be performed. Then, in the posterior premotor cortex, this image excites each successive pattern of muscle activity required to achieve the image. This posterior part of the premotor cortex sends its signals either directly to the primary motor cortex to excite specific muscles or, often, by way of the basal ganglia and thalamus back to the primary motor cortex.

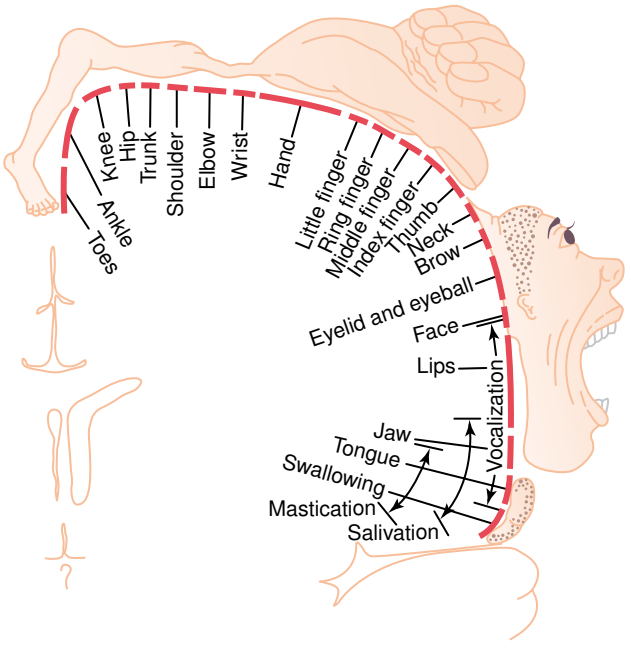


Figure 55-2 Degree of representation of the different muscles of the body in the motor cortex. (Redrawn from Penfield W, Rasmussen T: The Cerebral Cortex of Man: A Clinical Study of Localization of Function. New York: Hafner, 1968.)

A special class of neurons called *mirror neurons* becomes active when a person performs a specific motor task or when he or she observes the same task performed by others. Thus, the activity of these neurons "mirrors" the behavior of another person as though the observer was performing the specific motor task. Mirror neurons are located in the premotor cortex and the inferior parietal cortex (and perhaps in other regions of the brain) and were first discovered in monkeys. However, brain imaging studies indicate that these neurons are also present in humans and may serve the same functions as observed in monkeys—to transform sensory representations of acts that are heard or seen into motor representations of these acts. Many neurophysiologists believe that these mirror neurons may be important for understanding the actions of other people and for learning new skills by imitation. Thus, the premotor cortex, basal ganglia, thalamus, and primary motor cortex constitute a complex overall system for the control of complex patterns of coordinated muscle activity.

Supplementary Motor Area

The supplementary motor area has yet another topographical organization for the control of motor function. It lies mainly in the longitudinal fissure but extends a few centimeters onto the superior frontal cortex. Contractions elicited by stimulating this area are often bilateral rather than unilateral. For instance, stimulation frequently leads to bilateral grasping movements of both hands simultaneously; these movements are perhaps rudiments of the hand functions required for climbing. In general, this area functions in concert with the premotor area to provide body-wide attitudinal movements, fixation movements of the different segments of the body, positional movements of the head and eyes, and so forth, as background for the finer motor control of the arms and hands by the premotor area and primary motor cortex.

Some Specialized Areas of Motor Control Found in the Human Motor Cortex

A few highly specialized motor regions of the human cerebral cortex (shown in Figure 55-3) control specific motor functions. These regions have been localized either by electrical stimulation or by noting the loss of motor function when destructive lesions occur in specific cortical areas. Some of the more important regions are the following.

Broca's Area and Speech. Figure 55-3 shows a premotor area labeled "word formation" lying immediately anterior to the primary motor cortex and immediately above the sylvian fissure. This region is called *Broca's area.* Damage to it does not prevent a person from vocalizing but makes it impossible for the person to speak whole words rather than uncoordinated utterances or an occasional simple word such as "no" or "yes." A closely associated cortical area also causes appropriate respiratory function, so respiratory activation of the vocal cords can occur simultaneously with the movements of the mouth

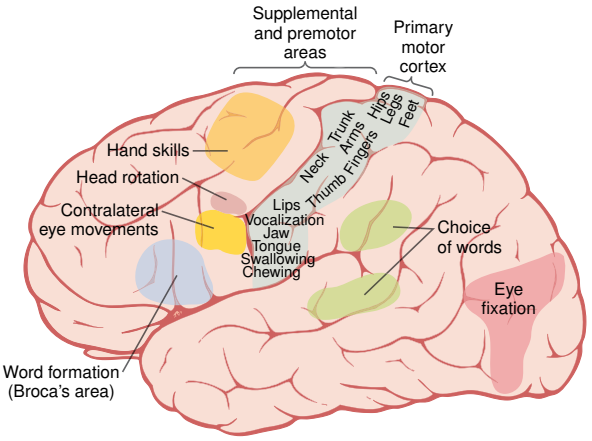


Figure 55-3 Representation of the different muscles of the body in the motor cortex and location of other cortical areas responsible for specific types of motor movements.

and tongue during speech. Thus, the premotor neuronal activities related to speech are highly complex.

"Voluntary" Eye Movement Field. In the premotor area immediately above Broca's area is a locus for controlling voluntary eye movements. Damage to this area prevents a person from *voluntarily* moving the eyes toward different objects. Instead, the eyes tend to lock involuntarily onto specific objects, an effect controlled by signals from the occipital visual cortex, as explained in Chapter 51. This frontal area also controls eyelid movements such as blinking.

Head Rotation Area. Slightly higher in the motor association area, electrical stimulation elicits head rotation. This area is closely associated with the eye movement field; it directs the head toward different objects.

Area for Hand Skills. In the premotor area immediately anterior to the primary motor cortex for the hands and fingers is a region that is important for "hand skills." That is, when tumors or other lesions cause destruction in this area, hand movements become uncoordinated and nonpurposeful, a condition called *motor apraxia.*

Transmission of Signals from the Motor Cortex to the Muscles

Motor signals are transmitted directly from the cortex to the spinal cord through the *corticospinal tract* and indirectly through multiple accessory pathways that involve the *basal ganglia, cerebellum,* and various *nuclei of the brain stem.* In general, the direct pathways are concerned more with discrete and detailed movements, especially of the distal segments of the limbs, particularly the hands and fingers.

Corticospinal (Pyramidal) Tract

The most important output pathway from the motor cortex is the *corticospinal tract,* also called the *pyramidal tract,* shown in Figure 55-4. The corticospinal tract originates about 30 percent from the primary motor cortex, 30 percent from the premotor and supplementary motor areas, and 40 percent from the somatosensory areas posterior to the central sulcus.

After leaving the cortex, it passes through the posterior limb of the internal capsule (between the caudate nucleus and the putamen of the basal ganglia) and then downward through the brain stem, forming the *pyramids of the medulla.* The majority of the pyramidal fibers then cross in the lower medulla to the opposite side and descend into the *lateral corticospinal tracts* of the cord, finally terminating principally on the interneurons in the intermediate regions of the cord gray matter; a few terminate on sensory relay neurons in the dorsal horn, and a very few terminate directly on the anterior motor neurons that cause muscle contraction.

A few of the fibers do not cross to the opposite side in the medulla but pass ipsilaterally down the cord in the *ventral corticospinal tracts.* Many, if not most, of these fibers eventually cross to the opposite side of the cord either in the neck or in the upper thoracic region. These fibers may be concerned with control of bilateral postural movements by the supplementary motor cortex.

The most impressive fibers in the pyramidal tract are a population of large myelinated fibers with a mean diameter of 16 micrometers. These fibers originate from *giant pyramidal cells,* called *Betz cells,* that are found only in the primary motor cortex. The Betz cells are about 60 micrometers in diameter, and their fibers transmit nerve impulses to the spinal cord at a velocity of about 70 m/sec, the most rapid rate of transmission of any signals from the brain to the cord. There are about 34,000 of these large Betz cell fibers in each corticospinal tract. The total number of fibers in each corticospinal tract is more than 1 million, so these large fibers represent only 3 percent of the total. The other 97 percent are mainly fibers smaller than 4 micrometers in diameter that conduct background tonic signals to the motor areas of the cord.

Other Fiber Pathways from the Motor Cortex. The motor cortex gives rise to large numbers of additional, mainly small, fibers that go to deep regions in the cerebrum and brain stem, including the following:

1. The axons from the giant Betz cells send short collaterals back to the cortex itself. These collaterals are believed to inhibit adjacent regions of the cortex when the Betz cells discharge, thereby "sharpening" the boundaries of the excitatory signal.
2. A large number of fibers pass from the motor cortex into the *caudate nucleus* and *putamen.* From there, additional pathways extend into the brain stem and spinal cord, as discussed in the next chapter, mainly to control body postural muscle contractions.

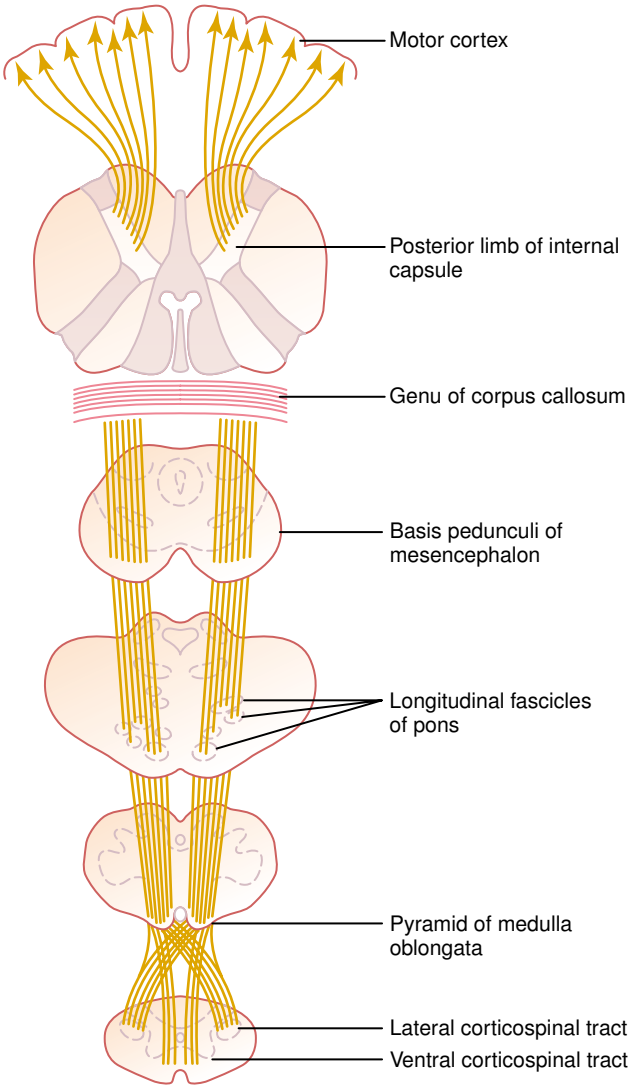


Figure 55-4 Corticospinal (pyramidal) tract. (Modified from Ranson SW, Clark SL: Anatomy of the Nervous System. Philadelphia: WB Saunders, 1959.)

3. A moderate number of motor fibers pass to *red nuclei* of the midbrain. From these, additional fibers pass down the cord through the *rubrospinal tract.*
4. A moderate number of motor fibers deviate into the *reticular substance* and *vestibular nuclei* of the brain stem; from there, signals go to the cord by way of *reticulospinal* and *vestibulospinal tracts,* and others go to the cerebellum by way of *reticulocerebellar* and *vestibulocerebellar tracts.*
5. A tremendous number of motor fibers synapse in the pontile nuclei, which give rise to the *pontocerebellar fibers,* carrying signals into the cerebellar hemispheres.
6. Collaterals also terminate in the *inferior olivary nuclei,* and from there, secondary *olivocerebellar fibers* transmit signals to multiple areas of the cerebellum.

Thus, the basal ganglia, brain stem, and cerebellum all receive strong motor signals from the corticospinal system every time a signal is transmitted down the spinal cord to cause a motor activity.

Incoming Sensory Fiber Pathways to the Motor Cortex

The functions of the motor cortex are controlled mainly by nerve signals from the somatosensory system but also, to some degree, from other sensory systems such as hearing and vision. Once the sensory information is received, the motor cortex operates in association with the basal ganglia and cerebellum to excite an appropriate course of motor action. The more important incoming fiber pathways to the motor cortex are the following:

1. Subcortical fibers from adjacent regions of the cerebral cortex, especially from (a) the somatosensory areas of the parietal cortex, (b) the adjacent areas of the frontal cortex anterior to the motor cortex, and (c) the visual and auditory cortices.
2. Subcortical fibers that arrive through the corpus callosum from the opposite cerebral hemisphere. These fibers connect corresponding areas of the cortices in the two sides of the brain.
3. Somatosensory fibers that arrive directly from the ventrobasal complex of the thalamus. These relay mainly cutaneous tactile signals and joint and muscle signals from the peripheral body.
4. Tracts from the ventrolateral and ventroanterior nuclei of the thalamus, which in turn receive signals from the cerebellum and basal ganglia. These tracts provide signals that are necessary for coordination among the motor control functions of the motor cortex, basal ganglia, and cerebellum.
5. Fibers from the intralaminar nuclei of the thalamus. These fibers control the general level of excitability of the motor cortex in the same way they control the general level of excitability of most other regions of the cerebral cortex.

Red Nucleus Serves as an Alternative Pathway for Transmitting Cortical Signals to the Spinal Cord

The *red nucleus,* located in the mesencephalon, functions in close association with the corticospinal tract. As shown in Figure 55-5, it receives a large number of direct fibers from the primary motor cortex through the *corticorubral tract,* as well as branching fibers from the corticospinal tract as it passes through the mesencephalon. These fibers synapse in the lower portion of the red nucleus, the *magnocellular portion,* which contains large neurons similar in size to the Betz cells in the motor cortex. These large neurons then give rise to the *rubrospinal tract,* which crosses to the opposite side in the lower brain stem and follows a course immediately adjacent and anterior to the corticospinal tract into the lateral columns of the spinal cord.

The rubrospinal fibers terminate mostly on the interneurons of the intermediate areas of the cord gray matter, along with the corticospinal fibers, but some of the rubrospinal fibers terminate directly on anterior motor neurons, along with some corticospinal fibers. The red nucleus also has close connections with the cerebellum, similar to the connections between the motor cortex and the cerebellum.

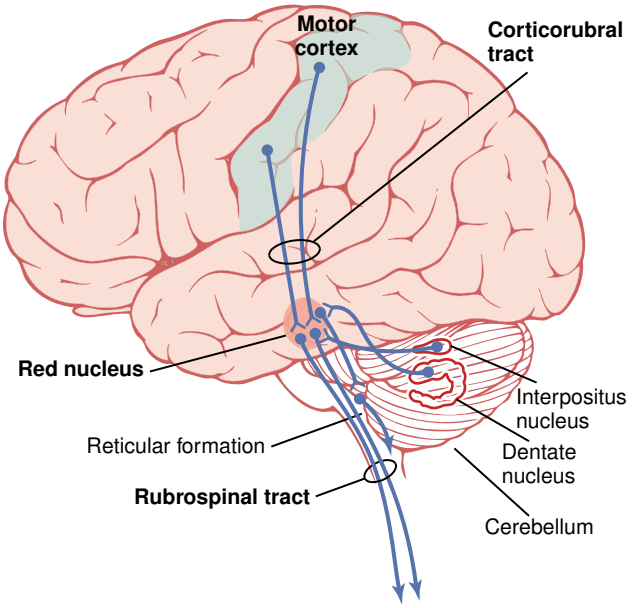


Figure 55-5 Corticorubrospinal pathway for motor control, showing also the relation of this pathway to the cerebellum.

Function of the Corticorubrospinal System. The magnocellular portion of the red nucleus has a somatographic representation of all the muscles of the body, as is true of the motor cortex. Therefore, stimulation of a single point in this portion of the red nucleus causes contraction of either a single muscle or a small group of muscles. However, the fineness of representation of the different muscles is far less developed than in the motor cortex. This is especially true in human beings, who have relatively small red nuclei.

The corticorubrospinal pathway serves as an accessory route for transmission of relatively discrete signals from the motor cortex to the spinal cord. When the corticospinal fibers are destroyed but the corticorubrospinal pathway is intact, discrete movements can still occur, except that the movements for fine control of the fingers and hands are considerably impaired. Wrist movements are still functional, which is not the case when the corticorubrospinal pathway is also blocked.

Therefore, the pathway through the red nucleus to the spinal cord is associated with the corticospinal system. Further, the rubrospinal tract lies in the lateral columns of the spinal cord, along with the corticospinal tract, and terminates on the interneurons and motor neurons that control the more distal muscles of the limbs. Therefore, the corticospinal and rubrospinal tracts together are called the *lateral motor system of the cord,* in contradistinction to a vestibuloreticulospinal system, which lies mainly medially in the cord and is called the *medial motor system of the cord,* as discussed later in this chapter.

"Extrapyramidal" System

The term *extrapyramidal motor system* is widely used in clinical circles to denote all those portions of the brain and brain stem that contribute to motor control but are not part of the direct corticospinal-pyramidal system. These include pathways through the basal ganglia, the reticular formation of the brain stem, the vestibular nuclei, and often the red nuclei. This is such an all-inclusive and diverse group of motor control areas that it is difficult to ascribe specific neurophysiologic functions to the so-called extrapyramidal system as a whole. In fact, the pyramidal and extrapyramidal systems are extensively interconnected and interact to control movement. For these reasons, the term "extrapyramidal" is being used less often both clinically and physiologically.

Excitation of the Spinal Cord Motor Control Areas by the Primary Motor Cortex and Red Nucleus

Vertical Columnar Arrangement of the Neurons in the Motor Cortex. In Chapters 47 and 51, we pointed out that the cells in the somatosensory cortex and visual cortex are organized in *vertical columns of cells.* In like manner, the cells of the motor cortex are organized in vertical columns a fraction of a millimeter in diameter, with thousands of neurons in each column.

Each column of cells functions as a unit, usually stimulating a group of synergistic muscles, but sometimes stimulating just a single muscle. Also, each column has six distinct layers of cells, as is true throughout nearly all the cerebral cortex. The pyramidal cells that give rise to the corticospinal fibers all lie in the fifth layer of cells from the cortical surface. Conversely, the input signals all enter by way of layers 2 through 4. And the sixth layer gives rise mainly to fibers that communicate with other regions of the cerebral cortex itself.

Function of Each Column of Neurons. The neurons of each column operate as an integrative processing system, using information from multiple input sources to determine the output response from the column. In addition, each column can function as an amplifying system to stimulate large numbers of pyramidal fibers to the same muscle or to synergistic muscles simultaneously. This is important because stimulation of a single pyramidal cell can seldom excite a muscle. Usually, 50 to 100 pyramidal cells need to be excited simultaneously or in rapid succession to achieve definitive muscle contraction.

Dynamic and Static Signals Are Transmitted by the Pyramidal Neurons. If a strong signal is sent to a muscle to cause initial rapid contraction, then a much weaker continuing signal can maintain the contraction for long periods thereafter. This is the usual manner in which excitation is provided to cause muscle contractions. To do this, each column of cells excites two populations of pyramidal cell neurons, one called *dynamic neurons* and the other *static neurons.* The dynamic neurons are excited at a high rate for a short period at the beginning of a contraction, causing the initial rapid *development of force.* Then the static neurons fire at a much slower rate, but they continue firing at this slow rate to *maintain the force* of contraction as long as the contraction is required.

The neurons of the red nucleus have similar dynamic and static characteristics, except that a greater percentage of dynamic neurons is in the red nucleus and a greater percentage of static neurons is in the primary motor cortex. This may be related to the fact that the red nucleus is closely allied with the cerebellum, and the cerebellum plays an important role in rapid initiation of muscle contraction, as explained in the next chapter.

Somatosensory Feedback to the Motor Cortex Helps Control the Precision of Muscle Contraction

When nerve signals from the motor cortex cause a muscle to contract, somatosensory signals return all the way from the activated region of the body to the neurons in the motor cortex that are initiating the action. Most of these somatosensory signals arise in (1) the muscle spindles, (2) the tendon organs of the muscle tendons, or (3) the tactile receptors of the skin overlying the muscles. These somatic signals often cause positive feedback enhancement of the muscle contraction in the following ways: In the case of the muscle spindles, if the fusimotor muscle fibers in the spindles contract more than the large skeletal muscle fibers contract, the central portions of the spindles become stretched and, therefore, excited. Signals from these spindles then return rapidly to the pyramidal cells in the motor cortex to signal them that the large muscle fibers have not contracted enough. The pyramidal cells further excite the muscle, helping its contraction to catch up with the contraction of the muscle spindles. In the case of the tactile receptors, if the muscle contraction causes compression of the skin against an object, such as compression of the fingers around an object being grasped, the signals from the skin receptors can, if necessary, cause further excitation of the muscles and, therefore, increase the tightness of the hand grasp.

Stimulation of the Spinal Motor Neurons

Figure 55-6 shows a cross section of a spinal cord segment demonstrating (1) multiple motor and sensorimotor control tracts entering the cord segment and (2) a representative anterior motor neuron in the middle of the anterior horn gray matter. The corticospinal tract and the rubrospinal tract lie in the dorsal portions of the lateral white columns. Their fibers terminate mainly on interneurons in the intermediate area of the cord gray matter.

In the cervical enlargement of the cord where the hands and fingers are represented, large numbers of both corticospinal and rubrospinal fibers also terminate directly on the anterior motor neurons, thus allowing a direct route from the brain to activate muscle contraction. This is in keeping with the fact that the primary motor cortex has an extremely high degree of representation for fine control of hand, finger, and thumb actions.

Patterns of Movement Elicited by Spinal Cord Centers. From Chapter 54, recall that the spinal cord can provide certain specific reflex patterns of movement in response to sensory nerve stimulation. Many of these same patterns are also important when the cord's anterior motor neurons are excited by signals from the brain. For example, the stretch reflex is functional at all times, helping to damp any oscillations of the motor movements initiated from the brain, and probably also providing at least part of the motive power required to cause muscle contractions when the intrafusal fibers of the muscle spindles contract more than the large skeletal muscle fibers do, thus eliciting reflex "servo-assist" stimulation of the muscle, in addition to the direct stimulation by the corticospinal fibers.

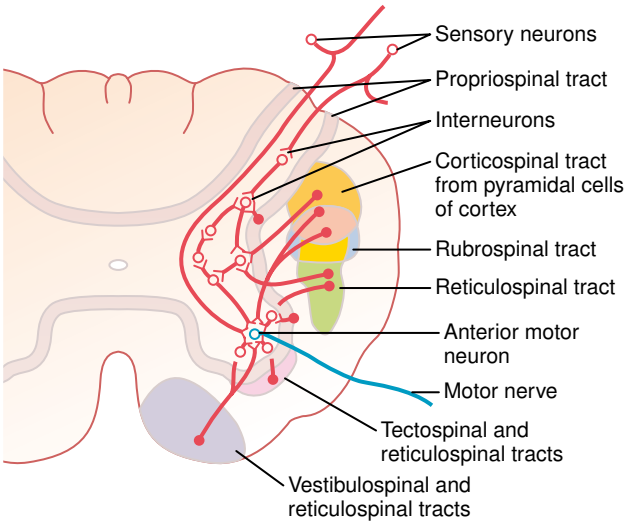


Figure 55-6 Convergence of different motor control pathways on the anterior motor neurons.

Also, when a brain signal excites a muscle, it is usually unnecessary to transmit an inverse signal to relax the antagonist muscle at the same time; this is achieved by the *reciprocal innervation* circuit that is always present in the cord for coordinating the function of antagonistic pairs of muscles.

Finally, other cord reflex mechanisms, such as withdrawal, stepping and walking, scratching, and postural mechanisms, can each be activated by "command" signals from the brain. Thus, simple command signals from the brain can initiate many normal motor activities, particularly for such functions as walking and attaining different postural attitudes of the body.

Effect of Lesions in the Motor Cortex or in the Corticospinal Pathway—The "Stroke"

The motor control system can be damaged by the common abnormality called a "stroke." This is caused by either a ruptured blood vessel that hemorrhages into the brain or by thrombosis of one of the major arteries supplying the brain. In either case, the result is loss of blood supply to the cortex or to the corticospinal tract where it passes through the internal capsule between the caudate nucleus and the putamen. Also, experiments have been performed in animals to selectively remove different parts of the motor cortex.

Removal of the Primary Motor Cortex (Area Pyramidalis). Removal of a portion of the primary motor cortex—the area that contains the giant Betz pyramidal

cells—causes varying degrees of paralysis of the represented muscles. If the sublying caudate nucleus and adjacent premotor and supplementary motor areas are not damaged, gross postural and limb "fixation" movements can still occur, but there is *loss of voluntary control of discrete movements of the distal segments of the limbs, especially of the hands and fingers.* This does not mean that the hand and finger muscles themselves cannot contract; rather, the *ability to control the fine movements is gone.* From these observations, one can conclude that the area pyramidalis is essential for voluntary initiation of finely controlled movements, especially of the hands and fingers.

Muscle Spasticity Caused by Lesions That Damage Large Areas Adjacent to the Motor Cortex. The primary motor cortex normally exerts a continual tonic stimulatory effect on the motor neurons of the spinal cord; when this stimulatory effect is removed, *hypotonia* results. Most lesions of the motor cortex, especially those caused by a *stroke,* involve not only the primary motor cortex but also adjacent parts of the brain such as the basal ganglia. In these instances, *muscle spasm* almost invariably occurs in the afflicted muscle areas on the *opposite side* of the body (because the motor pathways cross to the opposite side). This spasm results mainly from damage to accessory pathways from the nonpyramidal portions of the motor cortex. These pathways normally inhibit the vestibular and reticular brain stem motor nuclei. When these nuclei cease their state of inhibition (i.e., are "disinhibited"), they become spontaneously active and cause excessive spastic tone in the involved muscles, as we discuss more fully later in the chapter. This is the spasticity that normally accompanies a "stroke" in a human being.

Role of the Brain Stem in Controlling Motor Function

The brain stem consists of the *medulla, pons,* and *mesencephalon.* In one sense, it is an extension of the spinal cord upward into the cranial cavity because it contains motor and sensory nuclei that perform motor and sensory functions for the face and head regions in the same way that the spinal cord performs these functions from the neck down. But in another sense, the brain stem is its own master because it provides many special control functions, such as the following:

1. Control of respiration
2. Control of the cardiovascular system
3. Partial control of gastrointestinal function
4. Control of many stereotyped movements of the body
5. Control of equilibrium
6. Control of eye movements

Finally, the brain stem serves as a way station for "command signals" from higher neural centers. In the following sections, we discuss the role of the brain stem in controlling whole-body movement and equilibrium. Especially important for these purposes are the brain stem's *reticular nuclei* and *vestibular nuclei.*

Support of the Body Against Gravity—Roles of the Reticular and Vestibular Nuclei

Figure 55-7 shows the locations of the reticular and vestibular nuclei in the brain stem.

Excitatory-Inhibitory Antagonism Between Pontine and Medullary Reticular Nuclei

The reticular nuclei are divided into two major groups: (1) *pontine reticular nuclei,* located slightly posteriorly and laterally in the pons and extending into the mesencephalon, and (2) *medullary reticular nuclei,* which extend through the entire medulla, lying ventrally and medially near the midline. These two sets of nuclei function mainly antagonistically to each other, with the pontine exciting the antigravity muscles and the medullary relaxing these same muscles.

Pontine Reticular System. The pontine reticular nuclei transmit excitatory signals downward into the cord through the *pontine reticulospinal tract* in the anterior column of the cord, as shown in Figure 55-8. The fibers of this pathway terminate on the medial anterior motor neurons that excite the axial muscles of the body, which support the body against gravity—that is, the muscles of the vertebral column and the extensor muscles of the limbs.

The pontine reticular nuclei have a high degree of natural excitability. In addition, they receive strong excitatory signals from the vestibular nuclei, as well as from deep nuclei of the cerebellum. Therefore, when the pontine reticular excitatory system is unopposed by the medullary reticular system, it causes powerful excitation of antigravity muscles throughout the body, so much so that

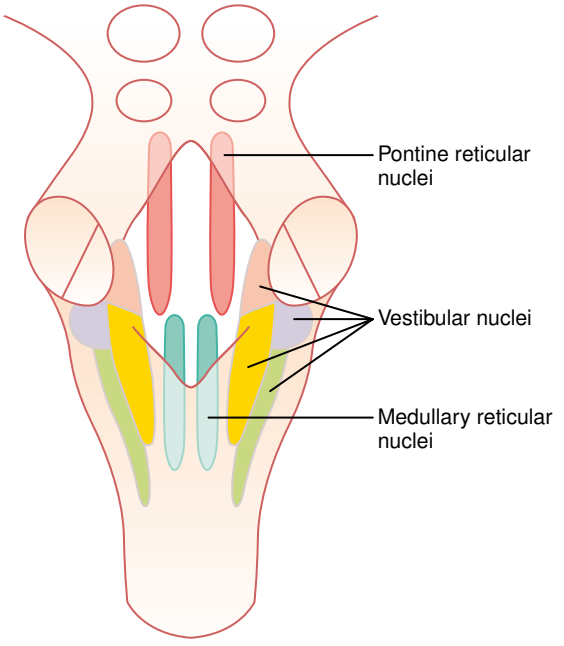


Figure 55-7 Locations of the reticular and vestibular nuclei in the brain stem.

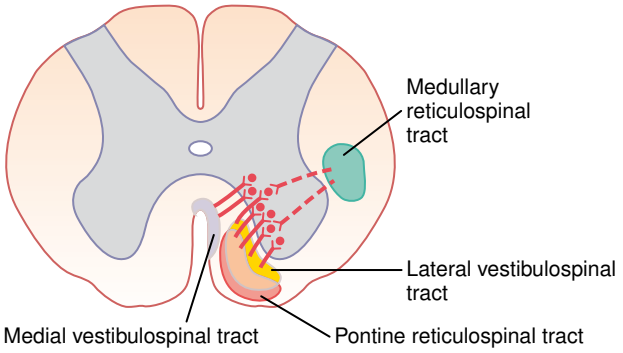


Figure 55-8 Vestibulospinal and reticulospinal tracts descending in the spinal cord to excite (*solid lines*) or inhibit (*dashed lines*) the anterior motor neurons that control the body's axial musculature.

four-legged animals can be placed in a standing position, supporting the body against gravity without any signals from higher levels of the brain.

Medullary Reticular System. The medullary reticular nuclei transmit *inhibitory* signals to the same antigravity anterior motor neurons by way of a different tract, the *medullary reticulospinal tract,* located in the lateral column of the cord, as also shown in Figure 55-8. The medullary reticular nuclei receive strong input collaterals from (1) the corticospinal tract, (2) the rubrospinal tract, and (3) other motor pathways. These normally activate the medullary reticular inhibitory system to counterbalance the excitatory signals from the pontine reticular system, so under normal conditions the body muscles are not abnormally tense.

Yet some signals from higher areas of the brain can "disinhibit" the medullary system when the brain wishes to excite the pontine system to cause standing. At other times, excitation of the medullary reticular system can inhibit antigravity muscles in certain portions of the body to allow those portions to perform special motor activities. The excitatory and inhibitory reticular nuclei constitute a controllable system that is manipulated by motor signals from the cerebral cortex and elsewhere to provide necessary background muscle contractions for standing against gravity and to inhibit appropriate groups of muscles as needed so that other functions can be performed.

Role of the Vestibular Nuclei to Excite the Antigravity Muscles

All the *vestibular nuclei*, shown in Figure 55-7, function in association with the pontine reticular nuclei to control the antigravity muscles. The vestibular nuclei transmit strong excitatory signals to the antigravity muscles by way of the *lateral* and *medial vestibulospinal tracts* in the anterior columns of the spinal cord, as shown in Figure 55-8. Without this support of the vestibular nuclei, the pontine reticular system would lose much of its excitation of the axial antigravity muscles.

The specific role of the vestibular nuclei, however, is to *selectively* control the excitatory signals to the different antigravity muscles to maintain equilibrium *in response to signals from the vestibular apparatus.* We discuss this more fully later in the chapter.

The Decerebrate Animal Develops Spastic Rigidity

When the brain stem of an animal is sectioned below the midlevel of the mesencephalon, but the pontine and medullary reticular systems, as well as the vestibular system, are left intact, the animal develops a condition called *decerebrate rigidity.* This rigidity does not occur in all muscles of the body but does occur in the antigravity muscles—the muscles of the neck and trunk and the extensors of the legs.

The cause of decerebrate rigidity is blockage of normally strong input to the medullary reticular nuclei from the cerebral cortex, the red nuclei, and the basal ganglia. Lacking this input, the medullary reticular inhibitor system becomes nonfunctional; full overactivity of the pontine excitatory system occurs, and rigidity develops. We shall see later that other causes of rigidity occur in other neuromotor diseases, especially lesions of the basal ganglia.

Vestibular Sensations and Maintenance of Equilibrium

Vestibular Apparatus

The vestibular apparatus, shown in Figure 55-9, is the sensory organ for detecting sensations of equilibrium. It is encased in a system of bony tubes and chambers located in the petrous portion of the temporal bone, called the *bony labyrinth.* Within this system are membranous tubes and chambers called the *membranous labyrinth.* The membranous labyrinth is the functional part of the vestibular apparatus.

The top of Figure 55-9 shows the membranous labyrinth. It is composed mainly of the *cochlea* (ductus cochlearis); three *semicircular canals;* and two large chambers, the *utricle* and *saccule.* The cochlea is the major sensory organ for hearing (see Chapter 52) and has little to do with equilibrium. However, the *semicircular canals,* the *utricle,* and the *saccule* are all integral parts of the equilibrium mechanism.

"Maculae"—Sensory Organs of the Utricle and Saccule for Detecting Orientation of the Head with Respect to Gravity. Located on the inside surface of each utricle and saccule, shown in the top diagram of Figure 55-9, is a small sensory area slightly over 2 millimeters in diameter called a *macula.* The *macula of the utricle* lies mainly in the *horizontal plane* on the inferior surface of the utricle and plays an important role in determining orientation of the head when the head is upright. Conversely, the *macula of the saccule* is located mainly in a *vertical plane* and signals head orientation when the person is lying down.

Each macula is covered by a gelatinous layer in which many small calcium carbonate crystals called *statoconia* are embedded. Also in the macula are thousands of *hair cells,* one of which is shown in Figure 55-10; these project *cilia* up into the gelatinous layer. The bases and sides of

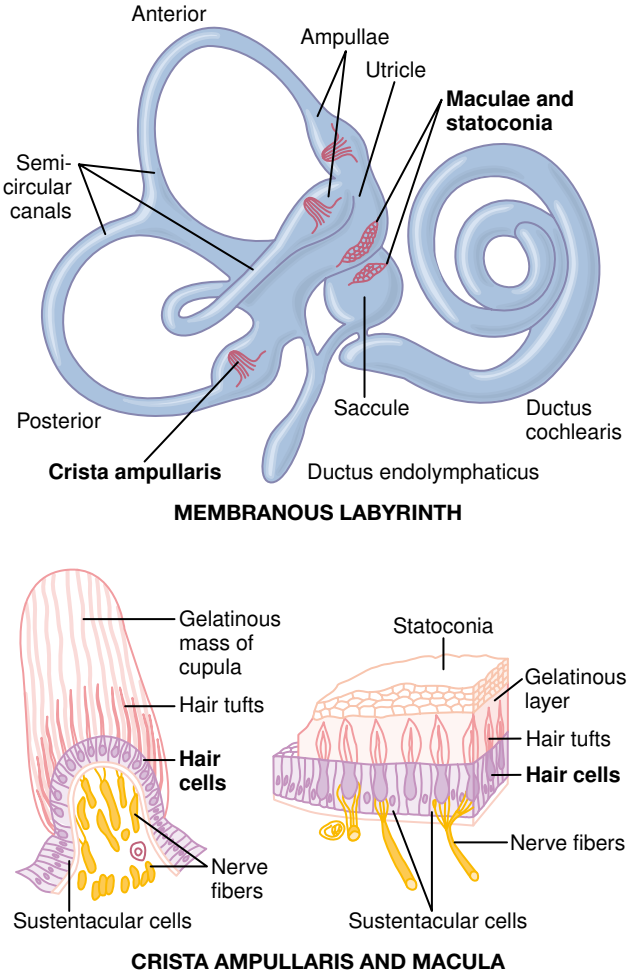


Figure 55-9 Membranous labyrinth and organization of the crista ampullaris and the macula.

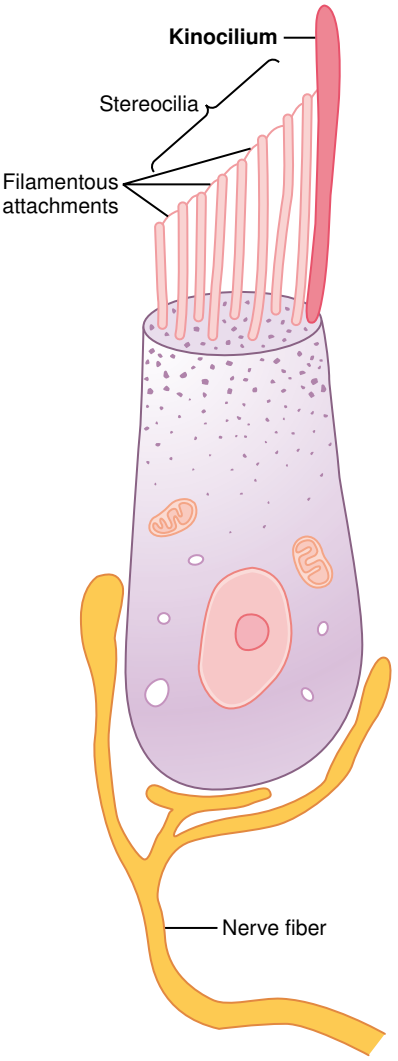


Figure 55-10 Hair cell of the equilibrium apparatus and its synapses with the vestibular nerve.

the hair cells synapse with sensory endings of the *vestibular nerve.*

The calcified statoconia have a *specific gravity* two to three times the specific gravity of the surrounding fluid and tissues. The weight of the statoconia bends the cilia in the direction of gravitational pull.

Directional Sensitivity of the Hair Cells—Kinocilium. Each hair cell has 50 to 70 small cilia called *stereocilia,* plus one large cilium, the *kinocilium,* as shown in Figure 55-10. The kinocilium is always located to one side, and the stereocilia become progressively shorter toward the other side of the cell. Minute filamentous attachments, almost invisible even to the electron microscope, connect the tip of each stereocilium to the next longer stereocilium and, finally, to the kinocilium.

Because of these attachments, when the stereocilia and kinocilium bend in the direction of the kinocilium, the filamentous attachments tug in sequence on the stereocilia, pulling them outward from the cell body. This opens several hundred fluid channels in the neuronal cell membrane around the bases of the stereocilia, and these channels are capable of conducting large numbers of positive ions. Therefore, positive ions pour into the cell from the surrounding endolymphatic fluid, causing *receptor membrane depolarization.* Conversely, bending the pile of stereocilia in the opposite direction (backward to the kinocilium) reduces the tension on the attachments; this closes the ion channels, thus causing *receptor hyperpolarization.*

Under normal resting conditions, the nerve fibers leading from the hair cells transmit continuous nerve impulses at a rate of about 100 per second. When the stereocilia are bent toward the kinocilium, the impulse traffic increases, often to several hundred per second; conversely, bending the cilia away from the kinocilium decreases the impulse traffic, often turning it off completely. Therefore, as the orientation of the head in space changes and the weight of the statoconia bends the cilia, appropriate signals are transmitted to the brain to control equilibrium.

In each macula, each of the hair cells is oriented in a different direction so that some of the hair cells are stimulated when the head bends forward, some are stimulated when it bends backward, others are stimulated when it

bends to one side, and so forth. Therefore, a different pattern of excitation occurs in the macular nerve fibers for each orientation of the head in the gravitational field. It is this "pattern" that apprises the brain of the head's orientation in space.

Semicircular Ducts. The three semicircular ducts in each vestibular apparatus, known as the *anterior, posterior,* and *lateral (horizontal) semicircular ducts,* are arranged at right angles to one another so that they represent all three planes in space. When the head is bent forward about 30 degrees, the lateral semicircular ducts are approximately horizontal with respect to the surface of the earth; the anterior ducts are in vertical planes that project *forward and 45 degrees outward,* whereas the posterior ducts are in vertical planes that project *backward and 45 degrees outward.*

Each semicircular duct has an enlargement at one of its ends called the *ampulla,* and the ducts and ampulla are filled with a fluid called *endolymph.* Flow of this fluid through one of the ducts and through its ampulla excites the sensory organ of the ampulla in the following manner: Figure 55-11 shows in each ampulla a small crest called a *crista ampullaris.* On top of this crista is a loose gelatinous tissue mass, the *cupula.* When a person's head begins to rotate in any direction, the inertia of the fluid in one or more of the semicircular ducts causes the fluid to remain stationary while the semicircular duct rotates with the head. This causes fluid to flow from the duct and through the ampulla, bending the cupula to one side, as demonstrated by the position of the colored cupula in Figure 55-11. Rotation of the head in the opposite direction causes the cupula to bend to the opposite side.

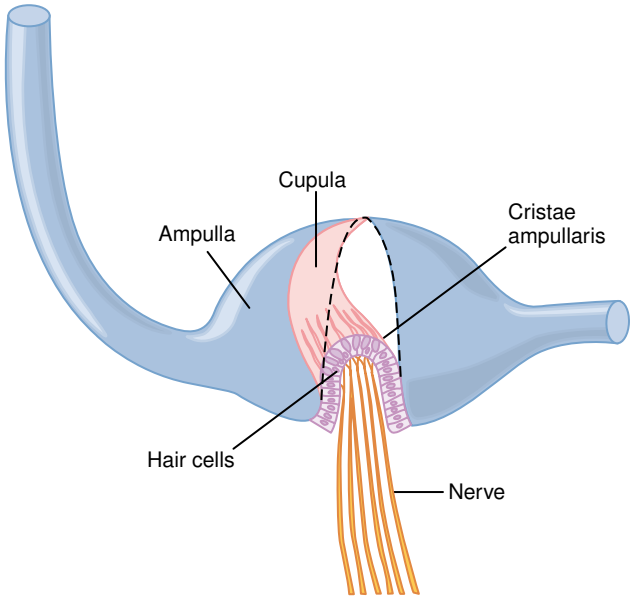


Figure 55-11 Movement of the cupula and its embedded hairs at the onset of rotation.

Into the cupula are projected hundreds of cilia from hair cells located on the ampullary crest. The kinocilia of these hair cells are all oriented in the same direction in the cupula, and bending the cupula in that direction causes depolarization of the hair cells, whereas bending it in the opposite direction hyperpolarizes the cells. Then, from the hair cells, appropriate signals are sent by way of the *vestibular nerve* to apprise the central nervous system of a *change in rotation* of the head and the *rate of change* in each of the three planes of space.

Function of the Utricle and Saccule in the Maintenance of Static Equilibrium

It is especially important that the hair cells are all oriented in different directions in the maculae of the utricles and saccules so that with different positions of the head, different hair cells become stimulated. The "patterns" of stimulation of the different hair cells apprise the brain of the position of the head with respect to the pull of gravity. In turn, the vestibular, cerebellar, and reticular motor nerve systems of the brain excite appropriate postural muscles to maintain proper equilibrium.

This utricle and saccule system functions extremely effectively for maintaining equilibrium when the head is in the near-vertical position. Indeed, a person can determine as little as half a degree of dysequilibrium when the body leans from the precise upright position.

Detection of Linear Acceleration by the Utricle and Saccule Maculae. When the body is suddenly thrust forward—that is, when the body accelerates—the statoconia, which have greater mass inertia than the surrounding fluid, fall backward on the hair cell cilia, and information of dysequilibrium is sent into the nervous centers, causing the person to feel as though he or she were falling backward. This automatically causes the person to lean forward until the resulting anterior shift of the statoconia exactly equals the tendency for the statoconia to fall backward because of the acceleration. At this point, the nervous system senses a state of proper equilibrium and leans the body forward no farther. Thus, the maculae operate to maintain equilibrium during linear acceleration in exactly the same manner as they operate during static equilibrium.

The maculae *do not* operate for the detection of linear *velocity.* When runners first begin to run, they must lean far forward to keep from falling backward because of initial *acceleration,* but once they have achieved running speed, if they were running in a vacuum, they would not have to lean forward. When running in air, they lean forward to maintain equilibrium only because of air resistance against their bodies; in this instance, it is not the maculae that make them lean but air pressure acting on pressure end-organs in the skin, which initiate appropriate equilibrium adjustments to prevent falling.

Detection of Head Rotation by the Semicircular Ducts

When the head suddenly begins to rotate in any direction (called *angular acceleration*), the endolymph in the semicircular ducts, because of its inertia, tends to remain stationary while the semicircular ducts turn. This causes relative fluid flow in the ducts in the direction opposite to head rotation.

Figure 55-12 shows a typical discharge signal from a single hair cell in the crista ampullaris when an animal is rotated for 40 seconds, demonstrating that (1) even when the cupula is in its resting position, the hair cell emits a tonic discharge of about 100 impulses per second; (2) when the animal begins to rotate, the hairs bend to one side and the rate of discharge increases greatly; and (3) with continued rotation, the excess discharge of the hair cell gradually subsides back to the resting level during the next few seconds.

The reason for this adaptation of the receptor is that within the first few seconds of rotation, back resistance to the flow of fluid in the semicircular duct and past the bent cupula causes the endolymph to begin rotating as rapidly as the semicircular canal itself; then, in another 5 to 20 seconds, the cupula slowly returns to its resting position in the middle of the ampulla because of its own elastic recoil.

When the rotation suddenly stops, exactly opposite effects take place: The endolymph continues to rotate while the semicircular duct stops. This time, the cupula bends in the opposite direction, causing the hair cell to stop discharging entirely. After another few seconds, the endolymph stops moving and the cupula gradually returns to its resting position, thus allowing hair cell discharge to return to its normal tonic level, as shown to the right in Figure 55-12. Thus, the semicircular duct transmits a signal of one polarity when the head *begins* to rotate and of opposite polarity when it *stops* rotating.

"Predictive" Function of the Semicircular Duct System in the Maintenance of Equilibrium. Because the semicircular ducts do not detect that the body is off balance in the forward direction, in the side direction, or in the backward direction, one might ask: What is the semicircular ducts' function in the maintenance of equilibrium? All they detect is that the person's head is *beginning* or *stopping* to rotate in one direction or another. Therefore, the function of the semicircular ducts is not to maintain static equilibrium or to maintain equilibrium during steady directional or rotational movements. Yet loss of function of the semicircular ducts does cause a person to have poor equilibrium when attempting to perform *rapid, intricate changing* body movements.

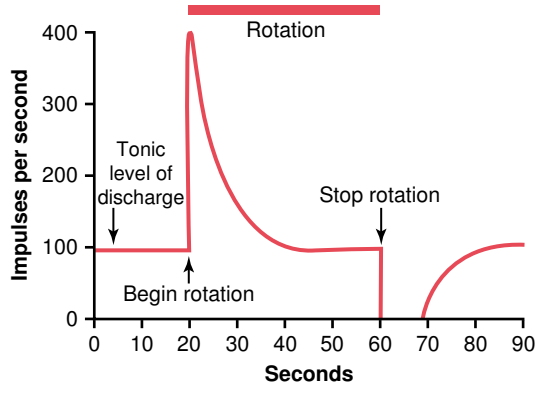


Figure 55-12 Response of a hair cell when a semicircular canal is stimulated first by the onset of head rotation and then by stopping rotation.

The function of the semicircular ducts can be explained by the following illustration: If a person is running forward rapidly and then suddenly begins to turn to one side, *he or she will fall off balance a fraction of a second later* unless appropriate corrections are made *ahead of time.* But the maculae of the utricle and saccule cannot detect that he or she is off balance until *after* this has occurred. The semicircular ducts, however, will have already detected that the person is turning, and this information can easily apprise the central nervous system of the fact that the person *will* fall off balance within the next fraction of a second or so unless some *anticipatory correction* is made.

In other words, the semicircular duct mechanism *predicts* that dysequilibrium is going to occur and thereby causes the equilibrium centers to make appropriate anticipatory preventive adjustments. This helps the person maintain balance before the situation can be corrected.

Removal of the flocculonodular lobes of the cerebellum prevents normal detection of semicircular duct signals but has less effect on detecting macular signals. It is especially interesting that the cerebellum serves as a "predictive" organ for most rapid movements of the body, as well as for those having to do with equilibrium. These other functions of the cerebellum are discussed in the following chapter.

Vestibular Mechanisms for Stabilizing the Eyes

When a person changes his or her direction of movement rapidly or even leans the head sideways, forward, or backward, it would be impossible to maintain a stable image on the retinas unless the person had some automatic control mechanism to stabilize the direction of the eyes' gaze. In addition, the eyes would be of little use in detecting an image unless they remained "fixed" on each object long enough to gain a clear image. Fortunately, each time the head is suddenly rotated, signals from the semicircular ducts cause the eyes to rotate in a direction equal and opposite to the rotation of the head. This results from reflexes transmitted through the *vestibular nuclei* and the *medial longitudinal fasciculus* to the *oculomotor nuclei.* These reflexes are described in Chapter 51.

Other Factors Concerned with Equilibrium

Neck Proprioceptors. The vestibular apparatus detects the orientation and movement *only of the head.* Therefore, it is essential that the nervous centers also receive appropriate information about the orientation of the head with respect to the body. This information is transmitted from the proprioceptors of the neck and body directly to the vestibular

and reticular nuclei in the brain stem and indirectly by way of the cerebellum.

Among the most important proprioceptive information needed for the maintenance of equilibrium is that transmitted by *joint receptors of the neck*. When the head is leaned in one direction by bending the neck, impulses from the neck proprioceptors keep the signals originating in the vestibular apparatus from giving the person a sense of dysequilibrium. They do this by transmitting signals that exactly oppose the signals transmitted from the vestibular apparatus. However, *when the entire body* leans in one direction, the impulses from the vestibular apparatus *are not opposed* by signals from the neck proprioceptors; therefore, in this case, the person does perceive a change in equilibrium status of the entire body.

Proprioceptive and Exteroceptive Information from Other Parts of the Body. Proprioceptive information from parts of the body other than the neck is also important in the maintenance of equilibrium. For instance, pressure sensations from the footpads tell one (1) whether weight is distributed equally between the two feet and (2) whether weight on the feet is more forward or backward.

Exteroceptive information is especially necessary for the maintenance of equilibrium when a person is running. The air pressure against the front of the body signals that a force is opposing the body in a direction different from that caused by gravitational pull; as a result, the person leans forward to oppose this.

Importance of Visual Information in the Maintenance of Equilibrium. After destruction of the vestibular apparatus, and even after loss of most proprioceptive information from the body, a person can still use the visual mechanisms reasonably effectively for maintaining equilibrium. Even a slight linear or rotational movement of the body instantaneously shifts the visual images on the retina, and this information is relayed to the equilibrium centers. Some people with bilateral destruction of the vestibular apparatus have almost normal equilibrium as long as their eyes are open and all motions are performed slowly. But when moving rapidly or when the eyes are closed, equilibrium is immediately lost.

Neuronal Connections of the Vestibular Apparatus with the Central Nervous System

Figure 55-13 shows the connections in the hindbrain of the vestibular nerve. Most of the vestibular nerve fibers terminate in the brain stem in the *vestibular nuclei*, which are located approximately at the junction of the medulla and the pons. Some fibers pass directly to the brain stem reticular nuclei without synapsing and also to the cerebellar fastigial, uvular, and flocculonodular lobe nuclei. The fibers that end in the brain stem vestibular nuclei synapse with second-order neurons that also send fibers into the cerebellum, the vestibulospinal tracts, the medial longitudinal fasciculus, and other areas of the brain stem, particularly the reticular nuclei.

The primary pathway for the equilibrium reflexes begins in the vestibular nerves, where the nerves are excited by the vestibular apparatus. The pathway then passes to the vestibular nuclei and cerebellum. Next, signals are sent into the reticular nuclei of the brain stem, as well as down the spinal cord by way of the vestibulospinal and reticulospinal tracts. The signals to the cord control the interplay between facilitation and inhibition of the many antigravity muscles, thus automatically controlling equilibrium.

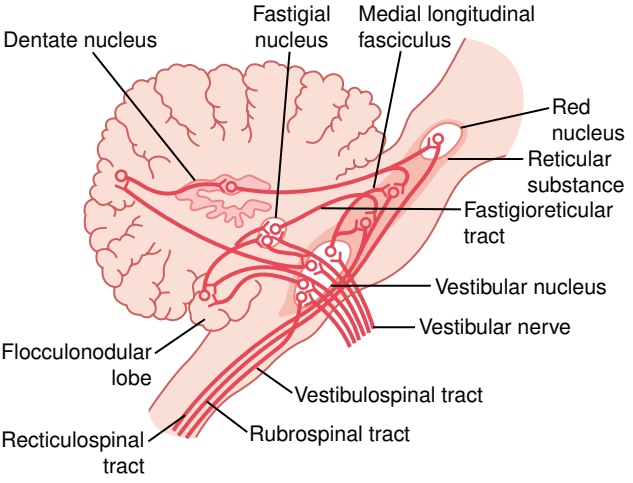


Figure 55-13 Connections of vestibular nerves through the vestibular nuclei (*large oval white area*) with other areas of the central nervous system.

The *flocculonodular* lobes of the cerebellum are especially concerned with dynamic equilibrium signals from the semicircular ducts. In fact, destruction of these lobes results in almost exactly the same clinical symptoms as destruction of the semicircular ducts themselves. That is, severe injury to either the lobes or the ducts causes loss of dynamic equilibrium during *rapid changes in direction of motion* but does not seriously disturb equilibrium under static conditions. It is believed that the *uvula* of the cerebellum plays a similar important role in static equilibrium.

Signals transmitted upward in the brain stem from both the vestibular nuclei and the cerebellum by way of the *medial longitudinal fasciculus* cause corrective movements of the eyes every time the head rotates, so the eyes remain fixed on a specific visual object. Signals also pass upward (either through this same tract or through reticular tracts) to the cerebral cortex, terminating in a primary cortical center for equilibrium located in the parietal lobe deep in the sylvian fissure on the opposite side of the fissure from the auditory area of the superior temporal gyrus. These signals apprise the psyche of the equilibrium status of the body.

Functions of Brain Stem Nuclei in Controlling Subconscious, Stereotyped Movements

Rarely, a baby is born without brain structures above the mesencephalic region, a condition called *anencephaly*. Some of these babies have been kept alive for many months. They are able to perform some stereotyped movements for feeding, such as suckling, extrusion of unpleasant food from the mouth, and moving the hands to the mouth to suck the fingers. In addition, they can yawn and stretch. They can cry and can follow objects with movements of the eyes and head. Also, placing pressure on the upper anterior parts of their legs causes them to pull to the sitting position. It is clear that many of the stereotyped motor functions of the human being are integrated in the brain stem.

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