Destruction of the Pyramidal Tract in the Monkey

The Effects of Bilateral Section of the Cerebral Peduncles*

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It has become increasingly apparent that the “pyramidal tract”§ is not the sole descending neural fiber system concerned with the production of voluntary movement of the skeletal musculature. This idea was brought to our attention 25 years ago by Tower. As a result of excellent studies on the destruction of the pyramidal tract in the monkey, she concluded that, “although traditionally, the pyramidal system has been considered the voluntary motor pathway, this is too sweeping. An impressive capacity for voluntary movement survives pyramidal section.”

At the time this observation attracted relatively little attention, perhaps because of Tower’s previous work on the cat. It is well known that the cerebral cortex in the cat is of far less importance in the neural organization of the muscular activity of that animal than is the case in man, and that the entire cerebral cortex can be removed bilaterally in the cat without materially affecting the animal’s ability to sit, stand, walk or run. Therefore Tower’s finding that destruction of the pyramidal tract in the cat “diminishes initiative and slows initiation and performance, but destroys no recognized element of the animal’s activity,” excited no surprise and relatively little interest.

The findings by Tower that a limited amount of useful muscular activity persists in the monkey after section of the medullary pyramids was apparently similarly regarded as having little relationship to human neurology. Most of Tower’s experiments with the monkey were of short duration and the animals did not exhibit the maximum recovery of which they might have been capable.

This inclination to discount observations made in animals on this point, as being unrelated to human beings, is clearly demonstrated in a letter written in 1947 (several years after Tower’s work) by the late Sir Charles Sherrington, which is quoted by Sir Francis Walshe. We are not given the exact question posed to Sir Charles by Sir Francis, but “speaking of the role of the pyramidal tract, he wrote—you chose a hard question, and one which the bedside is far better placed to solve than is the laboratory. I think the Py. [pyramidal tract] is such a human feature. In cat and dog it is a poor thing, in rabbit it is not easily traceable at all below the middle of the spinal brachial enlargement. In the common small monkey there is more, but not much. Rothmann’s cutting of the pyramids in the dog years ago caused little lasting defect. In Macaque the recovery is surprising, when contrasted with the degree and persistence of the human condition, which is often permanent, is it not?”

Sherrington and Walshe emphasized that the nervous system of man differs from that of any other animal and that facts demonstrated in animals must never be accepted as true for man until they have been proven to be so. Guion and his associates in France and Walker in the United States reported the results of sectioning of the human cerebral peduncle in an effort to abolish ab-
normal involuntary movements. The fact that several of their patients were not paral-
alyzed was initially thought to be due to spar-
ing of that portion of the peduncle contain-
ing the pyramidal tract. Later Bucy de-
liberately sectioned the central portion of the
cerebral peduncle which is known to contain the
pyramidal tract (Bucy and Keplinger 12). Sur-
prisingly such destruction did not pro-
duce the “pyramidal syndrome” but instead
left the patient with useful extremities which
were not spastic. Recently Bucy et al. 19 have
reported an anatomical study of the brain in
that patient who died 2 1/2 years after the pe-
duncle was sectioned. They found that 89%
of the cortico-spinal fibers on that side had
been destroyed. They pointed out that all of
the corticospinal fibers of precentral origin
appeared to have been destroyed and that the
remaining 17% of the fibers in the medullary
pyramid were probably cortico-
spinal fibers of parietal origin. So far as is
known, this is the only proven case of an al-
most complete and relatively selective de-
struction of the cortico-spinal pathways in
man. Although we, and others, 25-27,30,36,39,60,
87-89,92 have performed similar operations on
other human beings, the opportunity for de-
tailed examination and anatomical investi-
gation in human cases is very limited. It was
for this reason that this study in monkeys was
undertaken.

Recently Maspes and Pagni 26 have re-
ported 13 human pedunculotomies; each of
these patients regained some control of vol-
untary movement. In 3 of their cases the re-
cover of control of movement nearly
reached the preoperative level and in an-
other recovery was almost complete with
unimpaired motility of the fingers. These
authors made another valuable observation
which provides further evidence for the exis-
tence of ipsilateral innervation of the extremi-
ties from the cerebral hemispheres in man. In
2 of their 3 cases with two-stage bilateral
pedunculotomies there was a further impair-
ment of voluntary motion in the ipsilateral
extremities following the second peduncu-
lotomy. Unfortunately, as these authors have
noted, evaluation of their observation is
rendered difficult by 2 factors. First, all of
their patients were severely incapacitated
prior to operation. Second, no neuroana-
tomical studies were possible in any of their
cases.

Nehil 85 reported that following the stereo-
tactic destruction of the human pyramidal
tract in the internal capsule there was no
paralysis or at most only a very discrete
deficit.

Many workers in this field have found it
difficult to discard the classical teaching that
in man the pyramidal tract is the only neural
pathway from the cerebral cortex to the
spinal cord which is responsible for the pro-
duction of voluntary motor activity of the
skeletal musculature, and that destruction of
this tract results in the “pyramidal syn-
drome” of spastic paralysis with absence of
the abdominal reflexes, hyperactive tendon
reflexes and the appearance of Babinski’s
sign. Outstanding among these “classicists”
has been Sir Francis Walshe. 91 More recently
Brion and Guiot 4 have expressed the belief
that in the human case mentioned above we
did not divide the pyramidal tract but had
probably placed our surgical lesion so far
medially that the pyramidal tract was
spared. However, the study of the brain of
this patient 18 leaves no doubt that their as-
sumptions were in error and that the pyra-
midal tract was divided.

We recognize the limitations of related
animal experiments. However, the organiza-
tion of the neural mechanism controlling the
skeletal musculature in monkeys is much
closer to that in man than Sherrington
realized. The entire cerebral cortex of both cere-
bral hemispheres can be removed in the cat
without producing any very serious distur-
bance of activity of the skeletal musculature.
This is far from true for monkeys or man.
Removal of all of the cerebral cortex in
monkeys (Travis and Woolsey 86) results in
a very severe motor deficiency. Even cortical
extirpations limited to the precentral motor
cortex bilaterally produce profound paralysis
from which only minimal recovery is
possible.

The pyramidal tract is far more important
in man and monkey than in the rabbit, cat
and dog. In primates it arises from the cen-
tral cortex, particularly the precentral cor-
text, terminates in large measure on the an-
terior horn cells of the spinal cord and ap-
parently has motor functions. The obvious
conclusion from this greater importance of the precentral motor cortex in the neural control of the skeletal musculature in man and in monkey is that this control is exercised over the pyramidal tract. However this conclusion is erroneous. Our observations in man left little doubt that even though the pyramidal tract was destroyed, much very useful control of the skeletal musculature remained. The one patient on whom we subsequently performed a detailed autopsy study was able to walk well, hop on the affected leg alone, and move individual fingers and toes freely. The affected extremities were not quite as strong or as well controlled as the normal ones but the deficiency was not great. It is obvious that some pathway or pathways other than the pyramidal tract descend from the cerebrum and are responsible for the useful coordinated movements that remain after the cortico-spinal tract has been destroyed.

The experiments reported in this study were undertaken to determine the extent, severity and character of the paralysis resulting from the destruction of the pyramidal tract in one or both cerebral peduncles in the monkey, and the degree and rate of recovery following such a procedure. A complete section of the peduncle was attempted in order to insure complete destruction of all cortico-spinal fibers. We recognized that a complete section of the cerebral peduncle would destroy fibers other than the pyramidal tract, such as the cortico-pontine and cortico-bulbar fibers. Thus the deficit produced by complete section of the cerebral peduncle may well be considerably greater than that which would result from isolated destruction of the pyramidal tract; moreover, any subsequent recovery would be proportionately less.

Our experiments therefore were designed to answer the following questions. 1. Was the impressive useful movement which persisted in our human case attributable to the 17 per cent of cortico-spinal fibers which remained intact? 2. Were the observations in that case unusual or in some way related to the fact that the patient was suffering from a hemiballismus? 3. Can the facts observed in man be confirmed in the monkey? 4. Were the movements present following the destruction of the pyramidal tract in the cerebral peduncle produced by other unsectioned fibers in the cerebral peduncle? Were they produced by fibers in the opposite intact cerebral peduncle? Or were descending fibers outside the cerebral peduncle responsible?

Anatomical Consideration

The literature on the anatomy of the cortico-spinal tract was reviewed by Nathan and Smith in 1955.

In the monkey, as in man, the cerebral peduncles are relatively isolated, prominent structures at the base of the brain. Proximally, they merge into the base of the diencephalon where they receive the converging fibers of the respective internal capsules. Distally, their fibers continue in separate small bundles which pierce the transverse fibers of the pons. Each cerebral peduncle consists of bundles of descending tracts arranged topographically, although with some overlap (Fig. 1). The substantia nigra lies immediately dorsal to the peduncle, and may be damaged whenever extensive lesions of the peduncle are made. The posterior cerebral and superior cerebellar arteries cross transversely on the ventral surface of the peduncle and the 3rd cranial nerve emerges along its medial border. These are important landmarks in the surgical approach to the peduncle.

In transverse section each peduncle is crescent-shaped and is clearly demarcated from the substantia nigra. Many studies have been made in order to define the connections and functions of the peduncle, most of them based on patterns of degeneration following various lesions of the cerebrum. As Tower demonstrated, all the fibers in the medullary pyramid are descending. Although studies by Brodal et al. seemed to controvert this idea, Landau subsequently disproved any possibility of ascending fibers within the pyramid. Hoche, Sand, von Monakow and Quense also studied the degeneration patterns in the cerebral peduncle following lesions in the cerebrum.

In 1901, Dejerine published an anatomical description of the cerebral peduncle in man, based on studies of degeneration in 53 brains damaged by disease. He believed the lateral fifth of the cerebral peduncle to be oc-
ocupied by temporo-pontine tracts and the medial fifth by fronto-pontine and cortico-bulbar tracts. He also subdivided the fibers within the middle three-fifths; going from medial to lateral were those fibers for the face, pharynx and larynx, upper extremity and lower extremity respectively. Von Monakow concluded that the cortico-spinal tract occupied the middle third of the peduncle. Turck’s bundle, located in the lateral one-fifth or one-fourth, was assigned to fibers from the temporal cortex by Dejerine, but subsequently was thought to arise in the parietal lobe by Mettler, Rundles and Papez, Peele and Bucy and Klüver. Marin et al. from a study of human material concluded that the lateral segment of the cerebral peduncle is composed of cortico-pontine fibers from the parietal, occipital and temporal lobes. Their evidence as to occipito-pontine fibers is not conclusive and that dealing with a temporo-pontine component indicates only a very few such fibers. In fact in 1 of their 2 cases of isolated lesions of the temporal lobe there was no evidence of degenerating fibers in the peduncle, whereas in those cases in which the parietal cortex was also involved the degeneration in the lateral segment of the peduncle was intense.

In the monkey, Barnard and Woolsey found that fibers from somatic sensory areas I and II of the parietal cortex constitute the most lateral portion of the cortico-spinal fibers at a point where they are mixed with and flanked by more lateral cortico-pontine fibers. They also noted that although the descending fibers have a topographic arrangement, there is overlap.

In the monkey Levin surgically ablated various areas of the frontal cortex and studied the pattern of degenerated fibers descending through the cerebral peduncle (Fig. 2). He concluded that, having passed through the internal capsule, the mass of fibers from the precentral cortex gives off a moderately large number of fibers to the diencephalon. The remaining fibers course through the peduncle where they constitute its larger part, occupying the area from the medial border to the lateral one-fourth. The following groups were defined: 1. fibers arising from the prefrontal areas; 2. a small bundle of fibers arising from area 8; 3. large bundles from areas 6, 4S and 4 respectively

Fig. 1. Schematic diagram of the topographical arrangement of descending fibers in the cerebral peduncle.
Fig. 2. Fibers in the cerebral peduncle arising from the frontal cortex. The cortical lesions are shown in black above. The degenerated fibers in the cerebral peduncle which result from such a lesion are shown in the stippled areas below. The medial part of the peduncle lies to the right (modified after Levin).

(Fig. 2). Minckler et al.\textsuperscript{52} found that in man fibers originating from area 6 reach the second quarter of the cerebral peduncle from the midline. Beck\textsuperscript{4} in her studies of human brains following prefrontal leukotomy found the prefronto-pontine tract in the medial sixth of the cerebral peduncle.

The cortico-spinal tract or so-called "pyramidal bundle of Turck and Flechsig" is not a unified one.\textsuperscript{9,10,28,46} It is important in motor control but not essential to the useful activity of skeletal muscles.\textsuperscript{13} It has a diverse origin from the central cerebral cortex. Las-sek\textsuperscript{46-48} believed that 30–40 per cent of the pyramidal tract arises from the precentral gyrus and only 3–4 per cent from the giant cells of Betz. Levin and Bradford\textsuperscript{41} found that 20 per cent of the cortico-spinal fibers arise from the parietal cortex. Recently in a more exact study in the monkey, Russell and DeMyer\textsuperscript{55} showed that 40 per cent of the cortico-spinal fibers arise in the parietal lobe (Brodmann's area 3, 1, 2, 5 and 7); 31 per cent in area 4 and the remaining 29 per cent in area 6. In other words 60 per cent of the corticospinal fibers have a precentral origin and 40 per cent have a postcentral one. Descending through the brain stem, some of the fibers from the cerebral cortex diverge from the main course of the cortico-spinal tract to terminate in the pontine or cranial nerve nuclei, the cerebellum, and the reticular formation of the brain stem. Kuypers\textsuperscript{47,43} in studies of cortical projection in the monkey found that following lesions in the lower one third of areas 4 and 6, degenerating fibers passed to the lateral parts of the pontine and medullary tegmentum.

Furthermore, Kuypers found that the cortical projection from the postcentral gyrus terminated on cells of the spinal trigeminal complex and on cells in the posterior horns of the spinal cord; and that the cortical projections from the postcentral gyrus and some from the middle and upper third of the precentral gyrus passed through the medial lemniscus to terminate in the nuclei cuneatus and gracilis. These cortical projections to sensory nuclei also were noted in the cat by Walberg\textsuperscript{56} and Chambers and Liu.\textsuperscript{16} Swank\textsuperscript{18,79} describes both in man and in the cat a bundle which takes off from the cortico-spinal tract at the level of 12th cranial nerve. This bundle splits into 2 fascicles, one of which continues into the spinal cord, the other encircles the caudal end of the inferior olive and courses upward to enter the restiform body. The termination of these fibers is not yet known, but Marburg\textsuperscript{53} was of the opinion that they end at the ponto-bulbar body while Hajós\textsuperscript{49} concluded that they end in the cerebellum.

Having passed through the medullary pyramid the cortico-spinal tract splits at the lower end of the pyramid by partial decussation. It is believed that commonly about 75 per cent of the fibers decussate while 25 per cent remain uncrossed. The crossed fibers descend in the lateral column of the spinal cord, together with some 10 per cent of the uncrossed fibers, forming the lateral corticospinal tract. Fifteen per cent of all the pyra-
midal fibers which do not decussate in the medulla oblongata descend in the anterior column of the spinal cord as the ventral cortico-spinal tract which often is found as low as the thoracic spinal cord (Hoff and Hoff, \textsuperscript{34} Fulton and Sheehan\textsuperscript{22}).

Hoff\textsuperscript{34} and Hoff and Hoff\textsuperscript{34} found in the cat and the monkey that the cortico-spinal fibers end on cells in the basal region of the posterior horn and intermediate zone of the gray matter. They also found a few fibers ending directly on the cells of the anterior gray column. The terminations of the cortico-spinal fibers in cats differ considerably from those in primates. In the cat, Chambers and Liu\textsuperscript{17} and Kuypers\textsuperscript{41} found that cortico-spinal fibers end only on cells in the basal region of the posterior horn and intermediate zone of the gray matter of the spinal cord. In the monkey Chambers and Liu\textsuperscript{17} and Kuypers\textsuperscript{41, 42} found similar terminations on the cells of the posterior horn and intermediate zone. In addition Kuypers noted that the cortico-spinal fibers are distributed to the anterior horn cells directly. In the monkey, Kuypers has also shown that it is the descending fibers arising in the postcentral area which terminate predominantly on sensory nuclei such as the posterior horn cells of the spinal cord, the spinal root of the 5th cranial nerve and the nuclei cuneatus and gracilis. These last nuclei also receive fibers from the arm and leg areas of the precentral cortex.

Since there are few connections of the cortico-spinal tract to the motor neurons of the anterior horn of the spinal cord of the cat\textsuperscript{17, 41, 56} but many such connections in the monkey,\textsuperscript{42} it has been hypothesized that the increased direct termination of the cortico-spinal tract on the anterior horn cells in primates may be significant in the production of skilled voluntary movements in these higher animal forms.\textsuperscript{56}

In summary, on the basis of present evidence the cerebral peduncle is composed of the following descending fiber systems (Fig. 1).

1. Medial fourth or fifth:
   a. Fibers from the frontal cortex anterior to the precentral motor area. The termination and function of these fibers is poorly understood.
   b. Fibers from the precentral motor cortex (areas 4 & 6 of Brodmann) to the pons and cerebellum. All impulses conveyed over these fibers are destined for the cerebellum and are concerned with the coordination of skeletal muscular activity.
   c. Fibers from the precentral cortex to the tegmentum of the brain stem. These fibers serve a variety of functions including control of the motor nuclei of cranial nerves and regulation of muscular tone and of visceral and vascular functions through terminal synapses in the reticular formation.

2. Central half:
   This area contains cortico-spinal fibers from the precentral motor cortex, subdivided so that those for the upper extremity lie medially, just lateral to the cortico-bulbar fibers concerned with the cranial nerves. Lateral to these fibers concerned with the arm lie the cortico-spinal fibers to the trunk and then, still further laterally, to the lower extremity. This classical pyramidal tract of precentro-spinal fibers constitutes approximately 60 per cent of the fibers passing downward through the medullary pyramids. These fibers are predominantly concerned with the control of the skeletal musculature via the anterior horn cells.

3. Lateral fourth:
   This segment is composed predominantly of fibers from the parietal cortex. They can be subdivided into parieto-spinal and parieto-bulbar fibers. As Kuypers has shown, the parieto-bulbar fibers go in considerable number to nuclei gracilis and cuneatus and to the sensory nuclei of the fifth cranial nerve. The cortico-spinal fibers of parietal origin form approximately 40 per cent of the medullary pyramid\textsuperscript{73} and thus are part of the "pyramidal tract." Kuypers has shown that many of these pass to the cells of the posterior horn of the spinal cord. It is reasonable to assume that these descending parieto-bulbar and parieto-spinal fibers to sensory nuclei are concerned with the regulation of sensory threshold. Ex-
perimental evidence in support of this assumption has been obtained by Jabbur and Towe\textsuperscript{46,49} in the cat and we are informed that they have obtained similar, but as yet unpublished, evidence in the monkey. Whether some of the cortico-spinal fibers of parietal origin are also concerned directly with the production of movement of skeletal musculature, as Travis and Woolsey\textsuperscript{44} suspect, is not yet established.

4. The existence of any fibers of temporal origin in the cerebral peduncle in primates has been seriously questioned.\textsuperscript{14} If they exist they are few in number and occupy the most lateral extremity of the peduncle.

Physiological Considerations

Studies on the destruction of the pyramidal tract in animals made prior to 1936 have been well summarized by Marshall.\textsuperscript{56} Of these a few warrant special comment. Rothmann,\textsuperscript{79} one of the first (1901) to investigate this subject did most of his work on the dog, with only a few observations on the monkey. He chose to attack the pyramidal tract by the imprecise and incomplete method of sectioning its decussation, and he had no adequate anatomical controls. Nevertheless his observations that such lesions cause little motor deficit in monkeys and that even the finest finger movements returned after a few days are of historical interest. In 1910 Schäfer\textsuperscript{75} reported his attempts to destroy the pyramidal tract in the medulla oblongata and in the spinal cord. The resulting loss of motor function was far from complete. Unfortunately his experiments were poorly executed and the anatomical controls, made with the Marchi technique, were inadequate for demonstrating the completeness of the degeneration.

The most complete study on the results of destruction of the pyramidal tract in the monkey which has been made prior to the present study was that of Tower.\textsuperscript{52,58} She demonstrated that section of the medullary pyramid in the monkey results in a flaccid paresis without hyperactive reflexes. Her animals recovered a limited amount of useful movement. Six of her 7 monkeys with bilateral section died before the many months required for optimal recovery. The 1 monkey which survived was observed for only 1 month before a cortical ablation was performed. In those animals which were followed there was no spasticity with either unilateral or bilateral sections. She also found that following bilateral sections of the medullary pyramids, 2 animals, 1 adult and 1 infant, resumed spontaneous voluntary activity on the 10th post-operative day; they were also able to right themselves and to sit as did the animals with unilateral section. She found the muscular tone deficient in all the skeletal musculature including that of the trunk and neck which was preserved following unilateral section. However these animals preferred to take food directly from the food pan with the mouth like a cat or dog. We have found that recovery of the ability to grasp an object and to use the digits individually and precisely requires many months.

The cerebral peduncle is one of the few places, other than the medullary pyramids, where the cortico-spinal fibers can be attacked directly and with relatively little involvement of other fiber systems. Economo and Karplus\textsuperscript{81} described the ability of the pedunculotomized monkeys to carry food to their mouth 5 days postoperatively. Their animals were able to walk, run and to hang with either hand, all within 5 days of the operation. In the light of our observations we doubt that the cerebral peduncle was completely sectioned on either side. In 1944, Cannon \textit{et al.}\textsuperscript{18} found that after sectioning one cerebral peduncle the monkey’s opposite extremities were hypotonic, but the tendon reflexes were hyperactive. In these animals the destruction of the peduncle was almost complete, and the corticospinal tract which occupied the middle portions was severed, leaving only the most medial part of the cerebral peduncle intact. In some of their lesions, there was an involvement of the substantia nigra and other structures of the mesencephalon. They stated that the paralysis produced by a unilateral section of a cerebral peduncle was intermediate between spastic paralysis (like that following an appropriate cortical ablation) and flaccid paresis (like that following pyramidal section as in the case of Tower\textsuperscript{82}). In their studies following observation for a
few months to a year the animals could walk and run but were unable to use the affected hand to pick up food. In most instances the time of survival in their cases was probably not long enough to allow maximal recovery. Also the extent of degeneration of the descending cortico-spinal tract was not reported.

Walker and Richter have reported their observations on 5 monkeys with section of the left cerebral peduncle (3 partial and 2 complete). The 2 groups of animals differed mainly in the degree of the paresis produced. Their 2 animals with complete section appear to have had more paralysis than our animals with complete destruction of the pyramidal tract for although they could stand, walk and run and eventually bring the right hand awkwardly to the mouth there is said to have been a lack of spontaneous movement of the affected limb. It is likely that the failure of their animals to make a greater recovery after unilateral pedunculotomy is related to the very fact that the operation was unilateral. We repeatedly found that, following the second pedunculotomy, use of the originally paralyzed extremities soon improved, and often remained the better side. We agree with them that a section of all the fibers of the cerebral peduncle produces a severe motor deficit but point out that such a lesion includes far more than just the corticospinal fibers. Their speculation that the recovery which takes place following the destruction of the corticospinal tract is probably dependent upon a readjustment of the anterior horn cells to the more limited afferent impulses which now play upon them is in accord with our ideas. As they suggest whether this readjustment is entirely at the spinal level or whether new circuits to these cells develop, has not yet been determined. It seems probable that old existing circuits involving cerebral cortex, subcortical centers, brain stem and spinal cord become able to function in the absence of the pyramidal tract.

Several surgeons have divided the human cerebral peduncle in an attempt to abolish involuntary movement. These operations in many cases have caused only slight weakness and little change in tone or in deep reflexes, but have produced Babinski’s sign on the opposite side. The lesions made by these surgeons were in different portions of the peduncle, and none was complete. None of these reports, except that of Bucy et al. includes an anatomical study.

Materials and Methods

Nineteen adult monkeys (18 Rhesus, 1 rat-tail) and 1 infant Rhesus, the off-spring of one of our pedunculotomized monkeys, were studied. The initial operation performed was a unilateral section of the cerebral peduncle. In most animals the lesion was made bilateral at a second operation. Two animals (No. 2 and No. 4) underwent hemidecortication prior to contralateral section of the cerebral peduncle. In one animal (No. 12) a partial section of the dorsal part of the midbrain was made following recovery from bilateral section of the cerebral peduncles. Twelve animals reached a stage satisfactory for study. The time of survival ranged from 5 months to 22 months after the last operation except 1 (No. 14) which died 13 days after the second operation. After having reached maximal recovery, 8 monkeys were subjected to tests with various devices for the study of muscular strength, speed and precision.

Surgical procedure. All operations were carried out under general anesthesia induced with pentobarbital sodium given either intraperitoneally or intravenously. A standard 30 per cent solution of urea (1.5 mg. per Kg. of body weight) given intravenously was employed in most of our cases. This was given just prior to the operation to provide the adequate exposure so essential in making an exact lesion in the peduncle. There was no need to insert a catheter or to manipulate the urinary bladder; the animals were able to urinate spontaneously. Operations were accomplished under careful aseptic technique and penicillin was given for a few days following the procedure. None of our monkeys had infections postoperatively.

Usually the monkey was placed in a lateral position with the head slightly lower than the trunk. A vertical incision was used, beginning at the posterior end of the zygomatic arch and extending 2 cm. toward the vertex. The temporal muscle was split verticdly and retracted. A burr-hole was made in the squamous portion of the temporal bone and enlarged as needed. Usually the brain fell away from the base of the skull when the dura mater was opened. As much cerebrospinal fluid as possible was removed to provide a better exposure. In general, the cerebral peduncle was adequately exposed and the surrounding structures were easily identified. On some occasions a 60 cycle sine wave current of 2 to 4 volts was used to produce movements of the opposite extremities by stimulation of the cerebral peduncle.

The incision in the peduncle was made in an
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avascular area with a hook-knife. The knife was inserted 1–2 mm. deep, according to the size of the animal, and was carried across the peduncle. It was our intent to make a complete section of the peduncle but this was not always accomplished. In order to study the deficit and recovery pattern following simultaneous bilateral pedunculotomy, a "one-stage" bilateral pedunculotomy was performed on 2 animals (No. 51 and 52). Unfortunately these 2 monkeys survived only 24 and 48 hours after the operation. Six monkeys in which Tower's simultaneously sectioned both medullary pyramids also failed to survive long enough to make meaningful observations. As the one stage bilateral section was too drastic, another attempt was made using a 10-day interval between the operations on the 2 sides (animal No. 53). This monkey survived until he was sacrificed 10½ months later but the degree of recovery was less than in most other animals with a longer interval between the 2 operations because of extensive lesions involving other structures in the midbrain.

Methods of Observation. Postoperatively the animals were kept in individual cages. Special care was given to those that were helpless. Often animals were immediately placed in a hammock and turned frequently from side to side. They were bathed as circumstances required. Those that were unable to feed themselves because of difficulty in chewing and swallowing were fed with a gastric tube. In addition, fluids were given intravenously or subcutaneously during the first few postoperative days. When the animals were able to chew and swallow but were still unable to feed themselves adequately they were fed by hand. Manipulation of the paralyzed extremities was performed several times a day in order to prevent stiffness of the joints and to speed recovery. When the animals resumed their ability to walk and feed themselves they were transferred to larger cages with other monkeys. Here they could exercise by walking, climbing the walls of their cages, and jumping on and off the swings.

General observations and neurological examinations were recorded daily during the early postoperative period. Observations were made of posture and of the ability of the animal to right himself, to sit, walk, climb and to pick up food. Also, studies of muscle tone and tendon reflexes were made. Periodically, motion pictures were taken.

When the animals reached maximal recovery, i.e. when their condition became stationary, most of them were tested specifically for strength and speed of motion as well as their ability to perform fine movements, our purpose being to make a quantitative correlation between the motor deficit and the lesions in the cerebral peduncles.

The devices used in these tests included a food-board with a specific number of small food pellets, a varying speed rotating turntable, locked boxes, and an adjustablely weighted drawer. The monkeys having reached maximal recovery, were gradually trained to use the apparatus until they were able to perform to the best of their ability. Not all of the monkeys could be trained to use all of this equipment. Examinations were carried out before and following sections of the second peduncle. On some occasions a plaster cast was applied to one arm to facilitate assessment of ability of the opposite side.

At death, the brains and spinal cords were perfused with 10 per cent formalin and later imbedded in celloidin. Serial sections 20μ thick were made of the mesencephalon, the pre- and post-central cortices, medullary pyramids and spinal cord. Nissl's technique for neurons, Weil's technique for myelin and Klüver and Barrera's stains were employed routinely. In some cases De Myer's or Hirano's technique was used for study of the axons.

Results

In most instances, section of the cerebral peduncles was performed in 2 stages with a relatively long interval (several months to over a year) between the 2 operations. Except for the 2 monkeys with simultaneous bilateral pedunculotomies, and the 1 with only a 10 day interval between the 2 operations, these animals all rapidly regained control of their skeletal muscles and were able to care for themselves long before they were sacrificed. None of the animals had any disturbance of the function of the urinary bladder.

Of 20 animals, only 12 were suitable for study. They survived for a period of 11 months to 32½ months after the first operation and 5 months to 22 months after the last operation, except No. 19 which survived only 13 days after the second operation. All of these had reached maximal recovery following section of one or both cerebral peduncles. Although section of the second peduncle sometimes produced an immediately helpless quadriparetic animal, other animals used the previously paretic extremities as soon as they recovered from anesthesia following the second section. In fact, in most instances section of the second peduncle was followed ultimately by increased skill in the extremities which had been disabled following the first pedunculotomy. It seemed that when such an animal was deprived of his normal
side he began to use the extremities which had been handicapped earlier much more effectively.

In order to present a clear picture of the effects of peduncle section, we shall discuss in general the deficit following section of the first and second peduncle. Tables 1 and 2 show the results for each animal in our series. In the 12 monkeys, 23 peduncles were sectioned. Summaries of all individual observations will be presented in the reprints of this report.

**Paralysis.** In 20 out of 23 cerebral peduncles sectioned, there was immediate complete or nearly complete faciial paralysis of the contralateral extremities. Following the other 3 pedunculotomies there was only marked paresis of the contralateral extremities. In those instances in which nearly complete paralysis was produced, the slight persisting motion was at the proximal joints; there was complete loss of movement at the distal joints. In 2 instances paralysis in the arm was complete, but there was still slight motion in the legs. Facial weakness, varying in degree from slight to marked, was observed following section of 4 cerebral peduncles. This, however, disappeared in a few days to several weeks in all cases.

**Muscle tone.** Studies of muscular tone revealed that complete flaccidity was produced in 19 of the 23 instances. The postoperative flaccidity was obvious immediately. There was definite sagging of the shoulder and the arm hung motionless; there was slight internal rotation of the upper arm and pronation of the forearm. The wrist was in a more or less neutral position but the fingers were extended at the metacarpophalangeal and interphalangeal joints. When the animals

<table>
<thead>
<tr>
<th>Animal No.</th>
<th>Date of Operation</th>
<th>Operation</th>
<th>Immediate Contralateral Paralysis</th>
<th>Difficulty Swallowing</th>
<th>Time Required for Maximal Recovery</th>
<th>Survival Time After Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Extremities</td>
<td>Facial</td>
<td>Walking, Climbing, Picking up Food</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11-25-60</td>
<td>Left pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>2 months</td>
<td>104 months</td>
</tr>
<tr>
<td>1</td>
<td>1-16-61</td>
<td>Right pedunculotomy</td>
<td>Slight weakness</td>
<td>None</td>
<td>2 months</td>
<td>16 months</td>
</tr>
<tr>
<td>1</td>
<td>9-15-61</td>
<td>Right pedunculotomy (re-operated)</td>
<td>Almost complete</td>
<td>None</td>
<td>5 months</td>
<td>16 months</td>
</tr>
<tr>
<td>2</td>
<td>8-11-60</td>
<td>Left hemidecorticectomy</td>
<td>Complete</td>
<td>None</td>
<td>approx. 6 months</td>
<td>204 months</td>
</tr>
<tr>
<td></td>
<td>11-20-60</td>
<td>Right pedunculotomy</td>
<td>Marked paresis</td>
<td>None</td>
<td>2 months</td>
<td>5 months</td>
</tr>
<tr>
<td>12</td>
<td>3-27-61</td>
<td>Right pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>2 months</td>
<td>7 months</td>
</tr>
<tr>
<td>12</td>
<td>6-30-61</td>
<td>Left pedunculotomy</td>
<td>Complete</td>
<td>None</td>
<td>3 months</td>
<td>5 months</td>
</tr>
<tr>
<td>12</td>
<td>4-3-66</td>
<td>Left partial section of midbrain</td>
<td>Marked paresis</td>
<td>None</td>
<td>3 months</td>
<td>5 months</td>
</tr>
<tr>
<td>13</td>
<td>4-5-61</td>
<td>Right pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>2 months</td>
<td>70 months</td>
</tr>
<tr>
<td>13</td>
<td>2-20-62</td>
<td>Left pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>10 months</td>
<td>14 months</td>
</tr>
<tr>
<td>14</td>
<td>5-29-61</td>
<td>Right pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>2 months</td>
<td>3 months</td>
</tr>
<tr>
<td>14</td>
<td>9-40-62</td>
<td>Left pedunculotomy</td>
<td>Complete</td>
<td>None</td>
<td>8 months</td>
<td>14 months</td>
</tr>
<tr>
<td>19</td>
<td>7-10-61</td>
<td>Right pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>2 months</td>
<td>8 months</td>
</tr>
<tr>
<td>19</td>
<td>5-9-62</td>
<td>Right pedunculotomy</td>
<td>Complete</td>
<td>None</td>
<td>8 months</td>
<td>3 months</td>
</tr>
<tr>
<td>19</td>
<td>7-20-61</td>
<td>Left pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>14 months</td>
<td>8 months</td>
</tr>
<tr>
<td>22</td>
<td>8-1-61</td>
<td>Right pedunculotomy</td>
<td>Complete</td>
<td>None</td>
<td>3 months</td>
<td>9 months</td>
</tr>
<tr>
<td>22</td>
<td>8-6-62</td>
<td>Left pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>6 months</td>
<td>9 months</td>
</tr>
<tr>
<td>25</td>
<td>8-8-61</td>
<td>Left pedunculotomy</td>
<td>Marked paresis</td>
<td>None</td>
<td>3 months</td>
<td>894 months</td>
</tr>
<tr>
<td>25</td>
<td>8-7-62</td>
<td>Right pedunculotomy</td>
<td>Arm complete</td>
<td>None</td>
<td>5 months</td>
<td>8 months</td>
</tr>
<tr>
<td>25</td>
<td>8-17-61</td>
<td>Left pedunculotomy</td>
<td>Leg almost complete</td>
<td>None</td>
<td>6 months</td>
<td>204 months</td>
</tr>
<tr>
<td>25</td>
<td>9-40-63</td>
<td>Right pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>8 months</td>
<td>14 months</td>
</tr>
<tr>
<td>25</td>
<td>8-5-63</td>
<td>Left pedunculotomy</td>
<td>Almost complete</td>
<td>None</td>
<td>2 months</td>
<td>4 months</td>
</tr>
<tr>
<td>53</td>
<td>5-23-63</td>
<td>Left pedunculotomy</td>
<td>Complete</td>
<td>Marked</td>
<td>6 months</td>
<td>11 months</td>
</tr>
<tr>
<td>53</td>
<td>6-4-63</td>
<td>Right pedunculotomy</td>
<td>Almost complete</td>
<td>Pers.</td>
<td>6 months</td>
<td>104 months</td>
</tr>
</tbody>
</table>

**Table 1**

Clinical results of pedunculotomy
TABLE 2

Correlation of lesions and clinical status at time of maximal recovery

<table>
<thead>
<tr>
<th>Animal</th>
<th>Operation</th>
<th>Lesion in Peduncle</th>
<th>Lesion in Mesencephalic Tegmentum</th>
<th>Degeneration in Medullary Pyramid</th>
<th>Status in Extremities Contralateral to the Surgical Lesion</th>
<th>Tone</th>
<th>Tendon Reflexes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lt. ped.</td>
<td>Lateral ½</td>
<td>None</td>
<td>Complete</td>
<td>Good</td>
<td>Used thumb and fingers</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Rt. ped.</td>
<td>Lateral ½</td>
<td>None</td>
<td>Complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>2</td>
<td>Lt. hemidec.</td>
<td>Middle ½</td>
<td>None</td>
<td>Complete</td>
<td>Fair</td>
<td>Nil</td>
<td>Moderately increased</td>
</tr>
<tr>
<td></td>
<td>Rt. ped.</td>
<td>Middle ½</td>
<td>None</td>
<td>Partial</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>10</td>
<td>Lt. ped.</td>
<td>Lateral ½</td>
<td>None</td>
<td>Marked</td>
<td>Good</td>
<td>Used thumb and fingers</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Lt. ped.</td>
<td>Lateral ½</td>
<td>Ventrolat. portion (mod.)</td>
<td>Almost complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Lt. midbrain section</td>
<td>—</td>
<td>Lateral ½</td>
<td>Ventrolat. portion and tectum (Marked)</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>15</td>
<td>Lt. ped.</td>
<td>Almost complete except most medial fibers</td>
<td>None</td>
<td>Complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Lt. ped.</td>
<td>Almost complete except most medial and most lat. fibers</td>
<td>Ventrolat. portion (mod.)</td>
<td>Complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>16</td>
<td>Lt. ped.</td>
<td>Almost complete except most medial fibers</td>
<td>Lat. portion (mod.)</td>
<td>Complete</td>
<td>Moderate flexor spasm of leg</td>
<td>Used hand as a unit awkwardly</td>
<td>nil</td>
</tr>
<tr>
<td></td>
<td>Lt. ped.</td>
<td>Almost complete except most medial fibers</td>
<td>Ventrolat. portion (mod.)</td>
<td>Almost complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>19</td>
<td>Lt. ped.</td>
<td>Complete</td>
<td>Ventrolat. portion (mod.)</td>
<td>Complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Lt. ped.</td>
<td>Middle ½</td>
<td>Ventrolat. portion (mod.)</td>
<td>Complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>22</td>
<td>Lt. ped.</td>
<td>Lateral ½</td>
<td>None</td>
<td>Almost complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Lt. ped.</td>
<td>Complete</td>
<td>None</td>
<td>Complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>23</td>
<td>Lt. ped.</td>
<td>Lateral ½</td>
<td>None</td>
<td>Almost complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Rt. ped.</td>
<td>Ventral ½ of middle ½</td>
<td>None</td>
<td>Partial</td>
<td>Good</td>
<td>Used hand and fingers slowly</td>
<td>nil</td>
</tr>
<tr>
<td>25</td>
<td>Lt. ped.</td>
<td>Almost complete except most medial fibers</td>
<td>Ventral portion (slight)</td>
<td>Complete</td>
<td>Good</td>
<td>None</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Rt. ped.</td>
<td>Medial ½</td>
<td>None</td>
<td>Almost complete</td>
<td>Good</td>
<td>Used hand and fingers slowly</td>
<td>nil</td>
</tr>
<tr>
<td>45</td>
<td>Lt. ped.</td>
<td>Almost complete except most medial fibers</td>
<td>None</td>
<td>Complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td></td>
<td>Lt. ped.</td>
<td>Lateral ½</td>
<td>None</td>
<td>Almost complete</td>
<td>Good</td>
<td>Used hand as a unit</td>
<td>Not increased</td>
</tr>
<tr>
<td>53</td>
<td>Lt. ped.</td>
<td>Lateral ½</td>
<td>Lateral portion (marked)</td>
<td>Complete</td>
<td>Slow, moderate flexor spasm of leg</td>
<td>Nil</td>
<td>Slightly increased flexor tone in leg</td>
</tr>
<tr>
<td></td>
<td>Rt. ped.</td>
<td>Lateral ½</td>
<td>Lateral and central portion (marked)</td>
<td>Complete</td>
<td>Slow, moderate flexor spasm of leg</td>
<td>Nil</td>
<td>Slightly increased flexor tone in leg</td>
</tr>
</tbody>
</table>
were in sitting position, the leg lay flat on the floor; there was slight external rotation of the hip, extension of the knee, semiflexion of the ankle, and extension of the toes.

In our series hypotonia was more pronounced in the arm than in the leg. Like Tower, we found no change in the tone of the axial musculature. When the animals regained control of the involved extremities, tone gradually increased but at no time did it rise above the normal level except in 2 animals noted below. At the time of maximal recovery, when sitting quietly and relaxed, the animal would present a typical posture that was characterized by slight internal rotation of the upper arm, semiflexion at the elbow, pronation of the forearm and extension of the fingers. There was little resistance to passive manipulation unless the animal was excited and struggling. However, in animals No. 16 and No. 53 (4 pedunculectomies), we observed increased flexor tone in the legs following recovery of strength. This created a handicap for these animals when walking or performing tasks requiring smoothness and dexterity. They usually walked or climbed with their lower extremities partially flexed at hip and knee and when they progressed, they hopped or jumped along.

The tendon reflexes were always absent immediately after the operation. They returned to normal in all but 2 instances. In these 2 instances (both in No. 53) there were varying degrees of hyperreflexia. With unilateral lesions, one can compare the deep reflexes between two sides but with bilateral lesions, the muscular tone had to be compared with that previously observed in that animal, or related to an average.

Observation during recovery. Even those animals completely paralyzed following surgery began to recover motor control almost immediately. There was a tendency to sit still unless forced to move; usually it was 12 to 24 hours before they moved about by themselves. Variations depended upon the degree of paresis and the effect of the anesthetic in the individual animal. In attempting to walk the animal would mainly use the better arm and leg with only a little support from the opposite side; although the paralyzed limbs gave some support they were really dragged along as the animal walked. Some animals were unable to walk by alternation of the extremities; this would force them to hop or run in order to progress.

When the animals had recovered still more strength, the ability to jump was observed. First they would try to jump to the cage wall and later to the swing which was about 3–4 feet above the floor. Characteristically, recovery began in the proximal musculature and progressed to the distal muscles. (This is in contrast to the man reported by Bucy et al.12). The lower extremities usually regained power before the upper extremities. Toes seemed to recover before fingers. In 3 animals there was better recovery in the upper extremities than in the lower. Recovery of the fingers began with coarse movements such as the ability to seize large objects or to climb the walls of the cage; the ability to pick up food came later.

During recovery we also observed that when attempting to pick up food from the foodboard the animal’s motions were sometimes ataxic. Often he misjudged the distance and slammed his hand on the board. Some animals had an intention tremor of the hand. The fully recovered animal in addition to his ability to walk, climb and jump well was able to use the thumb and index finger alone to pick up small seeds accurately and steadily.

A few animals had difficulty chewing or using their tongue. Often, instead of moving backward toward the pharynx, the food would fall from their mouths; the animal would then use his hand to push the food back in again. Difficulties in chewing and swallowing only occurred in animals with severe deficits but when present often lasted till death. Surprisingly enough, the animals had little or no loss of weight. Even before they were able to pick up food with their hands they would take food directly with their mouth like a dog. In some instances they continued to eat in this fashion when very hungry even after they had regained the ability to use their hands.

The time required for maximal recovery varied in different animals. Most required approximately 2–3 months to walk and climb well but a few needed 8–10 months. Recovery of use of the hands for eating usually varied from 3–8 months but in some the re-acquisition of these skilled movements required more than a year. It was our experience that
the animal would not use the affected side to pick up food while he still had a normal hand. After the second peduncle had been sectioned the animal used the better hand, namely that opposite the first pedunculotomy. In a few instances the hand opposite the second pedunculotomy ultimately made the greater recovery.

In one animal (No. 12), after maximal recovery had been achieved following bilateral section of the peduncles, the dorsal part of the left side of the midbrain was sectioned. Prior to this last operation the animal had been able to walk and climb well and used the left thumb and index finger to pick up food accurately; he used the right hand as a unit awkwardly. Following the partial midbrain section this animal developed a transient paralysis of the right extremities. He soon recovered the ability to walk and climb but it was 3 months after the last operation before he was able to use the right hand to pick up food. Final examination indicated that his speed and precision had not been changed following section of the dorsal part of the midbrain.

Having reached maximal recovery in the ability to use their hands, most of these animals were given special tests. Some of the animals could not be tested because of the severity of their disability; others required a longer training period. Still others were unable to perform all the tests provided. Five animals were tested after unilateral pedunculotomy. These animals used their better hand except for 1 animal whose better hand was restrained in a plaster cast. We also tested 3 bilateral pedunculotomies which had not been previously trained or tested with these procedures. Four normal animals were also subjected to these tests as controls.

After the animals were thoroughly trained in these tests and an optimal response seemed to have been attained they were tested for 8 successive days. For the foodboard and weighted drawer test the animal's scores were computed as the average of the last 4 trials. For the turntable the highest speed at which the animal could pick up food with 80 per cent success on 50 consecutive trials in the last 2 successive days was used as the score. For locked boxes the score was the average time recorded during the final 2 days.

Table 3 demonstrates the varying ability of the animals in picking up 12 food pellets from the foodboard. The use of his normal hand by a monkey with unilateral pedunculotomy was equal to that in the entirely normal controls.

Table 4 shows the ability of the animals to

---

**TABLE 3**

*Mean time (in sec.) to retrieve 12 food pellets from foodboard*

<table>
<thead>
<tr>
<th>Normal Animal</th>
<th>Score</th>
<th>Use of Ipsilateral (Normal) Hand After Unilateral Pedunculotomy</th>
<th>Score</th>
<th>Use of Preferred Hand After Bilateral Pedunculotomy</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>13.5</td>
<td>22 (R)*</td>
<td>13.0</td>
<td>22 (L)</td>
<td>26.8</td>
</tr>
<tr>
<td>24</td>
<td>10.6</td>
<td>23 (L)</td>
<td>10.8</td>
<td>23 (L)</td>
<td>17.8</td>
</tr>
<tr>
<td>25</td>
<td>14.9</td>
<td>25 (L)</td>
<td>14.4</td>
<td>25 (L)</td>
<td>35.5</td>
</tr>
<tr>
<td>45</td>
<td>13.6</td>
<td>45 (R)</td>
<td>14.4</td>
<td>45 (R)</td>
<td>43.3</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>11.9</td>
<td>13 (L)</td>
<td>245.9</td>
</tr>
<tr>
<td></td>
<td>Group mean</td>
<td>13.2</td>
<td>Group mean</td>
<td>12.9</td>
<td>Group mean</td>
</tr>
</tbody>
</table>

* R = Right hand, L = Left hand.
† Based on 7 scores and does not include score for right (nonpreferred) hand of No. 23.
Paul C. Bucy, Roongtam Ladpli and Annette Ehrlich

TABLE 4

Maximum turntable speed achieved by monkey

<table>
<thead>
<tr>
<th>Normal Animal</th>
<th>Score</th>
<th>Use of Ipsilateral (Normal) Hand After Unilat. Pedunculotomy Animal</th>
<th>Score</th>
<th>Use of Preferred Hand After Bilateral Pedunculotomy Animal</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>100 rpm</td>
<td>22 (R) 120 rpm</td>
<td>22 (L)</td>
<td>25 rpm</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>85</td>
<td>23 (L) 100</td>
<td>23 (L)</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>120</td>
<td>25 (L) 120</td>
<td>25 (L)</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>120</td>
<td>45 (R) 95</td>
<td>45 (R)</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>19 (R) 115</td>
<td>18 (L)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16 (L)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Group mean</td>
<td>106</td>
<td></td>
<td>Group mean</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Group mean</td>
<td>20*</td>
<td></td>
</tr>
</tbody>
</table>

* Based on 6 scores and does not include score for right (nonpreferred) hand of No. 23.

pick up pellets of food from an adjustable speed turntable. This test was designed to measure the animal's speed in using his hand to retrieve the pellets. The maximum speed of the turntable at which the animal was able to pick up pellets is shown. There is again no significant difference between animals with a unilateral pedunculotomy using the hand ipsilateral to the pedunculotomy and the normal group.

Table 5 shows the ability of the animals to open 3 different kinds of locked boxes. Box "A" could be opened by grasping a projection on a small metal cylinder (bolt lock) and

TABLE 5

Mean time (in sec.) to open three types of locked boxes

<table>
<thead>
<tr>
<th>Normal Animal</th>
<th>Score</th>
<th>Use of Ipsilateral (Normal) Hand After Unilat. Pedunculotomy Animal</th>
<th>Score</th>
<th>Use of Preferred Hand After Bilateral Pedunculotomy Animal</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>1.4</td>
<td>22 (R) 1.3 1.3 1.1</td>
<td>22 (L)</td>
<td>1.8 0.8 1.8</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1.2</td>
<td>23 (L) 1.5 0.6 1.8</td>
<td>23 (L)</td>
<td>0.6 0.6 1.0</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>1.5</td>
<td>25 (L) 0.6 1.0 1.2</td>
<td>25 (L)</td>
<td>1.2 0.7 2.9§</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>0.7</td>
<td>45 (R) 1.0 1.3 1.1</td>
<td>45 (R)</td>
<td>4.6§ 0.9 -§</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>19 (R) 1.1 1.3 1.1</td>
<td>16 (L)</td>
<td>5.0§ 1.8 -‡</td>
<td></td>
</tr>
<tr>
<td>Group means</td>
<td>1.2</td>
<td>Group means 1.1 1.1 1.3</td>
<td>Group means</td>
<td>2.6 1.0 1.9</td>
<td></td>
</tr>
</tbody>
</table>

* Boxes A = Bolt lock, B = Hook lock, C = Lock with handle.
† Based on 5 scores and does not include score for right (nonpreferred) hand of No. 23.
‡ Animals Nos. 45 and 16 could not be tested on Box C.
§ Failed to reach criterion of 2.0 sec. on 2 successive days.
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TABLE 6

Mean weight of drawer pulled

<table>
<thead>
<tr>
<th>Normal</th>
<th>Use of Ipsilateral (Normal) Hand After Unilat. Pedunculotomy</th>
<th>Use of Preferred Hand After Bilateral Pedunculotomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal</td>
<td>Score</td>
<td>Animal</td>
</tr>
<tr>
<td>21</td>
<td>525.0 gm.</td>
<td>22 (R)</td>
</tr>
<tr>
<td>24</td>
<td>602.5</td>
<td>23 (L)</td>
</tr>
<tr>
<td>26</td>
<td>502.5</td>
<td>25 (L)</td>
</tr>
<tr>
<td>27</td>
<td>635.0</td>
<td>45 (R)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19 (R)</td>
</tr>
<tr>
<td>Group mean</td>
<td>581.3</td>
<td>Group mean</td>
</tr>
</tbody>
</table>

* Based on 4 scores and does not include score for right (nonpreferred) hand of No. 23.
† Animals Nos. 22 and 16 were unable to grasp the knob of the drawer following bilateral pedunculotomy and therefore could not be tested.

pushing it to one side, box "B" could be opened by unfastening a hook, and box "C" could be opened by grasping the handle of the lock and pulling it to the side. The time consumed in opening each type of box was measured in seconds between the first manual contact with the lock and the opening of the lid. There was no difference between the unilaterally pedunculotomized animal using the ipsilateral hand and the normal group. In the bilateral pedunculotomy group, only 3 animals (Nos. 25, 45 and 16), required longer time than the normal average with one or more of the boxes. Other monkeys which were tested were able to perform as well as the normal ones.

In pulling the weighted drawer (Table 6), only 4 bilateral pedunculotomized monkeys could be tested. In these 4 animals, one (No. 23) used the right hand as well as he did before the pedunculotomy. The other 3 animals had a considerable deficit in strength of the hand as shown by their ability to pull the weighted drawer. In the normal group all animals could pull the drawer weighted with over 500 gm. The normal animals and those with a unilateral pedunculotomy pulled a wide range of maximum weights.

During the tests animals were also observed for the smoothness of their performance. It was noted that some animals (Nos. 13, 16 and 45) were somewhat clumsy and awkward in using the hand to reach for food and often dropped the food before it reached their mouths. No. 13 often misjudged the distance to the food. Two other animals (No. 22 when forced to use the non-preferred hand and No. 25 when using the preferred hand) revealed some tremor of the hand on reaching for the food.

In most of our animals it was noted that the second pedunculotomy not only resulted in an immediate paralysis of the contralateral extremities but produced a further impairment of function of the ipsilateral ones as well. This is in accord with the observations made by Maspes and Pagni in man, and suggests that the cerebral peduncles contain fibers concerned with the control of the ipsilateral as well as the contralateral extremities.

Summary of physiological results. Section of the cerebral peduncles produced a motor deficit in the contralateral extremities that affected both speed and strength. Clumsiness, awkwardness, tremor and ataxia were noted in some animals. Most of the animals exhibited further impairment of function of the ipsilateral extremities following the second pedunculotomy. The degree of the deficit in both contralateral and ipsilateral extremities varied and this variation appeared to be related to the extent of the lesion in the pedun-
cles, the completeness of the destruction of the pyramidal tracts and the amount of involvement of neighboring parts of the mesencephalon.

Microscopic examination. Although it was our intention to section the cerebral peduncles completely in order to insure complete destruction of the cortico-spinal tracts, the destruction of the peduncles was not complete in every case, nor were the lesions always strictly limited to the peduncles. In most instances the substantia nigra was involved to some degree (Fig. 3). In 9 pedunculotomies (Nos. 12, left side; 13, right side; 16, left side; 18, both sides; 19, right side; 25, left side; 53, both sides), there was some involvement of the adjacent tegmentum of the midbrain. Only 2 peduncles (Nos. 19, right side and 22, left side) were completely sectioned. Seven peduncles were nearly completely sectioned. In these instances only a few fibers in the most medial or most lateral portions were left intact, and the pyramidal tracts were completely destroyed.

Degeneration of pyramids. In 10 other peduncles the sections were not complete but a complete or nearly complete degeneration of the medullary pyramids was produced (Figs. 4 and 5). In this group the lesions involved the lateral 3/4ths to lateral 4ths in 9 peduncles and the medial 3/4ths in one. Most of the remaining fibers in these animals with incomplete section of the cerebral peduncles descended to the pontine nuclei; only a few of them reached the medullary pyramids. In only 3 peduncles were the sections so incomplete that the degeneration of the medullary pyramids was inadequate (Nos. 2, 12 and 23, all on the right side). In one pedunculotomy (No. 19, left side) the pyramid showed no change with Weil's stain for myelin sheaths because the time between the operation on that peduncle and the animal's death was too short (13 days) to allow the degenerated myelin fragments to be removed. In all, following 23 pedunculotomies, 13 pyramids were completely degenerated and 6 pyramids were almost completely degenerated. These 13 completely degenerated pyramids belonged to 9 animals, 4 of which had complete degeneration of both pyramids. All the pyramids which underwent complete or nearly complete degeneration were markedly shrunk-en, the medullary pyramids appearing as

Fig. 3. Animal No. 13. Section through the midbrain, showing nearly complete surgical destruction of both cerebral peduncles. Note some involvement of the ventro-lateral portion of the mesencephalic tegmentum on the right side. Weil's method. (In all figures the left side of the brain is on the left side of the illustration.)
only a thin band on the ventral surface of the medulla. Dense gliosis usually replaced the degenerated fibers.

**Spinal cord degeneration.** Descending degeneration in the lateral columns of the spinal cord could be traced as low as the sacral segments. In those with complete degeneration the lateral columns were also shrunken and gliosis was noted in these areas. There was no decrease in the number of large neurons in the anterior gray columns of the spinal cord. Retrograde degeneration could be followed upward from the level of the pedunculotomy into the lower part of the internal capsule. The cerebral peduncles above the lesions were usually atrophic.

**Betz cells degeneration.** In the precentral cortex, the typical gigantic Betz cells disappeared in all cases which had complete degeneration of the pyramidal tract and in all but one (No. 18) which had nearly complete degeneration. In the pre-central cortex of

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**Fig. 4.** Animal No. 13. Section through the pons, showing degeneration of descending tracts in the basal pontis. On the left side degeneration is complete, while on the right it is nearly so. Weil's method.

**Fig. 5.** Animal No. 13. Section through the medulla oblongata, showing atrophic pyramids with complete degeneration of the cortico-spinal tracts on both sides. Weil's method.
animal No. 18, a very few Betz cells remained. In our series, there was also some loss of other pyramidal cells in the precentral cortex but an accurate count could not be made.

Correlation of anatomical and clinical findings. In a correlation of the anatomical findings with the clinical picture, we found that all but 2 of the 8 animals that had complete degeneration of the medullary pyramids on one or both sides were able to walk, climb and jump well. Six of these animals were also able to use one hand to pick up food and carry it to their mouth, but never tried to use the other hand for this purpose. They were able to use the poor hand as a unit slowly and awkwardly. One animal (No. 1) with complete degeneration of both pyramids could use one hand with thumb and index finger and the other as a unit to pick up food. One (No. 53) was unable to use either hand to pick up food. Two animals, Nos. 16 and 53, had some increased flexor tone especially in the lower extremities which created a semi-spastic gait. In these 2 animals, in addition to the complete degeneration of both medullary pyramids part of the tegmentum of the midbrain was involved. This was more extensive in No. 53.

The animals with almost complete degeneration of the pyramids were able to walk, climb and jump well. All of them except one (No. 25) used their hands as a unit to pick up food and carry food to their mouth. No. 25 was able to use the thumb and index finger slowly but adequately. Usually the animal with partial degeneration of the pyramids could walk, climb and pick up food almost as well as a normal animal. However, on testing for speed and strength, it was noted that the more degeneration there was in the pyramid the greater the deficit in speed and strength. No. 45, with almost complete degeneration of the pyramids was able to pick up food from the turntable rotating at 5 rpm, while No. 13 and 16 with complete degeneration of the pyramids could only pick up food pellets which were lying still. Strength of the hand also was markedly reduced in these cases.

Discussion

The more extensive lesions often involved the substantia nigra to varying degrees. In 9 instances portions of the tegmentum were involved. In these cases the animals had greater motor deficits than those which followed section of the peduncle alone or with the involvement outside of the peduncle limited to the substantia nigra.

Incomplete section. In cases of incomplete section of the peduncle, the intact fibers usually lay in the most medial or in the most lateral portion. The medial fibers are frontal cortical projections to the tegmental and pontine nuclei.\(^1^,5^,16^,69^\) This was confirmed by the fact that in our cases we noted that as those medial intact fibers descend through the pons they diverge from the descending cortico-spinal tract and pass to the pontine nuclei. The most lateral fibers which arise from the parietal cortex and possibly from the temporal cortex also end in the pontine nuclei.\(^1^,4^,37^,68^,72^\) In addition some of the parietal fibers form part of the cortico-spinal tract.\(^2^,73^\) These may be concerned with the control of sensory threshold, or with the production of movement, or both.

Skilled use of hands. Tower reported that, following bilateral section of the medullary pyramids, monkeys did not use either hand to pick up food. However, her animals were not observed long enough to allow maximal recovery of the hand. This is also true of the animals of Camon et al.\(^1^5^\) None of their animals used the hand contralateral to the pedunculotomy.

We found that those animals with complete destruction of the medullary pyramid required a long time to attain maximal recovery, often more than a year. Our experience also suggests that the animals need to be induced to use the affected hands. Recovery can be aided with proper restraints and training.

We now have little doubt that the useful movement which persisted in our human case\(^1^8^\) was not attributable to the 17 per cent of cortico-spinal fibers, probably parietospinal fibers, which remained intact in that case. On the other hand the animals with extensive lesions of the peduncle had a greater disability than those in which the lesion was restricted to the central portion of the peduncle where the destruction was more nearly confined to the pyramidal tract.

Cortico-pontine—cortico-bulbar fibers. The destruction of cortico-pontine and corticobulbar fibers, in addition to destruction of
the cortico-spinal fibers, increased the motor deficit. This increased deficit was notable in 2 ways—the loss of fine, accurate, discrete, well controlled movements of the hand and fingers and the difficulty in chewing and swallowing seen in a number of animals. The disturbance in usefulness of the hand and fingers was seen in the animals’ efforts to pick up food and was shown quantitatively in a series of special tests as shown in Tables 3–6. These studies indicate that the degree of disability was proportionate to the extent of the lesion in the cerebral peduncle and in the overlying mesencephalic tegmentum, and support the belief that the pyramidal tract is important to control of the skeletal musculature but is not essential to extensive and useful voluntary movement. These observations also reinforce our earlier concept that the movements which persist after destruction of the cerebral peduncles and the pyramidal tracts are dependent upon descending fiber pathways in the tegmentum of the midbrain. At the present time the nature and location of these other tracts are unknown. The suggestion of Brodal⁴ and Nyberg-Hansen and Rinvik⁶ that a cortico-rubrospinal pathway may be an important element in the production of the movements which persist after the destruction of the pyramidal tracts is interesting but unsubstantiated at this time.

Ipsilateral control. We have noted that our animals showed a further impairment of function of the ipsilateral extremities following the second pedunculotomy. Maspes and Pagni¹⁵ made a similar observation in man. Bucy and Fulton¹¹ and others have also reported evidence of motor control of the extremities by the ipsilateral cerebral hemisphere. Because of this fact it is probably wrong to refer to the ipsilateral extremities as “normal” following a single pedunculotomy even though our observations did not disclose any deficiency in them.

Hypotonia. We observed spasticity and hyperreflexia in only 2 animals both of whom had received damage to the mesencephalic tegmentum. This observation is in accord with those made previously.¹²,¹³,⁸² On the other hand Cannon et al.¹⁵ found the muscles to be hypotonic following unilateral section of the peduncle but the tendon reflexes were hyperactive. We cannot account for the apparent discrepancy in these observations. In our 2 animals in which tone was increased, the increase was in flexor tone in the legs and the tendon reflexes in the legs of 1 could not be elicited. In these animals apart from the lesions in the peduncles and substantia nigra there was also involvement of other structures in the mesencephalic tegmentum. Cannon et al.¹⁵ state that the fibers responsible for muscular tone probably diverge from the cortico-spinal tract at some point above the lesion in the cerebral peduncle and that those fibers responsible for the tendon reflexes descend through the peduncle. We cannot accept this concept of 2 separate neural mechanisms, 1 for muscular tone and 1 for tendon reflexes. It is now generally recognized that muscular tone, including the tendon reflexes, is under the control of other neural mechanisms in the reticular formation of the brain stem and not under the control of the cortico-spinal fibers. Our findings support this concept.

Facial palsy. One of the striking findings in our animals was that facial paralysis seldom occurred following the section of the peduncle. This is not surprising when one realizes that the cortico-bulbar fibers to the facial nuclei lie medially in the cerebral peduncle and also that of all parts of the body the face receives the most extensive bilateral cerebral innervation. This latter fact also explains why the facial paralysis disappeared so promptly. The only exception to this was animal No. 53 in which the facial weakness persisted for several weeks. This was probably due to the fact that the 2 peduncles were sectioned at a very short interval. In any event the facial musculature recovers from the paralysis sooner than that of the extremities.

Rate of recovery. The time required for recovery of useful movements following the destruction of the pyramidal tract is relatively longer than we had expected and varies in different animals with the extent of the lesion in the cerebral peduncle. It was also apparent that simple stereotyped movements recover faster than the complicated delicate ones. (This is not in accord with our human case¹⁹ in which recovery began in the hand and fingers, foot and toes and progressed as rapidly there as elsewhere.)

Hemidecortication with pedunculotomy. We
also had the opportunity to observe in one animal (No. 2) the motor deficit following the removal of the entire cortex from one cerebral hemisphere and the section of the opposite cerebral peduncle. In this animal although the degeneration in the medullary pyramid ipsilateral to the pedunculotomy was not complete, the effect of hemidecortication could be studied. This animal could use its extremities contralateral to the hemidecortication to walk and climb, and could use the paretic hand to hold a banana and to carry it to its mouth when the food was placed in its hand. However, these movements were slow and awkward. It never used this hand to pick up food from the floor or from the experimenter’s hand. The use of the hand contralateral to the hemidecortication to hold food was present only for the relatively short time that the opposite extremities were paralyzed following the incomplete pedunculotomy and disappeared as soon as the extremities affected by the pedunculotomy had recovered.

It has also been our experience with other hemidecorticate animals that these animals never tried to reach for food with the paretic hand. In general, even though these hemidecorticate animals could walk, climb and run they showed a much greater motor deficit than did animals with unilateral destruction of the pyramidal tract. In contrast with the latter the hemidecorticate animals also exhibited an increase in muscular tone and in the activity of the tendon reflexes. It is our belief that the considerably greater deficit noted after the decortication as compared with that seen after section of the cerebral peduncle is to be attributed to the destruction of other important motor pathways which descend from the cerebral cortex but which are separate from the pyramidal tract and do not pass through the cerebral peduncle. Bucy and Fulton expressed the belief that the limited movement seen following extensive cortical lesions is due to ipsilateral innervation. However, when the opposite peduncle was partially destroyed in this case (Animal No. 2) the animal used the hemidecorticate hand even better. This indicates that the ipsilateral innervation is not restricted to the cortico-spinal system but also descends through the mesencephalic tegmentum.

Movement after destruction of pyramids. Finally we would like to emphasize that our results in those animals with complete degeneration of the medullary pyramid following pedunculotomy confirm our preliminary report that useful movement can be achieved by animals with complete destruction of the so-called “pyramidal tract”. Even animals with extensive section of the cerebral peduncle can walk, climb and run and use one or both hands to pick up food. It is not sufficient to rely upon the usual postoperative care of the animals to insure maximal recovery. Intensive care at almost hourly intervals, turning of the animal, close attention to feeding, adequate fluids, prevention of infection, manipulation of the extremities and care of the skin are very important. Various means must be used to encourage active use of the extremities by the animal itself.

Summary

We have transected the cerebral peduncles in 12 monkeys (22 pedunculotomies), observed the animals postoperatively for many months, and have made a histologic study of the brains and spinal cords when the animals were sacrificed.

The results were as follows:

a. Eight animals had complete or almost complete degeneration of the medullary pyramids.

b. Ten animals could walk, climb, and feed themselves after several months; they had no hyperreflexia or hypertonicity. The other 2 animals had received additional mesencephalic damage at operation.

c. The degree of medullary pyramidal degeneration corresponded to the degree and quality of motor deficit demonstrated in special tests.

d. Most pedunculotomies were bilateral but in 2 unilateral stages. The second pedunculotomy invariably increased the deficit produced by the first; in other words, it affected both sides.

We have compared these results to those in an earlier human case. Our conclusions are as follows:

1. Both monkey and man are capable of useful movement after destruction of
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the pyramidal tract in the cerebral peduncle.
2. The cerebral peduncles contain fibers concerned with ipsilateral as well as contralateral motor activity.
3. The cortico-spinal tract is not the only pathway concerned with control of the skeletal musculature. Some other tract of related function descends from the cortex through the mesencephalic tegmentum.
4. Destruction of the pyramidal tract does not result in the so-called "pyramidal syndrome" of paralysis, spasticity and increased tendon reflexes.

Acknowledgements

We are indebted to Travenol Laboratories Inc. for having generously supplied the urea ("Urevert") used in these experiments.

The success of these experiments is in large measure attributable to the excellent care of the animals, which was given daily by Mr. Charles Loibl, not only immediately after operation but often for weeks and even months.

We are very much indebted to Dr. Asao Hirano of the Montefiore Hospital, New York City, who very kindly impregnated some sections for us.

References


66. Nyberg-Hansen, R., and Rinvik, E. Some com-


