CHAPTER 18

Motor System and Movement I: Reflex Activity, Central Pattern Generators and Cerebral Cortical Motor Functions

INTRODUCTION

In studying the motor system, we will consider reflex activity, central generators of patterns of movement, voluntary movement and learned movements .We will also consider two inter-related aspects: posture and movement. Under posture we will be studying static or tonic reactions. Under movement we will be studying short duration phasic reactions. We should keep in mind, as Sherrington has indicated, that the reflexes involved in posture and movement are the same. There are no reflexes exclusively for the maintenance of a correct posture, as opposed to those reflexes involved in a movement, We should note that with more detailed microelectrode studies we may find that some neurons in the cerebral cortex or spinal cord are predominantly involved in phasic activities and other predominantly in tonic activities. In the following discussion, we will examine motor function at the level of the spinal cord, the brain stem and cerebral cortex .It is important to realize that motor functions are represented at successively higher physiological and anatomical levels of the neural axis. As we go higher in the neural axis, we are utilizing and modifying mechanisms that have been integrated at a lower level of the neural axis a concept first expressed in the modern era by Jackson. Thus pattern generators make use of the motor mechanisms involved in reflexes without the necessity of afferent input. In turn voluntary and learned movements incorporate or impose a higher level of a more complex cortical control of these reflex and central pattern mechanisms.

In subsequent chapters the role of basal ganglia and the cerebellum in modulating movement will be considered.

REFLEX ACTIVITY.

The terms utilized in defining a reflex are presented in Table 18-1

CONCEPT OF CENTRAL PATTERN GENERATORS

Specific neural circuits or neuronal clusters or centers may be responsible for the generation of simple and complex patterns of movement in the absence of afferent input. In actuality, such central patterns are modified or modulated by afferent input, utilize many of the reflex components to be discussed below and are controlled and/or modified by descending control motor systems from higher centers. Such pattern generators have been described at the level of the spinal cord and the brain stem (mesencephalic locomotor system) for more complex behavior related to locomotion. The latter system is also involved in the motor components of emotional expression, as well as chewing, licking and sucking behavior. For the accurate performance of complex patterned movements, involving the limbs, afferent input and reflex activity, is essential. In the absence of such afferent input, the movements while repetitive are not as well coordinated. (See DeLong 1971, Harris-Warrick and Johnson 1989).

1. *The spinal pattern generator.* This is probably composed of bilateral clusters of interneurons in the intermediate gray matter at the base of the posterior horn. These interneurons are the same interneurons involved in the flexion reflex to be described below. In the spinal cord preparation to be discussed below the effects of dopaminergic and adrenergic agents in triggering behavior can be demonstrated.

2. T*he mesencephalic locomotion pattern generator:* this center is located in the periventricular tegmentum at the junction of midbrain and pons. Axons from this region descend to the medullary medial reticular formation.

E. M. Marcus et al., *Integrated Neuroscience*

TABLE 18-1:DEFINITION OF A REFLEX

TERM	EXAMPLES
Adequate stimulus	Nociceptive, proprioceptive, tactile, visual
Synapses involved	Monosynaptic in the stretch reflex. Polysynaptic in the flexion reflex.
Segments involved	Segmental-stretch reflex, Intersegmental-inter limb reflexes. Suprasegmental- brain stem–tonic neck/labyrinthine. Cerebral cortex, placing and long loop reflexes.
Movement or response	Flexion, extension, righting, standing, walking, grasp, avoidance, placing
Aim or purpose	Avoidance of pain, escape from predator, acquisition of food

From this region axons descend as the medial reticulospinal tract in the ventrolateral funiculus to the spinal locomotor system of the lumbar spinal cord. In the decerebrate preparation to be discussed below, glutaminergic effects can be demonstrated. Glutamate receptor antagonists will prevent the locomotion effects that occur on stimulation of the mesencephalic center.

3. *Other motor pattern centers:* the premotor cortex for visually guided movements, the subthalamic nucleus, the pontine reticular formation and the cerebellum will be discussed below.

EFFECTS OF SPINAL AND BRAINSTEM LESIONS ON THE MOTOR SYSTEM

TRANSECTION OF THE SPINAL CORD IN THE HUMAN:

In humans transection of the spinal cord reflects (1) the effects of spinal shock and (2) the prepotency of flexion reflexes as reflex recovery occurs.

Transection of the spinal cord in the human is reviewed in Table 18-2 and in chapter 9

TRANSECTION OF THE BRAIN STEM- THE DECEREBRATE PREPARATION

The decerebrate preparation, involves a transection of the brain stem a level between the vestibular nuclei and the red nucleus usually at the intercollicular midbrain level.

In man the decerebrate state may reflect several pathological processes such as basilar artery thrombosis with brain stem infarction, temporal lobe herniation with midbrain compression, or massive destruction of both cerebral hemispheres.

Decerebrate Rigidity - A state described as decerebrate rigidity develops almost immediately. Decerebrate rigidity may be defined as the exaggerated posture of extension of the antigravity muscles due to the enhancement of proprioceptive stretch reflexes. In four-legged animals, such as the cat and dog, the enhancement of these stretch reflexes results in extensor posture in all four limbs with extension of the tail and arching of the back and neck. This posture is also referred to as opisthotonos *(Fig. 18-2)*.

Sherrington has described the posture of decerebrate rigidity as "an exaggerated caricature of standing". This is most intense in those muscles that normally counteract the effect of gravity. In an animal such as the sloth that normally hangs upside down, it is the flexor posture that is exaggerated.

It is important to realize that with transection of the brain stem, the decerebrate rigidity develops almost immediately. Spinal shock does not result. It is important to note that though the extensor tone is sufficient to allow the animal to stand, the animal is pillar--like. The pillar-like limb seen in this extensor posture is indicative of the positive supporting reaction already seen in the "spinal" cat and dog. This is the tonic form of the extensor thrust reaction previously noted. The animal lacks righting reflexes and has no reactions to sudden displacement.

Modification of Decerebrate Rigidity - The posture of decerebrate rigidity may be modified by several influences: tonic neck reflexes, tonic labyrinthine reflexes noxious stimuli, and time .

Tonic Neck Reflexes (Fig.18-3). Tonic neck reflexes are studied best after destruction of the

TABLE 18-2: COMPLETE TRANSECTION OF THE SPINAL CORD IN MAN

ONSET	EVENT	MANIFESTATIONS
Immediate	Spinal shock	Below lesion: flaccid paralysis of limbs, no DTR's, Atonic bladder and bowel (overflow incontinence), Loss of autonomic control: hypotensive if erect[1]
	Sensory loss If section C1-C4	Absence of all sensation below lesion No spontaneous respiration (phrenic outflow -C4)
1-6 weeks	Recovery of flexion reflexes Note that flexion reflexes usually remain prepotent	Sign of Babinski, initially dorsiflexion of great toe and fanning of small toes, later flexor withdrawal of foot, leg and thigh
3-4 weeks	Onset of detrusor & bowel function Minimal return of DTR's	Reflex voiding and defecation begins to occur Achilles and patellar DTR's now present
2-3 months	Mass reflex	Flexion reflexes now exaggerated without local sign with flexor spasms, bladder emptying and profuse sweating,erection & ejaculation
	Autonomic reflexes	Sweating below level of lesion returns
6 +months	Local sign develops	Mass reflex less prominent, flexion reflexes more specific for point of stimulus (may recur with fever)
	Hyperactive extensor reflexes	Deep tendon reflexes become hyperactive, spasticity develops. Crossed extension (Fig 18-1) and alternate stepping may occur. Occasionally positive support reaction is sufficient for spinal standing

[1]Other aspects of autonomic control are also affected including sympathetic control of blood pressure - noted particularly with hypotension occurring in the upright position (orthostatic) and parasympathetic control of intestinal -peristalsis (ileus occurs).

labyrinth or after bilateral section of nerve VIII. These procedures eliminate various labyrinthine influences. The afferents for the tonic neck reflexes are conveyed via the upper cervical dorsal roots from joint receptors - for example, those located in the atlanto-occipital joint. The tonic neck reflexes produce several types of modification of the decerebrate posture. Rotation of the head produces a fencer's posture with extension of the forelimb on the side to which chin, nose, and eyes have rotated with flexion of the forelimb on the contralateral side. Correlated inter limb adjustments may occur in the lower extremities. Extension of the head at the neck produces extension of the forelimbs and flexion of the hindlimbs. One may imagine the posture of a cat that is attempting to look at objects upon a table. Flexion of the head onto the chest produces flexion of the forelimbs and extension of the hindlimbs. One may imagine the posture of a cat that is attempting to look under a shelf or door.

Tonic Labyrinthine Reflexes (Fig. 18-4). These tonic labyrinthine reflexes are studied best after the head has been immobilized in a plaster cast or after section of the upper cervical dorsal roots. The afferents are conveyed from the otoliths via the vestibular nerves to the vestibular nuclei.

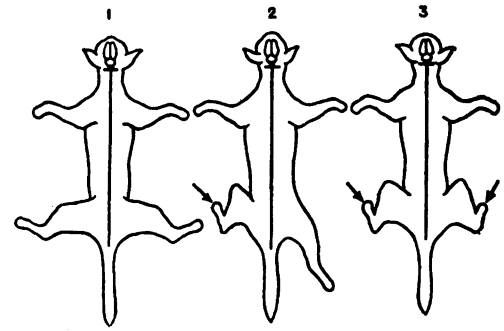


Figure 18-1. High spinal cat: flexion and crossed extension reflexes. (1) The initial posture of the animal. (2) Nociceptive stimulation of the left hind foot produces flexion of the left hind limb and crossed extension of the right hind limb. (3) Nociceptive stimulation of both right and left hind limbs leads to flexion of both hind limbs. Flexion reflex then remains prepotent. (From Sherrington, C.: The Integrative Action of the Nervous System. New Haven, Yale University Press, 1947, p.226).

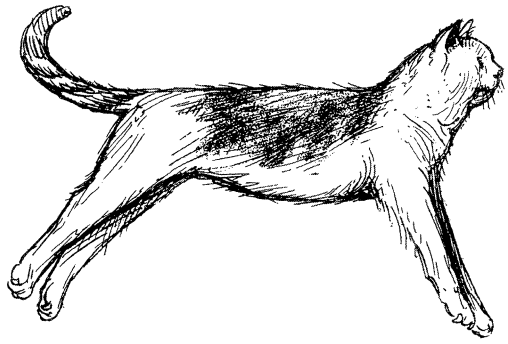


Figure 18-2 The posture of the decerebrate cat when suspended. The hyperextended, rigid posture of neck, back, limbs, and tail is to be noted (opisthotonos). From Pollack, L.J., and Davis, L.: J.Comp.Neurol., 50:384,1930 (Wiley).

Noxious stimulus to a limb produces the classic inter limb reflex figure *(18-4)*.

Time: With time (7-14 days), rigidity decreases and righting reflexes begin to emerge.

The anatomical basis of decerebrate rigidity: Refer to chapter 11.

The Midbrain Preparation (transected above the superior colliculus with red nucleus and portions of subthalamic nucleus and posterior hypothalamus intact). In this preparation, propriocentive reflexes are modified by contactual stimuli.

In the dog or cat midbrain preparation, a sequence of righting reflexes occurs. Righting responses in the animal with intact central nervous system are demonstarted in. *Fig. 18-6, 18-7.* Kinetic reactions such as standing and walking may also occur. In contrast, the primate midbrain preparation is unable to stand. There are some fragments of and of a traction grasp

Role of hypothalamus: The motor responses for rage are represented at a brain stem level. Stimulation of the midbrain of the decerebrate preparation will produce all of the motor components of anger. The hypothalamus however is essential for occurrenses of the sham rage of the decorticate animal. (Bard).

THE DECORTICATE PREPARATION

The cat and dog preparations are similar to the midbrain animal. In the primate, the tonic grasp reflex may be present. The decorticate

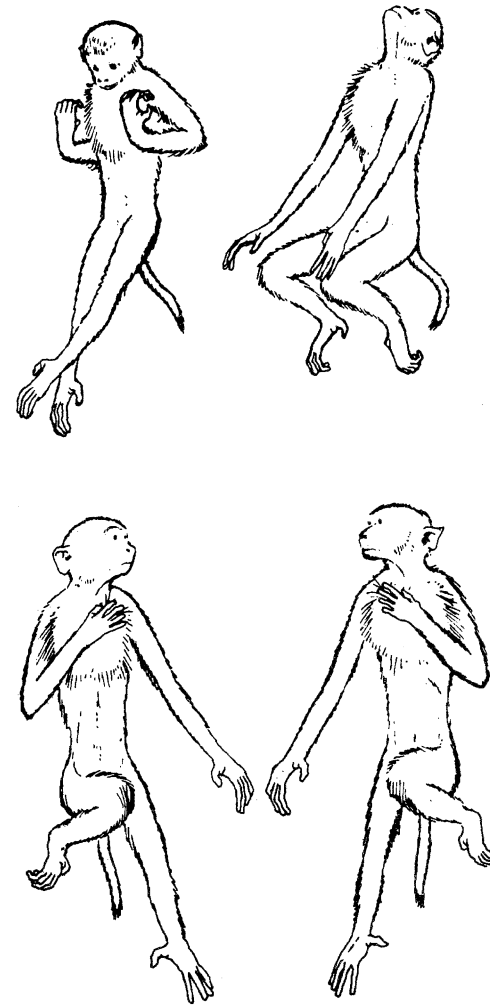


Figure 18-3. Tonic neck reflexes modify decerebrate rigidity (monkey preparation). Upper figures: flexion of head results in flexion of upper extremities; extension of head produces extension of upper extremities. Lower figures - rotation of head produces extension of upper limb on side to which face is turned and flexion of contralateral upper limb. Correlated adjustments occur in the lower extremities. (From Twitchell, T.E.: J.Amer.Phys.Ther.Ass., 45:413,1965).

human or primate manifests a considerable degree of spasticity often referred to as *decorticate rigidity.* The posture of the decorticate primate or human involves extension of the lower extremities and flexion of the upper extremities *(Fig.18-8)*. In a sense this is a double hemiplegic posture.

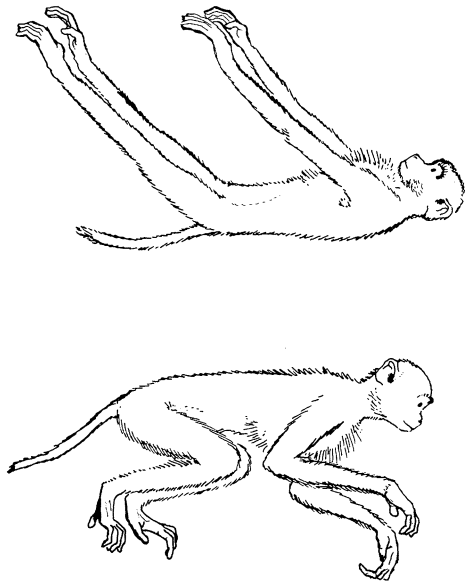


Figure 18-4. Tonic labyrinthine reflexes modify decerebrate rigidity: Upper Figure: With the animal held in the supine position and the head facing upwards, the limbs extend. Lower Figure - With the animal held in the prone position (face downwards) the limbs flex. The tonic neck influences must be eliminated by immobilization of the neck or by section of the upper cervical dorsal roots. Note that in man with neurological disease, the opposite pattern may occur so that a flexion posture predominates when the patient is supine and an extensor posture when prone. (From Twitchell, T.E.: J.Amer.Phys.Ther.Ass. 45:414, 1965).

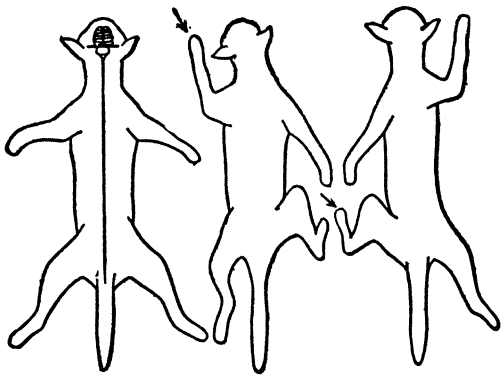


Figure 18-5. Reflex figures in the decerebrate cat preparation. Effects of nociceptive stimulation. a. Prior to stimulation. b. Change produced by stimulation of left fore foot. c. Change produced by stimulation of left hind foot. (From Sherrington, C.S.: The Integrative Action of the Nervous System. New Haven, Yale University Press, 1947, p.167).

REACTIONS DEPENDENT ON CEREBRAL CORTEX

The cerebral cortex may be considered as providing for a complex reaction to the external environment. The cerebral cortex analyzes afferent information from many sources and utilizes reactions which have been integrated at lower levels of the neural axis. Thus, the presence of the cerebral cortex allows for the accurate projection of the limb in space and for the interaction of various reflex activities with visual and tactile stimuli.

The following reflexes are associated with the cerebral cortex:

1. The *optical righting reflex. (Fig. 18-7).* This results in the righting of the head in relation to a visual stimulus. This response continues to occur after elimination of the labyrinths and dorsal roots from the upper cervical neck proprioceptors. The response can still be demonstrated after bilateral ablation of the motor and pre-motor areas in the primate. We

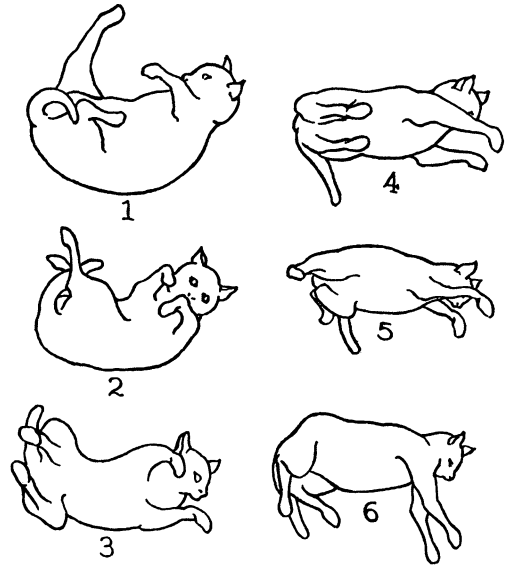


Figure 18-6. Righting reflexes in intact cat. Diagram showing series of maneuvers which a cat executes in order to turn itself in the air: (1) free fall; (2) head turns, forelimbs drawn in, hindlimbs extended; (3), (4), (5), continued turning with gradual extension of forelimbs while hindlimbs are drawn closer to axis of rotation; (6) turning completed. (Redrawn from Marey, C.R.: Acad.Sci.Paris, 1894, 119:714-717: From Fulton, J.F.: A Textbook of Physiology, 17th Edition. Phila-delphia, W.B. Saunders, 1955, p.221).

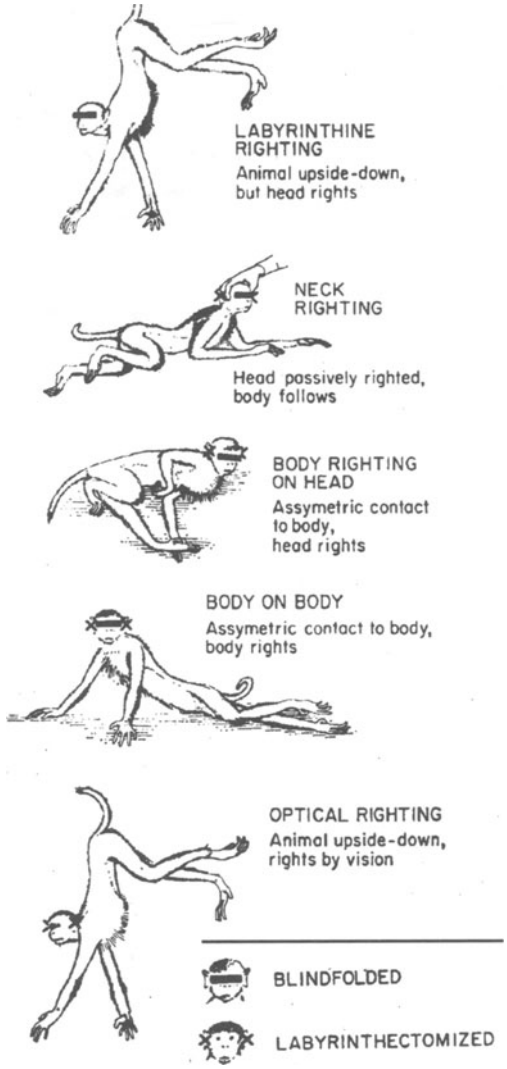


Figure 18-7. Righting reflexes in the monkey. With the exception of the optical righting reflex (which depends on cerebral cortex), all of the righting reflexes demonstrated above are within the capacity of the midbrain preparation. (From Twitchell, T.E.: J.Amer.Phys.Ther.Ass. 45:415, 1965).

should, of course, note that righting of the head when the head has been turned on to the side, is dependent not only on visual cues but also on labyrinthine cues and asymmetrical body contact stimuli.

2. *Placing Reactions.* A number of placing reactions are also noted in the intact animal. When the animal approaches a visible edge, the forelimb is advanced to be precisely placed on the surface. This is termed the visual placing reaction. On the other hand, if the animal is blindfolded and the dorsum of the foot or hand touches the edge of a surface, appropriate adjustments are then made to place the plantar or palmar surface of the extremity on the surface. This is termed the tactile placing reaction. Also noted in the intact preparation is a hopping response. If the animal's body is displaced to one side, the animal abducts the leg to that side to regain stability.

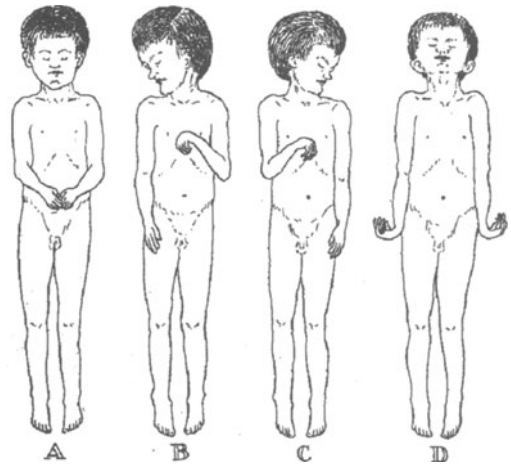


Figure 18-8 Decorticate rigidity in the human. The differences in man between (A) decorticate rigidity in neutral position (both arms are flexed) and (D) true decerebrate rigidity (legs are extended arms are rigidly extended and pronated.). (B) and (C), alterations produced in the decorticate human by head turning due to tonic neck reflexes. (From Fulton, J.F., A Textbook of Physiology, Philadelphia, W.B. Saunders, 1955, p.217).

3. The *grasp reflex*, as defined by Seyffarth and Denny-Brown, consists of a stereotyped progressive forced closure of the subjects hand on the slowly moving stimulus of the examiner's fingers across the palm. These authors considered the tactile pressure to be the appropriate stimulus. This reflex had emerged following frontal lobe ablation in the monkey (Rushworth and Denny-Brown). Local anesthesia infiltration of the palm abolished the reflex.

4. *Instinctive Grasp.* A more complex and variable response was also described by Seyffarth and Denny-Brown: the instinctive

tactile grasp reaction *(Fig. 18-9)*[2] . This response is also triggered by a tactile (or contactual) stimulus to the hand. The hand orients so as to grasp the object. Often the hand follows a moving object making moment-to-moment adjustments so as to grasp onto the object. This instinctive tactile grasping reaction allows for the exploration of space with the hand. The grasp reflex and instinctive tactile grasping reaction are of course, seen normally when the intact individual attempts to grasp onto an object or to reach for an object. It is not surprising that intact motor and parietal cortex is required. The movements involve distal finger and thumb movement and require precise feedback information.

At times, however, the reaction is seen to be released in abnormal form and degree and to occur in a context where voluntary grasping is inappropriate. Patients with release of the tactile grasp reaction usually have damage to the premotor cortex (areas 6 and 8) and the adjacent supplementary motor cortex and cingulate area on the medial surface of the hemisphere. The instinctive tactile grasp reaction, then, although requiring an intact motor and parietal cortex is released in an abnormal form by lesions of the premotor, supplementary motor, and cingulate areas. This is a form of transcortical release. The same lesion, of course, also acts to release various subcortical areas[3]

The instinctive tactile grasp reaction is to be compared to the instinctive tactile avoiding reaction (Fig. 18-10). The stimulus for this reaction is a distally moving tactile stimulus to the outer (ulnar) border of the hand or to the palmar surface of the hand or to the dorsum of the hand. This stimulus leads to a non-tonic orientation of the hand away from the stimulus. This is a more precise form of the tonic avoiding response noted in a decorticate preparation. The instinctive tactile avoiding response does not require the pyramidal system. The integrity of the cingulate area, area 8, and the supple-

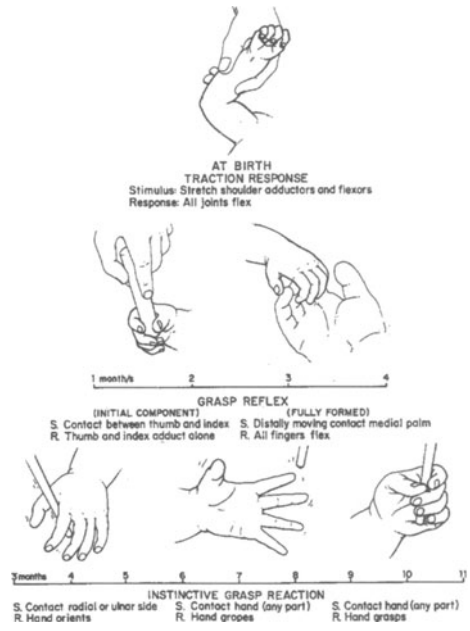


Figure 18-9. Evolution of the automatic grasping responses of infants. From Twitchell, T.E., Neuropsychologia, 3: 251, 1965 (Elsevier).

[2]*Seyffarth and Denny-Brown (1948) also described a group of behavioral responses to the same stimulus, which are more variable and appear to be more subject to factors of attention, distraction, etc.: These were grouped together as the* ***instinctive grasp reaction:*** *(a) the closing reaction, (b) the final grip, (c) the trap reaction, (d) the magnet reaction (the hand moves to follow the object), (e) instinctive groping (if the stimulus moves without capture, the hand pursues).*

[3]*A recent clinical review of the grasp reflex, in which CT scans were used to locate lesions (DeRenzi and Barbieri), indicates the strongest association with damage to medial frontal areas: predominantly, anterior cingulate gyrus and supplementary motor cortex and a lesser correlation with damage to the lateral premotor areas. Usually, the release was bilateral, unless the damage to adjacent motor cortex had produced a severe paresis of the contralateral hand. In such cases, only the ipsilateral hand could be tested. Considerable research data reviewed by DeRenzi and Barbieri suggests that the anterior cingulate area not only interconnects with the supplementary motor cortex but also has a similar pattern of connection to basal ganglia, cortical areas and spinal cord.*

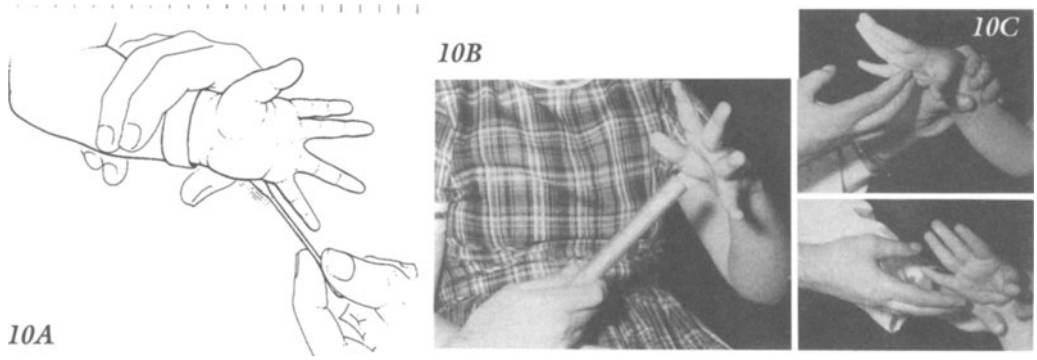


Figure 18-10. Avoiding responses. A. Elicitation of the avoiding response by contact stimulus to the ulnar border of hand as a normal response in infant of 4 to 6 weeks. From Twitchell, T.E., Neuropsychologia, 3:250, 1965 (Elsevier). B. Avoiding response as a pathological phenomenon. Over-extension and abduction of fingers as hand approaches object. (child with infantile spastic hemiparesis.) C. Avoiding response as a pathological phenomenon in another patient with infantile spastic hemiparesis. Reaction of hand to contact stimulation of the palm. From Twitchell, T.E.: Neurology, 8:17, 1958 (Lippincott/Williams and Wilkins).

mentary motor cortex are required. The reaction is released in abnormal degree by damage to the parietal lobe (and adjacent motor cortex). The instinctive grasp and avoidance responses normally are in equilibrium from an anatomical and physiological standpoint.

5. *Other Reflexes Associated with the Cerebral Cortex.* In addition to these tactile instinctive grasp and instinctive avoiding responses, various visual triggered responses of a similar nature may be seen. One may speak of a visual instinctive grasp reaction. This requires the integrity of the posterior parietal areas, the visual mechanisms, and the motor cortex. As discussed below the integrity of the lateral premotor cortex is undoubtedly required for visually triggered reaching and grasping. Damage to the temporal lobe releases this reaction in an abnormal form. The response does occur, of course, in a normal form as one normally reaches for an object, using visual stimuli. This type of phenomenon occurs in the Kluver-Bucy syndrome, which follows the production of bilateral lesions of the temporal lobe in the monkey. The release of various visual automatisms occurs. The animals tend to pick up all objects that appear in their field of vision and to bring these objects to their mouth. (See limbic system chapter for additional discussion). Magnani et al, studied the anatomical correlation of release of visually triggered grasping and groping response in man. In contrast to the experimental studies, the CT scan evidence suggested a medial frontal location of lesion responsible for such release.

Another variety of visually cued reaction is the visual instinctive avoiding reaction. This requires the integrity of the temporal lobe and visual mechanisms. The response apparently is independent of the pyramidal system. Again, in the intact individual, equilibrium of grasp and avoidance is to be noted.

While our discussion has focused on the upper extremity, similar grasp and avoiding reactions may also be noted in the lower extremities. Lesions of premotor cortex also affect gait: producing an apraxia in walking termed a frontal lobe gait apraxia. This will be discussed later in this chapter.

POSTNATAL DEVELOPMENT OF MOTOR REFLEXES

Some reflexes are present at birth and disappear with time: the startle reflex, sucking, rooting and the extensor plantar response. A sequence of reflex activities is noted in the developing human infant as regards the use of hands and fingers .In addition a sequence of changes occurs as regards sitting, standing and walking as summarized in table 18-2.

OVERVIEW OF THE RELATIONSHIP OF PRIMARY MOTOR, PREMOTOR AND PREFRONTAL CORTEX.

In order to understand voluntary and

learned behavior, it is necessary to explore the relationship of primary motor, premotor (including supplementary motor) and the prefrontal areas *(Fig.18-11)*. Voluntary and learned behaviors also reflect the motivational role of limbic structures to be considered in subsequent chapters.

The large and giant pyramidal cells in the *primary motor cortex* discharge producing movements in specific directions (flexion, extension, abduction, adduction) resulting from the contraction of muscles at a specific joint. Among other sources of input, the primary motor cortex receives information from somatosensory cortex of the postcentral gyrus and the ventral lateral nucleus of the thalamus. This input may allow the response of motor cortex to peripheral stimuli in what are termed long loop reflexes.

In contrast, *the premotor cortex* is concerned with patterns of movements that are motor programs Neurons in the premotor cortex discharge during the preparation phase prior to movement. The premotor cortex projects in parallel pathways to motor cortex, to basal ganglia and to spinal cord. The premotor cortex receives projections among other sources from the unimodal sensory association cortex (somatosensory auditory, and visual) as well as the primary somatosensory cortex and the ventral lateral nucleus of the thalamus.

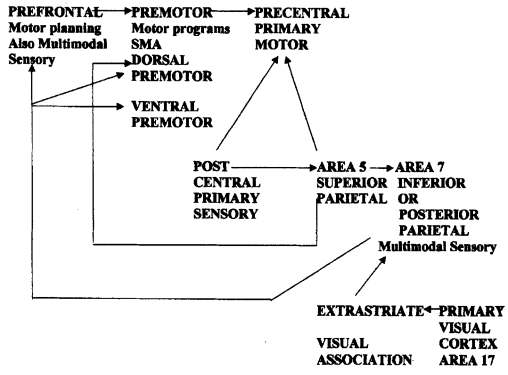


Figure 18-11. Interrelation of motor, premotor, prefrontal and posterior parietal multimodal sensory areas.The input of the somatosensory and visual systems to the multimodal posterior parietal area are presented. The input of the auditory system and the relationship of the multimodal sensory system to the limbic system are not demonstrated. In a general sense the basis for reaching and grasp are demonstrated.

TABLE 18-2: DEVELOPMENTAL CHANGES IN MOTOR RESPONSES[4]

RESPONSE	POSNATAL TIME
Sucking and rooting reflexes	Present at birth.
The Moro (startle) reflex	Present at birth and persisting until 2 months
Tonic neck reflexes	May be present at birth, fragments at 1-2 months
Traction response grasp elicited by traction at shoulder	May be present at birth
Grasp reflex: all fingers flex briefly as unit	Birth - 8 weeks
Instinctive grasp reaction	Begins at 4 - 5 months.
Projected grasp (pincer). Then thumb-finger opposition. Subsequently this is voluntary	Begins at 6 to 8 months
Plantar grasp response	Present at birth disappears at 9-12 months
Extensor plantar response on lateral plantar stimulation (due to immature corticospinal pathway)	Present at birth, disappears at 9-12 months
Plantar flexion on lateral plantar stimulus (dorsiflexion)	Present from 9-12 months and normal through life
Sitting	Infants usually sit unsupported at 6 to 7 months,
Standing with support	-At 8 to 9 months
Pulls self to standing position holding onto object	-At 10-12 months
Walking	Begins to walk with support at 10 to 12 months. Begins to walk independently at 9 to 16 months

[4]We have not considered here the prenatal motor development of the human fetus. Wolff and Ferber (1979) review many of the earlier studies (which demonstrated considerable capacity for swimming movements) and discuss the use of high-resolution ultrasound to study in a non-invasive manner movement's intra-utero. Such studies allow more precise establishment of actual fetal maturation. The suck reflex is actually present in the prenatal state.

The *prefrontal areas* have functions that relate to the limbic system and the motor system. While the orbital and mesial regions of the

prefrontal cortex are related to the limbic system and will be considered in a later chapter, the dorsal region of the prefrontal cortex is concerned with the executive functions involved in the planning, regulation and sequencing of behavior and movement over time. In this regard movement is simply the expression of behavior. This same area of prefrontal cortex functions as the anterior multimodal association cortex and receives projection from the posterior multimodal association cortex located at the intersection of the major sensory association areas. In turn this dorsal prefrontal area projects to the premotor cortex.

PRIMARY MOTOR CORTEX (Area 4)

Area 4 is distinguished by the presence of giant pyramidal cells in layer V. Occasionally giant pyramidal cells may also be found more anteriorly in area 6. In humans, much of area 4, particularly its lower half, is found on the anterior wall of the central sulcus. More superiorly, area 4 appears on the lateral precentral gyrus and continues onto the medial aspect of the hemisphere in the anterior half of the paracentral lobule.

It is important to note that the pyramidal tract is not named because of its cells of origin but rather on the basis of its passage through the medullary pyramid. Of the approximately one million fibers in the pyramidal tract, 31 per cent arise from area 4; 29 per cent arise from the premotor cortex of area 6; and 40 per cent arise from areas 3, 1, 2, 5, and 7 of the parietal lobe. Fibers with a large diameter (9 to 22 u) number about 30,000 and correspond roughly to the number of giant pyramidal cells. Most of these large fibers originate from area 4. It is also important to note that the same cortical areas that give rise to the pyramidal tract also give rise to other descending motor pathways: corticoreticular, and corticorubral, (as well as corticostriate and corticothalamic). From a phylogenetic standpoint this is a logical arrangement since this relatively new control center, the motor cortex, has available a relatively new fast conducting pathway to the anterior horn cells. At the same time the motor cortex also has available pathways to certain older brain stem centers, which formerly exercised primary control, e.g., the reticular formation and the red nucleus. Note that 70-90% of the fibers passing through the medullary pyramid will decussate and continue as the lateral corticospinal tract. These fibers originate primarily from those portions of area 4 representing the distal extremities and synapse directly on alpha motor neurons in the lateral sector of the ventral horn.

In contrast the remaining uncrossed fibers arise from area 6 and the portions of area 4 representing the trunk and neck areas. These uncrossed fibers as they descend through the brain stem, give off collaterals to the bilateral medial brain stem areas of the reticular formation. These uncrossed fibers continue as the anterior corticospinal tract and terminate bilaterally on interneurons, which in turn will synapse on neurons in the ventral medial cell column of motor neurons.

The fibers originating in the parietal cortex synapse in relationship to interneurons that in turn synapse in relationship to neurons of the dorsal horn.

The premotor sector of area 6 projects primarily to the medial pontomedullary areas. The spinal projections of this area consist of the ventromedial descending reticulospinal system and the vestibulospinal tracts.

The red nucleus receives inputs from the rostral (proximal) arm and leg sectors of area 4 and the adjacent premotor cortex and projects as the rubral-spinal system.

Area 4: Stimulation. Electrical stimulation of the motor cortex at threshold level produces isolated movements of the contralateral portions of the body. The movements may be described as a twitch or small jerk. With increased strength or increased frequency of stimulation, repetitive jerks occur; the movements involve a larger part of the contralateral side of the body and an orderly sequence of spread may occur. The repetitive jerks are similar to the movements of a focal motor seizure. The orderly sequence of spread is duplicated in the "Jacksonian March" of a focal motor seizure.

In the conscious patient, these movements,

which can be evoked by stimulation of the motor cortex during surgery, are not clearly the same as consciously willed voluntary movements. According to Penfield, the patient recognizes that these are not voluntary movements of his own and will often attribute them to the actions of the neurosurgeon.

There was considerable controversy as to whether muscles or movements were represented in the motor cortex. Single-unit recording studies have suggested a close topographic grouping of all the neurons for a given muscle. Occasionally stimulation will evoke the movement of a single muscle, usually a distal finger muscle, such as an interosseous. In general, however, stimulation produces contraction of a group of muscles concerned with a specific movement. Voluntary actions also involve the integrated contraction of several muscles rather than the isolated contraction of a single muscle. It should then be apparent that the motor cortex "thinks" in terms of movements. This is, in a sense, inherent in the intracortical connections between the neurons representing the various muscles related to a given movement.

Although there is considerable overlap and plasticity in the representation of movements on the surface of the motor cortex, a certain sequence is apparent *(Fig.18-12)*. In the classical homunculus, the representation of the pharyngeal and tongue movements is located close to the sylvian fissure. Unilateral stimulation of these areas results in bilateral movements. Next in upward sequence are movements of the lips, face, brow, and neck. In the middle third of the precentral gyrus, a large area is devoted to the representation of the contralateral thumb, fingers, and hand. In the upper third, the sequence of the contralateral wrist, elbow, shoulder, trunk, and hip is found. The remainder of the lower extremity in the sequence (knee, ankle, and toes) is represented on the medial surface of the hemisphere in the paracentral lobule. The representation of the anal and vesicle sphincters has been located lowest on the paracentral lobule. It is important to note how large the areas devoted to the thumb, fingers, and face (particularly the lips and tongue) are in the human, reflecting the evolution in use of these structures as regards speech, writing, tool making and manipulation.

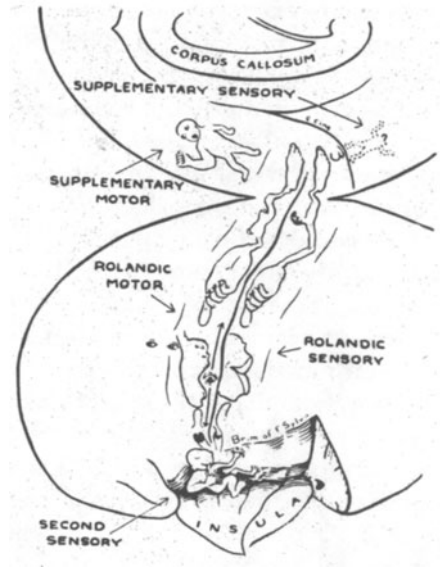


Figure 18-12. Somatic figurines. The primary motor and sensory representation and the effects produced by supplementary motor and second sensory stimulation are demonstrated. (From Penfield, W. and Jasper, H. Epilepsy and the Functional Anatomy of the Human Brain. Boston, Little Brown and Company 1954,p105).

It is also important to note that not all areas of the motor cortex have the same threshold for discharge. As studied in the baboon (Phillips, 1966) the thumb and index finger are the areas of lowest threshold. Slightly stronger shocks are required to produce a movement on stimulation of the great toe area; at slightly greater intensities of shock, movements of the face begin to occur on stimulation of the appropriate area. These findings may relate in part to the fact that those pyramidal fibers making direct connection to anterior horn cells are primarily those mediating cortical control of the distal finger and thumb muscles.

It must also be noted that at times on stimulation of the postcentral gyrus discrete movements will be produced similar to those elicited from the motor cortex. There is some evidence that such discrete movements are produced at a higher threshold than in the precentral cortex and that the ability to obtain

such discrete movements is lost after ablation of the primary motor cortex. However, not all of this neurosurgical data on stimulation of postcentral gyrus in the human is consistent.

Modern concepts of the plasticity of the primary motor cortex: More recent studies reviewed by Sanes and Donoghue (2000) indicate a considerable dynamic plasticity in the primate primary motor cortex. Thus although modules for the head region, upper extremity and lower extremity can be distinguished, there is within each module, a considerable overlap and plasticity with less of the specific localization for each movement suggested by the earlier maps. Instead a mosaic is present. The area devoted to specific movement representations may be modified by trauma to peripheral nerves, central nervous system damage, and most importantly by motor skill learning and cognitive motor actions.

Area 4: Ablation. The effects of ablation of the motor cortex must be distinguished from the more selective effects of limited section of the pyramidal tract in the cerebral peduncle or medullary pyramid. Damage to or ablation of the motor cortex affects not only the pyramidal tracts, but also the corticorubral, corticostriate, corticothalamic and corticoreticular pathways.

Studies of the recovery of function following motor cortex lesions in the monkey) are most useful in illustrating many aspects of the integration of reflex activity at successive levels of the neural axis and are reviewed on the CD ROM in table 18-3.

Studies of recovery of function in the human: The sequence of events in man following partial vascular lesions (infarcts) of the precentral cortex or of the motor pathways in the internal capsule has been studied by Twitchell (1951).

1. *Flaccid Paralysis.* Particularly with a large lesion there is a transient period of flaccid paralysis of the contralateral arm and leg and the lower half of the face, with a transient depression of stretch reflexes. The duration of this flaccid state (reflecting "cortical shock") is variable; it may be quite fleeting depending on the extent of the lesion (which is usually less than total). The sign of Babinski is present with an extensor plantar response on tactile or painful stimulation of the lateral border of the foot.

2. *Return of Deep Tendon Reflexes/Stretch Reflexes.* After a variable period of time, the deep tendon reflexes in the affected limbs return and become hyperactive. There is increased resistance on passive motion at the joints (when there are severe lesions even this stage may not be reached). This does not affect all movements equally but tends to have its greatest effect on the flexors of the upper extremity. *A hemiplegic posture and gait is noted:* the upper extremity is flexed at the elbow, wrist, and fingers and the leg is extended at the hip, knee, and ankle and externally rotated at the hip with circumduction in walking. Walking is possible with the hemiplegic limb as movement of the proximal limb begins to return. In general, recovery of function in the lower extremity is usually greater than in the upper extremity. Following the return of stretch reflexes, variation in the relative degree of spasticity in the flexor and extensor muscles in relation to tonic neck reflexes may be noted. With the return of tonic neck reflexes one will begin to note proximal limb movements.

3. *Return of Traction Response-* Abduction of the arm and shoulder will result in stretch of the abductors. There will then be an adduction of the arm at the shoulder. In addition, synergistic flexion of the arm at the elbow, wrist, and fingers will occur, and objects may be grasped in this manner. This flexion synergy, however, results in a whole hand grasp; all of the fingers flex together.

4. *Return of Selective Ability to Grasp.* This stage of recovery involves a more selective grasp of the entire hand albeit a tonic grasp. There is some dissociated synergy so that the hand alone tends to grasp. Finger and thumb opposition begin to return.

5. *Return of the instinctive tactile grasp reaction with the capacity for projectied movement.* This occurs with incomplete lesions. If a massive lesion is present, the instinctive grasp reflex does not return.

6. *Return of distal hand movement.* Eventually, depending on the extent of the lesion, some return of distal hand movement

may occur but such recovery is usually less than that which occurs for movements at more proximal joints, e.g., at the shoulder and hip.

From a physiological and anatomical standpoint, the logic of this pattern of recovery should be evident. One sees in this sequence a recovery of spinal reflex activities, then of brain stem reflex activities, as noted in the decerebrate preparation, then those noted in the decorticate preparation, and finally those reflexes integrated at a cortical level. (This analysis of recovery of function is to some extent an oversimplification: A small hemispheric lesion of the internal capsule in the adult may produce as great a deficit as a hemispherectomy performed on a hemisphere damaged extensively early in life; Freund 1991).

More recent studies by Freund (1987) of lesions limited to the precentral gyrus in the human indicate that the essential deficit consists of deficits in force generation and execution of independent finger movements. After partial recovery, force is regained and finger movements, although clumsy and slow, are purposive and appropriate to the object. It should be noted that in man, following massive lesions of the motor cortex, a long delay may occur before spasticity develops and deep tendon reflexes return. Such a long delay in the reappearance of stretch reflexes usually signifies a poor prognosis for complete recovery.[5]

The recent study of Warabi et al, 1990 utilized the CT scan to predict recovery of voluntary movement based on the degree of shrinkage of the cerebral peduncle. When the peduncle had shrunk to less than 60 percent of normal, recovery of distal limb function was incomplete. When cerebral peduncle was greater than 60 percent of normal, recovery of distal movement occurred.

Additional discussion regarding the possible reorganization of sensory and motor function at a cortical level that follows damage to these systems is provided in the review of Kaas, 1991 and the study of Jacobs and Donoghue (1991). Damage may unmask a considerable degree of latent cortical plasticity as discussed above .The intrinsic horizontal fibers within the primary motor cortex interconnect large areas and could provide the substrate for this reorganization. Some of the changes occur within hours suggesting some degree of prewiring. In the studies of Nudo et al (1996), experimental destruction of part of the hand area in the monkey resulted in loss of discrete finger movements .The monkey relied on proximal arm movements and the area of representation of the shoulder and elbow expanded into the otherwise undamaged hand and forearm areas. However if the lesioned animals were trained to use the hand, the remaining undamaged area of cortex representing the hand and digits expanded into the area of representation of elbow and shoulder. The trained animals regained the ability to use discrete finger movements in retrieving small objects in 3-4 weeks. The untrained animals did not achieve this level of recovery. These studies certainly indicate the potential role of rehabilitation (occupational and physical therapy) in helping patients recover from the effects of cerebrovascular accidents, trauma and other pathology involving the motor cortex. PET scan studies indicate increased functional activity in other areas of the same and contralateral hemisphere in patients who have recovered from a hemiparesis due to an infarct involving the internal capsule. This was noted in the posterior cingulate area on the side of the lesion and the premotor and caudate nucleus of the opposite intact hemisphere. During movement there was increased bilateral activation of anterior insular cortex, ventral premotor, anterior cingulate, and inferior parietal areas (39 and 40), as well as premotor cortex of the intact hemisphere (Weiller et al, 1992).

The following case history illustrates the effects of focal disease involving the motor cortex.

Case 18-1: Three months prior to admis-

[5]*The studies of Patano et al (1995) utilizing CT/MRI and SPECT scan have demonstrated that patients with a prolonged flaccid hemiparesis as opposed to a spastic hemiparesis had a greater structural involvement of the lentiform nucleus and lower perfusion in the lentiform nucleus, thalamus and cerebellum as well as cortical motor areas.*

sion, this 29-year-old, right-handed, white female manager developed an intermittent "pulling sensation" over the anterior aspect of the left thigh, lasting a few minutes which recurred about twice a week. On the evening of admission she again had the onset of this same sensation, then had numbness followed by "jerky movements" in her left foot which progressed to involve the whole left lower extremity. She was then observed to have tonic extension then clonus of all four limbs with loss of consciousness for a minute or less. She still appeared dazed and slightly confused for the next 5 minutes, and was subsequently amnestic for the secondarily generalized seizure

Physical Examination: Normal except for bite marks on the left lateral aspect of the tongue.

Neurologic Examination: Significant only for a slight asymmetry of deep tendon reflexes, left > right.

Clinical Diagnosis: Focal seizures originating right parasagittal motor cortex (foot area), with question of parasagittal meningioma.

Laboratory Data: *Electroencephalogram* (Fig.29-1B) demonstrated rare focal spikes, right Rolandic parasagittal consistent with the focal source of the secondarily generalized seizure.

CT scan (Fig.18-13) demonstrated an enhancing lesion in the right parasagittal region just anterior to the central sulcus.

Arteriograms (Fig.18-14) were consistent with a right parasagittal meningioma.

Subsequent Course: The patient did well after removal of a well-circumscribed right parasagittal meningioma by Doctor Bernard Stone. The patient received diphenylhydantoin (Phenytoin) to prevent additional seizures.

SELECTIVE LESIONS OF THE PYRAMIDAL TRACT

We have previously indicated that the student should consider as the primary manifestations of an upper motor neuron lesion a spastic paralysis with increased deep tendon reflexes and the sign of Babinski. A more detailed analysis indicates that the effects of selective pyramidal tract damage are not quite the same

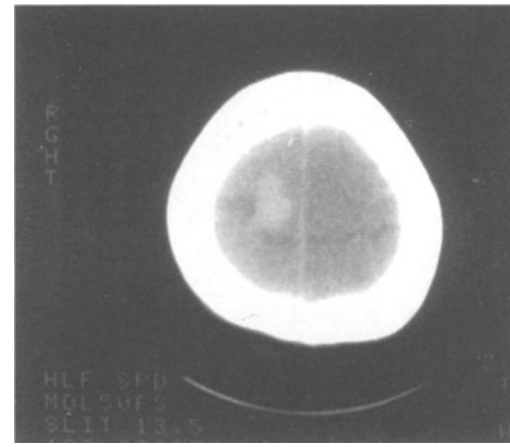
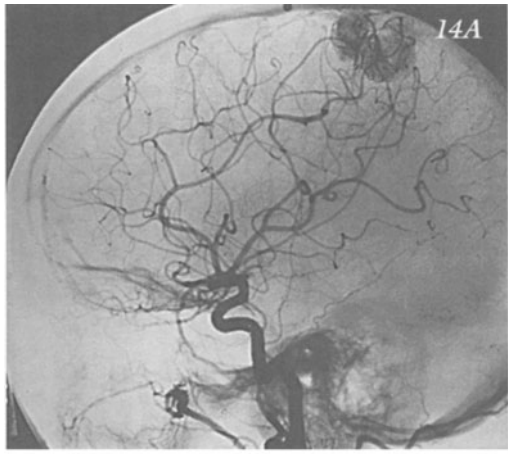


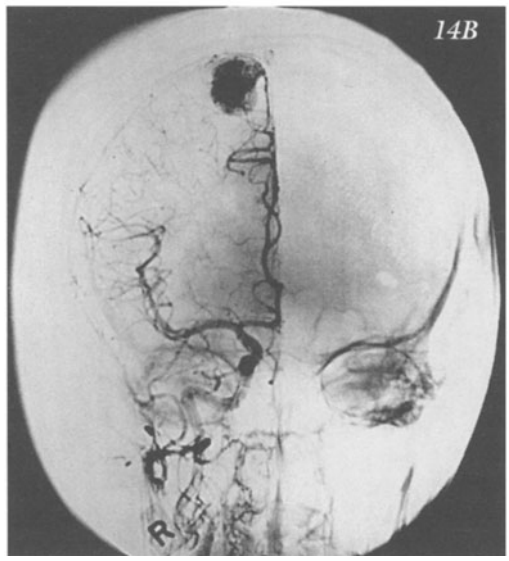
Fig. 18-13. Parasagittal meningioma. Case 18-1.CT scan demonstrates an enhancing lesion in the most rostral sections of the CT scan, just anterior to the right rolandic sulcus. See text for details.

or equivalent to those, which follow, in a general sense, upper motor neuron lesions. We should note that the ablation of the motor cortex destroys not only the origin of the pyramidal tract (the corticospinal tract) but also the origin of the cortico-reticular, the corticorubral, the corticothalamic, and the corticostriatal fibers. The effects of such a cortical ablation are to release these various subcortical and brain stem centers from cortical control and also to produce the effects of damage to the corticospinal tract. We should note that section of the pyramidal tract in the medullary pyramid or in the cerebral peduncle does not have the same anatomical and physiological effects as ablation of the motor cortex, which has been previously summarized

Furthermore selective section of the pyramidal tract or cerebral peduncle may yield different effects than section of the lateral column in the spinal cord. The descending rubrospinal and the lateral reticulospinal tract (from the bulbar inhibitory center of the medulla) are closely related to the corticospinal tract in the lateral column. In addition the medial reticulospinal tract from the pontine extensor facilitatory center descends in the anterior column and thus would be left undamaged by a lesion of the lateral column.

The studies of Bucy suggest that both man and the monkey were capable of useful move-





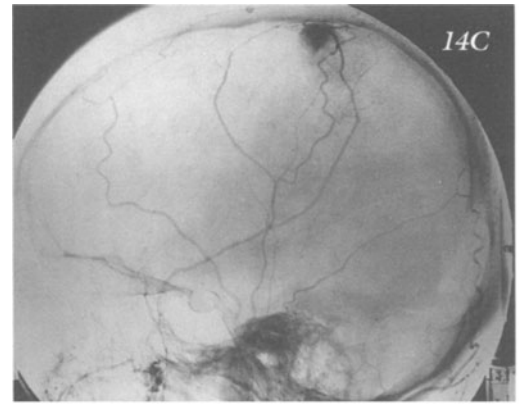


Fig. 18-14.Parasagittal meningioma. Case 18-1. Arteriograms demonstrate the characteristic features of a circumscribed vascular tumor in the parasagittal rolandic area, supplied by the right anterior cerebral artery and meningeal branches of the external carotid artery. A. Arterial phase lateral common carotid injection. B. Arterial phase AP view common carotid injection. C. Selective injection of the external carotid artery. D. Common carotid injection: venous phase - tumor blush with large draining vein. See text for details.

ments after section of the pyramidal tract in the cerebral peduncle. Thus, locomotor abilities returned. The monkey could use his hand in feeding and in manipulating small objects. With bilateral section, however, the hand was used as a claw with some deficiency in independent finger movements. It should be stressed that spasticity and increased deep tendon reflexes were not noted. The sign of Babinski was found in the human patient. In the human patient, the retention of discrete finger movements was remarkable. Somewhat different results were obtained by Denny-Brown (1966) following section of the pyramidal tract in the medul-lary pyramid. There was a moderate increase of deep tendon reflexes and a mild spasticity. Schwartzman (1978) found no spasticity, 3 years after section of the medullary pyramid in the monkey (A recent study by Jagiella and Sung (1989) does suggest the eventual development of spasticity in a patient with the bilateral ischemic infarction of the medullary pyramids).

What was clearly defective after section in all of these studies was the discrete fractionated distal finger movements required for the instinctive tactile grasp reaction that normally would allow for the precise orientation of fingers to a moving three-dimensional stimulus. The pyramidal tract fibers mediating cortical control of these distal muscles make direct connection to the anterior

horn cell. These direct fibers of the corticospinal system elicit predominantly flexor facilitation and extensor inhibition. In contrast, the indirect corticospinal fibers (those which do not synapse directly on anterior horns cells) synapse predominantly in relation to interneurons, which make synaptic contact with anterior horn cells innervating more proximal muscles. Additional discussion will be found in Kuypers 1987.

We have not considered in our discussion the possible role of the pyramidal tract in modifying transmission of sensory information at the spinal cord (posterior horn) and brain stem levels (nucleus gracilis and nucleus cuneatus). The various studies, which have suggested such a role, are considered in the review of Bizzi and Evarts (1971).

CORTICORUBRAL SPINAL SYSTEM

In the monkey and cat, if the pyramidal tracts are intact, destruction of the rubral spinal system produces no definite motor deficit. However, in monkeys and cats that have already had bilateral section of the pyramidal tract (a section which has produced very little qualitative change in limb movement) a complete loss of distal limb movement may occur after additional bilateral destruction of the rubrospinal tract. In the intact monkey, complex coordinated movements may be evoked by stimulation of the red nucleus. Flexor excitation predominates with extensor inhibition. The studies of Lawrence and Kuypers (1968) suggested that the rubrospinal tract is mainly concerned with steering movements of the extremities, particularly distal segments. On the other hand, the ventromedial brain stem reticulospinal tract is mainly concerned with steering movements and posture of head or body and synergistic movements of the extremities (Kuypers, 1987).

PREMOTOR CORTEX (Areas 6 and 8):

Overview of the functions of the premotor and supplementary motor cortex *(Fig. 18-15)*.

Penfield grouped area 6, area 8, and the supplementary motor cortex (the continuation of areas 6 and 8 onto the medial surface of the hemisphere) on clinical grounds as intermediate frontal areas. These areas may also be grouped from the functional standpoint as concerned with the preparation for movement and the temporal sequencing of movements (Halsband 1993, Halsband and Freund 1990, Passingham 1987, Rizzolatti 1987, Rome 1986, Shibasaki et al 1993, Wise 1988, Wiesendanger 1987,Wiesendanger and Wise 1992)

These areas receive a polysensory input from sensory association areas. These are widespread connections of these areas both within and between the hemispheres (see Pandya and Kuypers, 1969, Pandya and Vignolo 1971, Ward et al 1946).

There is considerable rationale for grouping these areas from the standpoint of the results of stimulation studies. Moreover, there is also considerable justification for such an approach from the cytoarchitectural standpoint. Histologically, area 6 is similar to area 4 but lacks, in general, giant pyramidal cells. Area 8 has some similarity to area 6 but is also transitional to the granular prefrontal areas. There are considerable variations when the several cytoarchitectural maps are compared as to

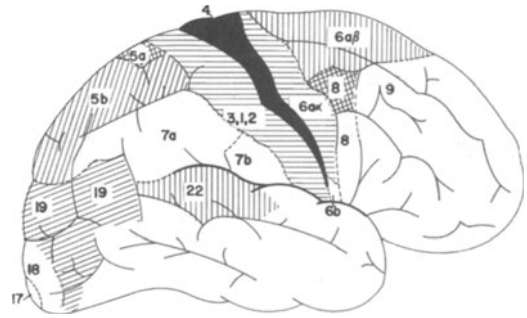


Figure 18-15. The motor cortical fields of man as determined by Foerster employing cortical stimulation. Stimulation of the area indicated in black produced discrete movements at low threshold and was designated pyramidal. Lines or cross-hatching indicate other areas producing movements and were designated in a broad sense as extrapyramidal. These movements were usually more complex synergistic and adversive movements and included the adversive responses obtained by stimulation of area 19. Each of the areas extending to the midline is continued on to the medial surface. Modified from Foerster, O.: Brain, 59:137, 1936 (Oxford Univ. Press).

the exact boundaries of area 8 in both man and monkey. Areas 44 and 45 in the inferior frontal convolution (Broca's motor speech or expressive aphasia centers) should also be included within this motor association or intermediate frontal grouping, from both the functional and cytoarchitectural standpoints. For simplicity of presentation, these areas will be considered later in relation to language function.

Note that clinical lesions, such as vascular infarcts and tumors, usually do not respect cytoarchitectural borders.Thus, vascular lesions that involve the lateral premotor aspect of area 6, usually also involve the primary motor cortex. Tumors such as parasagittal meningiomas may involve both the lateral premotor and the supplementary motor cortex or may involve the prefrontal and the several premotor areas.

With increasing research, there has come recognition that there are differential functions for the various sectors of these premotor areas, (Wise etal, 1997, Krakauer &Ghez, 2000).

An initial distinction may be made between the supplementary motor cortex (SMA) and the lateral premotor areas (PMA).

1. *The Supplemental Motor Area.* SMA is concerned with the sequencing of movements that are initiated internally without triggering from external sensory stimuli. SMA is concerned with the performance of learned sequences of movement. The area just anterior to the SMA, the pre SMA is involved along with other prefrontal areas such as area 46 in the actual process of learning the sequences (training of a motor skill). This same pre SMA area is also involved when the same complex movement sequence is imagined. Once a sequence has been fully and usually over learned, control may be centered in primary motor cortex.

The Readiness Potential (Bereitschafts Potential): In man, surface electrodes placed on scalp are able to record 1-2 seconds prior to voluntary movements, a significant surface negative potential with maximum amplitude over the midline of the frontal area corresponding primarily to the supplementary cortex. The process of initiation of more complex actions enhances this potential. In contrast, when the same movements were triggered by external stimuli, there was no such readiness potential. These non-invasive studies in man (as well as blood flow studies) confirm much earlier experimental data derived in studies of the monkey (Papa et al 1991, Deeke, 1987, Wiesendanger 1987).

2. *The Lateral Premotor Area.* In contrast to the SMA, the lateral PMA is concerned with the sequencing of movements that are triggered by external stimuli. In this regard, there is a close relationship of the lateral PMA to the sensory association cortex of the superior parietal cortex (area 5) and the posterior parietal multimodal sensory areas, which are directly connected, with the extra striate visual cortex. This relationship is complex as demonstrated in reaching for and grasping precisely an object presented at a particular point in visual space.

The lateral PMA has been divided into two major functional areas: the dorsal and the ventral.

a. *The dorsal lateral PMA* neurons are involved in reaching for that object. This area is also involved in learning to associate specific stimuli particularly visual with the motor response of reaching for that stimulus. As opposed to the learning of a repetitive motor act (pressing a key) involving the supplementary motor cortex, this is a different type of learning referred to as associative learning. Multiple bits of information must be integrated for this reaching activity, visual position of object, position of gaze, position of arm etc and this involves information received from various posterior parietal areas adjacent to the extrastriate cortex discussed in greater detail by Wise et al (1997.

b. *The ventral lateral PMA* is concerned with grasping. This area also must receive information from the extrastriate cortex regarding size and shape of the object as well as other multimodal and sensory association data so that an effective grasp of the object may occur.

Essentially stimulation of PMA and SMA results in a pattern of movement characterized by tonic abduction of the contralateral arm at shoulder with flexion at elbow plus deviation of

head and eyes to the contralateral field.. In addition with SMA stimulation bilateral lower extremity movements may occur. *(Fig. 21-12)* Ablation of these areas will result in a release of grasp reflex and an apraxia in limb movements. Bilateral lesions of the SMA may result in an akinetic mute state.

Case 18-2 provides an example of a low-grade glioma involving the premotor and supplementary motor cortex from the standpoint of focal seizure activity. The motor effects of frontal lesions are presented in case histories 22-2 and 22-3, which follows the discussion of the prefrontal areas.

Case 18-2: This 57-year-old right-handed single nun and occupational therapist, at age 47 had the onset of observed generalized convulsive seizures, which occurred without warning with sudden loss of consciousness. Shortly after the onset of the grand mal seizures, the patient began to have focal seizures, which increase in frequency to one per week. She described these as beginning with the abduction and raising of the right arm at the side, over her head, then a jerking of the right arm, and then she would fall to the ground. She would remain fully conscious but she would be unable to talk. She would have an awareness that something strange was occurring. She had a sinking sensation. She denied any impairment of memory after the episode. However, she would be aware that her right arm and leg were tingling and weak for perhaps 5 minutes afterwards and she would be unable to speak for 10-30 minutes afterwards. These focal seizures occurred once a month, but for the last 2 years, they had been occurring once a week. The patient indicated that over the last 10 years she has had problems with her memory.

She was reported to have had three "negative" CT scans over the years, and yearly EEG's, which did not reveal focal features or electrical seizure discharges.

Neurological examination: *Mental Status:* delayed recall without assistance, was 0 out of 5 and with assistance 2 out of 5. *Motor System:* intact except for a decreased swing of the right arm in walking. *Reflexes:* deep tendon reflexes were increased on the right at biceps and patellar. Plantar response was extensor on the right and equivocally extensor on the left.

Clinical diagnosis: Seizures of focal origin left premotor/supplementary motor cortex possibly secondary to low grade glioma. A meningioma was less likely due to the reports of "normal CT scans."

Laboratory data: *CT scan (Fig.18-16)* demonstrated an area of calcification with surrounding edema in the left premotor area.

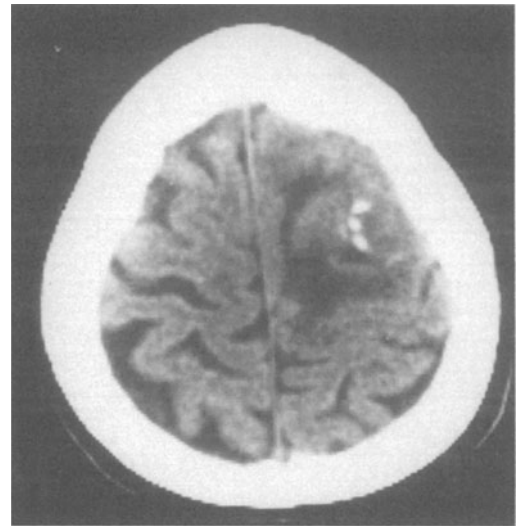


Figure 18-16. Case 18-2. Oligodendroglioma of premotor and supplementary motor cortex. CT scan. The non-contrast CT scan demonstrated an area of calcification with surrounding edema, involving the premotor cortex. See text.

MRI scan (Fig.18-17), demonstrated extensive involvement of the premotor and supplementary areas by tumor and edema.

Subsequent course: Doctor Bernard Stone performed subtotal resection of this tumor. Histological examination of the tissue confirmed the preoperative impression of an infiltrating glioma - predominantly oligodendroglioma in type. The patient received postoperative radiotherapy, 5000 rads to the left hemisphere and an additional 1000 rads to area of tumor. When last seen in follow-up 4 years after surgery, the patient was still experiencing infrequent (1-2 per month) short focal seizures of the same type involving focal movements of right arm, plus speech arrest. The neurological

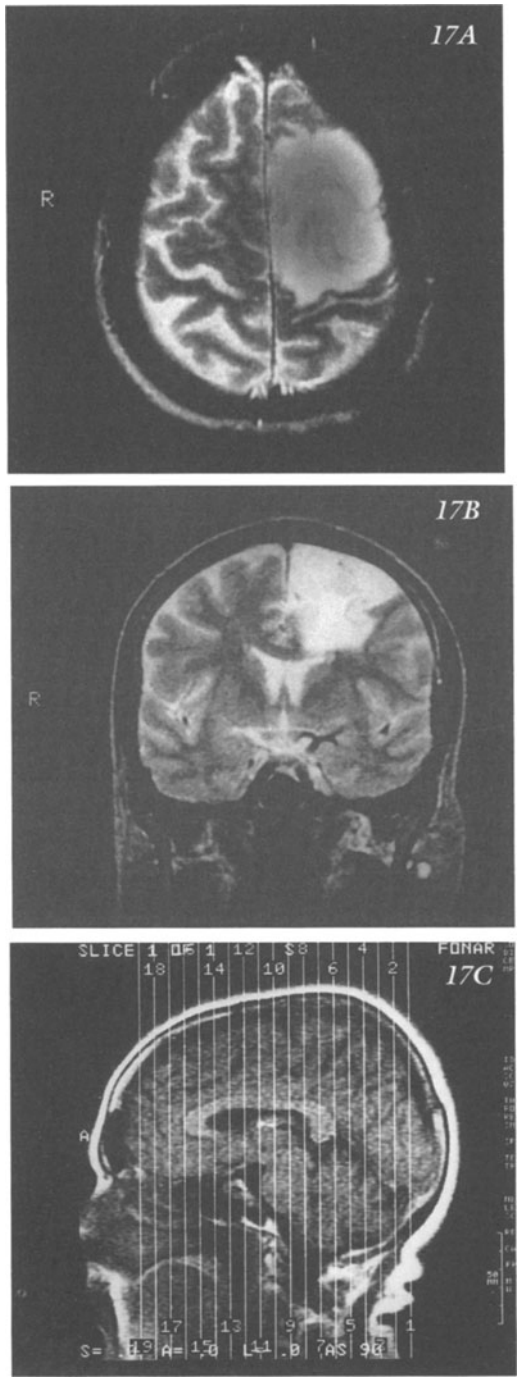


Fig. 18-17 Case History 18-2. Oligodendroglioma of premotor and supplementary motor cortex, MRI non-enhanced A) Horizontal T 2 weighted study demonstrates the wide extent of tumor and edema involving the premotor and frontal cortex. B) Coronal section T2 weighted demonstrates the involvement of the supplementary motor cortex. C. Reference diagram for coronal section (slice 13). See text.

examination demonstrated some decrease in spontaneous speech some blunting of affect. Bilateral extensor plantar responses were present. She had a moderate frontal type apraxia of gait and required a cane to avoid falls.

CORTICAL CONTROL OF EYE MOVEMENT: FRONTAL (AREA 8) AND PARIETO-OCCIPITAL EYE FIELDS.

Overview of eye movements: In chapters 11 and 12 –the basic cranial nerve and brain stem mechanisms for eye movement were considered. In this section, the mechanisms for control from other centers will be considered. This is a complex subject and has been presented in great detail in the studies of Goldberg (2000). More specific information regarding the frontal eye field will be found in Schall & Thompson (1999).

Vision is sharpest at the fovea, the center of the macular area of the retina. There are various mechanisms for moving the eyes so that points of interest are centered on the fovea of the two eyes. These may be listed as follows: saccadic eye movements, smooth eye movements, vergence eye movements, fixation system, vestibulo-ocular responses, and opticokinetic responses.

Definitions and anatomical localization:

1. *Saccadic eye movements: Rapid movements of gaze that shift the fovea rapidly to a point of interest are termed saccades.* These movements may be triggered by attending to a visual point of interest, by memories or by commands. The brain stem substrate for all horizontal saccades is the lateral gaze center of the paramedian pontine reticular formation. Several types of neurons are present in this center, Neurons referred to as medium lead burst cells provide direct excitation to motor neurons in the ipsilateral abducens nucleus and to the interneurons in that nucleus which give rise to the medial longitudinal fasciculus. Long lead burst cells drive the medium lead burst cells and receive excitatory input from the higher centers to be discussed below, The medium lead burst neurons also excite inhibitory burst neurons which in turn suppress the discharge

of contralateral abducens neurons. In addition, there are neurons located in the dorsal raphe nucleus of the pontomedullary area, which cease firing during saccades (omni pause neurons). These neurons if stimulated during a saccade will stop the saccadic movement. Additional neurons provide tonic discharges relevant to eye position and maintain the eyes in a position set by the saccade: the flocculus of the old vestibular portion of the cerebellum, the vestibular nucleus and the nucleus prepositus hypoglossi.

For vertical saccades, burst and tonic neurons are found in the rostral interstitial nucleus of the MLF in the mesencephalic reticular formation.

Central control of saccades: A complex system with redundant features is present. Essentially, two major cortical areas are involved: the contralateral frontal eye field (area 8) and the contralateral lateral intraparietal area of the posterior parietal area at the border of the extrastriate cortex. Area 8 provides the motor input for the response to the command e.g. "look to the left or right field". The frontal eye field has major interconnections in a topographic manner with areas that participate in the streams of information that flow out of the extrastriate visual cortex. These two streams, the dorsal and ventral will be discussed in the visual system chapter. The posterior parietal area in contrast is involved with visual attention, with representations of the location of objects of interest. Beyond a simple representation, there is a transformation of this information by parietal neurons into motor coordinates (Colby & Goldberg-1999). There is a significant interconnection with area 8 with an exchange of information. Both areas project to the intermediate and deep cell layers of the superior colliculus. The superior colliculus in turn projects to the mesencephalic and pontine reticular formation. The same areas of the superior colliculus also receive inputs from the prestriate areas of the posterior temporal gyri. The superficial layers of the superior colliculi receive input from both the striate cortex and the retina. The frontal eye field (area 8) projects not only to the superior colliculus but also directly to the pontine and mesencephalic reticular formation. Lesions of either area 8 or of the superior colliculus would produce a defect in saccades to the contralateral field and a transient visual neglect. The defect however would be temporary, since the alternative system would be intact. Lesions of the parietal cortex tend to produce longer lasting visual neglect syndromes. The interaction of area 8 and the superior colliculus is even more complex. Area 8 projects to the caudate nucleus. The caudate nucleus inhibits the S. nigra pars reticularis, which in turn acts to inhibit the superior colliculus.

Other cortical areas are also involved in saccades: the SMA eye field and the dorsolateral frontal cortex. The former area has neurons that direct movement to part of a target. The latter contains neurons that discharge when the saccade is made to a remembered target. Additional discussion of the role of the frontal eye fields will be found in Pierrot-Deseilligny et al, 1995.

2. *Smooth pursuit in contrast to saccades keeps the image of a moving target on the fovea.* Eye movement velocity must match the velocity of the target. The medial vestibular nucleus, the nucleus prepositus hypoglossi and the paramedian pontine reticular formation receive information from the vermis and flocculus of the cerebellum and project to the abducens nucleus and the oculomotor nucleus. Morrow & Sharpe, 1995 discuss the deficits in smooth pursuit after unilateral frontal lesions.

The cortical inputs for smooth pursuit arise from area 8:the frontal eye field. In the monkey, stimulation of area 8 produces ipsilateral pursuit. Area 8 receives input from the posterior sectors of the superior and middle temporal gyri. This area in turn receives input from the visual cortex. In man the posterior parietal area may serve this same function. Both the frontal and temporal (or posterior parietal) areas project to the dorsolateral pontine areas.

3. *The fixation system holds the eyes still during intentional gaze on an object.* During fixation, saccades must be suppressed. The most rostral segment of the superior colliculus has a representation of the fovea and neurons here

are active during fixation. These neurons act to inhibit neurons in the more caudal superior colliculus. In addition, these neurons excite the omni pause neurons in the lateral gaze center, which as discussed above inhibit saccades.

4. *Vergence movements (convergence and divergence) and accommodation* are controlled by neurons within the third nerve complex of the midbrain.

5. *Vestibulo-ocular movements* hold images stable on the retina during brief head movements. In put occurs from the vestibular system.

6. *Opticokinetic movements hold images stable during sustained head rotation.* Visual input is required. In rabbits, retinal neurons project to the nucleus of the optic tract in the pretectum which then projects to the medial vestibular nucleus. These neurons can distinguish between visual and vestibular stimuli. In primates, there is in addition, a "cortical system" that includes the magnocellular layers of the lateral geniculate, striate cortex, and the posterior portions of the middle and superior temporal gyri. Compared to the non-cortical system, which responds to stimuli moving slowly in a temporal to nasal direction, this "cortical system" can respond to stimuli moving with higher velocities in a nasal to temporal direction. This evolution in the system may reflect the changes, which have occurred in the placement of the orbits in the skull when the primates are compared to the rabbit.

Opticokinetic nystagmus occurs when a pattern of vertical black and white lines is moved slowly in front of the eyes. A similar nystagmus occurs as one sits in a moving train looking out the window at the series of telephone poles flashing by. A lesion in the cortical system produces defective opticokinetic nystagmus to visual stimuli moving towards the side of the lesion.

Area 8: Stimulation: there is disagreement regarding the exact boundaries of area 8 in the human. Some investigators (Vogts, Foerster, Penfield) *(Fig.17 -10, 18-10, 21-15,)* have limited area 8 to those portions of middle frontal and inferior frontal gyri just anterior to the precentral gyrus. These authors have then designated all of the superior frontal gyrus between the prefrontal areas and the motor cortex as area 6. It is clear that conscious, adversive eye and head movements to the contra-lateral field occur most frequently in relation to stimulation of that portion of the middle frontal gyrus just anterior to the precentral gyrus. In actuality in the studies of Penfield and Jasper 1954 and confirmed more recently by Luders et al (1988), the eye field for gaze actually extended onto the motor strip between the face and hand areas as demonstrated most particularly in *Fig. 18-10.* Adversive head and eye movements may also occur, of course, as part of a more complex movement on stimulation of area 6 or of the supplementary motor cortex. Moreover, adversive head and eye movements, as a seizure phenomenon following loss of consciousness, may occur with foci of seizure discharge more anteriorly placed in the prefrontal areas (compare *Fig. 18-18a and 18-18b)* but these have less localizing significance. Quesney et al (1990) concluded that seizures arising in parasagittal frontal area are more likely to involved conscious head turning; seizures originating in anterolateral dorsal-frontal convexity - unconscious head turning. In addition, stimulation in areas 18 and 19 will also produce eye turning. Thus, the clinical neurologist must in each case weigh the localizing significance of seizures characterized by head and eye turning. Such seizure components do not always have the more specific localizing significance of the focal motor seizure or of the olfactory hallucination (Refer also to the paper of Ochs et al, 1984, which discusses the variability of localization in terms of ipsilateral versus contralateral deviation of the eyes)

In addition to head and eye turning, opening and closing of the eyelids may occur on area 8 stimulation. At times, pupillary dilatation and eye movements, other than conjugate aversion, may occur, e.g., upward deviation of the eyes *(Fig.18-19).*

Area 8: Ablation. Ablation of area 8, or (in man) infarction of this area following occlusion of the blood supply, results in a transient paralysis of voluntary conjugate gaze to the contralateral visual field. In general, in man, this

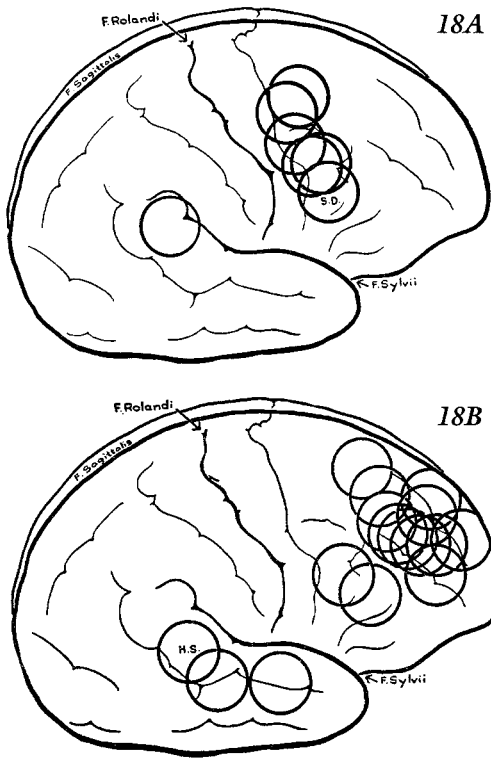


Figure18-18 A. Simple (conscious) adversive seizures at onset. The epileptogenic lesion localizes to the middle frontal gyrus anterior to motor cortex. (From Penfield, W., and Kristiansen, K.: Epileptic Seizure Patterns, Springfield, Ill., Charles C. Thomas, 1951, p.30.) B. Unconscious Adversive Seizures at onset. The epileptogenic focus in 16 patients whose seizures began with unconscious aversion of head and eyes localizes predominantly to the anterior portion of the frontal lobe (From Penfield, W., and Kristiansen, K.: Epileptic Seizure Patterns. Springfield, Ill., Charles C. Thomas, 1951, p.22.)

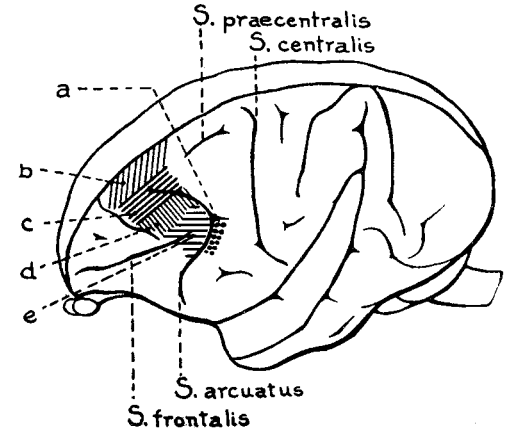


Figure 18-19. Functional subdivision of the frontal eye fields in the monkey under relatively light anesthesia: a) closure of eyes; b) pupillary dilatation; c) eyelid opening (awakening reaction"); d) conjugate deviation to the opposite side; and e) nystagmus to opposite side. (From Smith, W.K., (in) Bucy, P.: The Precentral Motor Cortex, Urbana, University of Illinois Press, 1944.) In the studies of Crosby, E.C., et al (J.Neurol. 97:357-383, 1952) oblique and vertical movements were also observed.

paralysis of voluntary gaze usually does not occur in isolation but is associated with a sufficient degree of infarction to have produced a severe hemiparesis. The patient then lies in bed with the contralateral limbs in a hemiplegic posture and with the head and eyes deviated towards the intact arm and leg. This deviation may perhaps reflect the unbalanced effect of the adversive eye center of the intact hemisphere. The effect is usually transient, clearing in a matter of days or weeks. These patients at times also appear to neglect objects introduced into the visual field contralateral to the lesion. The patients also neglect contralateral tactile and auditory stimuli. In the past, such a unilateral neglect has been attributed to associated involvement of the inferior parietal lobule. The studies of Kennard (1938) and of Welch and Stuteville (1958), however, suggest that these unilateral neglect syndromes may also occur as transient phenomena following ablation of area 8 in monkeys (area within the superior limb of the arcuate sulcus). These animals also had conjugate deviation of head and eyes to the side of the lesion and forced circling. Bilateral ablations within this area resulted in animals that, in a sense, had a bilateral neglect of the environment, remained apathetic, and neglected visual and auditory and tactile stimuli, although they could follow moving objects. Although some recovery occurred over a period of weeks to months, the animals continued to have a "wooden expression" and a fixed gaze. Some of these findings are seen in the human following bilateral frontal lobe damage. In addition, however, a similar state may occur in Parkinson's disease or in brain stem lesions producing akinetic mutism, which will be discussed later. More recent discussions of the "neglect" syndrome will be found in Watson et

al 1978 and Heilman et al 1983. Note also that bilateral discharge of this area may produce a similar state of "neglect of the environment" and arrest of movement (Marcus et al 1970).

SUPPRESSOR AREAS FOR MOTOR ACTIVITY (Negative Motor Response)

Dusser de Barenne and McCulloch found in the monkey that stimulation of that portion of area 4, adjacent to area 6 (designated area 4S), resulted in a suppression of the motor response elicited by stimulation of area 4. In addition, thresholds for obtaining responses from area 4 were raised, and after discharge was aborted. Stretch reflexes and muscle tone were decreased. It was soon discovered that these effects could be obtained by stimulation of a number of other cortical areas: area 8 (8S), 2S and 19S. On the medial aspect of the hemisphere, similar effects could be obtained from the anterior sector of the cingulate gyrus: areas 24S and 32. These "suppressor" areas cannot be distinguished on cytoarchitectural grounds from adjacent cortical areas. Similar effects have been elicited from stimulation of the caudate nucleus and of the bulbar medullary inhibitory center. There has been some evidence that the cortical motor suppressor effects are mediated via cortical reticular and corticostriate connections. In subsequent studies, Fangel and Kaada, 1960 indicated that arrest of movement could occur from stimulation of a number of distinct neocortical and rhinencephalic points. Note must of course be made that a nonspecific interference with voluntary movement may occur in relation to stimulation of the motor cortex. Thus, the patient who is experiencing a focal motor seizure involving the hand cannot use that hand in the performance of voluntary skilled movements. Similarly, arrest of speech is frequently produced by stimulation of the various speech areas of the dominant hemisphere, whereas vocalization is only rarely produced.

Recent studies by Luders et al (1988) with precise stimulation of the cerebral cortex of man in preparation for epilepsy surgery have revisited the concept of suppressor areas - renaming the phenomena as "Negative Motor Response" - an inability to perform or sustain a voluntary movement at a stimulation intensity that did not produce any symptoms or signs. The areas of cortex included (a) the inferior frontal gyrus, immediately anterior to primary motor area for face; (b) less often-premotor cortex just anterior to the frontal eye field or the hand area; (c) The supplementary motor cortex. The authors speculate that these effects are produced because the stimulation interferes with the preparation for movement.

PREFRONTAL CORTEX (Areas 9, 10, 11, 12, 46, 13, 14). Additional discussion will be found in chapter 22

The term prefrontal refers to those portions of the frontal lobe anterior to the agranular motor and premotor areas (areas 9,10,11,12). Three surfaces or divisions are usually delineated: 1) lateral - dorsal convexity, 2) medial and 3) orbital or ventral .All three are concerned with executive function and relate to the mediodorsal thalamic nuclei. In general the lateral-dorsal relates to motor association executive function, the orbital –ventral and the medial to the limbic –emotional control executive system. Recent studies have questioned this simplistic approach. Thus certain functions previously considered to be associated with dorsolateral location have been now localized to a medial location. (Stuss et al 2000). In addition, there is evidence that dorsal lateral lesions also alter affect and motivation. Moreover as the clinical examples of chapter 22 will demonstrate, most pathological processes involve the functions associated with more than one division either directly or through pressure effects.

Most studies of stimulation or of ablation lesions involving the prefrontal areas have included, within the general meaning of the term prefrontal, areas beyond areas 9, 10, 11, and 12. Posterior orbital cortex (area 13) and the posteromedial orbital cortex (area 14) have been added to the orbital frontal group (Fig. 18-20). These areas all share a common relationship to the medial dorsal nucleus of the thalamus. Areas 46 and 47, located in man on the lateral surface of the hemisphere, are also

included. The anterior cingulate gyrus (area 24) is also included in the prefrontal area, although it may be considered part of the limbic system and relates to the anterior thalamic nuclei.

Overview of the role of the prefrontal area in motor and cognitive function: *Our concern here is primarily with the dorsal prefrontal subdivision.* The ventral/orbital and medial subdivisions also will be considered here but also in the limbic system chapter. We are concerned with the sequencing of behavior, the planning of motor function and with a very short type of memory referred to as working memory. *Working memory* provides for the temporary storage of information that is needed for ongoing behavior. This may be verbal, visual or central executive. The concept of working memory is best demonstrated in the delayed response test in the monkey. Bilateral removal of prefrontal areas in monkeys and chimpanzees produced significant effects on two separate aspects of behavior: (1) delayed response and delayed alternation response, (b) emotional responses, particularly aggression (Jacobsen 1935, Fulton and Jacobsen 1935, Jacobsen and Nissen 1937). In the delayed response test, the hungry test subject observes food placed under one of two containers. A solid opaque screen is then interposed and after a delay of at least 5 seconds, the screen is raised - allowing the animal to select the appropriate container. Normal primates rapidly learn this task and a more complex task of delayed spatial alternation in which the choices must be alternated between the left and right containers. Both tasks, however, are difficult for the lesioned animal to perform if delays are imposed. Subsequent studies (see Butters and Pandya 1969) have demonstrated that a relatively small lesion around the middle one-third of the principal sulcus is sufficient to produce the deficit. Although Jacobsen initially attributed the disorder to a general deficit in short term memory, subsequent studies have indicated that this is not necessarily the case, since such animals can learn discriminations involving the selection of a specific object from among several presented. When appropriate tests are selected, similar deficits can be demonstrated in man. A more detailed discussion of this aspect of prefrontal disorder is provided by Milner and Teuber 1968 and Stuss and Benson (1986). In the human, the digit span test utilizes working memory.

Additional studies have defined three sectors of the dorsal subdivision, which are concerned with different aspects of working memory and motor planning. These areas may be specified based on their relationship to the principal sulcus in the monkey dorsolateral prefrontal cortex.(Fig. 18-20)

The *area surrounding the principal sulcus* contains neurons that begin to fire as the initial visual cue of food is presented in a particular position in the contralateral visual field, and continue to fire during the delay period. Lesions in the area of the principal sulcus will interfere with delayed response.

Neurons in the *cortex ventral to the principal sulcus* code information about what the object is in terms of shape and color. This area receives information via a ventral pathway from the visual cortex involving the inferior temporal lobe.

The *cortex dorsal to the principal sulcus* codes information regarding the location of the object. This area receives visual information via the posterior parietal area adjacent to the extrastriate cortex as discussed above.

There are other neurons that respond to both types of stimulus information.

In the human, aspects of prefrontal function are tested with a variety of tests. These include more complex forms of the delayed response and delayed alternation tests. The Luria motor sequences can be easily utilized in the office: the patient must reproduce a demonstrated sequence of hand movements (strike the thigh with the open hand then with the ulnar aspect of the open hand and then with the ulnar aspect of the closed fist). In the Wisconsin Card Sorting test, the patient must sort 60 cards based on color, or symbol or number of symbols. By changing the rules once the patient has developed a pattern set, it is possible to also determine how readily set can be changed. Failure to change set is termed

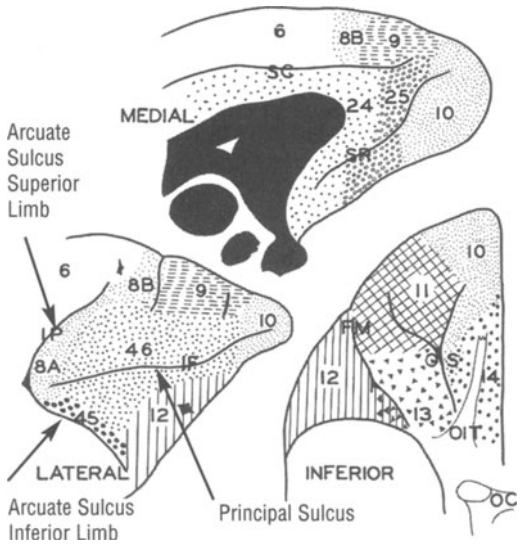


Fig. 18-20 Prefrontal areas of the Monkey (Macaca Mulatta). Note location of orbital areas 13 and 14, anterior cingulate area 28, in addition to motor prefrontal areas 9, 10, 11, 12. Modified from Walker, E.A.: J.Comp.Neurol. 73:81, 1940 (Wiley).

rigidity.

Fletcher & Henson (2001) have summarized PET scan and functional MRI studies, which suggest a role for lateral prefrontal areas both in working memory and long-term memory. Activation of the ventrolateral region (inferior to the inferior frontal sulcus) has been correlated with the updating and maintenance of information. Activation of the dorsolateral region (dorsal to the inferior frontal sulcus) has been correlated with the selection /manipulation /monitoring of that information. Activation of the anterior prefrontal cortex (anterior to a line drawn vertically from the anterior edge of the inferior frontal sulcus) has been correlated with the selection of processes/sub goals.

DISORDERS OF MOTOR DEVELOPMENT.

Non-progressive disorders of motor function or control recognized at birth or shortly after birth are referred to as cerebral palsy. Little, in 1862, first described "spastic rigidity". He was describing the most common form of cerebral palsy: spastic diplegia: severe bilateral spastic involvement of the lower extremities or a double hemiplegia. Other types of spastic cerebral palsy include: a. quadriplegia, and b. infantile hemiplegia.

In addition to the spastic varieties of cerebral palsy, other types have been identified: a. double athetosis, b. ataxic c. dystonic.

As reviewed by Paneth (1986), cerebral palsy affects at least 1 of 500 school age children. More severely affected patients may die in infancy. Severely affected children may have subnormal intelligence (50%) and seizure disorders (25%).

Little related the motor deficits to the circumstances of birth: premature delivery, breech presentations, or prolonged labor. Often respiration was impaired at birth. Convulsions often occurred in the neonatal period. Little's hypothesis regarding causation has had serious medical and legal implications for the practice of obstetrics.

Sigmund Freud (1897) prior to his investigations into hysteria and the psychoneuroses undertook detailed clinical and neuropathological studies of these developmental motor syndromes. Freud unified the various disorders into a single syndrome, and proposed the classification, which is presented above. He also proposed that the abnormalities of the birth process - noted by little, were in actuality the consequence and not the cause of the perinatal pathology.

The National Collaborative Perinatal Project followed 54,000 pregnancies and the subsequent offspring to age 7. The conclusions of that study (Nelson & Ellenberg 1986) tend to support Freud's hypothesis. Major prenatal malformations such as microcephaly and prenatal rubella infection, were more common in the 189 children with cerebral palsy. Maternal mental retardation, and low birth weight below 2000 grams were also significant predictors of cerebral palsy as was breech presentation but not breech delivery. In contrast, birth asphyxia did not add predictive power in the analysis.

GAIT DISORDERS OF THE ELDERLY.

The older patient is frequently at risk for

progressive disability in two areas of neurological function: (a) motor function: primarily manifested by disturbance of stance and gait, (b) higher cortical functions of cognition and memory manifested by dementia. (The latter problem will be considered in Chapter 30.) These major problems of geriatrics - both alone or in combination directly and indirectly, account for many of the prolonged admissions to acute care hospitals; and constitute the major reason for eventual placement of the elderly patient in chronic care facilities such as nursing homes. The cost impact on the health care system is massive because of the increasing age of the population and because of the frequency of the disorders.

Sudarsky (1990) discusses the several studies that indicate (a) 15% of patients over the age of 60 have some abnormality of gait; (b) 200,000 hip fractures occur annually in the United States - most due to falls by older individuals. (c) Accidental death is the sixth leading cause of death among the elderly - with the majority of these deaths the results of falls; (d) 40-50% of patients in nursing homes have difficulty with walking; (e) surveys of older patients (of average age 78) indicate a considerable fear of falling and insecurity of gait resulting in a self-imposed limitation of activities in 50%. [Tinettei and Speechley (1989) estimate the annual incidence of falls in the community: 25% at age 70 and 35% after age 75. For institutionalized patients fall incidence is 50%.];

Not all falls and not all gait disorders are related solely to neurological disorders. Joint and skeletal disorders may impair gait and result in falls. Age-related changes in vision, hearing, and vestibular function may all impair gait and postural stability.

In terms of the nervous system, changes in the peripheral nervous system - those related to aging and to such disorders as diabetes mellitus, and nutrition may all result in impaired proprioception with resultant changes in balance and gait. The deficits are compounded by concurrent changes in vision, hearing and vestibular dysfunction, (see also Tinetti et al 1988).

It is the frequent central nervous system changes resulting in falls, which concern us here. Sixteen % of these patients have a cervical myelopathy, 10% Parkinson's disease, 20% a frontal gait disorder due to normal pressure hydrocephalus or to multiple strokes or to involvement of white matter (Leukoaraiosis - or Binswanger's disease, Thompson and Marsden, 1987). Cerebellar degeneration occurs in 8%, sensory imbalance in 18% and toxic metabolic in 6%.

An example of a treatable cause: normal pressure hydro-cephalus (NPH) will be found in case history 18-3 and Figures 18-21, 18-22 presented on CD ROM. These patients present with a triad of gait impairment (apraxia or ataxia), urinary incontinence, and dementia. The gait impairment usually predates and is more severe that than the disorder of memory. In normal pressure hydrocephalus, a block is present in the subarachnoid space high over the convexity so that absorption of cerebrospinal fluid (CSF) fails to occur. In such cases, there is no obstruction to CSF flow within the ventricular system or within the CSF cisterns at the base of the brain. Such cases may be secondary (previous head traumatic or subarachnoid hemorrhage with the late effects of blood within the subarachnoid space) or primary, no prior history. The designation of "normal pressure" refers to the measurement of CSF pressure at lumbar puncture in those cases. Classically, removal of 20-30 cc of CSF produces a remarkable improvement. Not all cases of hydrocephalus in the elderly are of the "normal pressure" communicating variety. In some cases, also presenting with a similar gait disorder, there is a long-standing obstructive hydrocephalus, secondary to stenosis of the aqueduct of Sylvius, which was well compensated earlier in life, but has become symptomatic late in life. Rarely, a pineal region tumor or midline cerebellar tumor may produce obstructive hydrocephalus in the elderly. For additional discussion of NPH refer to Adams et al 1965, Fisher 1982.