



Antidromic and orthodromic responses evoked in cat cerebral cortex following brainstem stimulation :
contribution of the pyramidal tract and other fiber systems
by Kent Walter Frette

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE
in Zoology
Montana State University
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Abstract:

The physiological properties of two surface-positive potentials, recorded from the sensorimotor area of the cerebral cortex following brainstem stimulation were studied in adult cats. These potentials, designated the a and b potentials, had latencies of 0.3-0.5 msec and 0.9-1.0 msec, respectively, following midbrain stimulation. The a potential is known to result from antidromic activation of corticofugal fibers. The present study was designed to determine if the b potential results from antidromic activation of a more slowly conducting corticofugal fiber group, or whether it results from orthodromic activation of a corticopetal fiber system. Rostral pontine and midbrain stimulating sites were used because the two principle fiber systems under consideration, the pyramidal tract and medial lemniscus, are separated by 4 to 5 millimeters at this level. This separation reduced the problem of volume conduction of the stimulus current and allowed for the more effective study of each fiber system individually.

The a and b potentials of largest amplitude were recorded at separate cortical areas. The largest A potentials were recorded near the lateral tip of the cruciate sulcus, while the b potentials of largest amplitude were recorded near the coronal sulcus. The largest b potentials were evoked when the stimulating electrode was positioned dorsal to the corticospinal tract in the pons and dorsal to the basis pedunculi in the midbrain. The a potential was most readily evoked when the stimulating electrode was in the basis pedunculi. The b potential was suppressed by conditioning stimulation to the contralateral forepaw between conditioning-test intervals of 20 and 200 msec. The a potential was not significantly effected by such conditioning stimulation at any conditioning-test interval. The a potential could follow repetitive stimulus rates in excess of 100/sec, while the b potential was greatly attenuated at comparable frequencies. The a potential showed a greater resistance to asphyxia than the b potential.

The results in this study indicate that the a and b potentials are mediated by different fiber systems. The a potential is most likely antidromically mediated by the pyramidal tract, while the b potential probably results from activation of an afferent fiber system following midbrain stimulation.

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ANTIDROMIC AND ORTHODROMIC RESPONSES EVOKED IN CAT CEREBRAL
CORTEX FOLLOWING BRAINSTEM STIMULATION: CONTRIBUTION
OF THE PYRAMIDAL TRACT AND OTHER FIBER SYSTEMS

by

KENT WALTER FRETTE

A thesis submitted in partial fulfillment
of the requirements for the degree

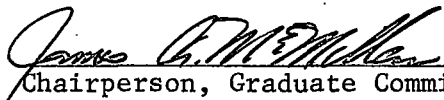
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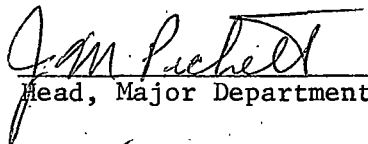
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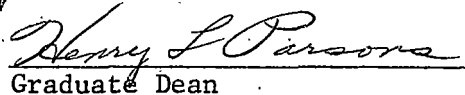
in

Zoology

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Bozeman, Montana

October, 1976

ACKNOWLEDGMENT

To Dr. James A. McMillan, I extend my deepest respect and gratitude for the unfailing guidance and support he has shown me during the past several years, both as a graduate advisor and friend. I would like to thank Drs. Dwight Phillips, Harold Picton, and John Robbins for their advice in the writing of this manuscript. My thanks is also extended to Dr. Ed Moody for consenting to be on my graduate committee.

A very special appreciation is offered to Messers. Terry Schumacher, Mark Neiter, Rick Morgan, and Dan Baker for their invaluable assistance and advice in the laboratory during the course of this program.

To Dr. Patricia Crowle and Diane Stockdill, I express my deep appreciation for their technical advice in the histology required in this study.

I would also like to thank the Billings Animal Shelter for donating the animals necessary for this study.

I offer my appreciation and thanks to Mrs. Della White for typing this manuscript.

A final, heartfelt thanks is extended to Don and Thelma Fulton, whose companionship through my years as a graduate student shall always be remembered.

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ABSTRACT

The physiological properties of two surface-positive potentials, recorded from the sensorimotor area of the cerebral cortex following brainstem stimulation were studied in adult cats. These potentials, designated the *a* and *b* potentials, had latencies of 0.3-0.5 msec and 0.9-1.0 msec, respectively, following midbrain stimulation. The *a* potential is known to result from antidromic activation of corticofugal fibers. The present study was designed to determine if the *b* potential results from antidromic activation of a more slowly conducting corticofugal fiber group, or whether it results from orthodromic activation of a corticopetal fiber system. Rostral pontine and midbrain stimulating sites were used because the two principle fiber systems under consideration, the pyramidal tract and medial lemniscus, are separated by 4 to 5 millimeters at this level. This separation reduced the problem of volume conduction of the stimulus current and allowed for the more effective study of each fiber system individually.

The *a* and *b* potentials of largest amplitude were recorded at separate cortical areas. The largest *a* potentials were recorded near the lateral tip of the cruciate sulcus, while the *b* potentials of largest amplitude were recorded near the coronal sulcus. The largest *b* potentials were evoked when the stimulating electrode was positioned dorsal to the corticospinal tract in the pons and dorsal to the basis pedunculi in the midbrain. The *a* potential was most readily evoked when the stimulating electrode was in the basis pedunculi. The *b* potential was suppressed by conditioning stimulation to the contralateral forepaw between conditioning-test intervals of 20 and 200 msec. The *a* potential was not significantly effected by such conditioning stimulation at any conditioning-test interval. The *a* potential could follow repetitive stimulus rates in excess of 100/sec, while the *b* potential was greatly attenuated at comparable frequencies. The *a* potential showed a greater resistance to asphyxia than the *b* potential.

The results in this study indicate that the *a* and *b* potentials are mediated by different fiber systems. The *a* potential is most likely antidromically mediated by the pyramidal tract, while the *b* potential probably results from activation of an afferent fiber system following midbrain stimulation.

INTRODUCTION

Physiological studies over the past twenty years have attempted to resolve conflicts concerning the organization of the pyramidal tract in terms of fast and slow conducting fiber groups. Some studies have proposed that longer latency potentials result from the antidromic activation of slower conducting pyramidal tract fibers following brainstem stimulation. Other investigations have indicated that such long-latency potentials result from orthodromic activation of afferent fibers adjacent to the pyramidal tract in the brainstem.

In this study, the physiological characteristics of two surface-positive potentials recorded from the cerebral cortex following brainstem stimulation were investigated. These potentials, the *a* and *b* potentials, have latencies of about 0.5 msec and 1.0 msec, respectively, following midbrain stimulation. This study was designed to determine if the *a* and *b* potentials represent the summation of antidromic action potentials mediated by fast and slow conducting pyramidal tract neurons, respectively.

REVIEW OF LITERATURE

General Considerations

The controversy over the functional significance and importance of the group of corticofugal neurons known as the pyramidal tract has existed for over a century. Although the quantitative data accumulated on the pyramidal tract is voluminous, the physiological role of this fiber system still remains speculative.

The pyramidal tract is an anatomical entity, not a physiological one. The term "pyramidal" refers to the passage of the descending axons through the bulbar pyramids in the caudo-ventral medulla. By definition, it comprises "those neurons with descending axons which traverse, longitudinally, the bulbar pyramids" (Patton and Amassian, 1960). Excluded from this definition are the arcuate fibers which transversely cross the ventral surface of the pyramid in route from the arcuate nucleus, which receives corticospinal terminations, to the cerebellum.

At the level of the bulbar pyramids, where the pyramidal tract is anatomically most pure, it is contaminated by functionally dissimilar fiber groups, while fiber groups bearing a closer functional relationship are not present. Inappropriately excluded from this definition are corticofugal fibers which terminate on the cranial motor nuclei. Although these fibers depart from the pyramidal system

at the level of the pons and, therefore, do not traverse the pyramids, they bear a close relationship in terms of motor function to the corticospinal fibers which terminate in the spinal cord nuclei.

Inappropriately included are those corticofugal neurons leaving the pyramids to terminate in the more dorsally located reticular formation. These fibers are potentially part of the "extra-pyramidal" system, since they do not constitute a direct projection system from the cerebral cortex to the spinal cord. These facts indicate the difficulty in obtaining a satisfactory functional definition for the pyramidal tract.

A thorough historical account of the early scientific investigations on the pyramidal tract (PT) is given by Marshall (1936). Turck first described the PT in 1851, dividing it into two fiber components based on the location of the fibers as they descend in the spinal cord. These components were identified as the capsular-lateral-column tract, known contemporarily as the crossed PT, and the capsular-anterior-column tract, which is equivalent to the uncrossed PT. Turck proposed that both of these fiber components originate in the basal ganglia.

Flechsig, in 1876, called the two components described by Turck the 'pyramidal tract', but held to the previous assumption that they originate in the basal ganglia. By use of the myelogenetic method, Flechsig later showed the origins of the PT to be in the cerebral

cortex in the monkey, particularly the precentral gyrus and the paracentral lobule. The pyramidal tract is unique in this respect since it is the only long descending tract to originate in the cerebral cortex; the other major descending tracts take origin in sub-cortical nuclei and the brainstem.

Origin of the Pyramidal Tract

The origin of the pyramidal tract (PT) in the mammalian cerebral cortex has been investigated by a variety of anatomical and electrophysiological techniques which have yielded varying results. As reviewed by Marshall (1936), Campbell in 1905 and Holmes and May in 1909 proposed that the PT originates exclusively from the giant Betz cells of the cytoarchitecturally defined motor area. This conclusion was based upon observations of retrograde chromatolysis in the Betz cells in a variety of mammals, including the monkey, following hemisection of the cervical spinal cord. Postcentral cortical areas were not observed for retrograde reactions. Since Lassek (1941) has shown that only approximately 18,000 Betz cells exist in the cerebral cortex of the monkey in comparison to the presence of about 500,000 fibers in the pyramids, it is apparent that the giant Betz cells account for less than 5% of the PT fibers.

Between 1905 and 1925, several anatomical reports demonstrated PT fibers originating in other cortical areas, principally the premotor

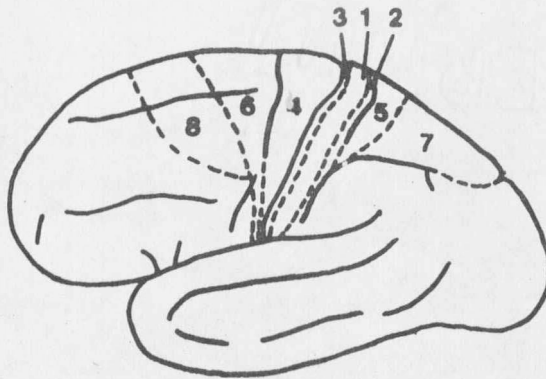
and postcentral areas (Marshall, 1936). Following cervical hemisection in the monkey, Levin and Bradford (1938) traced about 20% of the degenerating PT fibers to areas 3, 1, 2, and 5 of Brodmann; the rest were reported to originate in Brodmann's area 4 (Fig. 1). Using the same technique, Walberg and Brodal (1953) reported pyramidal origins in the temporal and occipital lobes in cats.

The extirpation of selected cortical areas followed by a histological examination of the pyramids for the presence of fiber degeneration is another anatomical technique used to determine the cortical origins of the PT. Barnard and Woolsey (1956) reported that about 60% of the PT fibers in the monkey, take origin anterior to the central sulcus, while 40% originate from more posterior regions, mostly from areas 3, 1, 2, 5, and 7 of Brodmann (Fig. 1). Peele (1942) reported degeneration in the pyramids of monkeys following ablation of Brodmann's areas 3, 1-2, 5, and 7.

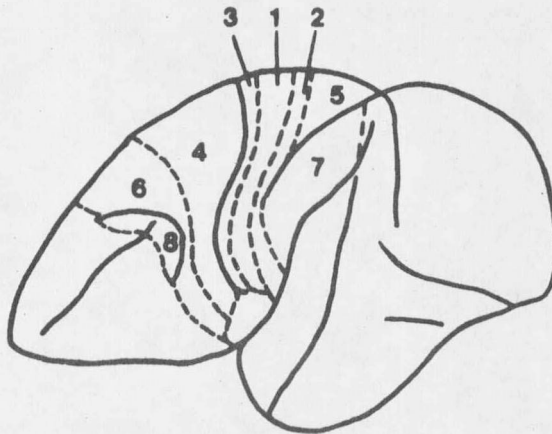
Lassek (1942) reported degeneration of only 27-40% of the pyramidal axons following the extirpation of Brodmann's area 4, most of which were larger diameter PT fibers. More recently, Lassek (1952) reported that approximately one-third of the PT fibers were intact following ablation of the complete frontal lobe in the monkey; the remaining fibers were of small diameter. These latter results suggest that PT fibers from the parietal cortex of the monkey are of a smaller caliber than those originating anterior to the central sulcus.

Figure 1. Diagramatic representations of Brodmann's cortical areas for (A) man, (B) monkey, and (C) cat. These areas are numerically labeled and enclosed by broken lines. The major sulci on the cerebral surface are represented by solid lines in all cases. In (C), the cruciate sulcus is represented by the solid line between Brodmann's area 4 and 6. Figure 1 (A) is taken from Barr (1974), 1 (B) is taken from Ariens Kappers *et al.* (1967), and 1 (C) is taken from Papez (1929).

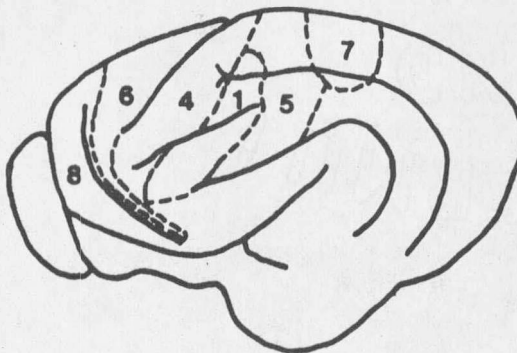
A



B



C



Electrophysiological techniques have been used more recently to study the cortical origins of the PT. Patton and Amassian (1954) reported that stimuli to the pericruciate cortex in the cat, including both somatosensory areas, evoke orthodromic discharges in cortico-spinal (PT) fibers in the bulbar pyramids. Lance and Manning (1954) recorded the largest orthodromic responses in the spinal cord of cats when stimulating on the lateral two-thirds of the anterior sigmoid gyrus or the entire posterior sigmoid gyrus.

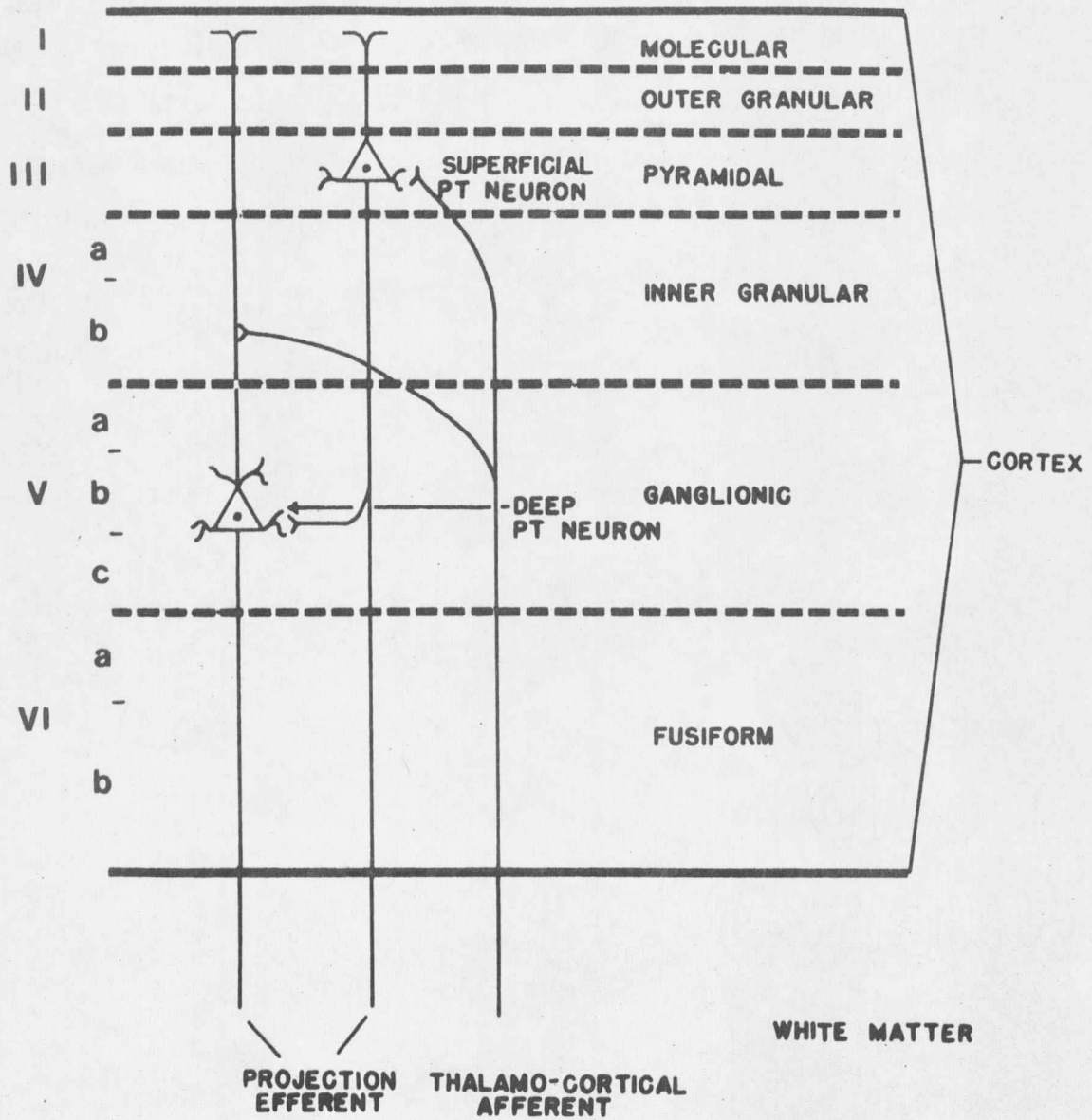
By stimulating in the pyramids, impulses can be generated in the axons of PT neurons and conducted to the cell soma in the cortex, where a potential can be recorded from the surface of the brain. This phenomena is referred to as antidromic conduction, and has also been used to map the cortical origins of the PT. In studies on rabbits, cats, and monkeys, Woolsey and Chang (1948) recorded antidromic cortical potentials from Brodmann's areas 8, 6, 4, 3, 1, 2, 5, and 7 following stimulation of the medullary pyramids (Fig. 1). Lance and Manning (1954) reported that about two-thirds of the PT neurons originate anterior to the rolandic homologue (about 2 mm posterior to cruciate sulcus) in the cat, the remaining one-third in the 'sensory' cortex. Both Lance and Manning (1954) and Towe and Kennedy (1962) reported that the largest antidromic cortical potentials were recorded near the lateral tip of the cruciate sulcus in the cat following stimulation in the pyramids.

Based upon histological studies of the cerebral cortex in a variety of mammals, Lorente de No (1949) reported that Betz cell axons arise mainly from layer V (Fig. 2). As reviewed by Patton and Amassian (1960), electrophysiological studies on cats have demonstrated corticospinal units in all layers of the cerebral cortex except layers I and II. Towe *et al.* (1963), Towe *et al.* (1964), and Towe *et al.* (1968) segregated PT neurons in the cerebral cortex of the cat into two major groups based on (1) depth and (2) their latency of antidromic firing following bulbar stimulation. An early firing population of PT neurons, activated 1 to 2 msec following bulbar stimulation, is concentrated in layer V of the cortex, 1100-1700 microns below the surface (Fig. 2). A later firing group is activated 4 to 5 msec following stimulation of the pyramids and is concentrated in layer III, 700-1000 microns deep.

In summary, although neurons contributing to the pyramidal tract are found over a wide area of the cortex, they are concentrated for the most part in the sensorimotor area in all species which have been studied.

The origin of the pyramidal tract in man is not exactly established. In a fiber analysis of the pyramids in a 51-year-old female who had been subjected to a complete ablation of the precentral gyrus 20 years prior to death, Jane *et al.* (1967) reported that about 60% of the PT fibers had degenerated. Wiesendanger (1969) concludes that data

Figure 2. Laminar organization of the cerebral cortex. The six major layers of the cortex are labeled with Roman numerals at the left and separated by broken lines. The name of each principle layer is at the right. The small letters at the left identify the sub-divisions of layers IV, V, and VI. The lower solid line demarcates the cerebral cortex from the underlying white matter, which is labeled. Superficial and deep pyramidal tract (PT) projection efferent neurons and a thalamo-cortical afferent fiber are illustrated.



on the cat, monkey, and man indicate a progressive constriction in the origin of the pyramidal fibers in the evolution from the cat to man. However, the origin of the PT in man cannot be accurately determined until more data from clinical cases is made available.

Composition of the Pyramidal Tract

Number of fibers. Comparative data on the pyramidal tract, as reviewed by Towe (1973a), indicate that only the primates, carnivores, lagomorphs, monotremes, and rodents possess extensive corticospinal tracts. It has been shown that the larger the mammal, the greater the number of PT fibers in the medullary pyramids. For example, the number of PT fibers per pyramid in the following mammals in order of decreasing body mass are: human, 1,000,000; chimpanzee, 800,000; macaque, 400,000; cat, 121,000; rat, 73,000; and mouse, 32,000. However, wide ranges in the number of PT fibers have been reported by investigators, indicating considerable overlap among species. For example, the reported counts in man vary from about 500,000 to nearly 1,400,000, while in studies on the domestic cat, the counts have varied from 56,000 to 186,000 (Towe, 1973a). Therefore, the chimpanzee overlaps the human range of PT fibers, while the rat overlaps the range of PT fibers for the cat.

It is often remarked that man is unique among mammals in having an enormous number of pyramidal tract fibers. Comparative data have shown that this statement is misleading; man has the expected number of PT

fibers for a mammal his size (Towe, 1973a). An animal such as the mouse has fifty times as many PT fibers as man in proportion to body weight. Although the PT has been classically regarded as mediating fine, non-stereotyped movements of the digits, it is interesting to note that Lassek *et al.* (1958) reported more PT fibers in the seal (748,000), an aquatic carnivore lacking digits, than in the monkey.

Size and conduction velocities. The fibers of the pyramidal tract are predominantly small in diameter. As reviewed by Towe (1973a), approximately 90% of the PT fibers in each of the species studied to date are less than 3 microns in diameter, and usually 70% are on the order of 1 micron or less. Lassek (1954), as reviewed by Patton and Amassian (1960), reported that 90% of the PT fibers in man are less than 4 microns in diameter (Group III or A delta), while only 1.75% are in the range of 11-22 microns in diameter (Group I). Sixty-one percent of the PT neurons in man were reported to be myelinated.

The conduction velocities for PT neurons have been determined electrophysiologically in cats, but with some disparity in the results. By stimulating the corticospinal tract in the cord and recording in the bulbar pyramids, Brookhart and Morris (1948) recorded a continuum of conduction velocities ranging from 165 M/sec down to 1.8 M/sec, corresponding to fiber diameters from 11.5 microns to less than 0.5 microns. However, Lance (1954b) takes issue with

these results, attributing such high conduction velocities to the to the activation of other fiber groups located more dorsally in the medulla.

By stimulating in the medulla and recording antidromic potentials from the cortex, Woolsey and Chang (1948), Bishop *et al.* (1953), and Lance and Manning (1954) identified two major populations of myelinated PT fibers with mean conduction velocities of approximately 60 M/sec and 20 M/sec, respectively. Lance (1954b) reported similar results by stimulating in the spinal cord and recording in the pyramids. These velocities are within the ranges calculated by Jabbur and Towe (1961a) for fibers contributing to two potentials recorded from the surface of the cortex following stimulation of the medullary pyramids. These potentials, called the α and beta potentials, are known to be associated with antidromic activation of PT fibers.

Similar results have been reported in the monkey. Woolsey and Chang (1948) reported two major myelinated groups of PT fibers with mean conduction velocities of approximately 60 M/sec and 20 M/sec, respectively. Bernhard and Bohm (1953) reported conduction velocities of 65-70 M/sec for the most rapidly conducting corticospinal fibers.

The above evidence suggests that the pyramidal tract is not a unique feature to the human nervous system. The pyramidal tract is not composed of large diameter, fast conducting axons in comparison to other descending pathways, such as the rubrospinal tract.

and medial longitudinal fasciculus (Nathan and Smith, 1955).

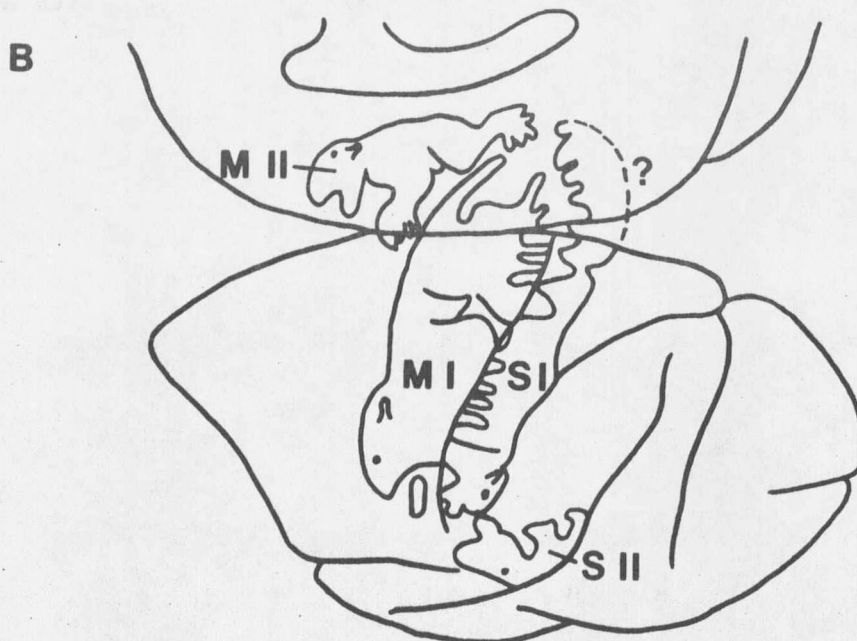
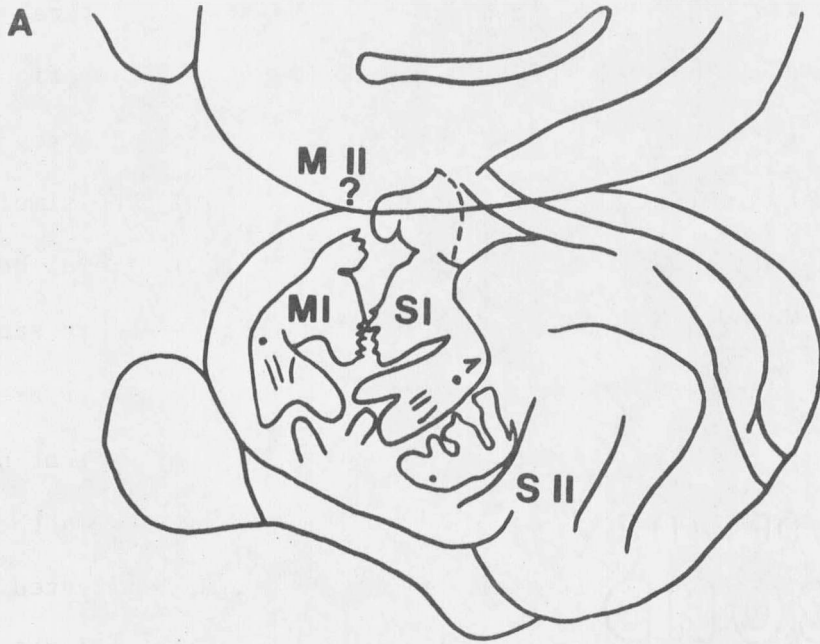
Topographical Organization and Course of the Pyramidal Tract

There is a general topographical organization of the sensorimotor area of the cerebral cortex in mammals such that the cells in a given area of the cortex have a close relationship, both with respect to afferent and efferent connections, with the dermatomal and myotomal distribution of peripheral nerve fibers. Woolsey (1958) has shown that the rolandic region of the cerebral cortex in primates consists of two major areas, each of which is topographically organized and appears to be concerned with both sensory and motor functions. Two other, less prominent, areas are present in primates, which are also considered to be involved in sensory and motor mechanisms to some degree.

The two prominent areas are located along the precentral and postcentral gyri in the monkey, and are designated the primary somatic sensory area (SI) and the primary motor area (MI) (Fig. 3). Based upon electrophysiological evidence, Woolsey (1958) has shown topographical representation of the monkey body such that the toes, ankle and lower leg are represented on the medial side of the cerebral hemisphere, with the knee, hip, and trunk represented on the convexity of the cerebral hemisphere. The fingers, arm, and shoulder are represented more laterally ending with the face representation on the superior bank of the Sylvian fissure. Considerable overlap in the

Figure 3. Principle somatic and motor areas on the (A) cat and (B) monkey brains (from Mountcastle, 1974). The lateral surface of the hemisphere is shown in the lower part of each figure. The medial surface of the hemisphere is displayed at the top of each figure by inverting it for purposes of allowing the simultaneous visualization of areas on both aspects of the cerebral hemisphere.

SI and SII are the primary and secondary somatic sensory areas, respectively. MI represents the primary motor area, MII the supplementary motor area. In view of the fact that no supplementary motor area, MII, has been determined in the cat, a question mark is placed where it may likely be located. The dotted lines signify that the topographical representation of these body parts has not been positively established, and represent unverified conclusions. This is also represented with a question mark in the drawing of the monkey brain.



topography exists between these two sensory-motor areas (Woolsey, 1958).

The less prominent areas are the secondary somatic area (SII) and the supplementary motor area (MII). Figure 3 shows that SII occupies the parietal cortex on the superior bank of the Sylvian fissure in primates, and on the anterior ectosylvian gyrus in cats. In contrast to the other topographical areas, both the ipsilateral and contralateral body halves are mapped on SII in cats and monkeys (Mountcastle, 1974). MII lies on the medial surface of the brain adjacent to the precentral motor area in the monkey; a supplementary motor area has not been localized in cats (Mountcastle, 1974). To date, MII has been shown to be involved in only motor mechanisms.

Woolsey (1958) recognized the close association on the cerebral cortex between the origin of input signals from a peripheral area and the destination of efferent volleys leaving the precentral and post-central gyri for the same area of the body. This association is evidenced in the works of Woolsey and Chang (1948) and Lance and Manning (1954), in which potentials resulting from antidromic activation of the PT were recorded in SI and SII, as well as in MI, in cats and monkeys. This evidence also supports the view that the PT takes origin in areas of the cerebral cortex previously thought to be strictly sensory.

Upon leaving the cortex, it is generally known that corticofugal fibers descend in the corona radiata to enter the ipsilateral internal capsule (Truex and Carpenter, 1969). Some exceptions have been cited, however. As reviewed by Marshall (1936), Kennard (1935) demonstrated that some degenerating fibers from area 6 pass back to area 4 of Brodmann before descending. Walberg and Brodal (1953) reported that a small number of fibers pass to the contralateral hemisphere via the corpus callosum before descending in the contralateral internal capsule.

The descending corticospinal (PT) fibers are generally thought to be located in the anterior two-thirds of the posterior limb of the internal capsule (Truex and Carpenter, 1969). Englander *et al.* (1975) take issue with this interpretation. They reported evidence in an isolated human case indicating that the PT is located more posteriorly in the posterior limb of the internal capsule. Barnard and Woolsey (1956) reported some degree of somatotopic organization of corticospinal (PT) fibers in the internal capsule. They reported that fibers destined for the lumbosacral region of the spinal cord are located caudally in the posterior limb of the capsule, with fibers destined for the cervical spinal segments being located anterior to the "leg" fibers.

The basis pedunculi in the ventral brainstem of the monkey receives converging fibers from the ipsilateral internal capsule at

the base of the diencephalon. Barnard and Woolsey (1956) demonstrated that the corticospinal tract occupies the middle three-fifths of the basis pedunculi ipsilateral to the hemisphere of origin. Somatotopic arrangement of corticospinal (PT) fibers exists in the basis pedunculi, but with some overlap. Corticospinal fibers destined for the cervical spinal cord are located medial to those going to the thoracic regions, with fibers destined for the lumbosacral segments of the cord located more laterally. Corticospinal fibers from the parietal cortex destined to all levels of the spinal cord constitute the most lateral part of the middle three-fifths of the basis pedunculi (Barnard and Woolsey, 1956).

By tracing fiber degeneration, Marin *et al.* (1962) found that the most lateral segment of the basis pedunculi (lateral one-fifth) is composed of cortico-pontine fibers, the majority of which are from the parietal cortex. Thus, even though the lateral segment of the peduncle is referred to as the temporo-pontine segment (Turcks Bundle), few fibers here actually originate from the temporal or occipital lobes. Levin (1936) reported that pontine fibers originating from the frontal lobe pass through the basis pedunculi in the innermost segment, referred to as the fronto-pontine segment (Arnolds Bundle).

The corticospinal (PT) fibers diverge and scatter into bundles upon passage through the pons, because of intersection with the

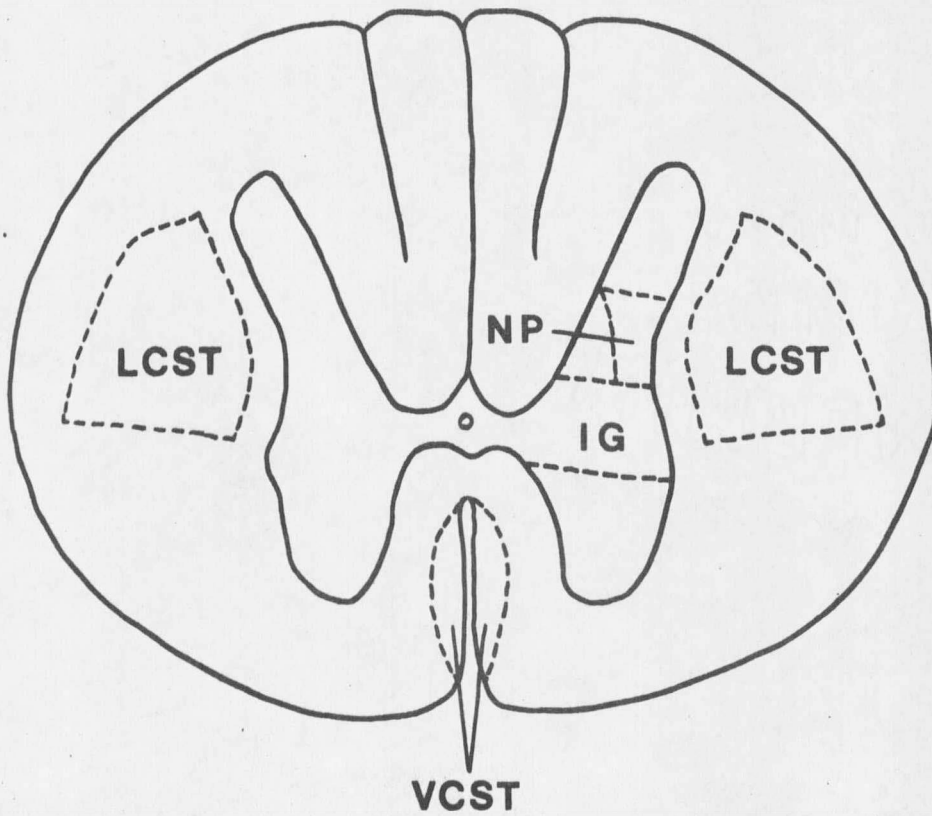
transversely oriented ponto-cerebellar fibers (Barnard and Woolsey, 1956). While some fibers terminate in the pontine nuclei (cortico-pontine), those continuing to the spinal cord converge again upon entering the medulla (Barnard and Woolsey, 1956). The only somatotopic arrangement of PT fibers in the medulla reported by Barnard and Woolsey (1956) is the medial concentration of fibers from the face area of the cortex medially, while PT fibers originating from the parietal lobe are more laterally positioned. Aside from this, there is a thorough mixture of PT fibers destined for the cervical, thoracic, and lumbosacral regions of the spinal cord.

In the caudal medulla, a majority of the corticospinal fibers decussate at the level of the pyramids. Hoff and Hoff (1934), as reviewed by Bucy (1966), calculated that 75% of the PT fibers in the monkey decussate in the medullary pyramids, while the remaining fibers descend in the ipsilateral spinal cord. Similar percentages were reported by Levin and Bradford (1938), who calculated that 85% of the PT fibers in the monkey decussate and 15% remain uncrossed.

By lesioning the bulbar pyramid and tracing fiber degeneration, Nyberg-Hansen and Brodal (1963) and Liu and Chambers (1964) reported crossed and uncrossed corticospinal (PT) fibers in both the lateral and ventral funiculi in the spinal cords of the cat and monkey (Fig. 4). Most of the decussating fibers enter the lateral corticospinal tract. The majority of the PT fibers from the cortex reaching the lumbar

Figure 4. Illustration of a cross-section of the human spinal cord.

The positions are labeled for both lateral corticospinal tracts (LCST) and both ventral corticospinal tracts (VCST). The nucleus proprius (NP) in the dorsal horn and the intermediate gray region (IG) of the spinal gray matter are also labeled. Taken from Barr (1974) and modified.



spinal segments are contained within the crossed lateral corticospinal tract, while few PT fibers in either ventral corticospinal tract descend below the cervical segments (Liu and Chambers, 1964). Liu and Chambers (1964) reported no somatotopic arrangement of PT fibers in the spinal cord of the monkey in experiments involving lesions of cortical areas. These results are in agreement with those of Barnard and Woolsey (1956), who used the same technique.

The concentration of the corticospinal fibers in the lateral and ventral columns of the spinal cord is a pattern which pertains only to the primates and carnivores. While the PT is concentrated largely in the lateral columns in these orders, it is located principally in the posterior columns in rodents and marsupials, and in the anterior columns in insectivores and proboscideans (Towe, 1973). Nathan and Smith (1955) suggest that this variation in position is related to the fact that the pyramidal tract is a phylogenetically new fiber system.

Pyramidal Tract Influences on 'Motor' Systems

The descending fibers of the lateral corticospinal tract have been shown, for the most part, to terminate on interneurons in the spinal gray matter at the base of the dorsal horn. In electrophysiological studies, Lloyd (1941) recorded considerable electrical activity in the spinal cord nuclei at the base of the dorsal horn following stimulation of PT fibers in the medulla, and concluded that

the lateral corticospinal tract enters the gray matter of the spinal cord in this area and synapses on interneurons. This conclusion is supported by the anatomical investigations of Nyberg-Hansen and Brodal (1963), who traced a majority of degenerating PT axons in the lateral corticospinal tracts to the basal region of the dorsal horn and the intermediate zone of the gray matter (Fig. 4). Using the same technique, Kuypers (1960) and Liu and Chambers (1964) found PT terminations in the same regions in the monkey, however, they also reported a significant number of direct cortico-motoneuronal projections. The majority of the direct fibers were reported to originate in the precentral gyrus.

There is a general difference between pyramidal tract fibers originating in the classical 'sensory' cortex and fibers originating in the 'motor' cortex in regard to the dorso-ventral extent of their terminations in the spinal gray matter. By tracing fiber degeneration through the bulbar pyramids and into the spinal cord following the ablation of selected cortical areas, Nyberg-Hansen and Brodal (1963) and Liu and Chambers (1964) reported that most of the PT fibers originating in the 'sensory' areas in the postcruciate cortex in cats and the postcentral cortex in monkeys terminate more posteriorly in the dorsal horn, especially in the nucleus proprius (Fig. 4). PT fibers from the 'motor' areas of the precruciate and rostral postcruciate cortices in cats, and the precentral cortex in monkeys were found to

terminate in the intermediate zone and base of the dorsal horn in cats and monkeys*, and also in the ventral gray horn in monkeys.

The influences of the descending PT fibers on neurons in the spinal gray matter have been studied electrophysiologically. Lloyd (1941), Morrell (1957), and Lundberg *et al.* (1962) reported a predominant increase in the tonic activity of spinal interneurons following activation of the PT. Lloyd (1941) and Morrell (1957) reported increases in the firing of spinal motoneurons following the activation of PT fibers, and proposed that this effect is mediated through interneurons. Following stimulation to the PT, Lundberg and Voorhoeve (1962) reported excitatory effects in motoneurons to flexor muscles and inhibitory effects in motoneurons to extensors, supporting the view that the PT influences mainly flexor muscles.

The influence of the pyramidal tract on spinal reflex arcs has been studied with an emphasis on the role of interneurons. Following stimulation to the PT at strengths evoking little or no alpha-motoneuron activity, Lundberg and Voorhoeve (1962) reported an enhancement in transmission in the Ia inhibitory, reciprocal Ib, and

*The cruciate sulcus in cats is not the rolandic homologue of the central sulcus in primates. This homologue where 'motor' cortex gives way to typical 'sensory' cortex appears to be near the dimple, about 2 mm posterior to the cruciate sulcus (Campbell, 1905, as reviewed by Lance and Manning, 1954). Rostrally located postcruciate cells, therefore, behave more like precruciate cells in many respects than the more caudally located postcruciate neurons.

the flexor reflex arcs. Each reflex arc involves interneurons and it was suggested that the PT exerts its control over these reflex pathways at the interneuronal level.

Fetz (1968) reported that the more dorsally located cells in the lumbar dorsal gray horn are predominantly inhibited by PT stimulation in the pyramids, while the more ventrally located cell groups are predominantly facilitated. Fetz (1968), Carpenter *et al.* (1962), and Anderson *et al.* (1962) also reported evidence of presynaptic depolarization of primary afferent terminals in the dorsal horn by recording dorsal root potentials* (DRP) when the pyramidal tract was stimulated. DRP's could not be recorded following sectioning of the pyramids.

In summary, it has been shown that a majority of postcruciate PT axons terminate in the more posterior regions of the cat lumbar dorsal horn. Precruciate and more rostrally located postcruciate neurons project to more ventral areas of the dorsal horn and the intermediate zone of the spinal gray matter (Nyberg-Hansen and Brodal, 1963). It has also been shown that most postcruciate PT neurons mediate predominantly inhibitory actions to more dorsally located dorsal horn cells, while precruciate PT neurons appear to project

*DRP's are electrotonic potentials with a characteristic 150-200 msec duration. They are indicative of the presence of one or more axo-axonic synapses which cause the presynaptic depolarization of primary afferent terminals.

predominantly excitatory influences to more ventrally located cells in the spinal gray (Fetz, 1968). On the basis of this evidence from the cat, Fetz (1968) proposed that most of the precruciate PT neurons are probably involved with organizing flexor movements, while most postcruciate PT neurons, through a combination of pre- and postsynaptic inhibition of cells in the spinal gray matter, complete a feedback loop, and thereby serve to modulate incoming information in peripheral afferents at the segmental level.

Pyramidal Tract Influences on 'Sensory' Systems

It has been shown by a variety of anatomical and electrophysiological methods that many axons in the pyramidal tract project via collateral branches to sub-cortical nuclei. As reviewed by Wiesendanger (1969), at least three neuronal systems receive PT axon collaterals. These are (1) the specific somatosensory relay nuclei, (2) the lateral reticular nucleus, and (3) the core of the mesencephalic reticular formation. Only the influences of the PT on the relay nuclei in the sensory systems will be considered in detail.

By lesioning selected cortical areas and tracing the fiber degeneration, Walberg (1957), Kuypers (1958), Zimmerman *et al.* (1963), and Liu and Chambers (1964) reported PT terminations in the dorsal column nuclei (DCN) of the rat, cat, and monkey. Kuypers (1958) reported that fibers originating from the "leg" region on the medial

convexity of the cerebral cortex concentrate mainly in the nucleus gracilis, while those from the more lateral "arm" region of the cortex project principally to the cuneate nucleus. These findings correlate with degeneration studies which show that sensory fibers in the dorsal white columns of the spinal cord are arranged such that peripheral afferents from the leg are concentrated in the fasciculus gracilis; those from the arm in the fasciculus cuneatus (Barr, 1974). Liu and Chambers (1964) reported that the majority of PT fibers terminating in the DCN originate from the classical 'sensory' cortex. This would suggest that neurons in the cerebral cortex modify the incoming sensory information via projection efferents, thus providing a feedback control system.

Electrophysiological studies by Towe and Jabbur (1961), Jabbur and Towe (1961b), Gordon and Jukes (1962), and Winter (1965) demonstrated both excitatory and inhibitory influences on the DCN following cortical stimulation. Winter (1965) demonstrated similar results following stimulation of the motor cortex, basis pedunculi, and the medullary pyramids. This would suggest that these effects are mediated through the pyramidal system. Anderson *et al.* (1962) reported presynaptic inhibition in the DCN following cortical stimulation. It was proposed, although not conclusively proven, that this effect, is mediated by the PT.

Towe (1973b) reported that the excitory effect of cortical stimulation on the dorsal column nuclei is abolished following transection of the pyramids, while the inhibitory effect is only slightly diminished. However, the inhibitory effect is steadily reduced as the transection is placed more rostrally. Transection of all of the medulla except for the pyramids produces little or no effect on excitation, but greatly attenuates the inhibitory action. In this case, as the transection is placed more rostrally, interruption of the inhibitory effect is lessened. These results suggest that the PT exerts excitory effects on the DCN directly, while inhibitory effects are relayed more rostrally in the brainstem by PT collaterals to an extrapyramidal fiber system such as the reticular formation (Towe, 1973b). This conclusion is supported by the degeneration studies of Walberg (1957), who reported that some PT fibers destined for the DCN pass through the reticular formation of the medulla.

Although the anatomical relationship between the monkey and cat is similar, Towe (1973b) cautions that the physiological conditions of the cortical-dorsal column nuclei interaction are different between the monkey and the cat. This is reflected in the fact that the excitability of 83% of the cuneate neurons in the cat are modified by activation of the cerebral cortex, while only 29% are so affected in the monkey (Towe, 1973b). There is also a greater predominance of cells in the cuneate nuclei of the monkey which are responsive to

touch and pressure in comparison to the cat, an observation which agrees with the fact that monkeys have considerably larger quantities of glabrous skin. However, it also suggests that these two species have diverged through evolution to the point where correlations between them, concerning corticofugal influences on the DCN, become difficult.

Most sensory information from the face is conducted to the CNS via the trigeminal nerve; a synaptic relay occurs in the trigeminal nuclei which is comparable to the synaptic relay at the dorsal column nuclei in the transmission of somatic information. Evidence shows that the PT influences sensory information from the face at the trigeminal nuclei. Kuypers (1958) observed degenerating PT fiber terminals in the trigeminal nuclei of the cat following lesioning of the face area of the motor cortex. Zimmerman and Chambers (1963) reported the same results in the rat and opossum. Darian-Smith and Yokota (1966) reported both excitatory and inhibitory corticofugal effects in all cell populations of the trigeminal nuclei. They also identified presynaptic inhibitory mechanisms.

A cortico-thalamic connection via PT collaterals has been proposed by Clare *et al.* (1964) based upon results from electrophysiological studies. It was demonstrated that the thalamus-cortex-pyramid conduction time (1.5 msec) was less than the sum of the thalamus to cortex and cortex to pyramid conduction times (1.65 msec). It was concluded that the thalamus-cortex-pyramid conduction time (1.5 msec)

results from the activation of PT collaterals terminating in the thalamus, which conduct antidromically to the bifurcation of the collateral branch and main axon, and subsequently to the medullary pyramids by orthodromic conduction without involving a cortical synapse.

Excitatory effects of cortical and pyramidal tract stimulation on the transmission of somatosensory information to the cerebral cortex have been demonstrated. Anderson *et al.* (1967) recorded a decreased synaptic latency of activation of cells in the primary somatosensory nucleus of the thalamus in response to peripheral nerve activation following repetitive stimulation to the cat postcruciate cortex. Adkins *et al.* (1966) reported the effect of the PT on somatosensory relay nuclei by recording the response properties of cells in the somatosensory cortex. Increases in the size of cutaneous receptive fields and the number of submodalities which effectively excite somatosensory cells in the cerebral cortex were reported when transmission of cutaneous information was conditioned by stimulation of the medullary pyramids.

The functions of the pyramidal tract are obviously more complex than just serving as a cortical projection system to spinal motoneurons for purposes of mediating volitional movement. It also has the capacity to "edit" incoming sensory information at a number of levels in the central nervous system from the spinal cord to the cerebral cortex.

Recurrent Collaterals of Pyramidal Tract Neurons

In addition to their main descending axon, efferent cortical neurons distribute collateral axon branches that course throughout the cortical gray matter. These collateral branches provide a potential feedback mechanism, whereby pyramidal tract neurons can either effect their own level of activity or that of neighboring cortical neurons. By using Nissl and Weigert stains, Lorente de No (1949) reported that the axon collaterals of cortical neurons branch profusely within the cortical gray matter. It was reported that collaterals of the Betz cells located predominantly in layers V and VI are found not only in these layers but also among layers I, II, and III. Layer IV, which receives most of the specific thalamo-cortical input to the cerebral cortex, receives few collaterals from neurons in other cortical layers.

Electrophysiological studies have indicated that axon collaterals of PT neurons mediate both excitatory and inhibitory effects. Takahashi *et al.* (1967) reported recurrent facilitation in cat pyramidal tract cells, and proposed that the collaterals of small PT neurons cause recurrent facilitation of larger PT cells, including the larger Betz cells. This proposal was based upon their inability to record pyramidally evoked EPSP's from PT cells in pyramidotimized cats, in which Betz cells had degenerated even though small PT cells were still present.

Blum (1974) described inhibition of slower conducting PT neurons by the antidromically activated collaterals of larger, faster conducting PT fibers. Purpura and Grundfest (1956) reported both facilitation and inhibition of cortical dendritic firing following the antidromic activation of PT fibers. These effects were reversibly blocked by tubocurarine, indicating the involvement of post-synaptic mechanisms. Stefanis and Jasper (1964b) reported intracellular IPSP's in cortical cells following stimulation of the medullary pyramids, which they attributed to activation of PT axon collaterals.

The exact role of recurrent collaterals of cortical cells, including PT cells, remains speculative. Stefanis and Jasper (1964b) and Blum (1974) proposed that they function to distinguish a local group of active cortical cells from surrounding cells, which would be inhibited during firing. This surround inhibition would have the effect of increasing the precision of cortical influence on lower motor neurons. Chang (1955b) proposed that in cases of excitation, PT axon collaterals are part of a facilitatory circuit which feeds back, via interneurons, to the parent soma, as well as other PT cells. In the latter case, axon collaterals would allow a small cortical area to command a large number of effectors not directly under its control.

Afferents in the Pyramidal Tract

Tower (1940), on the basis of anatomical investigations, proposed

that all fibers in the monkey pyramid are descending. Brodal and Walberg (1952), as reviewed by Lance (1954a), reported degeneration of about 4% of the fibers in the pyramids following transection of the lateral and ventral white columns of the cervical spinal cord and the dorsal column nuclei; they attributed this to the presence of afferents in the PT. Brodal and Kaada (1953) recorded action potentials in the pyramids following stimulation of peripheral afferents, which they attributed to ascending fibers in the PT.

Lance (1956) took issue with this interpretation, attributing Brodal and Kaada's (1953) results to current spread from the adjacent medial lemniscus in the medulla. The results of Lassek (1942), as reviewed by Lance (1954a), do not show anterograde degeneration in the pyramids following transection of the lateral and ventral white columns in the spinal cord. The possibility exists that Brodal and Walberg (1952) were observing retrograde degeneration of large PT fibers (Lance, 1954a). In view of the conflicting reports, the hypothesis that afferents exist in the PT cannot be supported without more conclusive evidence.

Afferent Input to the Pyramidal Tract

Stimulation of the cerebral cortex is an unnatural method of activating the pyramidal system. A more natural method of activation is through stimulation of afferent pathways. Action potentials are

recorded in the PT following stimulation of the contralateral primary afferent neurons (Adrian and Moruzzi, 1939; Patton and Amassian, 1960). Adrian and Moruzzi (1939) recorded synchronous discharges for approximately 15 msec in the PT of the cat following the activation of contralateral peripheral afferents. Patton and Amassian (1960) state that a single orthodromic volley from stimulation of the contralateral forepaw evokes a burst of action potentials in the medullary pyramids consisting of 1-11 spikes at frequencies of 500-700/sec.

The latency of discharge of the pyramidal tract neurons following the arrival of afferent impulses to the cortex has been calculated. Amassian *et al.* (1955), as reviewed by Patton and Amassian (1960), recorded an initial response in the pyramids 4.6 msec after the start of the primary evoked potential*. By subtracting a 0.52 msec cortex-to-medulla conduction time, approximately a 4.1 msec delay exists between the initial cortical response and discharge of the PT neurons. The earliest firing Betz cells were reported to discharge during the positive phase of the primary evoked potential, with the bulk of the

*The primary evoked potential is a slow potential recorded extracellularly from the surface of the somatosensory cortex following the activation of peripheral afferent fibers. It is mediated to the cortex by the dorsal column-lemniscal fiber system, is in the range of 40-80 msec in duration, and is usually biphasic (positivity-negativity). In the cat, it's latency is about 10 msec following stimulation to the contralateral forepaw.

activity between the peaks of positivity and negativity.

Studies have been made on the response of the PT to stimulation of specific and nonspecific thalamic nuclei. Parma and Zanchetti (1956) reported that PT discharges are elicited by stimulating the primary somatosensory nucleus of the thalamus. Brookhart and Zanchetti (1956), as reviewed by Patton and Amassian (1960), found that stimulation of non-specific thalamic nuclei does not elicit PT discharges. These reports suggest that the PT may be part of a cortical reflex center involving the specific thalamo-cortical projection system.

The effects of afferent stimulation on the deep and superficial populations of pyramidal tract neurons in the cerebral cortex indicates a difference in the afferent input to these two PT groups. Towe *et al.* (1963) reported that the deep PT group (layer V) exhibits a prolonged discharge following afferent stimulation, which lasts through the positive and negative peaks of the primary evoked potential; the superficial PT group (layer III) discharges only during the negative phase. From these results, Towe *et al.* (1963) proposed that two afferent inputs contribute to PT discharges. An early afferent input is proposed to fire only the deep population of PT neurons, while a slower afferent input discharges both the deep and superficial group of PT neurons.

A general classification scheme of cortical neurons, developed by Buser and Imbert (1961), distinguishes between (1) specific somatosensory

neurons (those responding to only one modality), (2) polysensory somatic neurons (those responding to more than one modality), and (3) polyvalent neurons (those responding to stimulation of more than one limb). Although Buser and Imbert (1961) give the approximate locations of each of these population types within the cortex, no distinction is made between PT and non-PT systems.

Modality specific (specific somatosensory) PT neurons have been reported by Brooks *et al.* (1961a). The existence of polysensory PT neurons in the cerebral cortex has also been shown by Towe and Kennedy (1961), who found that stimulation of cutaneous afferents has the same effect upon eliciting PT discharges as does the stimulation of muscle afferents. Brooks *et al.* (1961a) reported that PT neurons in the anterior sigmoid gyrus of the cat respond to hair, touch, pressure, and joint movement, while PT neurons in the posterior sigmoid gyrus respond to touch and pressure.

The distribution of cortical PT neurons in the cerebral cortex that respond to stimulation over local and wide areas of a limb or the body has been studied. Brooks *et al.* (1961b), using unanaesthetized cats, reported about an equal distribution of PT neurons with local and wide receptive fields in the precruciate and postcruciate cortices. Towe *et al.* (1964) reported similar results in cats anaesthetized with alpha-chloralose. Eighty-eight percent of the precruciate PT cells and 87% of the postcruciate PT cells were polyvalent; that is, they

responded to stimulation of more than one limb. This equal distribution is not consistent for the rest of the cerebral cortex; the size of the peripheral receptive fields of cortical neurons increases as the recording site moves rostrally from the postcruciate cortex to the precruciate cortex (Brooks *et al.*, 1961b; Towe *et al.*, 1964; Towe *et al.*, 1968).

It is evident that PT neurons in the cerebral cortex qualify for each of the three categories of cortical neurons given by Buser and Imbert (1961). In terms of their responses to peripheral stimulation, pyramidal tract cells in the precruciate and postcruciate cortices behave similarly in experimental situations. How they interact with non-PT neurons, which exhibit different response properties in the anterior and posterior sigmoid gyri, and how this affects the pattern of PT discharge, remains problematic.

Pyramidal Deficit

The role of the pyramidal tract in the control of motor output has been studied by observing the physical effects following its' transection at different levels in the central nervous system. Interruption of the axons has produced surprisingly subtle effects on motor output in view of the widely held belief that the PT underlies volitional movement. Transection of the PT in the pyramids has been performed in rats, cats, and monkeys. Barron (1934) reported the

predominant result of unilateral transection of the pyramids in the rat to be an initial paresis in contralateral flexor muscles. This effect only lasts for 14-20 days, after which the animal regains normal use of the affected muscles. Decreased flexor activity lasting for a period of several days following pyramidal transection was also reported in cats; the hindlimbs being more severely affected than the forelimbs (Liddell and Phillips, 1944).

Limb extension is commonly observed in pyramidotomized animals. Ranson (1932) and Liddell and Phillips (1944) attributed this result to extensor hypertonus, while Tower (1940) and Laursen and Wiesendanger (1966a) proposed a decrease in flexor activity to be responsible for the effect. Lundberg and Voorhoeve (1962) and Laursen and Wiesendanger (1966b) reported an excitation of flexor muscle activity and an inhibition of extensor activity following stimulation of the PT. This evidence supports the view that limb extension results from a deficit in flexor activity, and that PT influences are directed primarily toward flexor muscles. Other effects of pyramidotomy in the cat are a permanent loss of placing and hopping reactions (Liddell and Phillips, 1944) and a conversion of cortically induced tonic movements to phasic movements (Mettler and Mettler, 1940).

In experiments on monkeys, more severe effects have been reported to result from pyramidal lesion. Tower (1940) and Lawrence and Kuypers (1965) reported that contralateral paresis occurs in unilateral

lesions, effecting the hindlimb more than the forelimb. This response has been attributed to the effectiveness of uncrossed corticospinal paths in the cervical region (Fulton, 1935, as reviewed by Patton and Amassian, 1960). In addition, the elimination of non-stereotyped, discrete movements of the digits, diminished cutaneous reflexes, slow and full tendon reflexes, and lowered temperature in the paretic limb have been observed (Tower, 1940). These effects lasted for as long as the animals survived, which in some cases was up to 32 months. In contrast to these results, Bucy *et al.* (1966) reported that monkeys, in which the basis pedunculi were severed, regain almost complete control of their skeletal muscles several months after sectioning, as evidenced by their ability to walk, climb, and feed themselves. Lawrence and Kuypers (1965) reported an inability of pyramidotomized monkeys to release their grip, which results in the animals becoming "hung up" when performing such tasks as ladder climbing. Although the results of studies on the transection of pyramidal tract in monkeys show minor differences, it is obvious from these studies that motor systems other than the PT play an important role in the production of voluntary movement.

The classical "pyramidal syndrome" of clinical neurology, which is attributed to the interruption of the descending PT fibers, is characterized by spastic paralysis, absence of abdominal reflexes, hyperactive tendon reflexes, and the sign of Babinski, which consists

of dorsiflexion of the big toe and fanning of the other four (Wiesendanger, 1969). However, there is little scientific basis for this contention since lesions in man are invariably mixed and are rarely confined strictly to the PT. Bucy *et al.* (1964) reported a near complete recovery of motor function in a patient 8 months after sectioning one of the basis pedunculi for purposes of arresting hemiballismus. Only a slight deficit in ambulation and the sign of Babinski remained on the contralateral side.

The recovery of the classical "pyramidal function" following transection of the pyramids may be due to the ability of PT neurons to remain active through collateral connections with extrapyramidal systems. Lance (1954a) reported retrograde chromatolysis in the cell bodies of PT neurons, without complete axonal degeneration, following transection of the PT in the pyramids. According to Patton and Amassian (1960), such a reaction is characteristic of neurons which spawn many collaterals, as do the PT fibers between the cortex and the pyramids.

It is evident from these studies that transection of the pyramidal tract in the medullary pyramids and basis pedunculi has been only partially successful in localizing its functions. It is also apparent that there is insufficient evidence to support the classical view that transection of the pyramidal tract in man produces permanent spastic paralysis. These studies do indicate the importance of

extrapyramidal motor systems in the production of voluntary movement.

Antidromic Activation of the Pyramidal Tract

The antidromic conduction of action potentials along axons does not occur naturally in the nervous system, but must be artificially induced. In view of this, antidromic potentials exist as an important means for analyzing the physiological properties of neurons, either individually or collectively. The interpretation of antidromic records depends upon the combination of stimulating and recording techniques used by the investigator, as well as the use of proper experimental precautions to eliminate the spread of the stimulus current to fiber systems not being considered for study.

Antidromic conduction in the PT has been used to map its origins on the cerebral cortex. Using this technique, Woolsey and Chang (1948) reported the cortical origins of the PT to be in the pericruciate region of the cat. The medullary pyramids were stimulated and the antidromic potentials were recorded extracellularly on the surface of the cortex. All fiber systems other than the PT were transected at the medullary and mesencephalic levels to eliminate conduction to the cortex over fiber systems other than the PT.

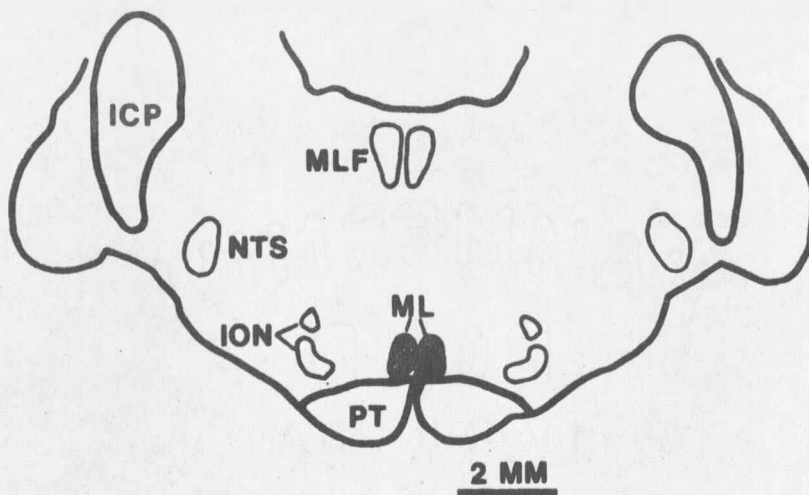
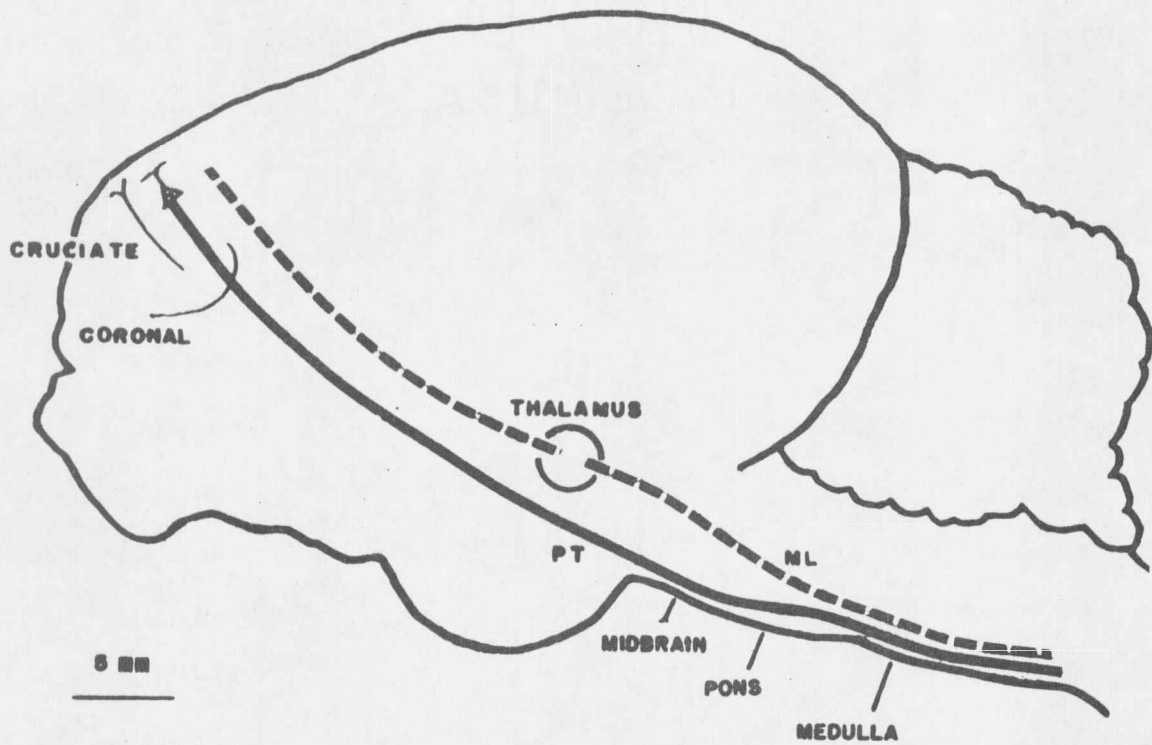
Studies to determine the cortical origins of the pyramidal tract in cats, phalangers, and rabbits, by use of the same method, were repeated by Lance and Manning (1954), Porter (1955), and Chang (1955a,b).

In none of these studies were fiber systems other than the PT transected. Lance and Manning (1954) assumed that all action potentials they recorded, regardless of latency, resulted from antidromic activation of the PT. In studies on cats, rabbits, and phalangers by Porter (1955) and on rabbits by Chang (1955a,b), the earliest, surface-positive potential recorded following bulbar stimulation had a latency of approximately 1.5 msec; this potential was assumed by both investigators to be antidromically mediated by the PT. Porter (1955) reported that this surface positive potential was not attenuated when the stimulus rate was as high as 20 to 30/sec; he used this as the only criterion to distinguish between antidromic activation of pyramidal fibers and orthodromic activity mediated by the medial lemniscus.

Landau (1956) contested the interpretations of Porter (1955) and Chang (1955a,b) that the cortical potentials with a 1.5 msec latency following bulbar stimulation were the result of antidromic activation of the PT. Instead, he proposed that these potentials resulted from spread of the stimulus current to the medial lemniscus, which is adjacent to the pyramidal tract in the medulla (Fig. 5). A surface-positive potential (latency-1.4 msec) recorded from the posterior sigmoid gyrus disappeared following transection of the medial lemniscus. A shorter-latency potential (0.75 msec) was recorded from the anterior sigmoid gyrus, which survived transection of all fiber systems except the PT. It was concluded that this potential was

Figure 5. Diagrammatic representation of the cat brain. The approximate locations of the prominent cruciate and coronal sulci and the thalamus are shown. The routes of the descending pyramidal tract (PT) and ascending medial lemniscus (ML) through the brain-stem and cerebrum are illustrated. Particular attention should be given to the close contiguity of the two fiber systems in the medulla. In the midbrain, they are separated by 4 to 5 millimeters. Taken from Snider and Niemer (1970) and modified.

The lower illustration represents a cross-section of the medulla at the level of the pyramids. Particular attention should be given to the close association of the pyramidal tract (PT) and the medial lemniscus (ML). The inferior cerebellar peduncle (ICP), medial longitudinal fasciculus (MLF), nucleus of the trigeminal spinal tract (NTS), and the inferior olivary nucleus (ION) are also labeled for reference. Taken from Snider and Niemer (1970) and modified.



antidromically mediated by the pyramidal tract.

Contradiction also exists in regards to the frequency of stimulation necessary to distinguish between antidromic responses and responses mediated by fiber systems with at least one synapse. Towe and Jabbur (1959) and Kennedy and Towe (1962) have reported that surface-positive, cortical potentials with latencies of 1.5 msec following bulbar stimulation are not completely attenuated at repetitive stimulus rates of 50/sec. The stimulus rates of 20 to 30/sec used by Porter (1955) apparently do not conclusively distinguish between antidromically mediated potentials and those mediated orthodromically.

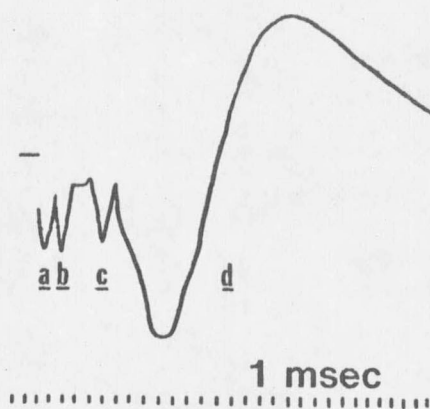
The antidromic cortical response. Jabbur and Towe (1961a) described a complex series of electrical potentials recorded from the surface of the sensorimotor area of the cat cerebral cortex when a supramaximal, electrical stimulus is applied to the medulla. Three, and sometimes four, potentials can be observed. These potentials have been designated the *a*, *b*, *c*, and *d* potentials (Towe and Jabbur, 1959; Jabbur and Towe, 1961a), respective to their increasing latencies (Fig. 6). This entire complex is known as the antidromic cortical response.

Another response, the beta potential, is a long duration, surface-positive potential with a latency of 1.5 to 2.0 msec following bulbar

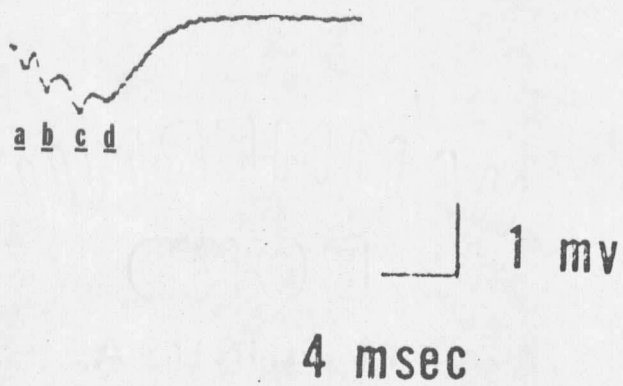
Figure 6. Figure showing two complex series of electrical potentials recorded from the sensorimotor cortex following brainstem stimulation, demonstrating the *a*, *b*, *c*, and *d* potentials. A. Illustration of a photograph of an oscilloscope recording taken from Jabbur and Towe (1961a) following stimulation of the surface of the medullary pyramids. The figure represents a typical trace across the oscilloscope face; the start of the sweep corresponds to the application of the stimulus. The distance between each time calibration mark is one millisecond; the peak to peak amplitude of the *d* potential is 0.8 millivolts. Positive voltage is down. The latency of the *a* potential is 0.5 msec; *b* potential, 1.5 msec; *c* potential, 4.5 msec; and *d* potential, 7.0 msec.

B. Photograph of an oscilloscope recording from an experiment where the stimulating electrode was in the midbrain. Time and voltage calibrations are to the right. The latency of the *a* potential is 0.3 msec; *b* potential, 0.9 msec; *c* potential, 2.6 msec; and *d* potential, 4.3 msec.

A



B



stimulation (Jabbur and Towe, 1961a). This potential is usually obscured by the *b*, *c*, and *d* components, however, it can be recorded following low intensity stimulation to the pyramidal tract.

Evidence has strongly indicated that only the *a* potential, with a latency of 0.3-0.4 msec, and the beta potential result from antidromic activation of the PT. Towe and Jabbur (1959) reported that only these potentials can be elicited following antidromic activation of a strand of the PT which is surgically isolated from the ventral medulla. This procedure eliminates spread of the stimulus current to other fiber systems in the medulla. The *b*, *c*, and *d* potentials are not recorded when such a strand is stimulated. Also, the *a* and beta potentials invariably follow high-frequency stimulation at rates greater than 100/sec, a frequency that causes attenuation of potentials mediated by pathways involving one or more synapses* (Kennedy and Towe, 1962). Under these conditions the *c* and *d* potentials are completely absent, while the *b* response is significantly attenuated.

The view that the *a* and beta potentials are antidromically mediated by the pyramidal tract is further supported by data on their conduction velocities. Based upon their latencies of activation, the conduction velocities of the *a* and beta potentials are approximately

*The beta potential actually attenuates at stimulus rates greater than 50/sec, however, this attenuation levels off and it can then follow stimulus rates of 100/sec or greater.

55 M/sec and 17-25 M/sec, respectively (Jabbur and Towe, 1961a). These values are consistent with those of about 60 M/sec and 20 M/sec calculated for the two major PT populations by Bishop *et al.* (1953). This evidence, therefore, suggests that the *b*, *c*, and *d* potentials are associated with fiber systems other than the PT.

The *c* potential, which has a 4.5 msec latency following bulbar stimulation, has characteristics associated with both orthodromic and antidromic responses. It is similar to orthodromic potentials in that (1) it is attenuated by conditioning stimuli to the contralateral forepaw (Towe and Jabbur, 1959; Kennedy and Towe, 1962) and (2) it is attenuated at moderate rates of stimulation (Jabbur and Towe, 1961a). However, it resembles known antidromic potentials with respect to the rate of change of voltage with respect to time. Such a rapid voltage gradient in a synaptic system is unlikely (Jabbur and Towe, 1961a).

The *d* potential, with a 7.0 msec latency following bulbar stimulation, is similar in all respects to known orthodromic potentials. It is attenuated by conditioning stimuli to the contralateral forepaw (Towe and Jabbur, 1959; Kennedy and Towe, 1962). The amplitude and duration of the *d* potential and its' time course of excitability recovery following brainstem stimulation are identical to those of the primary evoked potential following cutaneous stimulation. Also, both potentials interact in precisely the same way (Jabbur and Towe, 1961a).

Kennedy and Towe (1962) found the reversal in polarity of the $\bar{d}$ potential at the same cortical depth as the primary evoked potential. The $\bar{d}$ potential is most likely mediated by the medial lemniscus and apparently represents the same cortical phenomena as the primary evoked potential (Kennedy and Towe, 1962).

Different studies have shown that the b potential, with a latency of 1.5 msec following bulbar stimulation (Fig. 6), has attributes of both known antidromic and orthodromic potentials. However, the evidence is in favor of the view that it is orthodromically mediated. It has been proposed that the b potential results from the antidromic activation of an efferent fiber system dorsal to the PT in the brainstem, possibly an aberrant pyramidal tract (Jabbur and Towe, 1961a). This conclusion was based upon the greater resistance of the b response, relative to the c and $\bar{d}$ potentials, to high-frequency stimulation and asphyxia.

The b potential is similar to known orthodromic potentials in that it is attenuated by a conditioning stimulus to the contralateral forepaw (Kennedy and Towe, 1962). The b potential is attenuated to as much as 30% of its control value at some conditioning-test intervals, while the α potential is never attenuated by conditioning stimuli.

Several studies have reported evidence indicating that the b potential is not antidromically mediated by a slowly conducting PT

fiber group. Kennedy and Towe (1962) and McMillan *et al.* (1975) reported that the maximum *a* and *b* potentials are recorded at different foci on the cerebral cortex. The maximum amplitude for the *a* potential is recorded along the cruciate sulcus, while that for the *b* potential is recorded near the coronal sulcus. In studies using midbrain stimulation, McMillan *et al.* (1975) reported that the *b* potential is evoked most readily when the stimulating electrode is positioned dorsal to the basis pedunculi, while the *a* potential is most easily evoked when the stimulating electrode is in the basis pedunculi. This suggests that the *b* potential is mediated to the cortex by a fiber system other than the pyramidal tract, and that this fiber system is located dorsal to the PT in the brainstem.

Evidence from electrophysiological studies has also indicated that the *b* potential is not caused by the post-synaptic activity of recurrent PT collaterals within the cerebral cortex. McMillan *et al.* (1975) reported that the *b* potential does not reverse polarity as the recording microelectrode is advanced in successive depth intervals through the cortex. These results are supported by studies in which the *b* potential was recorded in the absence of a cortex (Kennedy and Towe, 1962). These results indicate that the *b* potential is produced by action potentials approaching the cerebral cortex from below.

The *b* potential is apparently equivalent to the surface-positive potentials with a latency of 1.5 msec, following bulbar stimulation,

reported by Porter (1955) and Chang (1955a,b), which these investigators attributed to antidromic activation of a slowly conducting PT fiber group. No potential corresponding to the α potential was described by these authors. However, examination of their published records shows that the shock artifact resulting from stimulation, lasted long enough to obscure the α potential. Landau (1956) first proposed that the b potential equivalent was the result of orthodromic activation of the medial lemniscus due to volume conduction of the stimulus current.

Evoked cortical potentials were further investigated by recording intracellularly with microelectrodes following stimulation in the midbrain (Stefanis and Jasper, 1964a). Action potentials were recorded following stimulation; the average latency was 1.4 msec. It was assumed by the authors that these were antidromic action potentials rather than postsynaptic discharges resulting from orthodromic activation of the medial lemniscus.

Humphrey (1968) also investigated the antidromic cortical response following midbrain stimulation. He concluded that the surface-recorded α and b potentials were the result of antidromic activation of the PT and orthodromic activation of the medial lemniscus, respectively. Recording with microelectrodes at successive depths in the cortex, he reported an early negative potential (N_1), with a latency of 1.6 msec, and a late negative potential (N_2), with a latency of 3.8 msec.

N_1 is an amplification of the negativity between the surface α and beta potentials, and was presumed to more accurately represent the arrival at the cortex of antidromic activity conducted by the fast PT fiber component. N_2 is a reverse in polarity of the beta potential, and was presumed to result from both the antidromic conduction in a slowly conducting PT fiber group, and collateral induced post-synaptic responses. These latter conclusions were based upon the separation of the N_2 potential into two current components at separate depths in the cortex.

The effects of conditioning thalamic stimulation on PT neurons were investigated by Sasaki and Prelevic (1972). They reported that conditioning stimulation of specific and non-specific thalamic nuclei had both excitatory and inhibitory influences on fast and slow negative, "antidromic" potentials, which were recorded intracortically following stimulation of the basis pedunculi. These negative potentials are apparently different from those recorded by Humphrey (1968), because of the differences in their latencies of activation; the latencies of N_1 and N_2 in this study were approximately 0.80 and 2.7 msec, respectively. McMillan *et al.* (1975) could reproduce the results of Sasaki and Prelevic (1972) only if jaw movement occurred in the animal, and most readily if the stimulating electrode had penetrated the ventral surface of the brainstem. Furthermore, the potentials corresponding to the N_1 and N_2 potentials could be abolished by the

administration of a paralyzing agent. It is questionable, therefore, whether the N_1 and N_2 potentials of Sasaki and Prelevic (1972) represent antidromic conduction in pyramidal tract neurons.

It is obvious that considerable debate still exists regarding the anatomical and physiological organization of the pyramidal tract. The present project was designed to investigate one aspect of the controversy, namely the electrophysiological characteristics of the *b* potential. The specific goal of this study was to determine if the *b* potential is antidromic or orthodromic in nature and if it is mediated to the cerebral cortex by a fiber system other than the pyramidal tract.

In this study, the stimulating electrodes were positioned at the level of the rostral pons and the midbrain, where the pyramidal tract and medial lemniscus are separated by 4 to 5 millimeters (Fig. 5). The segregation of the fiber systems made available by this stimulating procedure allowed for a more efficient investigation of each fiber tract individually, and reduced the problem of volume conduction of the stimulus current.

The data obtained during the study supports the view that the *b* potential is orthodromically mediated to the cerebral cortex by an afferent fiber system, probably the medial lemniscus.

MATERIALS AND METHODS

Surgical Procedures

Adult cats ranging in weight from approximately 2 to 5 kilograms were used for this study. Sodium pentobarbitol (Nembutal) anaesthesia was administered at dosages of 30-35 mg/Kg by intraperitoneal injection. The femoral vein was cannulated for the purpose of administering additional anaesthesia and isotonic saline solution to prevent dehydration. The trachea was cannulated for administration of artificial ventilation. Intravenous injections of a paralyzing agent, decamethonium bromide (Syncurine), were then administered at dosages of 1 mg/hr.

The animals were then placed in a stereotaxic frame and the body was placed on a circulating water blanket for the purpose of maintaining the body temperature at 37° C, which was monitored by a rectal thermometer. The body temperature was maintained at 37° C by a control system which automatically adjusted the water temperature in the circulating water blanket as required. A bilateral pneumothorax and drainage of the cisterna magna were performed to eliminate cerebral pulsation due to respiratory movement and blood pressure. In some experiments the carotid artery was cannulated to record the blood pressure.

The sensorimotor area of the cerebral cortex ipsilateral to the cannulated femoral vein was exposed by rongeurs for recording procedures and the cerebral cortex overlying the rostral part of the brainstem was exposed by trephination for stimulation of the midbrain (Fig. 7). The dura mater was reflected from the stimulating and recording sites, after which dessication of the cortex was minimized by irrigating it with warm, isotonic saline solution and covering the exposures with sheets of thin polyethylene.

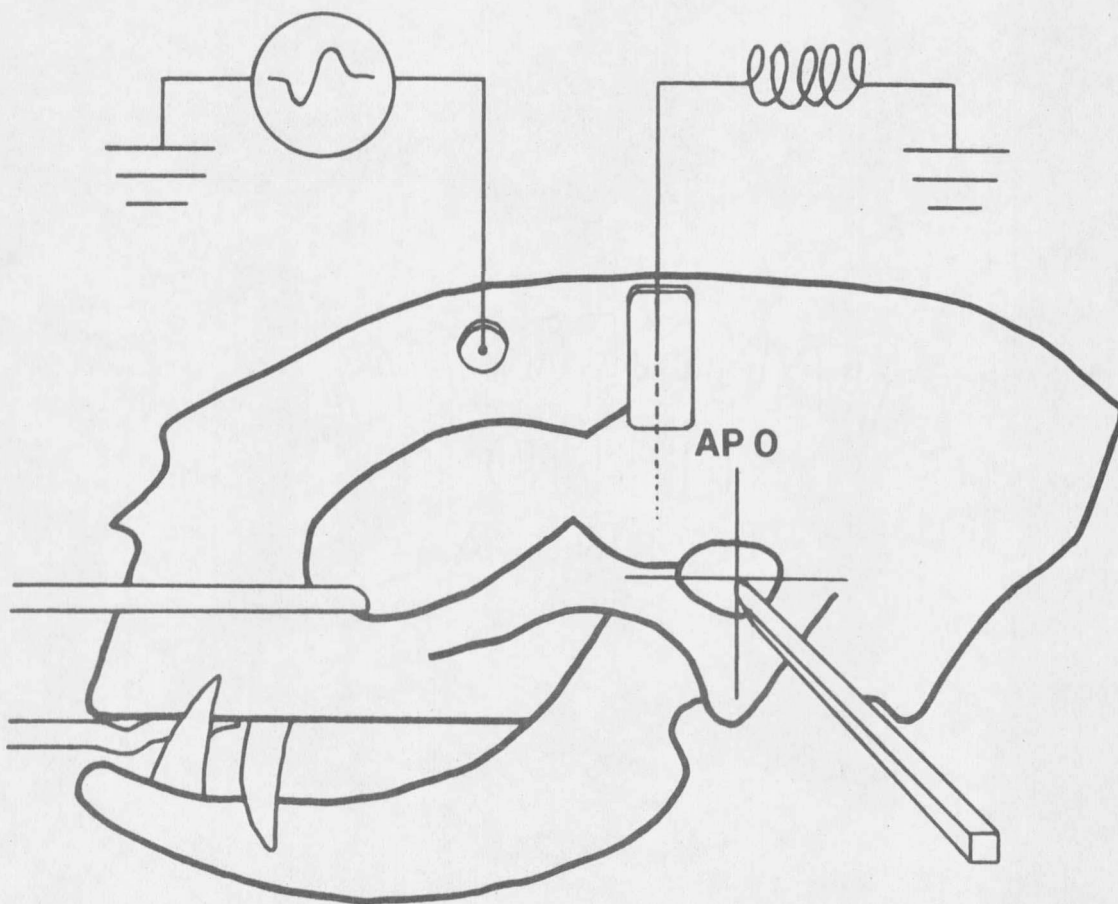
Stimulation and Recording Procedures

Bipolar needle electrodes were inserted into the central footpad of the forepaw contralateral to the recording site for stimulation of peripheral afferent fibers. Square wave pulses approximately one to five msec in duration were administered to the forepaw by a W-P Instruments Company Model 302-T Anapulse Stimulator and an isolation transformer unit.

Bipolar concentric stainless steel electrodes (0.50 mm outside diameter) were used for stimulation of the midbrain; the electrodes were stereotaxically positioned in appropriate midbrain sites (Fig. 7). Stimuli to the midbrain, which were 0.5-1.0 msec in duration, were delivered from the second channel of the stimulator.

Monopolar surface recordings from the sensorimotor area of the cerebral cortex were made with an Ag-AgCl ball electrode (Fig. 7).

Figure 7. Illustration of the cat skull showing the relative positions of the eye, ear, and mouth bars of the stereotaxic holder. The approximate locations of the exposures used in the study for recording from the sensorimotor area of the cerebral cortex and stimulating in the brainstem are shown. The vertical plane of the coordinate axis over the external auditory meatus corresponds to the stereotaxic reference plane (AP 0) in the brainstem. Taken from Storer and Usinger (1957) and modified.



An alligator clip attached to the temporalis muscle served as the indifferent electrode. Recordings were led into the differential amplifier of a 5103N Tektronix dual beam oscilloscope and displayed on the screen. All records were photographed on Kodak linagraph model 1930 35 mm photographic paper with a Grass Instrument Company Model C4R oscilloscope camera.

Experimental Procedures

Identification of the α and b potentials. The criteria used to identify the different components of the complex potential recorded from the cerebral cortex following midbrain stimulation were (1) latency of activation and (2) ability to follow high rates of stimulation. The α potential has been reported to have a 0.3-0.5 msec latency following midbrain stimulation, while that for the b potential is 0.9-1.0 msec (McMillan *et al.*, 1975). The α potential responds to repetitive stimulation in excess of at least 100/sec without a change in amplitude or configuration; the b potential is attenuated at stimulus rates in excess of 50/sec (Kennedy and Towe, 1962; McMillan *et al.*, 1975).

Cortical mapping procedures. Cortical foci for the maximum b potentials evoked by midbrain stimulation were determined by recording the potentials from several points in a grid pattern across the

surface of the cortex while stimulating at one position in the mid-brain at a current intensity adjusted to twice the threshold value. Recordings were taken at 1.0 mm intervals across the coronal plane of the cortex at a given anterior-posterior level, starting as close to the midline as the exposure would allow and recording laterally. This procedure was performed at coronal planes 1.0 mm apart until the exposed surface of the cerebral cortex was mapped with a grid of 1.0 mm squares. A minimum of three responses were recorded at each 1.0 mm interval in the coronal plane and the mean voltage of the 3 *b* potentials was determined. A voltage contour map was constructed for each experiment by plotting isopotential lines at voltages which were 100, 75, 50, and 25 percent of the maximum *b* voltage recorded during the individual trial.

Brainstem mapping procedures. The location of sites in the brainstem which, upon stimulation, produced the *b* potentials of maximum amplitude were determined by a procedure similar to that described above for mapping cortical foci. The recording electrode was placed on the cerebral cortex at the site where the largest primary evoked potential was recorded following stimulation of the contralateral forepaw. The stimulating electrode was then vertically driven into the brainstem at 1.0 mm intervals in accordance with the brainstem dimensions given in a standard stereotaxic atlas (Snider

and Niemer, 1970). This procedure was performed at 1.0 mm intervals lateral to the midline of the brainstem until a grid of 1.0 mm squares was completed for a given transverse plane in the brainstem; the deepest position of each electrode penetration was recorded. This was repeated for transverse planes at other anterior-posterior levels in the brainstem. In most cases, the stimulus intensity was not raised above twice the threshold value. A minimum of three responses was recorded at each stimulating position and the mean voltage of the 3 *b* potentials was determined. For each individual trial, a voltage contour map was constructed by plotting isopotential lines at voltages which were 100, 75, 50, and 25 percent of the maximum *b* voltage recorded.

Conditioning experiments. The *a* and *b* potentials evoked by brainstem stimulation were conditioned by afferent input from the periphery in several experiments. The conditioning stimulus consisted of a supramaximal shock to the contralateral forepaw, and was given at various time intervals ranging from 0-200 msec prior to stimulating the brainstem. At least three responses were recorded at each conditioning-test interval and the mean voltage of the *a* and *b* potentials was determined and compared with control values.

Asphyxiation experiments. In two cats, the α and b potentials were recorded for several minutes after artificial ventilation was stopped at the end of the experiment. The amplitudes of the α and b potentials were compared with control values at 15 msec intervals until both potentials were completely attenuated.

Verification of the Stimulating Sites

At the termination of each experiment, electrolytic lesions were made at stereotaxically determined positions in the brainstem to aid in the verification of the stimulating electrode sites. These lesions were made by applying a D.C. current from a 90 volt battery to the brainstem electrode for 30 seconds. The center lead of the bipolar concentric stimulating electrode was the negative pole; an electrode attached to the temporalis muscle served as the positive pole.

The animals were then given a lethal injection of sodium pentobarbitol. The cerebral vascular system was cleared with physiological saline administered through the carotid artery; the brain was subsequently perfused with 10% formalin. The cranium was cleared of as much tissue as possible, separated from the body, and immersed in 10% formalin. The temporal bone and most of the occipital bone was removed to permit more efficient external perfusion.

After a period of at least one week, the crania were removed from formalin solution and re-centered in the stereotaxic holder. Blocks

containing the stimulating electrode tracts were cut with a vertically oriented spatula blade attached to a stereotaxic driver. The blocks were frozen and 50 micron sections were cut with a sliding microtome. Selected sections were mounted and stained by the cresyl-violet technique.

The location of the stimulating electrode tracts were reconstructed by microscopic examination of the stained slides. The known distance between the deepest position of the stimulating electrode and the electrolytic lesion served as a calibration for length in the cross-sections.

In some experiments, the stimulating electrode penetrated through the base of the brain. Data from these experiments were not included in the study because it was impossible to determine the precise location of the stimulating sites.

RESULTS

Cortical Maps of the *b* Potential

The maximum amplitudes of the *b* potentials were recorded at areas on the cerebral cortex considerably apart from where the largest *a* potentials were recorded. Figures 8 through 11 show the voltage contour maps of the foci on the cerebral cortex at which the *b* potentials of largest amplitude were recorded following stimulation at one position in the brainstem in different experiments. Interpretation of the results was complicated by the variability in the control values of the *a* and *b* potentials, since this makes conclusions about the results less precise.

The *b* potentials of largest amplitude were recorded near the coronal sulcus ranging from approximately 5-6 mm caudal to the cruciate sulcus and from 6-10 mm lateral to the midline of the brain. In two experiments, *b* potentials with an amplitude 25% of the largest *b* potential were recorded at the cruciate sulcus (Figures 10 and 11).

The maximum *a* potentials were recorded along the lateral part of the cruciate sulcus in these experiments, but were not mapped.

Brainstem Foci Eliciting the *b* Potential

The foci in the brainstem of 7 cats which elicited the *b* potentials of largest amplitude, following stimulation at an intensity twice the threshold value, were determined for the transverse plane 1.0 mm

posterior to the stereotaxic reference plane (Fig. 12), the stereotaxic reference plane (Fig. 13), and for eleven transverse planes between 1.0 and 6.5 mm anterior to the stereotaxic reference plane (Figures 14-24). In all cases, the foci of stimulation in the pons and midbrain, which elicited the *b* potentials of largest amplitude on the cortex, were located dorsal to the corticospinal (PT) fibers in the pons and in the midbrain. In a majority of the experiments, these foci were near the medial lemniscus (Figures 13, 14, 16, 18-20, 23 and 24). The position of the medial lemniscus was determined by comparison of comparable sections in the stereotaxic atlas (Snider and Niemer, 1970). There were some instances in which the focus appeared to be dorsal to the medial lemniscus (Figures 12, 15) or between the medial lemniscus and the basis pedunculi of the midbrain (Figures 21, 22). In the latter case, however, no *b* potentials greater than 50% of the maximum *b* potential were recorded when the stimulating electrode was determined to be in the basis pedunculi. Responses with a magnitude of at least 75% of the maximum *b* potential were always recorded when the stimulating electrode was projected to be in the medial lemniscus (Fig. 21).

The foci in the brainstem which elicited the largest *a* potentials following stimulation were recorded when the stimulating electrode was determined to be in the basis pedunculi. The variation in the control values of the potentials also made interpretation of the results more

difficult in these experiments.

Conditioning Experiments

Stimulation of the contralateral forepaw had a strong inhibitory effect on the *b* potential evoked by subsequent stimulation of the brainstem. Figure 25 shows this conditioning-test interaction in one experiment at 0, 50, 100, and 150 msec C-T intervals. The *b* potential was attenuated to about 0.05 mv, approximately 50% of its control value (0.1 mv), when the interval between forepaw and midbrain stimulation was 50 msec. The *b* potential was partially recovered at a 100 msec conditioning-test interval, and was almost back to control values at a 150 msec interval.

Figure 26 shows the effect of contralateral forepaw stimulation on the *b* potential evoked by subsequent brainstem stimulation in eight cats. There was a consistent decrease in the *b* potential amplitude when the C-T interval was between 30-200 msec (95% confidence limits, one-tailed test). The greatest attenuation of the *b* potential was recorded when the test stimulus was given between 50 and 60 msec after the conditioning stimulus; the *b* potential was attenuated to as much as 30% of its control value at this C-T interval.

There was a consistent increase in the *b* potential at a 10 msec conditioning-test interval. Using 80% confidence limits, the lower limit of the calculated range was greater than the test-control

percentage of 100 as determined by the Student's *t* distribution with a one-tailed test.

The α potential was not affected by a conditioning stimulus to the contralateral forepaw at any C-T interval (Fig. 27). These values were well within the range of predicted values calculated by using 95% confidence limits with the two-tailed Student's *t*-test. The amplitude of the α potential did show a small increase over control values at most of the C-T intervals up to 200 msec, but the increase was not statistically significant. Even though the increase in the amplitudes of the α potential at all C-T intervals was not statistically significant, it was consistently present in all experiments.

Asphyxiation Experiments

In two experiments, the α and b potentials showed a differential sensitivity to conditions of asphyxia. Both potentials were completely attenuated after a few minutes; however, the α potentials showed a greater resistance. Figure 28 shows the effect of asphyxia on the α and b potentials for one experiment. The b potential was completely attenuated approximately 2.7 minutes after discontinuing artificial ventilation, while the α potential was not abolished until approximately 4.8 minutes after the start of asphyxia. The b potential was completely attenuated before the amplitude of the α potential dropped below control values.

An increase in the amplitudes of both the a and b potentials occurred immediately after the start of asphyxiation. This period lasted approximately 3.5 minutes in the case of the a potential and approximately 1.5 minutes for the b potential (Fig. 28). These results are similar to those recorded in another experiment in which complete attenuation of the a and b potentials was reached 7 and 4 minutes after the start of asphyxia, respectively.

Figure 8. Isopotential contour map of the foci on the cerebral cortex from which the *b* potentials of largest amplitude were recorded following brainstem stimulation: Experiment # CM-4. The *b* potentials of maximum voltage were recorded slightly rostro-medial to the coronal sulcus, considerably posterior to the cruciate sulcus, where the largest *a* potentials were recorded.

The cruciate (Cr), Coronal (Co), and Ansate (An) sulci are labeled and their relationship to the general cerebral topography is shown in the inset. The lateral sulcus (La) is also labeled in the inset.

The horizontal line at the top of the figure is calibrated in reference to the cruciate sulcus, with positive values being millimeters posterior to the cruciate sulcus, negative values being millimeters anterior. The vertical line at the left is calibrated in millimeters lateral to the midline. The voltage contour map is constructed so that the isopotential lines represent voltages which were 100, 75, 50, and 25 percent of the maximum *b* voltage recorded.

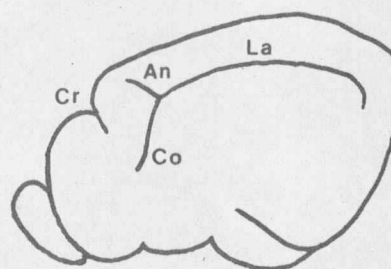
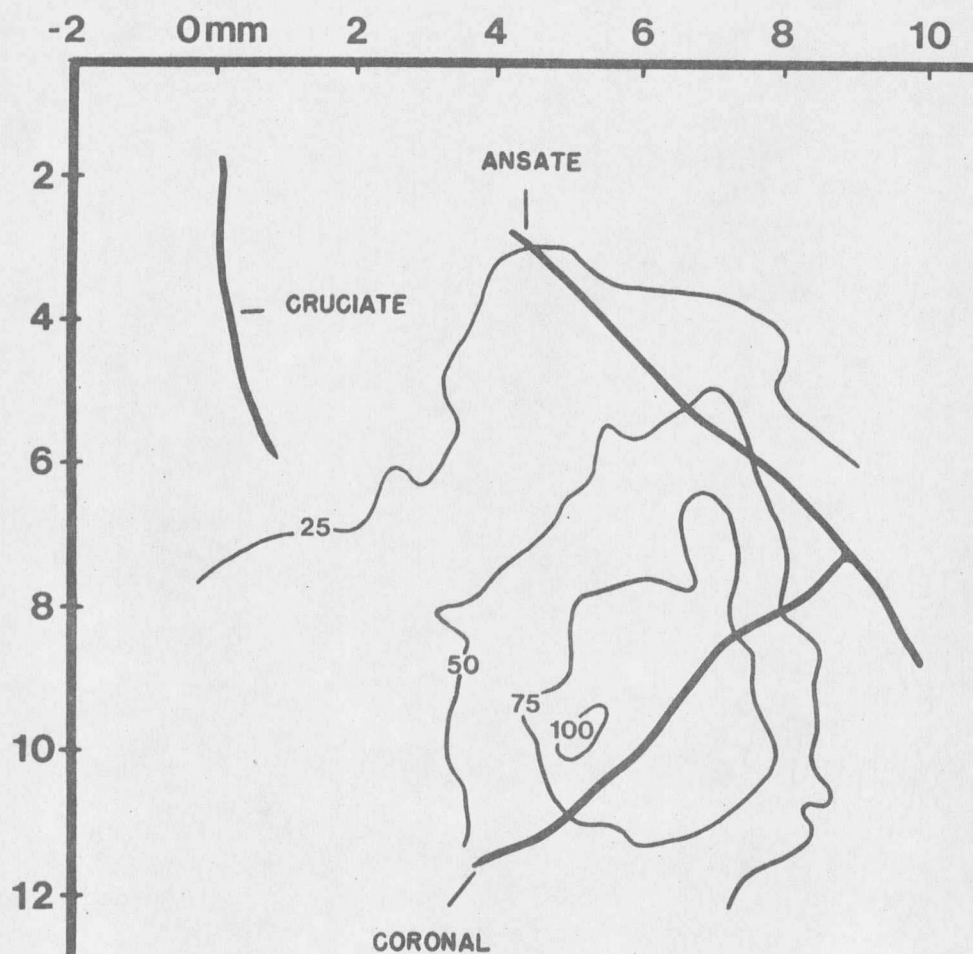


Figure 9. Isopotential contour map of the *b* potential:

Experiment # CM-1. The *b* potentials of maximum voltage were recorded rostral and medial to the coronal sulcus.

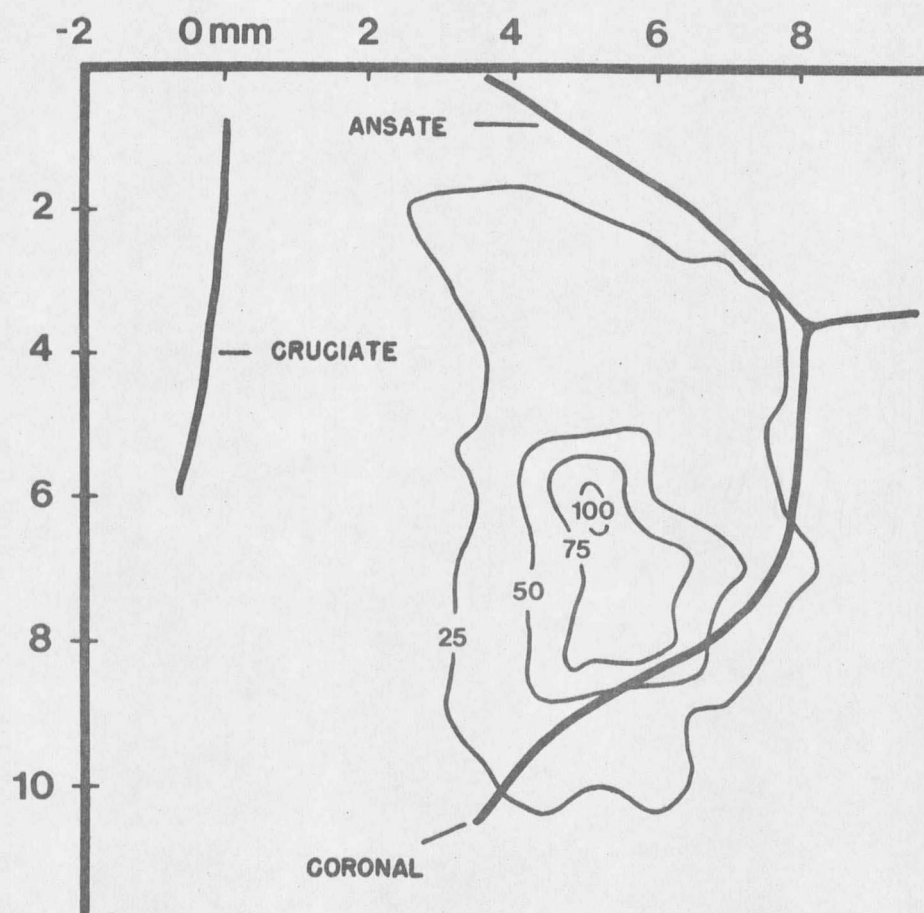


Figure 10. Isopotential contour map of the *b* potential:

Experiment # CM-2. The *b* potentials of maximum voltage were recorded just rostral and medial to the coronal sulcus. The 25% isopotential line is broken, indicating that *b* potentials with voltages 25% of the maximum *b* potential were recorded at the cruciate sulcus.

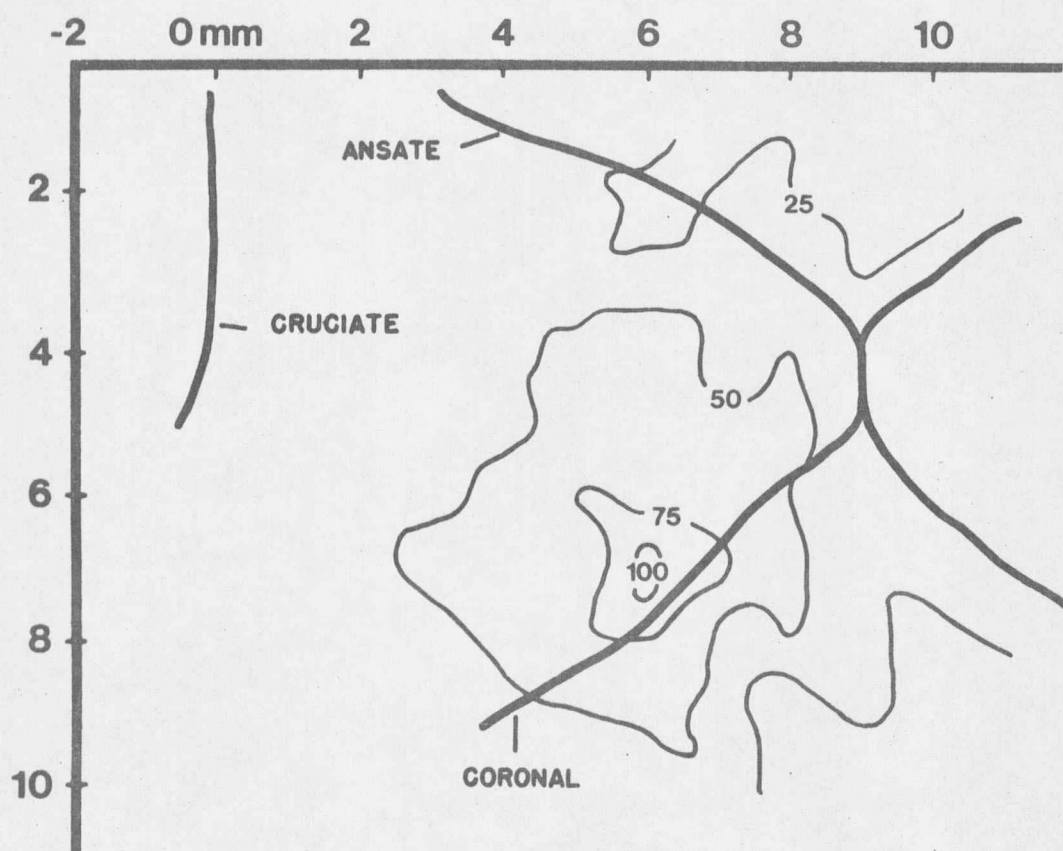


Figure 11. Isopotential contour map of the *b* potential:

Experiment # CM-3. The *b* potentials of maximum voltage were recorded just rostral and medial to the coronal sulcus.

The 25% isopotential line crosses the cruciate sulcus indicating that *b* potentials with voltages 25% of the maximum *b* potential were recorded here.

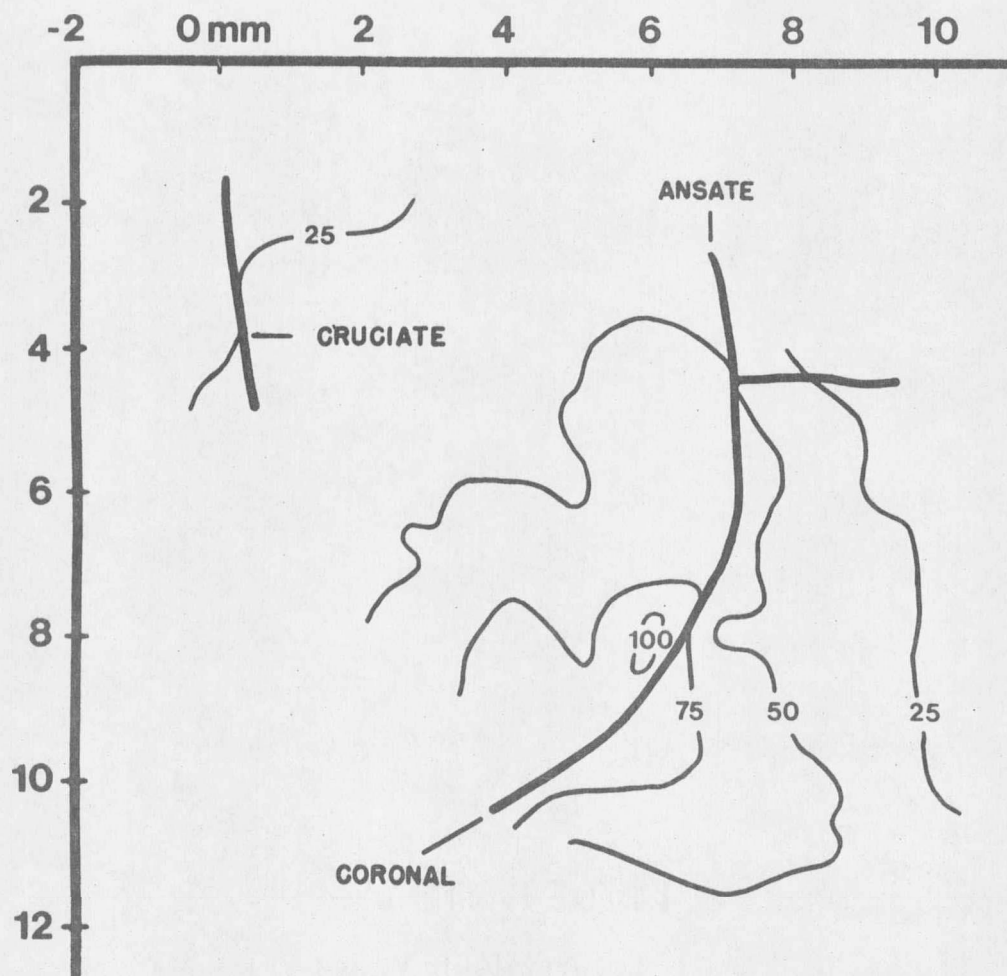


Figure 12. Transverse section of the brainstem 1.0 mm posterior (P 1.0) to the stereotaxic reference plane showing the isopotential contour map of the mid-pontine foci which evoked *b* potentials on the cerebral cortex: Experiment #BSM-5. The stimulating foci at P 1.0 which elicited the *b* potentials of largest voltage are located dorsal to both the pyramidal tract (PT) and the medial lemniscus (ML). The principle stimulating foci are near the mesencephalic reticular formation (MRF) at this level.

The superior colliculus (SC), cerebral aqueduct (CA), central gray (CG), and the spinal lemniscus (SL) are also labeled for reference. The abbreviations for these brainstem structures will remain the same for all succeeding diagrams in which they appear. Additional anatomical landmarks will be referenced as they first appear in succeeding diagrams.

The isopotential contour maps are constructed so that the isopotential lines are at voltages 100, 75, 50, and 25 percent of the maximum *b* voltage recorded. The isopotential contour map is incomplete because the stimulating electrode, positioned in reference to a stereotaxic atlas, was projected to be at the lateral edge of the brainstem, when it was actually positioned farther medially. In several of the succeeding figures, the isopotential contour maps are largely incomplete due to the same reasons.

P 1.0

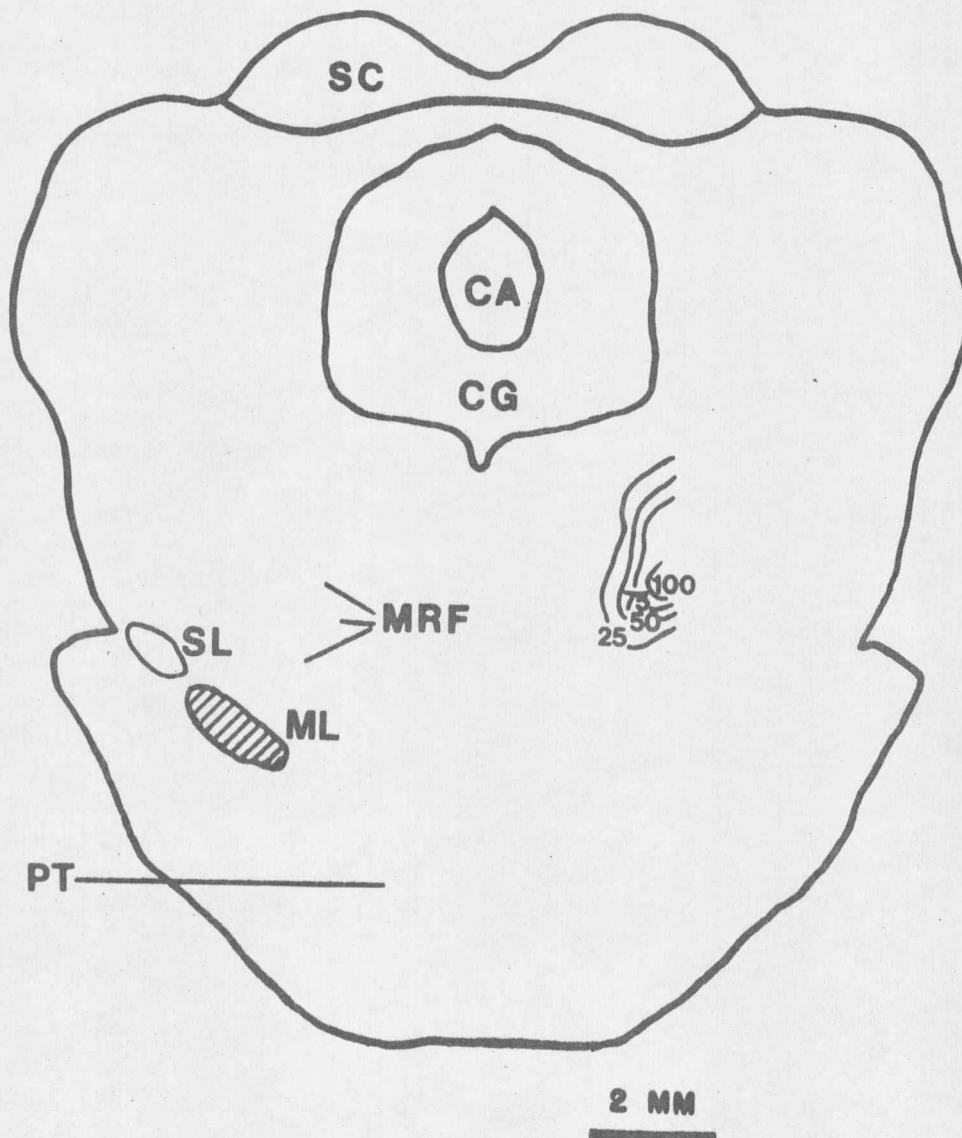


Figure 13. Transverse section of the brainstem at the mid-pontine level showing the isopotential contour map at the stereotaxic reference plane (AP 0): Experiment # BSM-3. The foci at AP 0 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus. The 100% isopotential line is even shaped similar to the medial lemniscus at this transverse level. Potentials 25 and 50 percent of the maximum *b* potential were recorded in the corticospinal tract. The interpeduncular nucleus (IN) is labeled for reference.

AP O

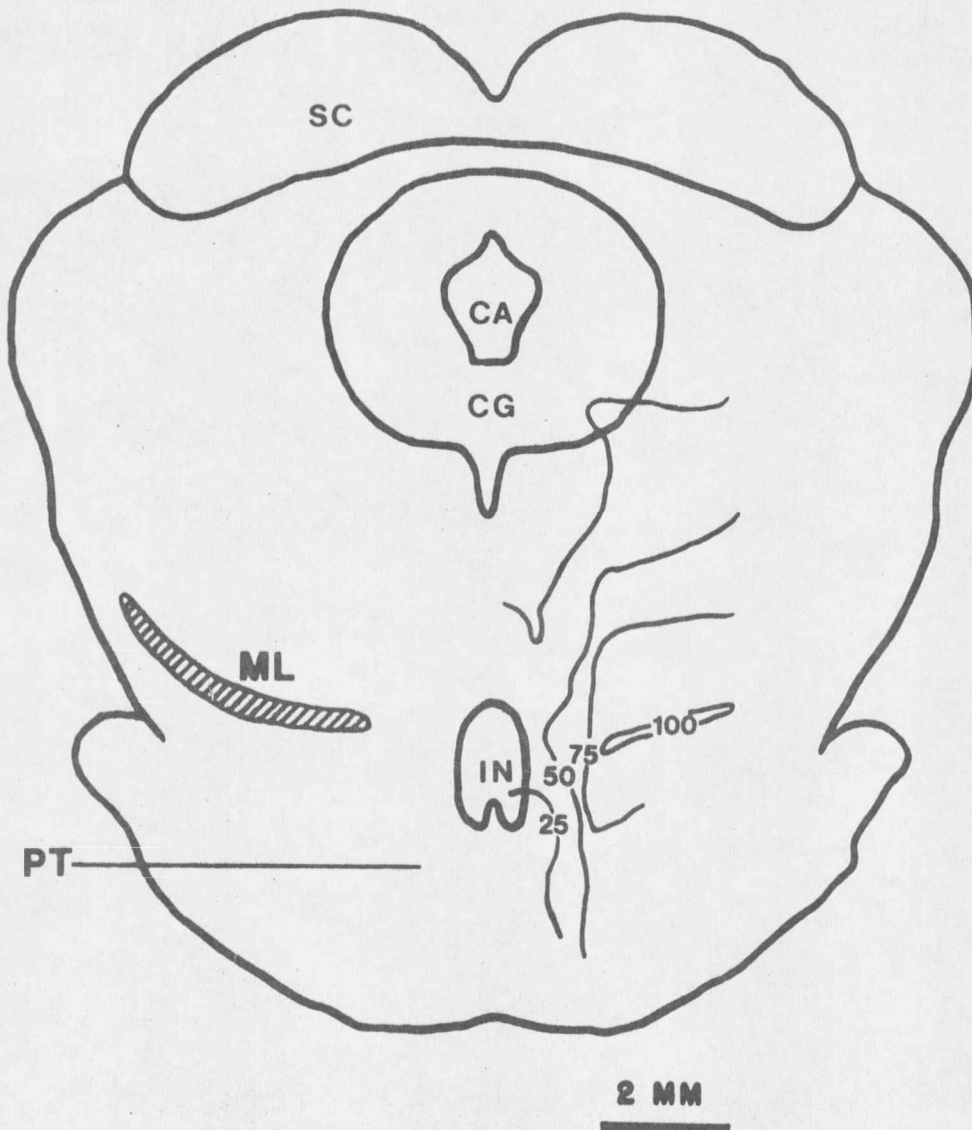


Figure 14. Transverse section of the brainstem in the rostral pons showing the isopotential contour map 1.0 mm anterior (A 1.0) to the stereotaxic reference plane: Experiment # BSM-7. The foci at A 1.0 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML).

A 1.0

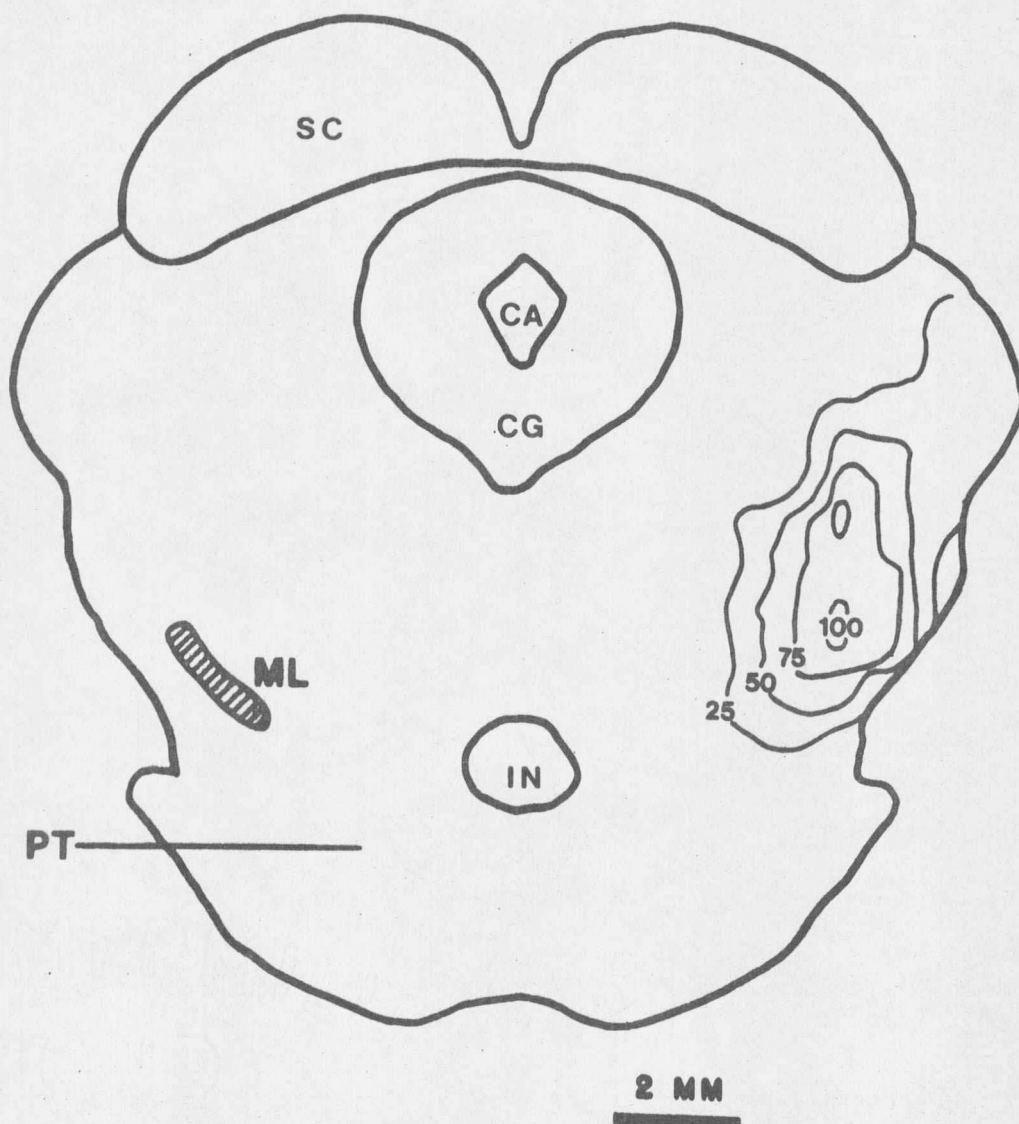


Figure 15. Transverse section of the brainstem at the border of the pons and midbrain showing the isopotential contour map 2.5 mm anterior (A 2.5) to the stereotaxic reference plane: Experiment # BSM-3. The foci at A 2.5 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to both the pyramidal tract (PT) and the medial lemniscus (ML). The medial geniculate nucleus (MG) is keyed for reference.

A 2.5

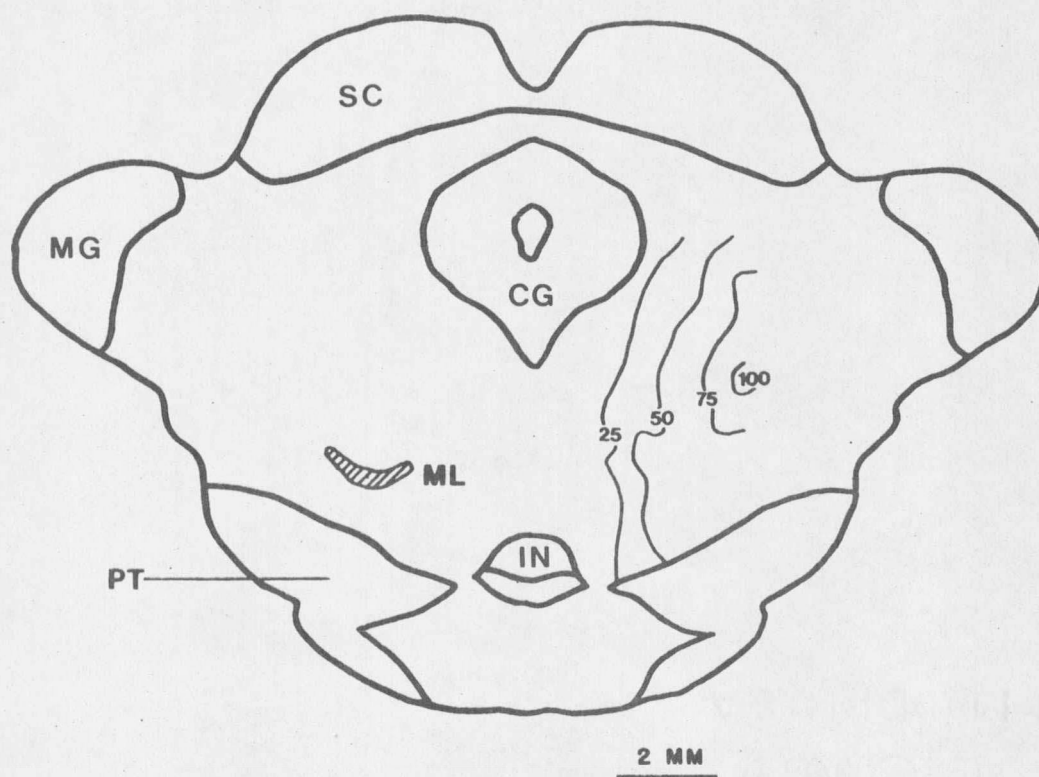


Figure 16. Transverse section of the brainstem in the caudal part of the midbrain showing the isopotential contour map 3.0 mm anterior (A 3.0) to the stereotaxic reference plane: Experiment # BSM-5. The foci at A 3.0 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML).

A 3.0

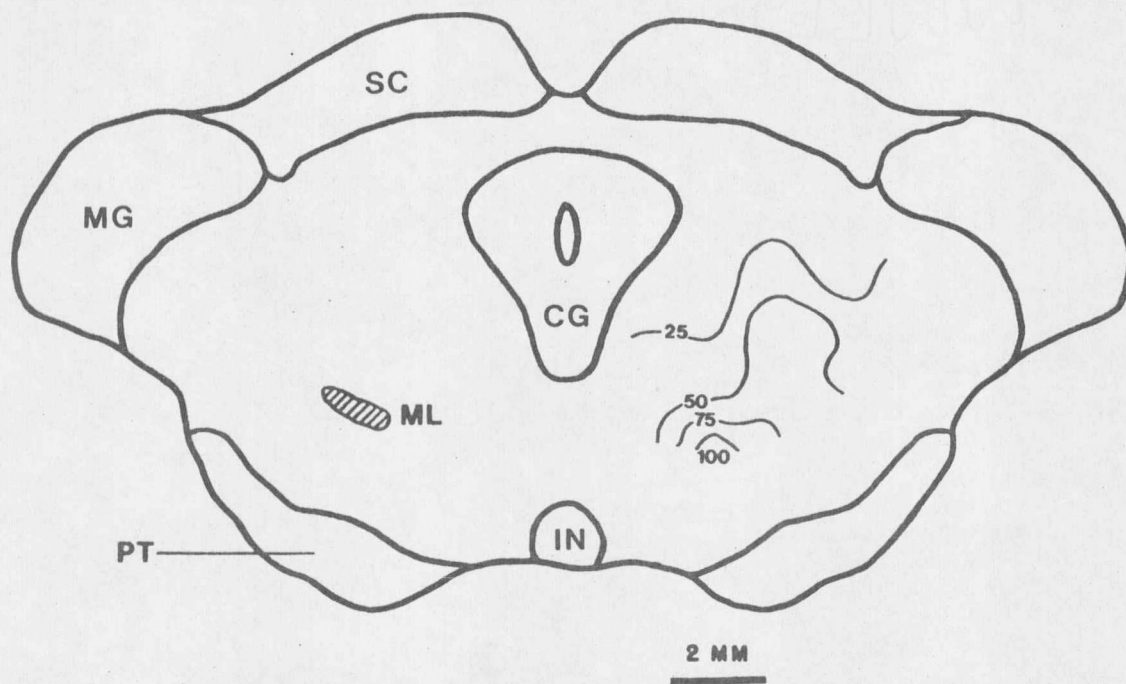


Figure 17. Transverse section of the brainstem in the caudal part of the midbrain showing the isopotential contour map 3.5 mm anterior (A 3.5) to the stereotaxic reference plane:

Experiment # BSM-7. The foci at A 3.5 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML). The principle stimulating foci for the *b* potential are also close to the mesencephalic reticular formation (MRF) and the spinal lemniscus (SL). The red nucleus (RN) and the substantia nigra (SN) are also labeled for reference.

A 3.5

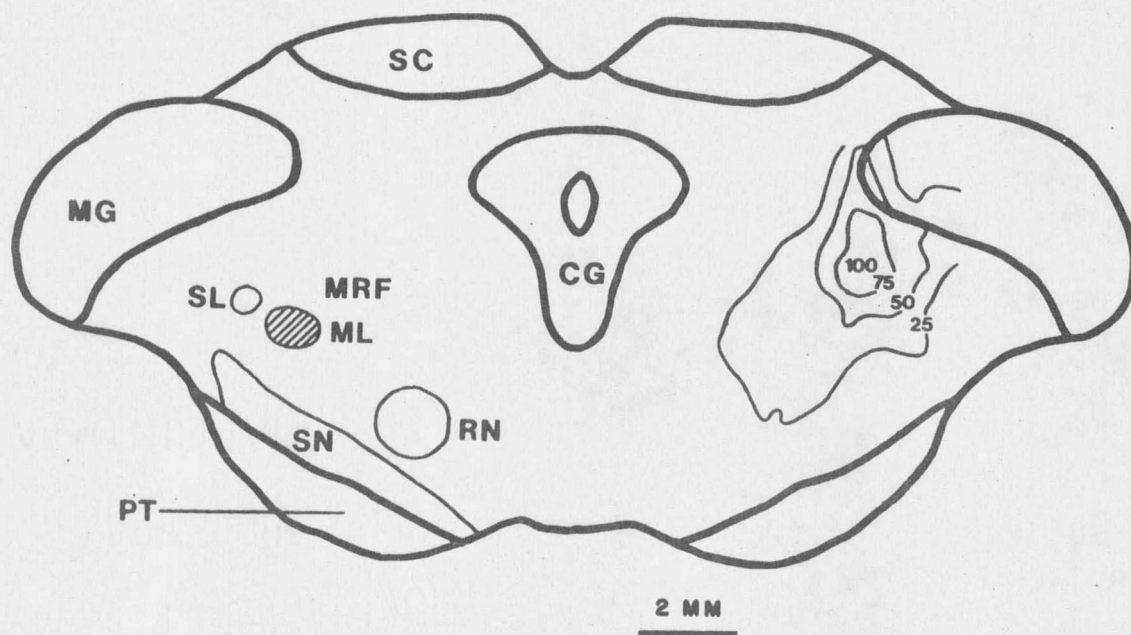


Figure 18. Transverse section of the brainstem in the central part of the midbrain showing the isopotential contour map 4.0 mm anterior (A 4.0) to the stereotaxic reference plane:

Experiment # BSM-2. The foci at A 4.0 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML). The lateral geniculate nucleus (LG) is labeled for reference.

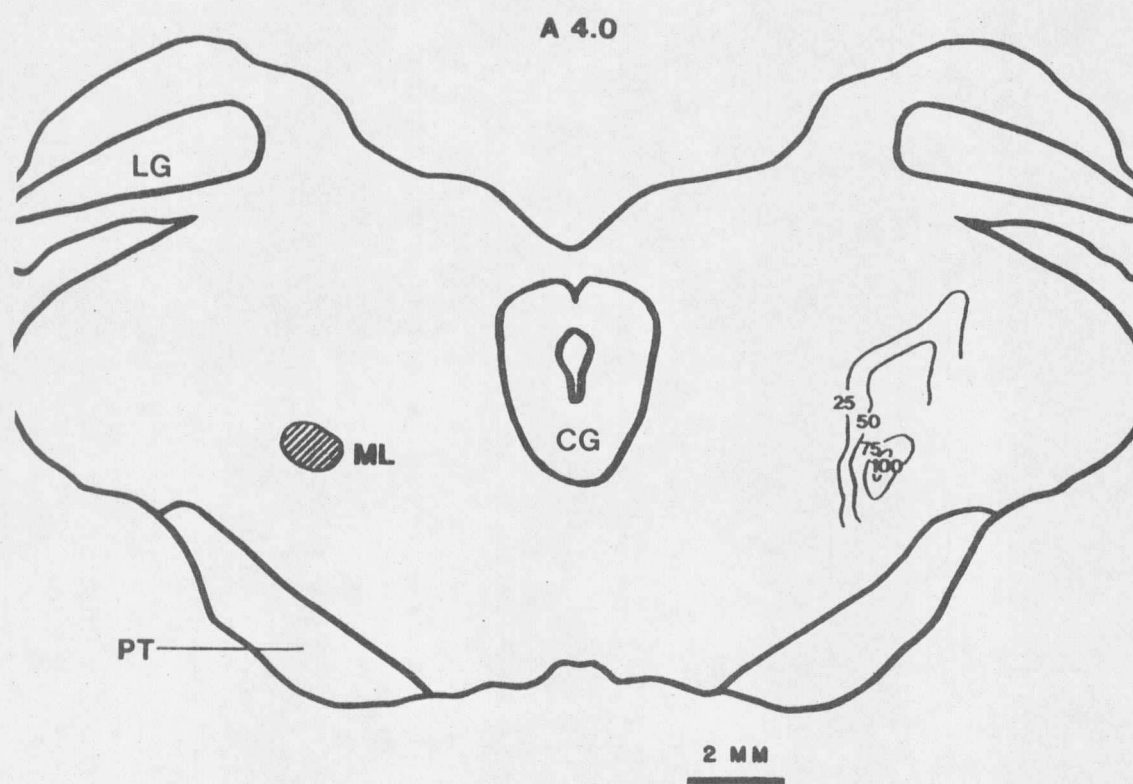


Figure 19. Transverse section of the brainstem in the central part of the midbrain showing the isopotential contour map 4.5 mm anterior (A 4.5) to the stereotaxic reference plane:

Experiment # BSM-1. The foci at A 4.5 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML).

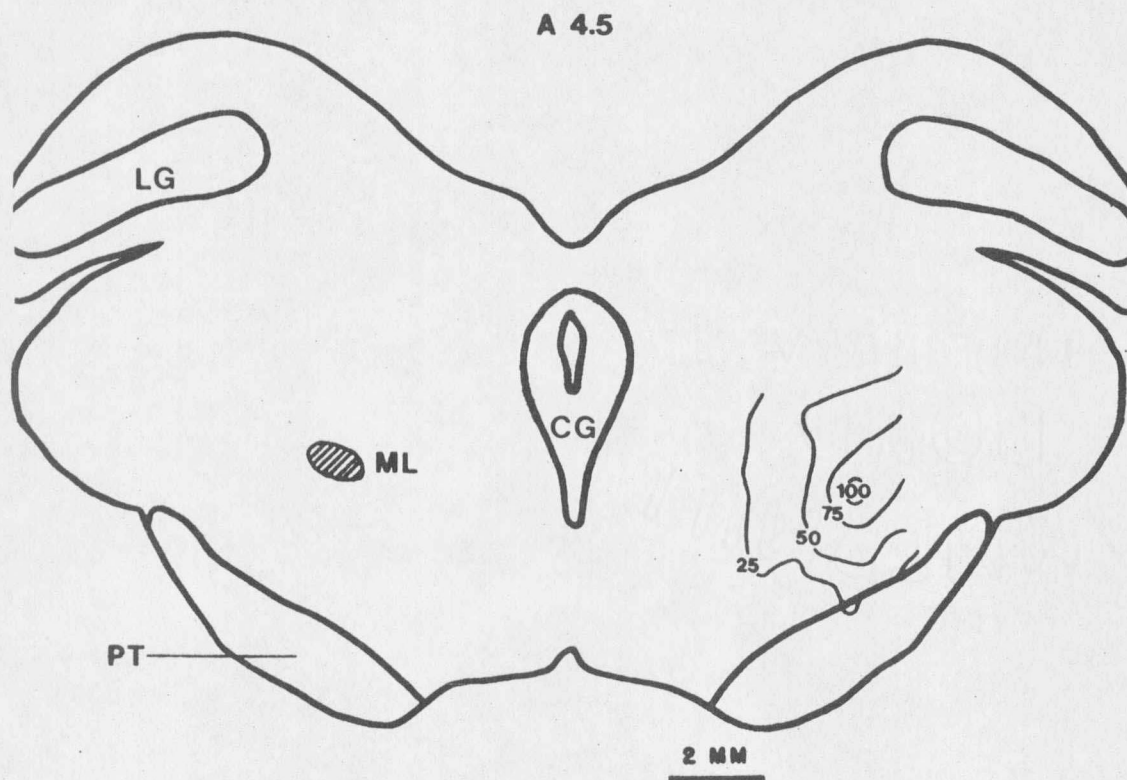


Figure 20. Transverse section of the brainstem in the central part of the midbrain showing the isopotential contour map 4.5 mm anterior (A 4.5) to the stereotaxic reference plane:

Experiment # BSM-4. The foci at A 4.5 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML).

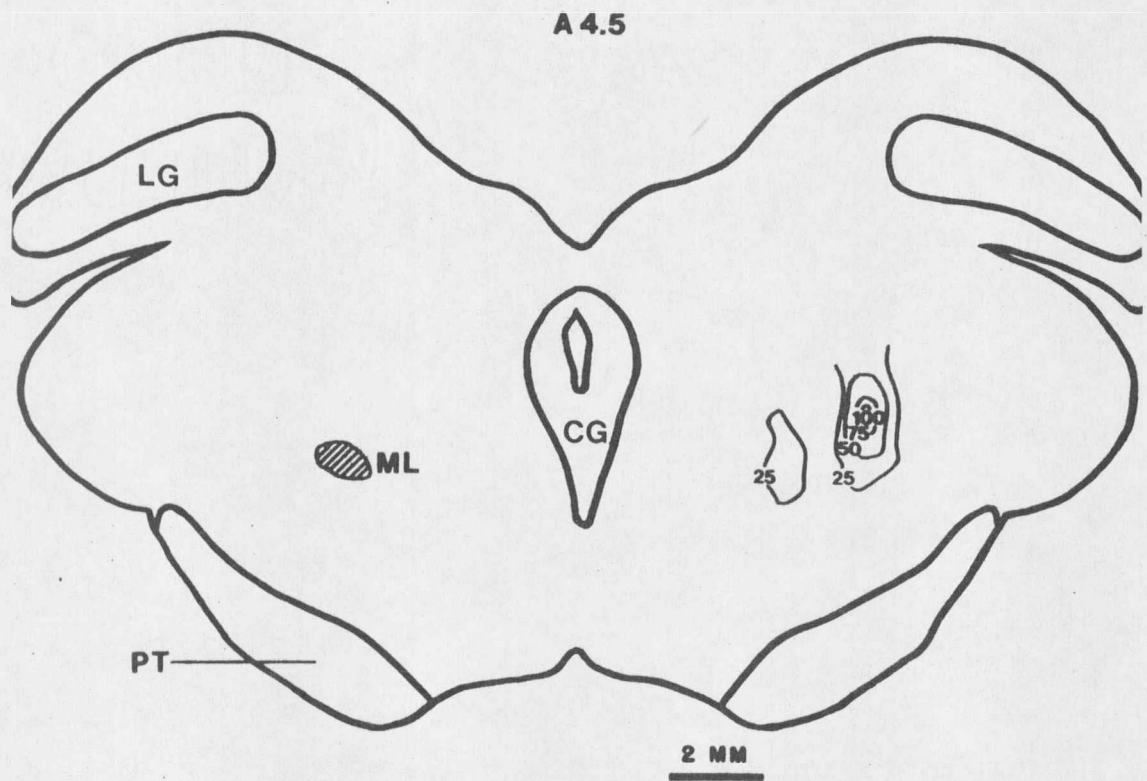


Figure 21. Transverse section of the brainstem in the rostral part of the midbrain showing the isopotential contour map 5.0 mm anterior (A 5.0) to the stereotaxic reference plane:

Experiment # BSM-6. The foci at A 5.0 which elicited *b* potentials of largest amplitude following stimulation are located between the pyramidal tract (PT) and the medial lemniscus (ML). The 25 and 50 percent isopotential lines are located in the dorsal part of the basis pedunculi.

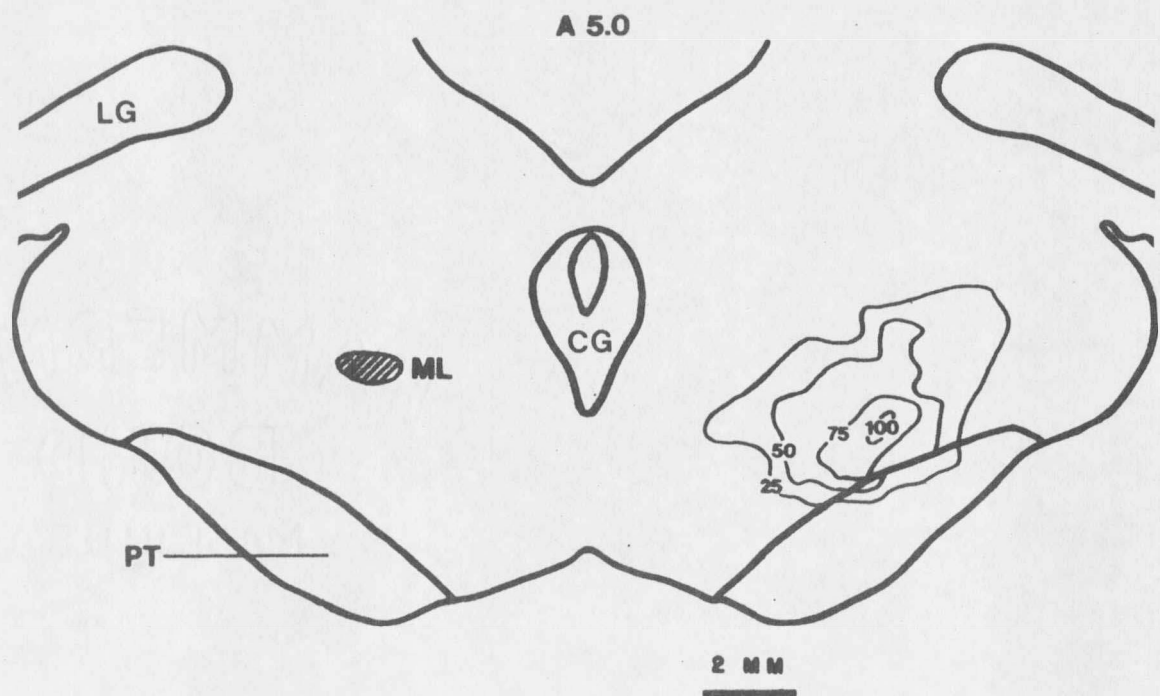


Figure 22. Transverse section of the brainstem in the rostral part of the midbrain showing the isopotential contour map 5.5 mm anterior (A 5.5) to the stereotaxic reference plane:

Experiment # BSM-7. The foci at A 5.5 which elicited the *b* potentials of largest amplitude following stimulation are located between the pyramidal tract (PT) and the medial lemniscus (ML).

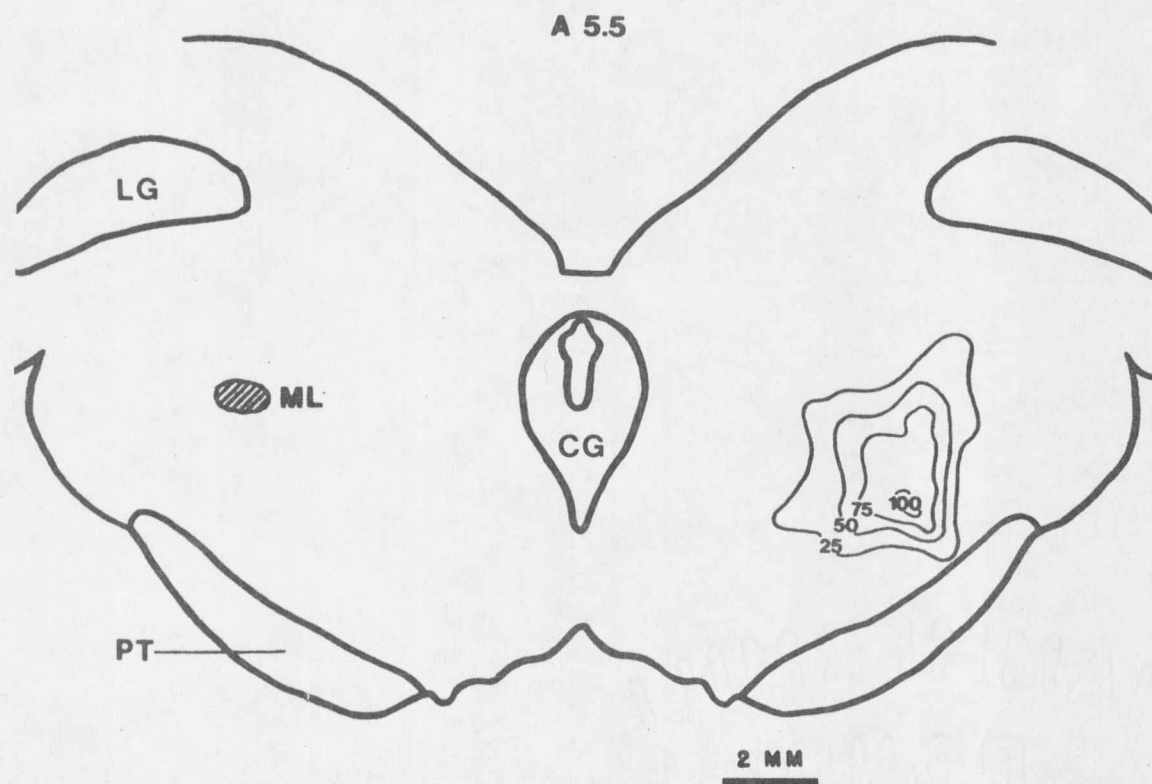


Figure 23. Transverse section of the brainstem in the rostral part of the midbrain showing the isopotential contour map 6.5 mm anterior (A 6.5) to the stereotaxic reference plane:

Experiment # BSM-3. The foci at A 6.5 which elicited *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML). The habenular nucleus (HN) and the third ventricle (III) are labeled for reference.

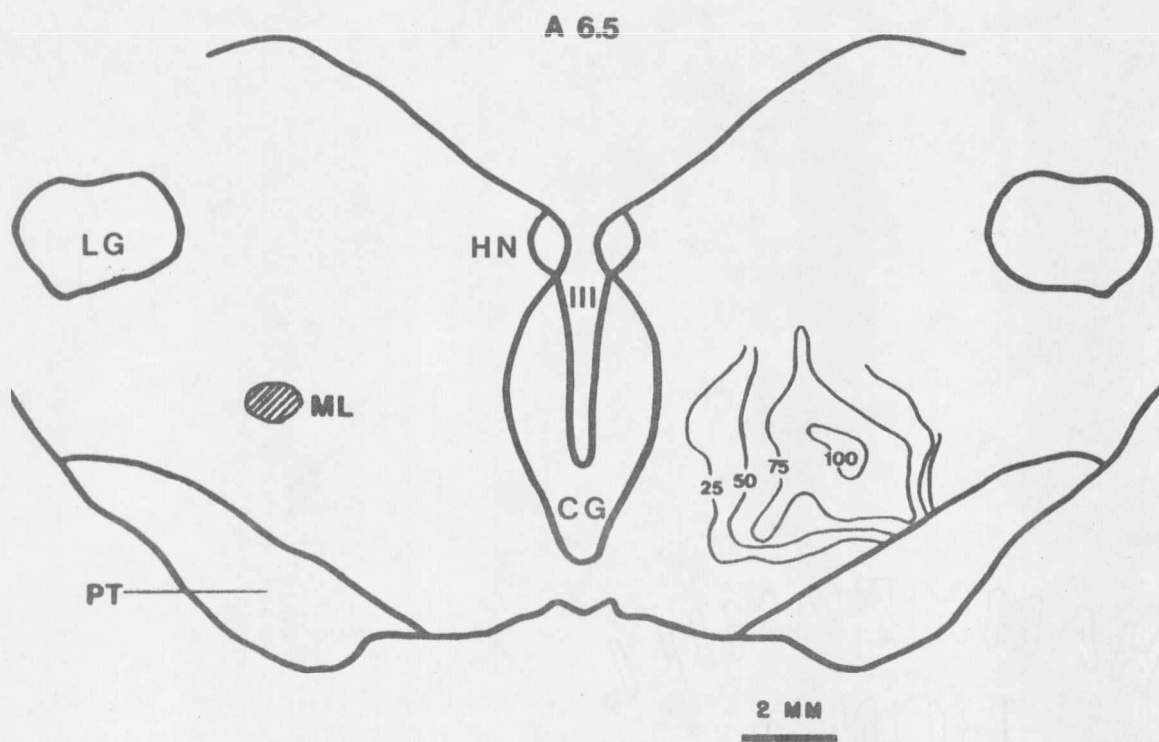


Figure 24. Transverse section of the brainstem in the rostral part of the midbrain showing the isopotential contour map 6.5 mm anterior (A 6.5) to the stereotaxic reference plane:

Experiment # BSM-4. The foci at A 6.5 which elicited the *b* potentials of largest amplitude following stimulation are located dorsal to the pyramidal tract (PT) and near the medial lemniscus (ML).

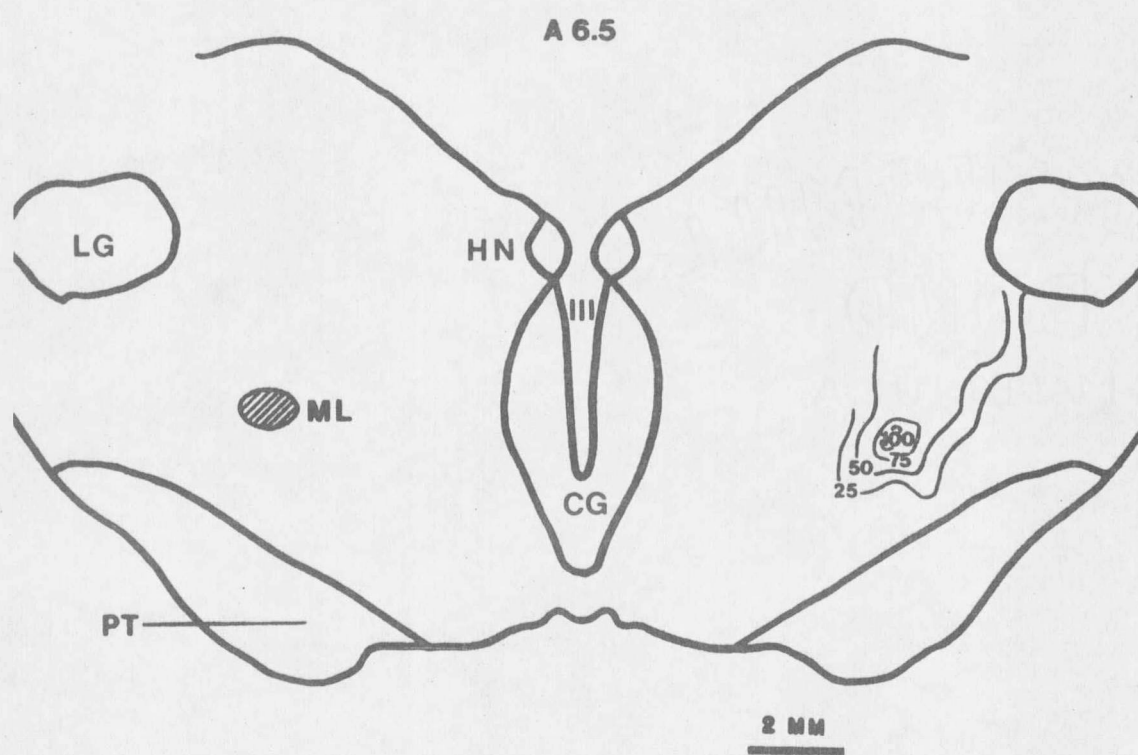


Figure 25. Effect of conditioning stimulation to the contralateral forepaw on the *b* potential evoked by brainstem stimulation, at conditioning-test (C-T) intervals of 0, 50, 100, and 150 msec. The *b* potential is labeled in the upper-most trace. The record at the 0 msec C-T interval represents the control record. Each record is the photograph of the trace across the oscilloscope face; the start of the sweep was triggered by the brainstem stimulation. Time and voltage calibrations are at the right.

The *b* potential is attenuated by conditioning stimulation to the contralateral forepaw; it is attenuated to approximately 50% of its control value at a 50 msec C-T interval. The amplitude of the *b* potential is partially recovered at a 100 msec C-T interval and it is almost back to its control value at a 150 msec C-T interval.

C-T INTERVAL
(MSEC)

0



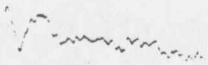
50



100



150



0.1 mv
2 msec

Figure 26. Effects of conditioning stimulation to the contralateral forepaw on the amplitude of the *b* potential over a range of conditioning-test (C-T) intervals from 0 to 200 msec for eight experiments. The C-T intervals are marked on the abscissa and the ordinate values represent the amplitude of the *b* potential as compared to control values. Mean values are represented by the curve, while the vertical bars show the range of values by connecting the maximum and minimum points.

There is an increase in the amplitude of the *b* potential at a 10 msec C-T interval, followed by a rapid attenuation, and a slow recovery. Attenuation of the *b* potential is maximum when the interval between the forepaw and brainstem stimulation is between 50 and 60 msec. At these C-T intervals, the mean attenuation is approximately 50%. The suppression in the amplitude of the *b* potential is long-lasting; the mean amplitude is not fully recovered at a 200 msec C-T interval.

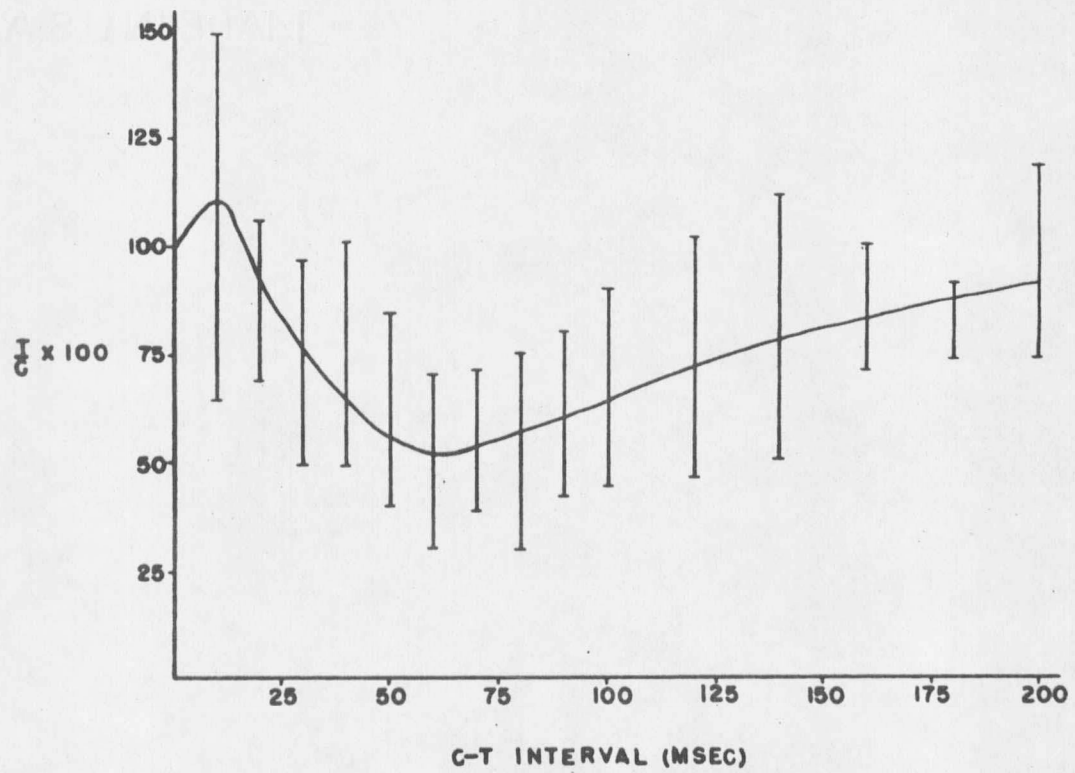


Figure 27. Effects of conditioning stimulation to the contralateral forepaw on the α potential over a range of conditioning-test (C-T) intervals from 0 to 200 msec for four experiments. The graph is labeled the same as in Figure 26, except that X represents the mean values.

The α potential does not interact significantly with conditioning stimulation at any C-T interval, although a small increase in the amplitude was recorded at most of the C-T intervals. These increases were not statistically significant, but the possible physiological implications of this result are discussed in the text (p. 115).

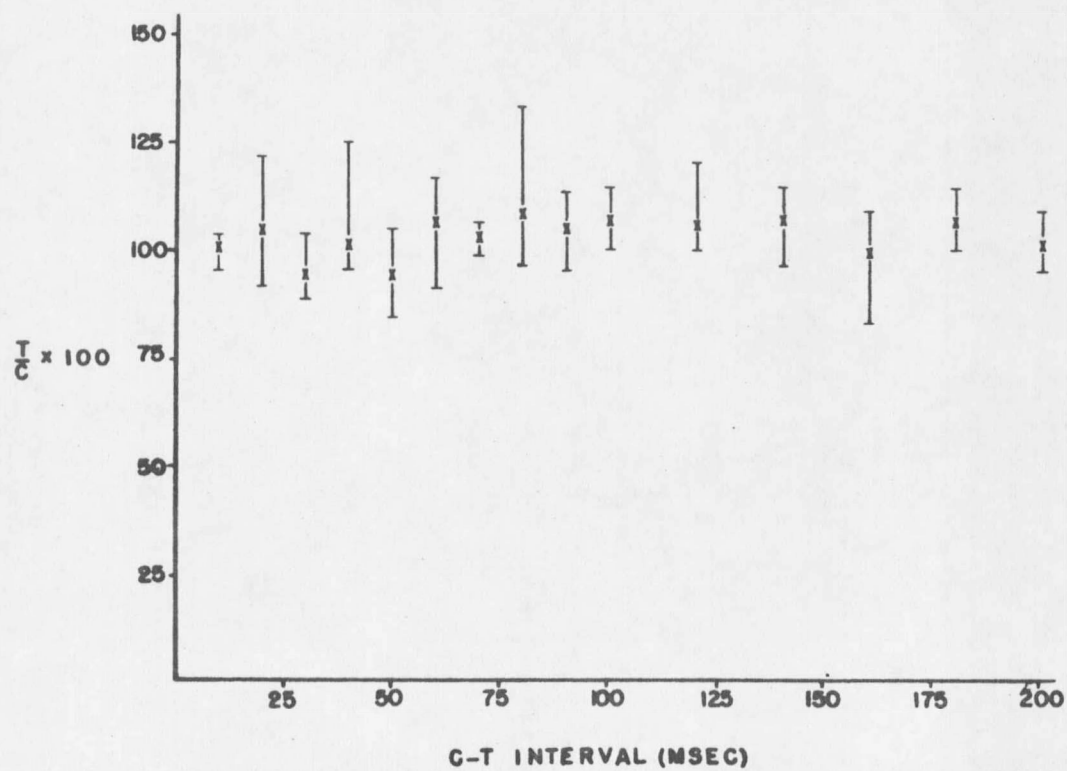
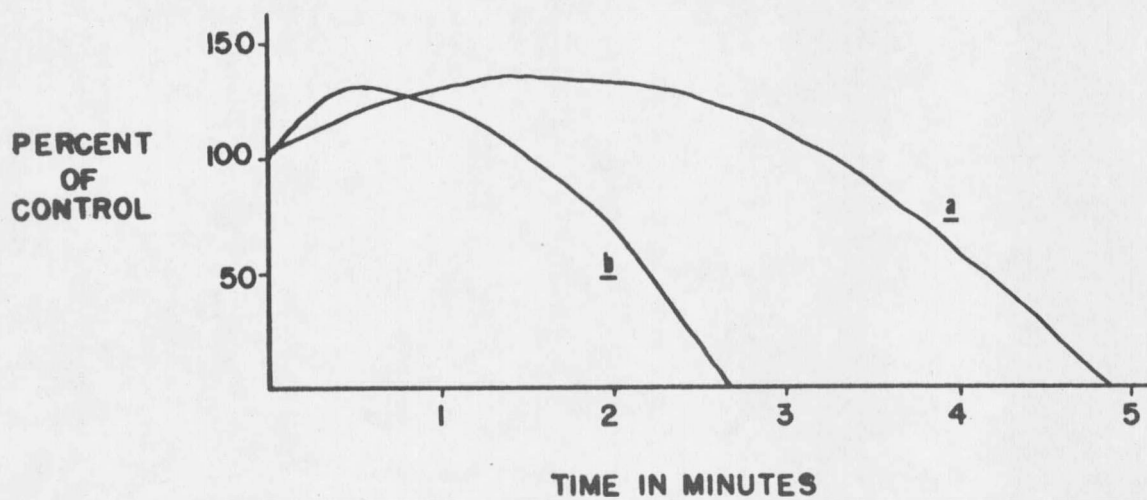


Figure 28. Effects of asphyxia on the α and b potentials.

The values on the abscissa represent the time in minutes after discontinuation of the artificial ventilation, or the start of asphyxia. The ordinate values represent the amplitude of the α and b potentials as compared to control values.

The b potential is completely attenuated about 2 minutes before the α potential, which is not completely attenuated until approximately 4.8 minutes after the start of asphyxia. The b potential is completely attenuated before the amplitude of the α potential decreases below control values.



DISCUSSION

When considering all the results of this study together, it is apparent that the *b* potential is not antidromically mediated by a slower conducting population of pyramidal tract fibers. These results do indicate that action potentials producing the *b* response are conducted orthodromically by one or more afferent fiber systems.

The results from this study indicate that the *a* and *b* potentials are not mediated to the cerebral cortex by the same fiber system. This conclusion is supported by the records showing that, following brainstem stimulation, the principle foci of activity for the *a* and *b* potentials are at different areas on the cerebral cortex. The *a* potentials of largest amplitude are recorded near the lateral tip of the cruciate sulcus, while the largest *b* potentials are recorded near the coronal sulcus. These results are in agreement with those of Kennedy and Towe (1962) and McMillan *et al.* (1975). If the *a* and *b* potentials were mediated to the cortex by the same fiber system, one would expect to record the largest *a* and *b* activity at contiguous, if not identical, foci on the cerebral cortex. This would be predicted, since adjacent corticospinal fibers in the basis pedunculi are somatotopically related (Barnard and Woolsey, 1956) and, therefore, originate at contiguous areas on the cerebral cortex.

The results of this study show that the largest *b* potentials are evoked when the stimulating electrode is positioned dorsal to the corticospinal tract in both the pons and midbrain. These results are in agreement with those of McMillan *et al.* (1975), who reported that the principle midbrain focus for the *b* potential at A 4.0 was dorsal to the red nucleus and lateral to the central gray. In addition, however, this study has shown that the principle stimulating foci for the *b* potential in the brainstem is consistently located near the major somatic sensory fiber groups for a considerable distance, from the mid-pontine level through the entire length of the midbrain. Since previous studies have shown that the largest *a* potentials are evoked when the stimulating electrode is in the basis pedunculi (McMillan *et al.*, 1975), further support is given to the conclusion that the *a* and *b* potentials are mediated by different fiber systems.

Several lines of evidence in this study suggest that the *b* potential is not conducted to the cerebral cortex antidromically, but that it is orthodromically mediated by a pathway which probably involves at least one synaptic relay. The first line of evidence supporting this conclusion is that the *b* potential was significantly attenuated by a conditioning stimulus to the contralateral forepaw. If the *b* potential was antidromically mediated to the cortex, afferent activity would not be expected to significantly alter its conformation.

The α potential, which has been shown to be antidromically mediated by the pyramidal tract (Towe and Jabbur, 1959; Jabbur and Towe, 1961a), is not significantly effected by conditioning stimulation to the contralateral forepaw at any conditioning-test interval. This conditioning phenomena further supports the conclusion that the b potential is not antidromic in nature.

The α potential did show a small increase in amplitude over control values at most of the conditioning-test intervals. Mann *et al.* (1975) reported that partial depolarization of PT collaterals terminating in specific somatosensory relay nuclei occurs when stimulation to the medullary pyramids is conditioned by shocks to the contralateral forepaw. This would have the effect of subliminally activating more pyramidal tract fibers and bringing a higher percentage of them closer to their thresholds of activation. Since the α potential results from the summated activity in antidromically conducting PT neurons (Towe and Jabbur, 1959), an increase in the number of PT neurons discharging upon test stimulation would increase the amplitude of the α response.

It would seem likely that this effect would occur at the dorsal column nuclei, since this somatosensory relay nuclei is near the site of stimulation. Since this excitatory effect on the α potential lasted at least 200 msec, the subthreshold depolarization of the PT terminals may likely result from presynaptic depolarization by

collaterals of lemniscal fibers. The relatively subtle increase in the amplitude of the α potential in this study in comparison to the results of Mann *et al.* (1975), may be due to the more rostral location of the stimulating electrode. This would be expected, since the depolarizing effect of presynaptic activity spreads electrotonically back up the pre-terminal axon, decrementing in strength as the distance from the axo-axonic synapse increases.

The b potential's greater sensitivity to asphyxia relative to the α potential further suggests that it is not antidromic in nature. This conclusion is based on the assumption that synaptic systems are probably less resistant to asphyxia than non-synaptic ones, such as the antidromically activated pyramidal tract. If the b potential were antidromically mediated by a slower conducting neuronal group, the fibers mediating it would be of smaller diameter. In this case, the resistance of the b potential to asphyxia would be expected to be greater than the α response, since fibers of smaller diameter are known to be more resistant to asphyxia than larger caliber fibers (Clark *et al.*, 1935).

The increase in the amplitudes of the α and b potentials commencing immediately after the start of asphyxia may result from a decrease in the level of spontaneous activity in the cerebral cortex. This "baseline" activity normally interferes to some degree with the recording of experimentally induced neural activity (Towe, 1956).

Lower levels of spontaneous firing of corticofugal neurons, which would result from a decrease in the "baseline" activity of the cerebral cortex, may also account for the increased amplitudes of the *a* and *b* potentials during asphyxia. It is known that when orthodromic and antidromic action potentials meet along the same pyramidal axon that they effectively "cancel out" each other (Towe *et al.*, 1963). Therefore, a decrease in the number of spontaneous, orthodromic action potentials in pyramidal tract neurons would allow more antidromic action potentials to approach the cerebral cortex, increasing the amplitude of the *a* response. This effect would be expected to continue until the PT neurons, themselves, became anoxic.

An explanation for the increase in the amplitude of the *b* potential during asphyxia is more difficult using this model. It is possible that a decrease occurs in the net inhibitory corticofugal influences on sensory transmission. This effect on sensory transmission would probably occur in the thalamus, since the stimulating site in this study was rostral to the dorsal column nuclei. However, the evidence supporting this view is inconclusive, since both excitatory (Anderson *et al.*, 1967) and inhibitory (Widen and Marsan, 1960) cortico-thalamic influences on sensory transmission have been reported.

The increase in the amplitudes of the *a* and *b* potentials following asphyxia may also be accounted for by increases in the lactate concentration. This would likely increase the firing of neurons as a

result of metabolic acidosis.

Inactivation of the sodium pump, which would have a depolarizing effect on axons, is probably not responsible for the increases in the amplitudes of the α and b potentials during asphyxia. Since neurons have been known to remain electrically excitable for several hours following inactivation of the sodium pump (Davies, 1968), the appearance of the facilitatory effect of asphyxia is probably too soon to be attributed to effects on active transport mechanisms.

The inability of the b potential to follow high-frequency stimulation at rates greater than 100/sec is further evidence that it is an orthodromic potential. It has been shown that synaptic systems cannot invariably follow stimulus rates greater than 100/sec without attenuation (Towe and Jabbur, 1959; Jabbur and Towe, 1961a). The α potential, a known antidromic response, has been reported to follow stimulus rates of over 400/sec (Jabbur and Towe, 1961a).

Results from this study suggest that the b potential may result from activation of the medial lemniscus. This conclusion is supported by records showing that in a majority of cases, the largest b potentials were evoked when the stimulating electrode was in or near the medial lemniscus. This support is strengthened when considering both of the voltage contour maps at A 4.5 and A 6.5, which represent results taken from different animals (Figures 19, 20, 23, and 24). All of these figures show that the largest b potentials were evoked when

the stimulating electrode was near the medial lemniscus.

Results showing that the *b* potential has an occlusive interaction with known lemniscal activity further support the conclusion that it is mediated by the medial lemniscus, since action potentials generated by cutaneous electrical stimulation, which contribute to the primary evoked potential, have been shown to be conducted principally in the dorsal column-lemniscal system (Towe, 1956).

The long-lasting attenuation of the *b* potential for at least 200 msec indicates a suppression of synaptic transmission in the thalamus, probably at the primary somatosensory nucleus (VPL). Since the stimulating site in this study was rostral to the dorsal column nuclei, suppression of synaptic transmission could not occur at these afferent relay nuclei. Suppression of synaptic transmission within the cerebral cortex does not likely account for the occlusive effect of conditioning peripheral stimulation on the *b* potential, since previous studies have shown that the *b* response is not the result of post-synaptic activity within the cortex (Kennedy and Towe, 1962; McMillan *et al.*, 1975).

The records of the conditioning experiments show an increase in the amplitude of the *b* potential at a 10 msec conditioning-test interval. This also supports the conclusion that the *b* potential is lemniscally mediated. Since the latency of the primary evoked potential following contralateral forepaw stimulation has been shown to be

approximately 10 msec in the cat (Towe, 1956), impulses contributing to the primary evoked potential would be passing the midbrain stimulation site simultaneous to the application of the test stimulus. This would cause a synchronous activation of additional lemniscal fibers at the midbrain stimulating site, resulting in an increase in the total neuronal activity in the medial lemniscus, which would increase the amplitude of the *b* potential. Since the latency of the *b* potential following midbrain stimulation has been reported to be 0.9-1.0 msec (McMillan *et al.*, 1975), stronger support can be offered if more technical studies show the peak of the increase in the *b* potential to be at a 9.0-9.1 msec C-T interval.

The possibility that the other major sensory systems in the brainstem, namely the spinothalamic and trigeminothalamic pathways, conduct action potentials which produce the *b* response following midbrain stimulation must be given consideration. Both of these afferent pathways are contiguous with the medial lemniscus at the pontine and midbrain levels (Snider and Niemer, 1970).

The ventral and lateral spinothalamic tracts converge with the spinotectal tract in the medulla to form the spinal lemniscus (Barr, 1974). In the medulla of the cat, the spinal lemniscus is separated from both the medial lemniscus and the pyramidal tract by about 4 mm (Snider and Niemer, 1970). However, at the pontine and mesencephalic levels, the medial and spinal lemniscal systems are adjacent to each

other, and both are a considerable distance from the pyramidal tract (Figures 12 and 17). Although action potentials contributing to the *b* response may have been mediated solely by the medial lemniscus in previous studies stimulating in the medulla (Jabbur and Towe, 1961a; Kennedy and Towe, 1962), the spinal lemniscus may also contribute action potentials to this response when stimulating in the pons and midbrain.

The evidence supporting this conclusion is based principally on the correlation of the results in this study with known anatomical data. Since action potentials in the spinal lemniscus reach the cerebral cortex in carnivores with only one synaptic relay (Ariens Kappers *et al.*, 1967), the latency of activation of neural activity mediated by this pathway could also be as low as one millisecond.

An occlusive interaction with conditioning stimuli to the contralateral forepaw may likely occur if the *b* response is mediated by the spinal lemniscus following midbrain stimulation. This can be predicted, since electrical stimulation to the periphery may activate neurons in the anterolateral white columns, as well as the dorsal white columns.

It is also likely that action potentials contributing to the *b* response are mediated by the trigeminothalamic tract following midbrain stimulation, as well as by the medial and spinal lemniscal systems. Since the sensory endings for the trigeminal nerve are in

the head in carnivores and primates (Ariens Kappers *et al.*, 1967), conditioning stimulation to the limbs would not be predicted to effect activity in this afferent system. However, the *b* potential was not completely attenuated by conditioning peripheral stimulation, which may have resulted from impulse conduction in the trigeminothalamic pathway and unaffected lemniscal fibers. This conclusion agrees with the results of Kennedy and Towe (1962), which show that the occlusive effect of conditioning peripheral stimulation is greater when the test stimulus is applied to the medullary pyramids. At this level, the trigeminothalamic tract is a considerable distance from the medial lemniscus, and is probably not activated by the brainstem stimulus.

Several experiments in this study show that the principle stimulating foci for the *b* potential were equally close to two prominent midbrain nuclei, the red nucleus and the substantia nigra, as to the medial lemniscus (Figures 21 and 22; see Figure 17 for reference anatomy of the midbrain). Results from several other experiments show that the principle stimulating foci for the *b* potential are actually located closer to the mesencephalic reticular formation than to the medial lemniscus (Figures 12, 15, and 17; see Figure 17 for reference). The possibility that the *b* potential results from the activation of these neuronal elements warrants discussion.

Ascending, efferent fibers from the red nucleus and substantia nigra have been shown to project to the cerebral cortex of carnivores

and primates with only one synaptic relay (Ariens Kappers *et al.*, 1967). Therefore, the latency of activation of corticopetal activity following activation of these brainstem nuclei could also be as low as one millisecond.

However, several considerations strongly suggest that the *b* potential does not result from activation of either the red nucleus or the substantia nigra. The red nucleus and substantia nigra are not found caudal to the midbrain in cats (Snider and Niemer, 1970). Therefore, records in this study and results by Kennedy and Towe (1962), which show that the *b* potential can be evoked by stimulating caudal to the mesencephalon, contradict the view that this response results from activation of the red nucleus and substantia nigra. The *b* potential is not likely the result of the activation of rubral or nigral afferents when stimulating caudal to the midbrain, since an extra synaptic relay (0.5 msec) would result in a latency of activation greater than one millisecond.

Conditioning stimuli to the contralateral forepaw would not be expected to effect rubro-thalamic or nigro-thalamic activity, since a majority of the direct, ascending input to the red nucleus and substantia nigra do not originate in the periphery (Ariens Kappers *et al.*, 1967).

The principle cortical foci for the *b* potential would be expected to considerably anterior to the coronal sulcus, if this response

resulted from activation of the red nucleus or substantia nigra. This conclusion is based upon anatomical data for humans, which show that efferents from the red nucleus and substantia nigra terminate in thalamic nuclei which project to the motor and premotor areas of the frontal lobe (Truex and Carpenter, 1969). If this anatomical relationship also exists for carnivores, the principle *b* activity would likely be anterior to the cruciate sulcus.

The principle brainstem stimulating foci for the *b* potential were determined to be in the mesencephalic reticular formation in several experiments in this study (Figures 12, 15, and 17). If the contemporary view is accepted that the brainstem reticular formation is a multi-neuronal network (Truex and Carpenter, 1969), then the latency of activation of ascending reticular activity would surely be greater than one millisecond.

A statement about the organization of the pyramidal tract can be made from the results in this study. It is evident that not all potentials recorded from the cerebral cortex following stimulation to the pyramids, regardless of latency, can be assumed to be antidromically mediated by the pyramidal tract. Previous studies have largely assumed that longer-latency potentials are mediated by a slower conducting population of PT fibers (Bishop *et al.* 1953; Porter, 1955; Stefanis and Jasper, (1964a). Since the *a* potential has been shown to be antidromically mediated by the pyramidal tract, it might be

assumed that the *b* potential is antidromically mediated by a slower conducting PT population. The results in this study indicate that this is not the case, since the threshold of activation of the *b* potential was lower than that of the *a* potential when stimulating dorsal to the basis pedunculi in the midbrain. If the *b* potential was mediated by a slow conducting group of PT fibers, its threshold of activation would always be higher than the *a* potentials, since smaller diameter myelinated fibers are harder to activate than larger caliber myelinated fibers (Brinley, 1974).

It is evident that other fiber systems in the brainstem, which are adjacent to or near the pyramidal tract, may become activated following the application of an electrical stimulus to the surface of the pyramids. This activation can result from spread of the stimulus current by volume conduction. These activated fiber systems can subsequently mediate impulses to the cerebral cortex, and account for the longer latency potentials which are often observed. The results in this experiment indicate this is likely to be the case with the *b* potential when electrical stimulation is applied to the medullary pyramids. It is apparent that caution must be exercised when interpreting the source of evoked potentials recorded following brainstem stimulation.

SUMMARY

1. A series of surface-positive potentials, recorded from the sensorimotor area of the cat cerebral cortex following electrical stimulation to the brainstem, were stereotaxically investigated to determine the physiological properties of two potentials in the complex. These potentials, known as the *a* and *b* potentials, had respective latencies of 0.3-0.5 msec and 0.9-1.0 msec following midbrain stimulation. The brainstem stimulating sites in this study were in the rostral pons and the midbrain. At this level of the nervous system, the pyramidal tract and medial lemniscus are separated by 4 to 5 mm. Therefore, it is easier to restrict the effective stimulating current to one or the other pathways.
2. Following brainstem stimulation at a single site, the *a* and *b* potentials of largest amplitude were recorded at separate areas on the cerebral cortex. The largest *b* potentials were recorded near the coronal sulcus, approximately 5-6 mm caudal to the lateral tip of the cruciate sulcus, where the largest *a* potentials were recorded.
3. The *b* potentials of largest amplitude were recorded when the stimulating electrode was positioned dorsal to the corticospinal tract in the pons and in the midbrain. In most cases, the largest *b* potentials were recorded when the stimulating electrode was in or near the medial lemniscus. The *a* potential was most easily evoked when the

stimulating electrode was in the basis pedunculi of the midbrain.

4. The *b* potential was significantly attenuated by a conditioning stimulus to the contralateral forepaw given at intervals of 20 to 200 msec prior to the brainstem stimulation. A characteristic increase in the amplitude of the *b* potential was consistently recorded at a 10 msec conditioning-test interval. The *a* potential was not significantly affected by contralateral forepaw stimulation at any conditioning-test interval in four experiments.

5. The *b* potential was less resistant to asphyxia than the *a* potential in two experiments. In one experiment, the *b* potential was completely attenuated 2.7 minutes after the start of asphyxia, while the *a* potential was not abolished until 4.8 minutes thereafter.

6. The results in this study indicate that the *a* and *b* potentials are mediated by different fiber systems; the *b* potential apparently results from activation of an afferent fiber system, probably the medial lemniscus. The results in this study are discussed in relation to the physiological organization of the pyramidal tract. It is concluded that not all components of a series of cortical potentials evoked by electrical stimulation to the medullary pyramids result from antidromic conduction in pyramidal tract fibers of varying diameter. It is apparent that volume conduction of the stimulus current can activate adjacent fiber systems in the brainstem.

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