THE THALAMIC CONNECTIVITY OF THE PRIMARY MOTOR (MI) AND THE SUPPLEMENTARY MOTOR (MII) CORTICES IN THE RACCOON

By

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ABSTRACT

THE THALAMIC CONNECTIVITY OF THE PRIMARY MOTOR (MI) AND THE SUPPLEMENTARY MOTOR (MII) CORTICES IN THE RACCOON

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The thalamic connectivity of the primary motor (MI) and the supplementary motor (MII) cortices was investigated in the raccoon using both anterograde and retrograde neuroanatomical tracing procedures. The purpose of this study was to determine the pattern of thalamic projections of the motor cortices in a carnivore species noted for neural specialization of sensorimotor function.

Following electrophysiological identification, a pressure and at times combined with electrophoretic injection of horseradish peroxidase (HRP) and tritiated amino acids was made into circumscribed regions of MI or MII in 18 chloralose anesthetized animals. Animals survived for 17-67 hours and were intracardially perfused with a buffered aldehyde fixative. The brains were processed for HRP histochemistry using tetramethyl benzidine and dihydrochlorobenzidine as the chromogens on adjacent sections. Another series of adjacent sections were coated with photographic emulsion and processed for autoradiography.

The MI thalamic cells of origin were found predominantly in the ipsilateral ventral lateral nucleus (VL). For a given cortical injection site within MI, labelled neurons in VL formed a crescent shaped band which extended in a dorsoventral direction. These bands were topographically organized. Following an injection into the MI hindlimb area, both retrogradely labelled neurons and anterograde terminal label were observed in a thin band in the lateral edge of VL. Following an injection into the proximal forelimb representation of MI, the labelled neurons were observed forming a wider band occupying the dorsal extent of VL and continuing into the ventrolateral aspect of the ventral anterior nucleus (VA). Following an injection of the distal forepaw representation in MI, the labelled neurons and anterograde fields were observed in a wide band in the ventral apsect of VL. An injection of the MI face area resulted in both anterograde and retrograde label in medial VL and the principal division of the ventromedial nucleus (VMp). Neurons of the intralaminar nuclei were also labelled following the MI injections. The paracentral nucleus (PC) and the central lateral nucleus (CL) contained the majority of labelled cells.

The thalamic projections of the distal limb representation in MII were observed in the lateral one third of the mediodorsal nucleus (MD). The thalamic cells of origin and the terminal projections of MII exhibited a patch-like distribution as seen in transverse sections. Labelled cells

were also observed in the central medial nucleus (CM) of the intralaminar nuclei. Sparse labelling was also present in VA and a few scattered cells were observed in the dorsal cap zone of VL.

These results demonstrate for the first time that the primary thalamic dependency of MI is VL in the raccoon. No labelled cells were observed in the somatosensory thalamic nucleus, the ventrobasal complex. Furthermore, the result that a major projection to MII arises from lateral MD in the raccoon is an unique finding in a carnivore species. The MI and MII pattern of connectivity observed in the present study suggests that within the carnivore order, there are variations in the organization of thalamocortical relations, perhaps related to the specialization of sensorimotor function.

ACKNOWLEDGMENTS

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I dedicate this dissertation to my husband, Rod, whose advice and encouragement have sustained me throughout my years in graduate school.

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INTRODUCTION

Neural specialization of sensorimotor function is well documented in the raccoon as compared to other carnivores. In contrast to either the dog or cat, the raccoon is noted for the manipulative capabilities of the forepaw (Welker, 1959; Welker, Johnson and Pubols, 1964; Welker and Seidenstein, 1959). Concomitant with this behavioral specialization is the neuroanatomical elaboration of the sensory regions devoted to the forepaw representation (Johnson, Welker and Pubols, 1968; Pubols, Welker and Johnson, 1965; Welker and Johnson, 1965; Welker and Seidenstein, 1959). In the raccoon, over half of the total primary somatosensory cortex (SI) is devoted to the forepaw representation (Welker and Seidenstein, 1959). Furthermore, sulci separate the forepaw projection region from that of the hindlimb and face and individual gyral crowns mark the representation of each of the different digits of the forepaw (Welker and Campos, 1963; Welker and Seidenstein, 1959). In addition to the sensory specialization, an increased corticalization of motor function has been reported in the raccoon. A still larger but less extensive area of the primary motor cortex (MI) is devoted to the forepaw representation. When MI is defined as the cortical area in

which the lowest threshold electrical stimulation elicited muscle movement, approximately 35% of the total MI area is devoted to the forepaw representation in the raccoon (Hardin, Arumugasamy and Jameson, 1968). The electrophysiological map of MI revealed a motor pattern capable of mediating a greater variety of exploratory behaviors than in either the dog or cat (Hardin, Arumugasamy and Jameson, 1968). Thus the raccoon's highly developed manipulative capabilities correspond to specialization of neural structures.

In the study of a species which exhibits behavioral specialization, a particular feature of neural organization may become evident which might otherwise have remained obscure (Welker and Seidenstein, 1959). In accordance with this edict of comparative neurology, the investigation of thalamic connectivity of MI in the raccoon was undertaken.

Previous work on the thalamic projections of MI in other species had not clearly established a representative pattern of projections. In primates, the primary source of thalamic afferents has been reported to arise from the oral division of the ventral posterior lateral nucleus (VPLo) and ventral lateral nucleus (VL) (Jones, Wise and Coulter, 1979; Kievit and Kuypers, 1977; Strick, 1976). In cats, the ventral anterior (VA), the ventromedial nucleus (VM) and VL are the major thalamic inputs to the motor cortex (Hendry, Jones and Graham, 1979), while in the dog, VPL, VA, VL and ventral posterior medial nucleus (VPM) are all reported to

project to the motor cortex (Sych, 1977). One controversial issue regarding these projections concerned the question of overlapping projections. That is, the possible anatomical convergence of the somatosensory relay nucleus and VL upon MI. Such overlapping projections had been reported in the dog (Sych, 1977). However, since the advent of sensitive neuroanatomical tracing procedures it has been established at least in the cat that MI receives nonoverlapping projections (Hendry, Jones and Graham, 1979). Part of the confusion in the literature may be due to a lack of standard nomenclature of the dorsal thalamus applicable across species and the relative obscurity in distinguishing subnuclei of the thalamus.

One advantage of studying a specialized system such as that of the raccoon is that is possesses a distinctive thalamus. Welker and Johnson (1965) first described the outstanding cytoarchitectonic features of the raccoon somatosensory thalamic nucleus, the ventrobasal complex (VBC). The lobulation present in the raccoon VBC is in marked contrast to VL in which the cellular packing density is sparser and large fiber fascicles are less prominent. The distinctive features of the thalamus in the raccoon make it an advantageous species in which to examine the thalamic connections of MI.

The thalamic connectivity of the MI body regions and its thalamic counterparts was explored in the raccoon using the horseradish peroxidase technique (HRP) and the

autoradiographic tracing method (ARG). HRP is taken up by terminals and transported in a retrograde direction (LaVail and LaVail, 1974). In ARG, tritiated amino acids are conveyed in an anterograde direction (Cowan, Gottlieb, Hendrickson, Price and Woolsey, 1972). Hence, the use of HRP and ARG permits the visualization of both the thalamic afferents and efferents of MI. In addition, several workers have recently shown that HRP can also be transported in an anterograde direction (Colman, Scalia and Cabrales, 1976); Hadley and Trachtenberg, 1978; Itaya, Williams and Engel, 1978; Mesulam, 1978). Electron microscopic studies have shown HRP bound vesicles in presynaptic terminals (Colman, Scalia and Cabrales, 1976; Itaya, Williams and Engel, 1978). Thus, the HRP technique alone can be employed to visualize afferents as well as efferents.

In an ancillary portion of the present study, the thalamic connectivity of the supplementary motor cortex (MII) was investigated in the raccoon. A second body representation of somatic musculature defined by electrical stimulation was observed lying rostral to MI in the raccoon (Jameson, Arumugasamy and Hardin, 1968). This cortical area termed MII was localized to the medial 2/3 of the anterior cruciate gyrus. Although MII has been similarly localized to the medial aspect of the hemisphere rostral to the MI hindlimb representation in primates (Woolsey, 1958; 1963), the location of MII varies across carnivores. In the dog, MII has been localized to the lateral 2/3 of the anterior

sigmoid gyrus (Gorska, 1974). In the cat, MII has been hypothesized to be located on the rostramedial bank of the cruciate sulcus (Woolsey, 1958). The thalamic projections of MII have not been explored in carnivores using axonal transport techniques. Therefore, it was also deemed profitable to investigate the thalamic connectivity of the MII area in the raccoon.

METHODS

Eighteen raccoons (Procyon lotor) of both sexes were used in this study. The animals were live trapped on the grounds and surrounding areas of Michigan State University.

The raccoons were anesthetized with chloralose (17 mg/kg) administered intraperitoneally. The head was held rigid in a stereotaxic apparatus and the cranium exposed. Small burr holes, 1-2 mm in diameter, were made into the bone overlying the cortical area of interest and a small opening was made in the dura. The cortical area was then explored electrophysiologically. A glass insulated tungsten microelectrode was slowly lowered onto the cortical surface and the contralateral body surface was mechanically stimulated. The recording signals were amplified and displayed through an oscilloscope and an audio monitor. When slow wave potentials were reliably evoked following mechanical stimulation of a particular body area, the receptive field was considered identified. The site was then readied for injection.

All injections were accomplished by means of a glass micropipette sealed to a 1.0 ul Hamilton syringe. The tip diameter of the glass micropipette ranged from 30-100 um. In order to prevent clogging, the tip was beveled to

approximately 30 degrees. Injections were made under either pressure or pressure and electrophoresis simultaneously. The plunger of the syringe was driven by an infusion pump and the rate of infusion ranged from 0.5 ul/hour to 1.0 ul/hour. The injection apparatus was a modification of a device designed by Price, Fisher and Redstone (1977). Additionally, an electrical lead was attached to an outlet on the syringe needle for electrophoresis. Positive DC current (2 uamps) was applied in square wave pulses for total on-times of 30 minutes to one hour.

Nine raccoons received combined injections of HRP and tritiated amino acids. Initially, an injection of 30-50% HRP and 5% poly-L-ornithine (Itaya, Williams and Engle, 1978; Hadley and Trachtenberg, 1978) in Tris/KCl buffer pH 8.6 was made into the circumscribed regions of MI or MII via the simultaneous application of pressure and electrophoresis. Then the pipette was withdrawn and filled with a second solution containing 0.5-1.0 ul of 30-50% HRP and a 1:1 mixture of ^{3}H proline (L-5-^{3}H proline, specific activity 3 Ci/mmol., 10-30 uc) and ^{3}H leucine (L-4,5-^{3}H-leucine, specific activity 2 Ci/mmol., 10-30 uc) which was injected under pressure only. Seven raccoons received only single HRP injections into MI. Two raccoons received single bilateral HRP injections in different regions of MI. Following the injection, the pipette was left in place for 5-15 minutes. The wound was then covered with a piece of saline soaked Gelfoam (Upjohn) and the overlying skin was

sutured in place. At the conclusion of the injection procedure, 20-40 cc of 0.9% saline and 5% dextrose was administered intraperitoneally in order to replace lost body fluids and the animals were returned to the home cage for recovery.

Following survival times of 17-67 hours, all animals were re-anesthetized with 35% chloral hydrate administered intraperitoneally and intracardially perfursed with 0.9% saline followed by a mixture of 1.25% glutaraldehyde and 1.0% paraformaldehyde in 0.1 M phosphate buffer pH 7.4 according to the protocol of Rosene and Mesulam (1978). The fixative was followed by a cold phosphate buffer rinse (10% sucrose in 0.1 M phosphate buffer pH 7.4). The brains were removed immediately and stored in 30% sucrose in 0.1 M phosphate buffer pH 7.4 for 24-96 hours at 4°C.

The brains were cut on a freezing microtome at 40 um and the sections were placed in cold 0.1 M phosphate buffer pH 7.4. Three adjacent sections out of 10 were collected for HRP histochemistry using tetramethyl benzidine (TMB) and dihydrochlorobenzidine (BDHC) as the chromogens and for autoradiographic processing.

One series of sections were treated according to the procedure of Mesulam (1978). The sections were incubated in 0.01% TMB for 20 minutes prior to adding 0.03% hydrogen peroxide. Following the reaction, the sections were stabilized and rinsed in cold acetate buffer pH 3.3. The sections were then mounted onto chrome alum slides and allowed

to air dry. The slides were counterstained in a 1% solution of buffered neutral red pH 4.8.

An adjacent series of sections were treated according to the protocol of Mesulam (1977). The sections were incubated in 0.05% BDHC for 20 minutes prior to adding 0.03% hydrogen peroxide. The sections were stabilized in a cold ethanolic solution of 9% sodium nitroprusside. Otherwise, the treatment of the tissue was the same as the above procedure.

The last series of sections were processed for ARG. The sections were mounted onto chrome alum coated slides and allowed to air dry. The slides were dehydrated and rehydrated in a graded series of alcohols. They were coated in 50% NTB-2 emulsion (Kodak) in water and stored in light tight containers at 4°C. Following exposure times of 6-16 weeks, the slides were developed in D-19 developer (Kodak), fixed and washed. The slides were subsequently counterstained in thionine.

Drawings of the sections were made with the aid of a Leitz projector. Each section was then microscopically examined for the presence of HRP reaction product or autoradiographic silver grains under both light and dark field. The results were mapped onto the tracings.

The delineation of subnuclear boundaries within raccoon dorsal thalamus was based upon: a) careful study of a series of thionine and Weil stained sections of normal raccoon thalamus, b) examination of a series of raccoon brains

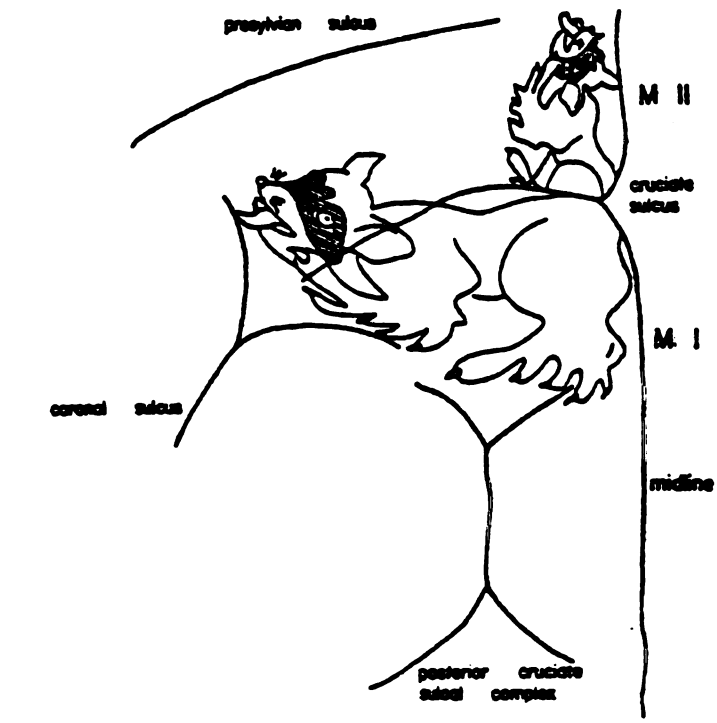
with partial or complete SI ablations obtained from W. I. Welker, and c) comparison of the cytoarchitectonic features of raccoon dorsal thalamus with the macaque (Jones, Wise and Coulter, 1979; Olszewski, 1952) and cat (Hendry, Jones and Graham, 1979).

RESULTS

Slow wave potentials were evoked in MI by the stimulation of the contralateral peripheral body parts and the underlying musculature. The MI body regions electrophysiologically identified for injections were the forepaw, hindpaw and face representations. Slow wave potentials were evoked in MII from the bilateral stimulation of distal body parts and the underlying musculature. The anatomical localization of the injection sites identified by this method correlated with the maps of Hardin et al. (1968) and Jameson et al. (1968). A cartoon map of MI and MII is shown in Figure 1. The experiments are summarized in Table 1.

The HRP injection sites were characterized by the presence of deeply stained reaction product throughout the neuropil surrounding the penetration of the pipette. While HRP reaction product was contained within many cortical neurons, other cells appeared to be evenly coated with overlying HRP positive granules in the area of the injection site. Injection sites of BDHC treated sections typically contained a dense central core of dark blue reaction product surrounded by a halo of lighter more evenly stained area. It is this dense central core that has been interpreted to be the zone within which HRP is effectively taken up and

Figure 1. Cartoon of the approximate body representations in MI and MII based on the electrophysiological maps of Hardin et al. (1968) and Jameson et al. (1968).


presylvian sulcus
M II
cruciate sulcus
M I
coronal sulcus
midline
posterior cruciate sulcal complex

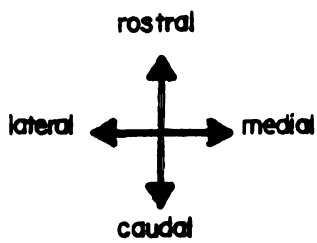

rostral
lateral
medial
caudal

Figure I

TABLE 1

Summary of the Experiments

Injection Site	Animal Number	Tracer Injected	Survival Time
MI forepaw	78576	HRP/ARG	28 hours
MI forepaw	78579	HRP/ARG	42
MI forepaw	78592	HRP/ARG	24
MI forepaw	78595	HRP/ARG	25
MI forepaw	78501	HRP/ARG	46
MI forepaw	79583	HRP	48
MI forepaw	79535	HRP	48
MI forepaw	78598	HRP/ARG	24
MI hindpaw	78507	HRP/ARG	47
MI hindpaw	79529	HRP	48
MI hindpaw	79531	HRP	44
MI hindpaw	79534	HRP	44
MI face	78517	HRP	17
MI face	78502	HRP	42
MI face	79528	HRP	48
MI face	79532	HRP	44
MI face	79534	HRP	44
MI face	79535	HRP	48
MII	79504	HRP/ARG	42
MII	78589	HRP/ARG	67

transported (Kievit and Kuypers, 1978; Jones, 1975). The injection sites illustrated in Figure 2 indicate the maximum extent of the dense core area. In contrast, the injection sites of TMB treated sections were characterized by the lighter evenly stained halos which extended over a greater area than was evident from the injection sites of BDHC treated sections. In view of the increased sensitivity of the TMB procedure over the BDHC procedure, the boundary of the effective injection site is difficult to establish unequivocally (Hardy and Heimer, 1977; Mesulam, 1978).

The optimum survival time for the demonstration of thalamocortical projections was 48 hours. In some TMB reacted cases, densely stained fibers underlying the injected cortex was observed coursing toward the internal capsule. Clusters of thalamic neurons contained HRP positive granules. In all cases, the number of retrogradely labelled neurons was greater in the TMB reacted sections than in the BDHC treated tissue. Labelled neurons were of two types (Figure 6b and 7b). Some neurons were blackened with densely packed HRP positive granules. The labelling extended throughout the soma and often defined apical and basal dendrites. More often, the labelling of neurons was lighter with the granular reaction product confined to the soma.

Anterograde transport of HRP was observed in some TMB reacted cases. HRP positive reaction product was observed overlying retrogradely labelled neurons and in the

Figure 2. Brightfield photomicrographs of transverse sections through a HRP injection site in MII. Neutral red stain.

A. Section treated with dihydrochlorobenzidine as the chromogen. Note the dense central core zone and the surrounding halo.

B. Section treated with tetramethyl benzidine as the chromogen. Note the wide extent of the halo zone and the lightly stained central zone.

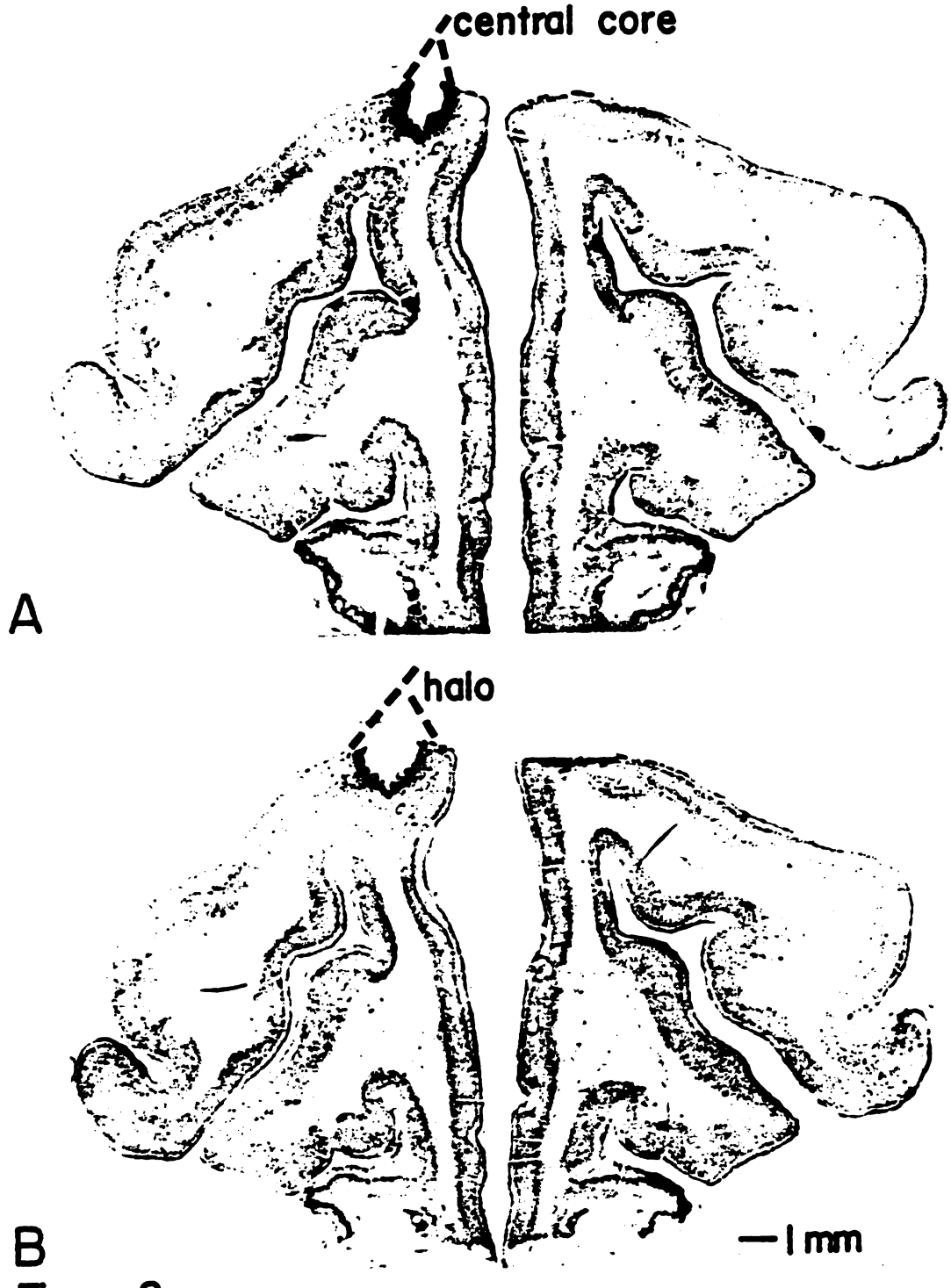


Figure 2

surrounding extraperikaryl space. The reaction product appeared to be slightly larger and more ovoid in appearance than the HRP positive granules found within retrogradely labelled neuronal somata. It was difficult to eliminate the possibility that the label may be due to dendritic ramifications or to fibers of passage rather than terminal fields. However, the HRP terminal labelling was consistent with the results obtained from autoradiography.

The injection sites of tritiated amino acids were typically smaller than the HRP injection sites. The ARG injection sites were defined as those areas blackened by the presence of silver grains above background levels. The ARG injection sites contained a dense core area surrounded by a halo of lower grain density. Although the dense core areas of the ARG injection sites were smaller, they correspond to the HRP central dense core regions of the adjacent BDHC reacted sections.

ARG terminal labelling was determined by the presence of densely packed silver grains in the thalamus. The patches of silver grains were observed in the regions identified as containing anterogradely transported HRP in adjacent sections. However, the HRP terminal fields extended over a wider thalamic area than the patches of ARG silver grains.

Cytoarchitecture of the Primary Motor Cortex

In comparison to either the dog or cat, the motor area of the raccoon is displaced caudally out of the cruciate

sulcus (Hardin, Arugumugasamy and Jameson, 1968; Welker and Seidenstein, 1959). The primary motor cortex has been shown to occupy the posterior cruciate gyrus and the lateral one third of the anterior cruciate gyrus (Figure 1). The primary motor cortex of the raccoon is cytoarchitecturally defined as the area containing layer V giant (75-100 um diameter through the perikarya) and large 50-70 um) pyramidal cells, a wide undifferentiated layer III and lack of a distinctly granular layer IV (Hassler and Muhs-Clement, 1964). Figure 3 shows a series of four parasaggital sections through successive mediolateral levels through the posterior cruciate gyrus. The depth of the cruciate sulcus and the anterior wall of the posterior cruciate gyrus consistently contain the layer V giant pyramidal cells. In addition, the giant pyramidal cells extend rostrally onto the lateral anterior cruciate gyrus (Figure 3c). However, there is a diminution of the giant pyramidal cells in the region from the gyral crown extending toward the caudal extent of the posterior cruciate gyrus (Figure 3c). This cortical area is still largely agranular. A distinct layer IV is not present. Layer III exhibits some widening and slight differentiation. This area of diminished layer V pyramidal cells corresponds to the MI digit area. When this area was electrically stimulated, digit adduction occurred.* The region caudal to this within the rostral bank of the coronal sulcus does not appear to be part of the motor cortex. There is a distinctly

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*Hardin, W. B., unpublished material obtained from Dr. T. A. Woolsey, Washington University.

Figure 3. Photomicrographs of parasaggital sections through the posterior cruciate gyrus at four successive mediolateral levels (A-D). Solid arrows indicate the cruciate sulcus. Thionine Stain.

A. Section through the MI hindlimb representation in the medial bank of the posterior cruciate gyrus. The giant pyramidal cells extend along the anterior and posterior banks of the cruciate sulcus. A decrease in the giant pyramidal cells can be seen in the anterior bank of the coronal sulcus.

B. Section through the MI trunk representation approximately 6 mm lateral to A.

C. Section through the MI forepaw representation. Layer V pyramidal cells continue from the posterior and anterior banks of the cruciate sulcus rostrally to the anterior cruciate gyrus. Note the distinct diminution of layer V pyramidal cells in the caudal half of the posterior cruciate gyrus.

D. Section through the MI face representation.

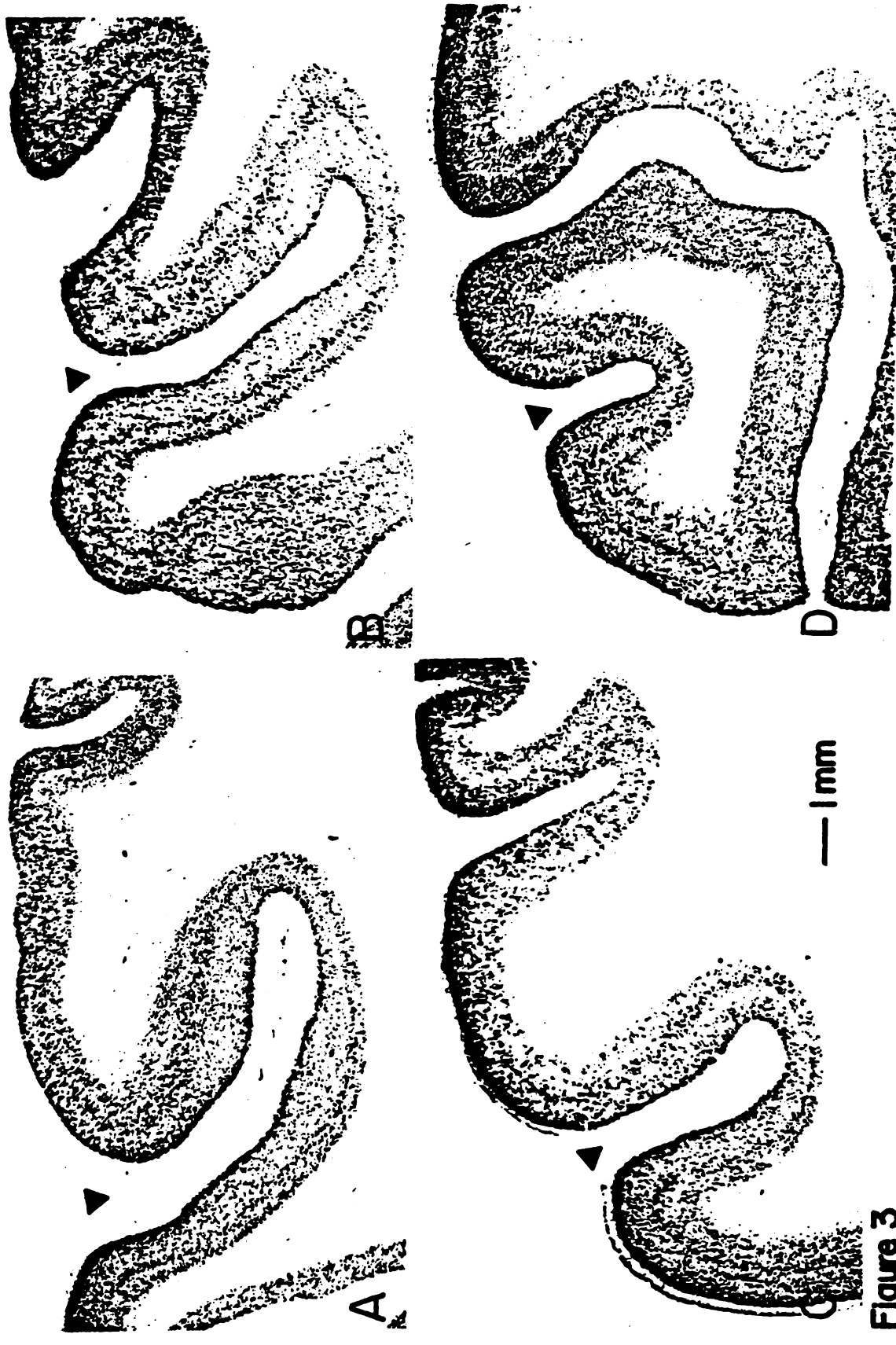


Figure 3

granular layer IV, a differentiated layer III and the absence of layer V giant pyramidal cells. The cytoarchitectural analysis of MI is in good agreement with the physiological delineation of MI by Hardin et al. (1968).

Cytoarchitecture of the Ventral and Intralaminar Thalamus

In as much as little data is available on the raccoon ventral thalamus (Welker and Johnson, 1965), the delineation of thalamic subnuclear boundaries follows the description of Hendry, Jones and Graham (1979) based on the cat and Jones, Wise and Coulter (1979) based on monkeys. The nomenclature follows that of Hendry, Jones and Graham (1979).

The ventral anterior (VA) and ventral lateral (VL) nuclei make up a nuclear complex present within the anterior pole of the thalamus. VA is present most rostrally in the thalamus and is distinguishable from VL primarily due to its sparser cellular density (Figure 4a). Ventral to VA, VL emerges from the dorsolateral edge of the external medullary lamina. As VA diminishes caudally by occupying the dorsal most cap of the thalamus, VL occupies a wide mediolateral extent of the thalamus. Cytoarchitecturally, VL is characterized as a heterogeneous nuclear mass containing darkly stained cells organized into small irregular clusters which are segregated by fiber bundles.

In the raccoon, the largest and most distinctive thalamic nucleus is the ventrobasal complex (VBC). VBC emerges ventral to VL hugging the external medullary lamina (Figure 4b). The VBC/VL border is highly discriminable due to an

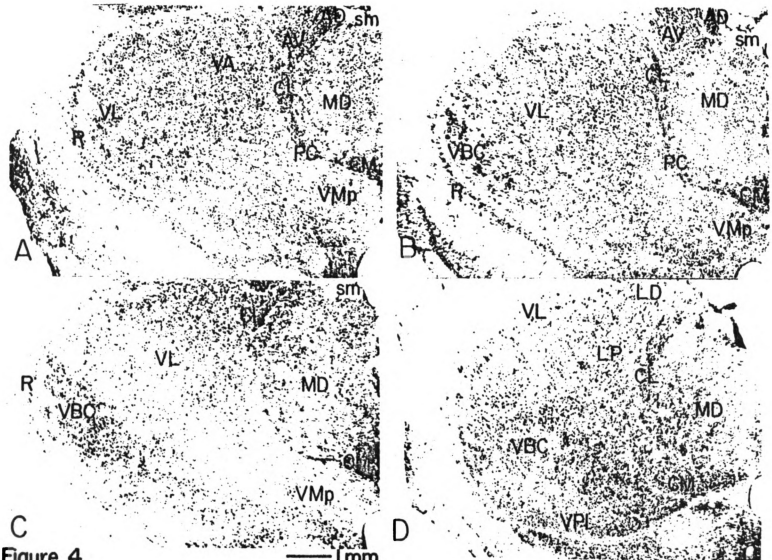
Figure 4. Standard transverse sections at four rostrocaudal levels thorugh the raccoon thalamus. Thionine stain.

A. Section through the rostral thalamus. Note the cell clustering and lamination present in the ventral lateral nucleus (VL).

B. Section through VL and the most rostral extent of the ventrobasal complex (VBC).

C. Section showing the dorsal displacement of VL as VBC emerges.

D. Section showing the dorsal displacement of VL by the small celled lateral posterior nucleus (LP) and VBC.


A
AD
sm
AV
VA
CL
MD
VL
R
PC
CM
VMp
B
AD
AV
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VBC
PC
R
CM
VMp
C
sm
CL
VL
R
MD
VBC
CM
VMp
D
LD
VL
LP
CL
MD
VBC
CM
VPL

Figure 4

mm

TABLE 2

Nomenclature and Abbreviations of Thalamic Nuclei

AD	anterodorsal nucleus
AM	anteromedial nucleus
AV	anteroventral nucleus
CM	central medial nucleus
CL	central lateral nucleus
H	habenular nucleus
LD	lateral dorsal nucleus
LP	lateral posterior nucleus
MD	mediodorsal nucleus
MV	medioventral nucleus
PC	paracentral nucleus
PF	parafascicular nucleus
R	reticular nucleus
sm	stria medullaris
VA	ventral anterior nucleus
VBC	ventrobasal complex
VL	ventral lateral nucleus
VMb	basal ventromedial nucleus
VMp	principle ventromedial nucleus
VPI	ventral posterior inferior nucleus

increase in cellular packing density and large clusters of cells with darkly stained cell bodies. Mediolaterally, delineation of VBC subdivisions is marked by the presence of large fiber fascicles. VL occupies the medial border of VBC for some distance. However, as VL diminishes caudally, it occupies a dorsal cap zone separated from VBC by the presence of the small celled lateral posterior nucleus (LP).

Medial to VA, VL and VBC is the ventromedial nucleus. The ventromedial nucleus is comprised of the principal ventromedial nucleus (VMp) and the basal ventromedial nucleus (VMb) (Hendry, Jones and Graham, 1979). In the raccoon, VMp lies medial to VA and VL and is composed of small cells sparsely packed (Figure 4a and 4b). VMb occupies the nuclear mass medial to VBC arc. Its cells are small and more densely packed than in VMp.

The mediodorsal nucleus (MD) is the prominent nuclear structure lying medial to PC and CL (Figure 4c and 4d). There are at least two major subdivisions of the raccoon MD. Medial MD consists of a relatively homogeneous collection of large uniformly stained cells. Lateral MD is a heterogeneous collection of small and large cells. A striking feature of these cells is the darkly staining Nissi substance. Irregular clustering of neurons is observed in lateral MD. The lateral and medial subdivisions of MD remain fairly constant throughout the rostrocaudal extent of the nucleus. However, a dorsal displacement of MD is observed in its most caudal aspect.

The intralaminar nuclei lie medial to the internal medullary lamina. The most distinctive of the intralaminar nuclei is the central medial nucleus (CM) which lies closest to midline and is composed of small densely packed cells. CM extends laterally into the paracentral nucleus (PC) and even more laterally into the central lateral nucleus (CL). The cells of PC and CL are primarily small and densely packed. However, larger spindle shaped cells are not uncommon in PC or PL (Figure 4b).

Distribution of MI Thalamic Connections

Following HRP injections of MI, a characteristic pattern of thalamic labelled neurons emerged. As seen in transverse sections, retrogradely labelled neurons clustered to form a crescent-like band. HRP positive neurons were distributed in a dorsoventral orientation and occupied a wide extent of VL. The dorsoventral extent of the band extended beyond VL into the ventrolateral aspect of VA and into VMp. The bands of HRP positive neurons remained fairly constant throughout the rostrocaudal extend of VL. However, as VL diminishes in size caudally, the extent of labelled neurons also diminished. The band configuration was consistantly obtained following MI injections.

The bands of labelled thalamocortical projection neurons were bordered by unlabelled neurons. In many cases, the bands contained densely packed HRP positive neurons with few unlabelled cells within the band. However, progressively toward the outer edge of the bands, HRP labelled cells

were interspersed with unlabelled neurons. Occasionally bands were defined by sparsely distributed retrogradely labelled cells.

VL neurons containing HRP reaction product varied widely in size. The diameter of the perikarya through the nucleus ranged form 8 to 25 um. However, the typical VL projection neuron was medium and multipolar in shape.

Some neurons of the intralaminar nuclei project to MI. Although the HRP granules were observed in sparsely distributed cells of CM, the heaviest projection of the intralaminar nuclei to MI arises from CL and PC. A specific topographic relationship between CL and regions of MI is not readily apparent.

MI Forepaw Thalamic Projections

The forepaw representation of MI occupies the middle one half of the posterior cruciate gyrus (Hardin, Arumugasamy and Jameson, 1968). (Refer to Figure 1). A series of HRP injections were made into different rostrocaudal locations within this area. The results indicate a topographic relationship in the thalamocortical projections of the forepaw representation.

In experiment 79583, evoked potentials were electrophysiologically recorded following tactile stimulation of the contralateral forepaw. A HRP injection was made onto the gyral crown of the posterior cruciate gyrus. The mediolateral extent of the HRP injection site measured 2.2 mm. Its location is shown in figure 5a. The distribution

of neurons retrogradely labelled with HRP reaction product is shown in Figure 5 b-h and Figure 6 a-b. A single band of HRP positive neurons and HRP terminal label was observed extending dorsoventrally through VL. The HRP terminal labelling resembled a fine dust overlying and generally extending beyond the band of retrogradely labelled neurons (Figure 6 a). A cluster of labelled cells and HRP terminal label was present in the dorsolateral aspect of VMp. Retrogradely labelled neurons also continued into the ventrolateral aspect of VA. However, HRP terminal labelling did not extend into VA.

In experiment 78501, a combined injection of HRP and tritiated amino acids was made into MI following electrophysiological identification of the forepaw representation. This injection centered on the rostral bank of the posterior cruciate gyrus. A band of retrogradely labelled neurons was observed in dorsal VL bordering the lateral edge of CL (Figure 7 a-b). The ARG terminal label indicates that the corticothalamic projection is reciprocal (Figure 8 a-b).

In experiment 79535, a HRP injection was made into the MI forepaw area. The injection centered on the caudal aspect of the posterior cruciate gyrus. The injection site measured 1.5 mm mediolaterally. Its location is shown in Figure 9 a. The resulting band of HRP positive neurons was in the ventral VL (Figure 9 b-h). At the level of the emergence of VBC, the thalamic label occupied the ventrolateral aspect of VL (Figure 10 b). A small group of large

Figure 5. The distribution of HRP positive neurons in ventral thalamus following an injection into the MI forepaw representation in experiment 79583.

A. A dorsolateral view of the raccoon brain. The blackened circle and stippling indicate the central core and halo of the injection site in TMB reacted sections.

B-H. A series of transverse hemisections through successive anterior-posterior levels through the ventral nuclear group of dorsal thalamus. The dots indicate the approximate density of labelled cell bodies in the sections. Note the band-like distribution of the HRP positive neurons.

Figure 6. Photomicrographs of MI thalamic projection neurons in experiment 79583. Arrows indicate the same landmark. (60 um TMB reacted section counterstained with neutral red).

A. Low power photomicrograph of the band-like distribution of HRP positive neurons and HRP terminal label. The labelling extends through VL and into VMp. Taken from a transverse section at the level of section E in Figure 5.

B. High power photomicrograph showing the blackened cells retrogradely labelled with HRP and the diffuse HRP terminal labelling surrounding the cells.

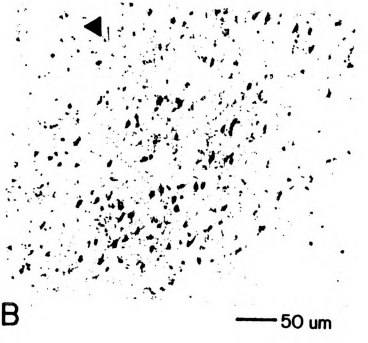


Figure 6

Figure 7. Photomicrographs of the distribution of HRP labelled cell bodies following an injection of the proximal forelimb representation in rostral posterior cruciate gyrus in experiment 78501. Arrows indicate the same landmark. (60 um TMB reacted section counterstained with neutral red).
A. Low power photomicrograph showing the band-like distribution of the HRP labelled cells. Note the dorsal extent of the labelled cells. Taken from a transverse section at approximately the level shown in section G in Figure 5.
B. High power photomicrograph of HRP positive neurons in VL.
C. High power photomicrograph of HRP positive neurons in CL.

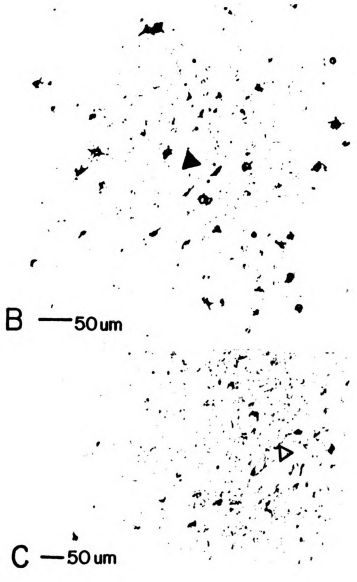


Figure 7

Figure 8. Photomicrographs showing the ARG terminal labelling following an injection of isotopes into the proximal forelimb area of MI in experiment 78501. Arrows indicate the same landmark.

A. Brightfield low power photomicrographs of a 60 um transverse section adjacent to the TMB reacted section shown in Figure 7. (Thionine stain).

B. Darkfield photomicrographs showing the ARG silver grains in dorsal VL.

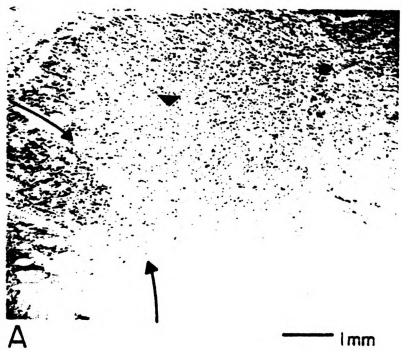
Figure 8

Figure 9. The distribution of HRP positive neurons in ventral thalamus following an injection into the MI forepaw representation in experiment 79535.

A. A dorsoventral view of the raccoon brain. The blackened circle and stippling indicate the central core and halo of the injection site in TMB reacted sections. The injection site centered on the caudal aspect of the posterior cruciate gyrus.

B-H. A series of transverse sections through successive anterior-posterior levels through ventral thalamus. The dots indicate the approximate density of labelled cell bodies in the sections. Note the band-like distribution of HRP positive neurons in ventral VL.

Figure 10. Photomicrographs of 60 um transverse sections taken at the level shown in section E in Figure 9 in experiment 79535. Arrows indicate the same blood vessels.
A. Low power photomicrographs of a thionine stained section. Note the distinct VBC/VL border between the curved arrows.
B. Darkfield photomicrographs of an adjacent section showing the HRP labelled cells distributed as a band in ventral VL.



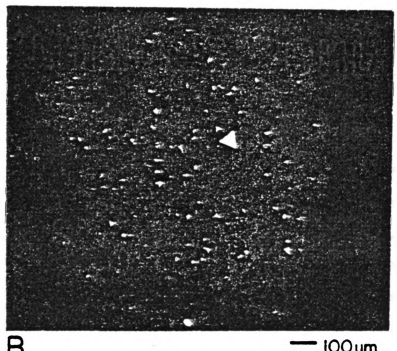


Figure 10

darkly stained neurons is present within ventral VL. HRP labelled neurons were observed interspersed throughout this region.

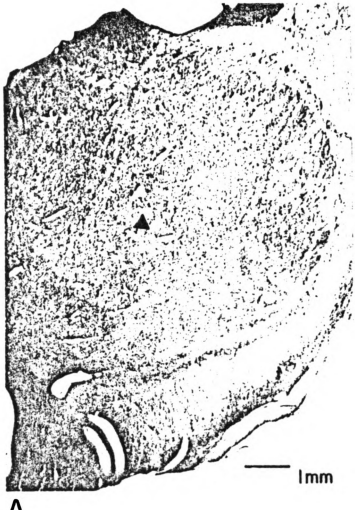
Although the bands of neurons overlap considerably from case to case, a topographic relationship exists between the MI forepaw and VL: the rostral MI forepaw area receives projections from dorsal VL and caudal MI forepaw area receives projections from ventral VL. This observation is in part confirmed by experiment 78595 in which the injection of HRP and tritiated amino acids occurred in two sites: one injection centered in rostral posterior cruciate gyrus and a second injection was made into caudal posterior cruciate gyrus. The HRP positive cells and ARG silver grains were organized into two distinct bands oriented dorsoventrally through VL (Figure 11-13). Based on the results of single injections, it is inferred that the dorsal most band contains the projection neurons of rostral posterior cruciate gyrus and the ventral band contains the projection neurons of the caudal posterior cruciate gyrus.

All of the MI forepaw injections resulted in HRP positive neurons in the intralaminar nuclei. Labelled cells were consistently observed in PC and CL (Figure 7 c). These neurons varied in size and were typically spindle shaped. The intralaminar neurons that project to MI forepaw area appear to be distributed in a rod-like configuration. The neurons containing HRP reaction product formed a cluster apparent in consectutive transverse sections. Occasionally,

Figure 11. Photomicrographs of the distribution of HRP labelled cell bodies following combined injection of HRP and tritiated amino acids into rostral posterior cruciate gyrus and an injection into caudal posterior cruciate gyrus in experiment 78595. Arrows indicate the same landmark. (60 um TMB reacted section counterstained with neutral red).

A. Low power photomicrograph showing the relative location of the HRP positive neurons in VL.

B. Brightfield photomicrograph indicating the two parellel dorsoventral bands of HRP positive neurons in VL.



A

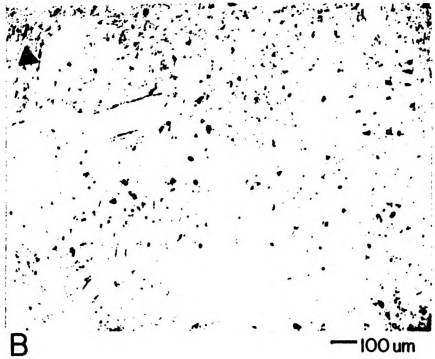


Figure II

Figure 12. Low power brightfield photomicrograph of a 60 um transverse section treated for autoradiography adjacent to the TMB reacted section shown in Figure 11. Arrows indicate reference points for the darkfield photomicrographs shown in Figure 13. (Thionine stain).

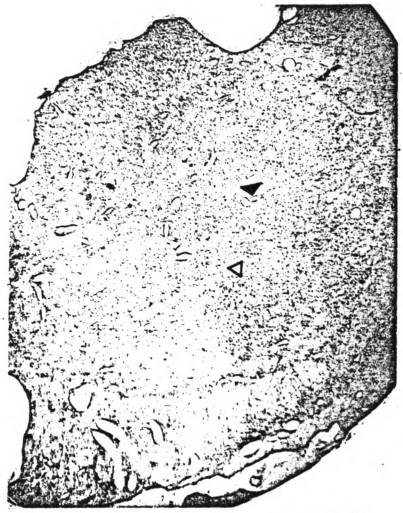
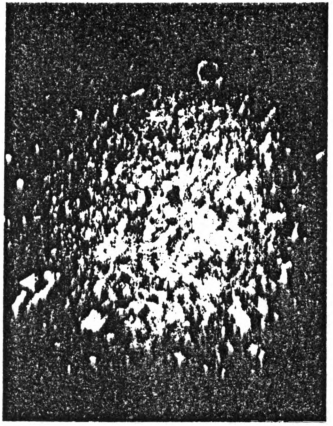


Figure 12

Figure 13 a-b. Darkfield photomicrographs showing the ARG silver grains in VL following the combined injections of HRP and tritiated amino acids in experiment 78595. Arrows correspond to the points shown in Figure 12.



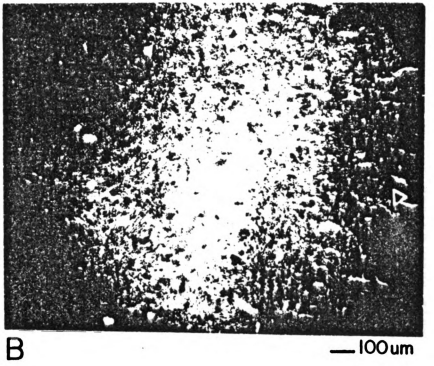


Figure 13

HRP positive neurons were observed in CM. Neither HRP anterograde label or ARG silver grains were clearly evident in the intralaminar nuclei following the MI forepaw injections.

MI Hindlimb Thalamic Projections

The MI hindlimb representation largely occupies the medial bank of the posterior cruciate gyrus (Hardin, Arumugasamy and Jameson, 1968). (Refer to Figure 1). In five cases, injections were made into the MI hindlimb representation following electrophysiological identification. A band of retrogradely labelled neurons was consistently localized to the lateral aspect of VL.

A HRP injection was made into MI hindlimb area in experiment 79534. The injection site measured 2 mm mediolaterally and did not encroach on the postcruciate dimple caudally. The location of the injection site and the distribution of HRP positive neurons is shown in Figures 14-16. A long thin arc of labelled cells was observed throughout a 4 mm dorsoventral extent of VL (Figure 14 b-h and 16 a-b). Overlying and extending beyond the cluster of labelled cells was the fine dust of HRP terminal label. The continuity of the labelled band of cells was disrupted by VBC and occupied two zones: one on the lateral edge of VL and the other along the ventral edge of Vl (Figure 14 e). The labelled neurons did not invade VBC. As VL diminished caudally, the arc of labelled neurons moved progressively more dorsally to occupy the lateral aspect of VL as VL

Figure 14. The distribution of HRP positive neurons in ventral thalamus following an injection into the MI hindlimb representation in experiment 79534.

A. A dorsoventral view of the raccoon brain. The blackened circle and stippling indicate the central core and halo of the injection site in TMB treated sections. The injection site centered on the medial aspect of the posterior cruciate gyrus just rostral to the post cruciate dimple.

B-H. A series of transverse sections through successive anterior-posterior levels through ventral thalamus. The dots indicate the approximate density of labelled cell bodies in the sections. Note the distinct arc of labelled neurons in lateral VL.

Figure 15. Low power photomicrograph of the HRP injection site in experiment 79534. Taken from a 60 um transverse section treated with TMB as the chromogen and counterstained with neutral red.

Figure 15 — 1mm

Figure 16. Brightfield photomicrographs showing the distribution of HRP labelled cell bodies and HRP terminal labelling following an injection into the MI hindlimb representation in experiment 79534. Arrows indicate the same landmark. (60 um TMB reacted section counterstained with neutral red).

A. Low power photomicrograph taken at the level shown in section c in Figure 14. Note that the HRP terminal labelling extends over a wider area than the HRP positive cells.

B. High power photomicrograph showing the morphology of the blackened HRP positive neurons and the coextensive distribution of the HRP terminal dust.

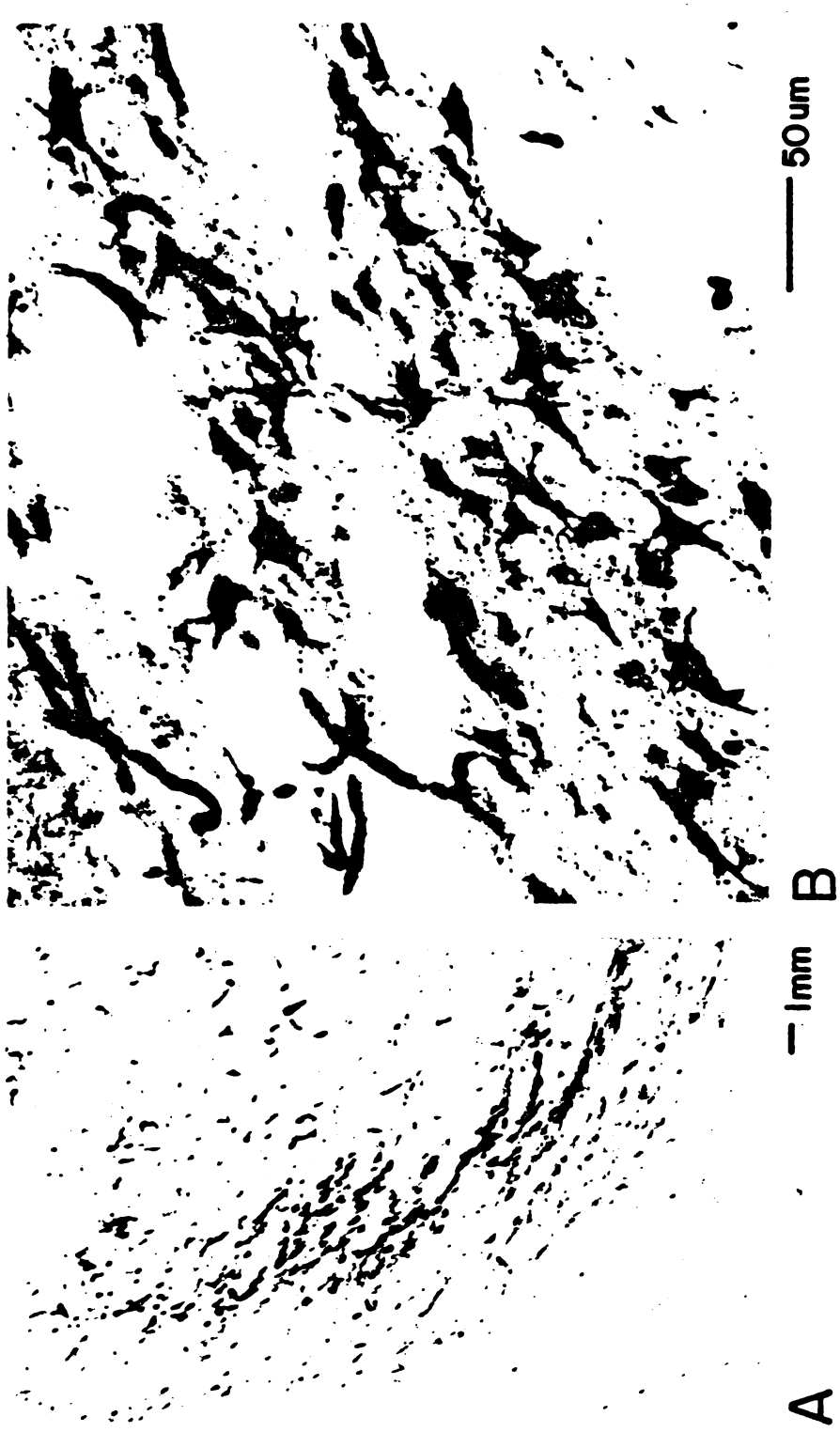


Figure 16

assumes a position dorsal to LP.

The localization of the thalamocortical projection neurons to the lateral aspect of VL was consistently observed following MI hindlimb injections. However, the dorsoventral extent of the neuronal band varied with the size of the injection. Small HRP injections resulted in an abbreviated neuronal band as in experiment 78507 (Figure 17). Within a band of HRP positive neurons, there were relatively few unlabelled cells. Many of the labelled neurons were medium sized with multipolar somata.

Following the MI hindlimb injections, neurons containing HRP reaction product were observed in the intralaminar nuclei. Within the caudal aspect of PC and CL, HRP positive cells were clustered in the central region of PC and CL. The caudal aspect of CM also contained labelled neurons. HRP terminal label was not clearly apparent within the intralaminar nuclei. HRP labelled neurons were not observed in Pf.

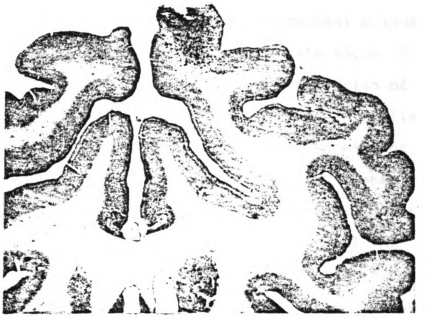
MI Face Thalamic Projections

The area from approximately the lateral one third of the anterior cruciate gyrus to the lateral wall of the rostral limb of the coronal sulcus contains the MI face representation (Hardin, Arumugasamy and Jameson, 1968). (Refer to Figure 1). A series of six HRP injections were made into different locations of the MI face representation. Injections of the MI face area consistently resulted in labelled neurons in medial VL and VMp.

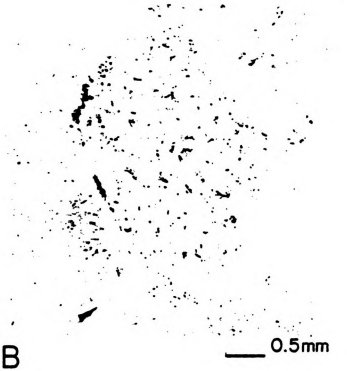
Figure 17. Photomicrographs of the injections site and the distribution of HRP label following a small injection into the MI hindlimb representation in experiment 78507.

A. Low power photomicrograph of the HRP injection site taken from 60 um transverse section treated with TMB as the chromogen and counterstained with neutral red.

B. Photomicrograph of an uncounterstained transverse section taken at approximately the level shown in section c of Figure 14. Note the limited distribution of the retrogradely labelled neurons and the HRP terminal dust.



A



B

Figure 17

A HRP injection was made into the lateral bank of the anterior cruciate gyrus in experiment 79534 (Figure 18 a). The halo of the injection site indicated that the enzyme had spread to the ventral wall of the coronal sulcus. Furthermore, the caudal extent of the halo encroached upon the MI forepaw area. The heaviest concentration of neurons containing HRP positive granules was found in ipsilateral VMp (Figure 18 b-h and 19 a). The labelled neurons were generally small and spindle shaped. The HRP label continued laterally into the medial tip of VL. Sparsely distributed HRP neurons were also observed in ventromedial VA.

An injection rostromedial in the MI face area resulted in HRP labelled neurons in VMp, VL and VA in experiment 79535. The cells containing HRP reaction product were distributed into the dorsomedial aspect of VL and the dorsolateral aspect of VMp. Scattered labelled neurons were also observed in ventromedial VA.

Following the injection into the MI face area, HRP label was observed in ipsilateral CL, PC and CM. Both retrogradely labelled neurons as well as anterograde terminal label was observed in CL (Figure 19 b).

MII Thalamic Projections

MII lies rostral to MI and has been localized to the caudomedial two thirds of the anterior cruciate gyrus (Jameson, Arumugasamy and Hardin, 1968). (Refer to Figure 1). The somatopic localization is not as precise in MII as compared to MI. Evoked potentials were electrophysiologically

Figure 18. The distribution of the HRP positive neurons in ventral thalamus following an injection into the MI face representation in experiment 79534.

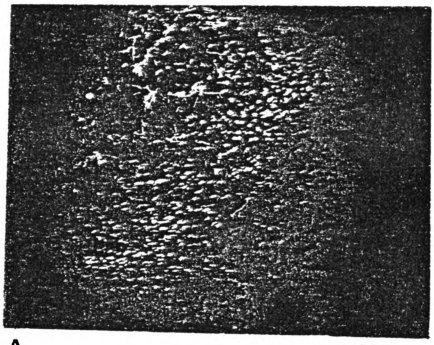
A. A dorsolateral view of the raccoon brain. The blackened circle and stippling indicate the central core and halo of the injection site in TMB treated sections. The injection site centered on the lateral tip of the anterior cruciate gyrus and extended to the ventral bank of the rostral limb of the coronal sulcus.

B-H. A series of transverse sections through successive anterior-posterior levels through ventral thalamus. The dots indicate the approximate density of labelled cell bodies in the sections. Note that the labelled neurons extend from medial VL into VMp.

Figure 19. Darkfield photomicrographs of HRP positive neurons and HRP terminal dust following an injection into the MI face area in experiment 79534.

A. Low power photomicrograph showing the HRP label in VMp and medial VL taken from the level of section d in Figure 18.

B. Photomicrograph showing the HRP terminal label and retrogradely labelled neurons in CL taken from the level of section H in Figure 18.



A — 100 um

B — 50 um

Figure 19

recorded following bilateral tactile stimulation of the distal forelimb and hindlimb. A combined injections of HRP and tritiated amino acids was made into this region of MII in two cases.

In experiment 78504, the injection site was localized to the medial anterior cruciate gyrus just rostral to the cruciate sulcus (Figure 20 a). The injection site measured 2.0 mm at its widest mediolateral extent and did not invade the underlying white matter. The heaviest accumulation of neurons that were retrogradely labelled with HRP reaction product was in lateral MD (Figure 20 b-h and 21). The labelled cells exhibited a patch-like distribution nestled within the lateral arc of the ipsilateral MD. The patch-like distribution was relatively constant throughout the rostrocaudal extend of MD. Both HRP terminal label and ARG silver grains indicate that the corticothalamic projection is reciprocal (Figure 22). The HRP granular reaction product was primarily contained in the cells bodies of the large MD neurons.

In the dorsal aspect of MD lying medial to stria medullaris, a small discrete group of large darkly stained cells contained HRP positive granules. This nuclear group may correspond to nucleus centralis superioris lateralis of Olsewski (1952). Sparsely distributed labelled neurons were also observed in VA and dorsal VL.

Following the MII injections, retrogradely labelled cells and anterograde terminal label was observed in CL, PC

Figure 20. The distribution of HRP positive neurons in thalamus following an injection into the distal limb representation of MII in experiment 78504.

A. A dorsolateral view of the raccoon brain. The blackened circle stippling indicate the central core and halo of the injection site in TMB treated sections. The injection site centered on the caudomedial aspect of the anterior cruciate gyrus.

B-H. A series of transverse sections through successive anterior-posterior levels through thalamus. The dots indicate the approximate density of labelled cell bodies in the sections. Note that the preponderance of labelled neurons exhibit a patch-like distribution in lateral MD.

Figure 21. Brightfield photomicrographs showing the distribution of HRP labelled cell bodies and HRP terminal labelling following an injection into the distal limb representation of MII in experiment 78504. Arrows indicate the same blood vessels. (60 um TMB reacted sections counterstained with neutral red).

A. Low power photomicrograph taken at the level shown in section f of Figure 20. Note that the HRP label occupies the lateral aspect of MD.

B. High power photomicrograph showing the morphology of the blackened HRP positive neurons and the coextensive distribution of the HRP terminal dust.

Figure 21

Figure 22. Photomicrographs showing ARG terminal label following an injection of the isotopes into the distal limb representation of MII in experiment 78504. Arrows indicate the same blood vessel.

A. Brightfield low power photomicrograph of a 60 um transverse section adjacent to the TMB reacted section shown in Figure 21. (Thionine stain).

B. Darkfield photomicrograph showing the ARG silver grains in the same patch-like distribution in lateral MD as that shown for the HRP label in Figure 21.

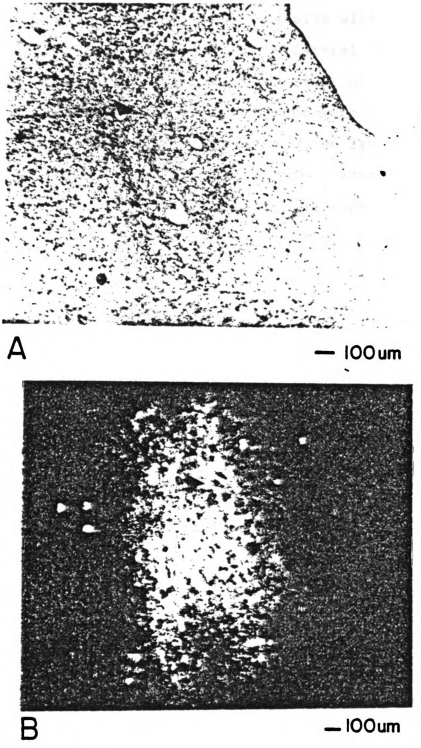


Figure 22

and CM. The HRP positive cells of PC and CL were typically medium sized spindle shaped neurons. The HRP terminal label as well as ARG silver grains was coextensive with the HRP labelled cell bodies in PC and CL. The lateral tip of CM contained the preponderance of labelled cells of the intralaminar nuclei (Figure 23). These neurons were small and oval in shape. Surrounding and overlying the labelled CM cells was HRP terminal dust and ARG silver grains. The labelled neurons of the intralaminar nuclei were located exclusively ipsilateral to the injection site.

Figure 23. Brightfield photomicrographs showing the distribution of HRP labelled cell bodies and HRP terminal labelling in CM following an injection into the distal limb representation of MII in experiment 78504. Arrows indicate the same blood vessel. (60 um TMB reacted section counterstained with neutral red.

A. Low power photomicrograph taken at the level shown in section g of Figure 20.

B. High power photomicrograph showing both retrogradely labelled neurons and terminal labelling in CM.

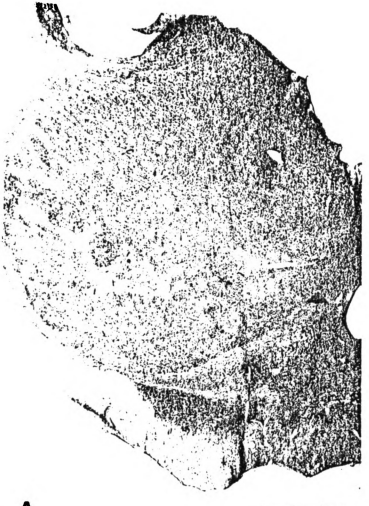


Figure 23

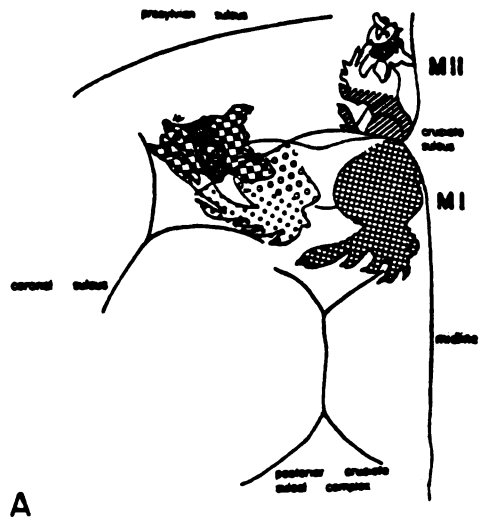
DISCUSSION

The present study demonstrates that in the raccoon the principal thalamic source of MI is the ventral lateral nucleus and the primary source thalamic projection of MII is the mediodorsal nucleus. Within VL, the MI cells of origin and MI terminal projections were distributed as dorsoventrally oriented bands. These bands are topographically organized (Figure 24). The thalamocortical and corticothalamic projections of MII exhibit a patch-like distribution in lateral MD.

The Distribution and Topography of MI Thalamic Projections

The present study findings that the MI thalamic afferents and efferents are distributed as topographically organized bands is consistent with previous reports based on both cats and primates. The elongated strips of thalamic projection neurons and cortical terminal fields have been variously termed bands (Kievet and Kuypers, 1977; Nowakowski and Penny, 1979; Hendry, Jones and Graham, 1979), crescents (Kunzle, 1976; Strick, 1976) or concentric lamella (Jones, Wise and Coulter, 1979). Although considerable overlap exists between thalamic bands, a topographic relationship is preserved in both the dorsoventral and mediolateral planes (Figure 24). The topography of the raccoon MI thalamic

Figure 24. Diagrammatic representation of the thalamic bands related to localized injections into MI and MII. A. A dorsolateral view of the raccoon brain showing the functional localization of the injection sites. B-E. A series of four transverse sections showing the approximate distribution of the corresponding thalamic bands.



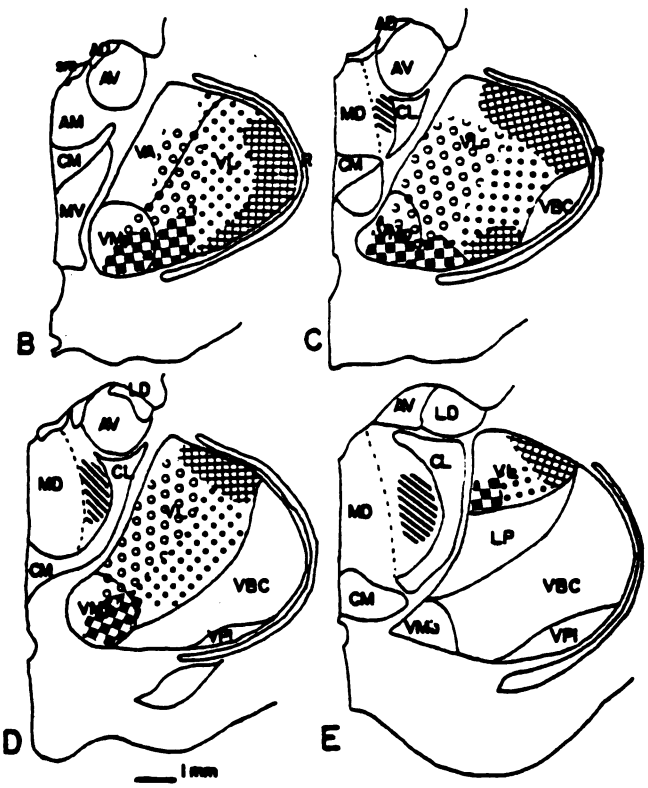


Figure 24

projections is in agreement with that reported in cats (Strick, 1973) and primates (Kunzle, 1978). Furthermore, the finding that the thalamocortical and corticothalamic projections of MI originate and terminate in the same locus supports the suggestion that a principle of thalamocortical organization is the reciprocity of projections (Hendry, Jones and Graham, 1979).

Based on electrophysiological evidence, it has been suggested that within VL, there is a discrete topography of the medial and lateral aspects and a diffuse organization of central VL in cats (Rispal-Padel, Massion and Granetto, 1973). In the present study, the thalamic bands were defined by densely packed HRP positive cells. Such bands were consistently observed in medial VL following the MI face injections and lateral VL following the MI hindlimb injections. However, in some MI forepaw cases, the labelled thalamic neurons of a band were diffusely distributed. (Figure 7 and 10). Unlabelled VL neurons were observed interspersed throughout the band. Although comparative electrophysiological data is lacking for the raccoon, this finding may reflect the anatomical correlate of the VL neuronal distribution defined electrophysiologically. In view of the neural specialization of the raccoon forepaw representation, it is an unexpected finding that the MI forepaw afferents are sparsely distributed in comparison to the thalamic input of MI face or hindlimb. The diffuse distribution of central VL neurons may exert its influence

over a wider area, perhaps through interneurons, thereby mediating a greater complexity of movements involving more than one muscle group. The possibility that the differences in the density of HRP labelled neurons may be due to slight procedural differences in the HRP histochemistry cannot be ruled out. However, a diffuse projections from a large area of VL to a circumscribed area of motor cortex has recently been confirmed in the cat (Larsen and Asanuma, 1979).

Non-Overlapping Thalamic Projections of MI

A major issue concerning representative patterns of thalamocortical connectivity is the existence of overlapping projections. That is, the question of possible anatomical convergence of VBC and VL upon a single cortical area is unsettled across species. The present results indicate that the motor cortex of the raccoon maintains nonoverlapping thalamic projections. The thalamic cells of origin of MI arise primarily from ipsilateral VL. Although sparser projections were observed in VA and VMp, no labelled cells were observed in VBC.

Several studies indicate that the oral division of ventroposterolateral nucleus (VPLo) and the caudal division of the ventrolateral nucleus (VLc) both project to motor cortex in macaque and saimiri (Jones, Wise and Coulter, 1979; Kievit and Kuypers, 1977; Strick, 1976). However, based on the result that VPLo and VLc project exclusively to motor cortex, Jones et al. (1979) suggested that VPLo and VLc form part of the same nucleus. In contrast, Whitsel,

Rustioni, Dreyer, Loe, Allen and Metz (1978) reported that VPLo projects to SI in the macaque. In galago, VPLo has been reported to project to both MI and SI (Nowakowski and Penny, 1979). (Note: the caudal division of ventroposterolateral nucleus (VPLc) and ventroposteromedial nucleus (VPM) together make up VBC in primates (Rose and Mountcastle, 1952).

Both overlapping and non-overlapping projections to motor cortex have been reported among carnivores. In cats, non-overlapping projections have been reported to motor cortex arising primarily from VL while VBC has been reported to project exclusively to SI (Hendry, Jones and Graham, 1979; Strick, 1973). However, the retrograde degeneration study of Sych (1977) indicated that motor cortex receives projections from both VPL and VL in dogs. More recently, this projection from both VPL and VL to motor cortex in the dog has been confirmed using the HRP technique (Weeks and Tanaka, personal communication). This result is significant in the light of Gorska's (1974) electrophysiological study which suggested that there may be a partial overlap of MI and SI for the hindlimb representation in the dog. A HRP injection of this region resulted in retrogradely labelled neurons in both VPL and VL (Weeks and Tanaka, personal communication).

The electrophysiological mapping data obtained in the raccoon suggests that there is a complete separation of MI and SI (Hardin, Arugumusamy and Jameson, 1968; Welker and

Seidenstein, 1959). Furthermore, Herron (1979) reported that SI receives thalamic projections from VBC and not VL in the raccoon. This finding is consistent with the results of the present report indicating that MI both receives and sends projections to VL and not VBC. While the finding that MI face area receives projections from both VL and VMp may initially suggest that overlapping projections may characterize a part of raccoon MI, VMp is not considered to be part of the thalamic somatosensory face representation (Welker and Johnson, 1965). In the cat, the afferents of VMP have been shown to arise from the entopeduncular nucleus and substantia nigra, nuclei implicated in motor behavior (Hendry, Jones and Graham, 1979). In the present study, occasionally the band of labelled thalamic neurons extended continuously from VL into lateral VA. This observation that traditional cytoarchitectonic boundaries fail to delimit thalamocortical afferents concurs with the results based on the cat. Hendry, Jones and Graham (1979) suggest that lateral VA and VL be considered part of the same nucleus on the basis of the finding that lateral VA and VL both receive cerrebellar afferents and both project to motor cortex. However, the distribtion of cerebellar efferents remain to be determined in the raccoon.

The present results support Petras' (1969) suggestion that the pathways of postural stability and locomotion may evolve at different rates between families of the same order. The existence of nonoverlapping thalamic projections

of MI in the raccoon suggests that among carnivores, there are variations in the organization of thalamocortical relations, perhaps related to the specialization of body parts.

Possible Sources of Peripheral Input to Motor Cortex

In the present study, peripheral stimulation resulted in evoked potentials in raccoon motor cortex. A number of investigators have described a short latency peripheral input to motor cortex in both cats (Welt, Aschoff, Kameda and Brooks, 1967) and primates (Kruger, 1956; Lemon and Van der Burg, 1979; Malis, Pribram and Kruger, 1953; Rosen and Asanuma, 1972). The cortical neurons have been described as receiving input from both deep and superficial tissues via a fast conducting pathway (Lemon, 1979; Lemon and Van der Burg, 1979). This input is considered to play a significant role as the generator of afferent feedback during tactile exploration.

The pathways of motor cortex mediating such responses are unclear. Electrophysiological studies of VL have revealed that the majority of neurons are unresponsive to peripheral stimulation in cats (Asanuma and Fernandez, 1974; Nyquist, 1975) and primates (Strick, 1976). Clearly, VBC is not the source of such input in primates (Jones, Wise and Coulter, 1979; Strick, 1976), cats (Hendry, Jones and Graham, 1979; Strick, 1973) or raccoons. In view of the extensive corticocortical projections from SI to motor cortex in primates (Jones, Coulter and Hendry, 1978; Kunzle,

1978), cats (Jones and Powell, 1968) or raccoons (Sakai and Herron, 1979), an intrahemispheric projection has been suggested as a possible source (Wiesendanger, 1973). However, elimination of SI input does not alter the sensory response of the motor cortex in primates (Malis, Pribram and Kruger, 1953; Rosen and Asanuma, 1973) and only minimally attenuates it in cats (Asanuma, Larsen and Zarzecki, 1979).

The cortical response to peripheral stimulation can be abolished by bilateral section of the cuneate fasciculus in primates (Brinkman, Bush and Porter, 1978). Furthermore, VPLo contains neurons responsive to peripheral stimulation (Horne and Tracey, 1979). Thus, a pathway via the cuneate or external cuneate nucleus to VPLo may account for the sensory responses in motor cortex (Horne and Tracey, 1979). However, due to the difficulty in establishing a consistent VPLo/VPLc border the issue of dorsal column projections to VPLo is controversial (Boivie, 1978; Kalil, 1976).

A clear homologue of VPLo is not evident in carnivores. In contrast to primates, in the cat elimination of cuneate afferents minimally influences motor cortical responses to peripheral stimulation. However, section of both the spinothalamic tract and spinocervical tract greatly reduces the cortical response in cats (Asanuma, Larsen and Zarzecki, 1979). Hand and Van Winkle (1977) failed to report a projection from the dorsal column nuclei to VL in cats. However, Berkley (1975) reported that a border zone between VL and VBC is the recipient of projections from the

cerebellum, dorsal column nuclei and the spinothalamic tract in the cat. Neurons in this border area project to motor cortex (Hendry, Jones and Graham, 1979; Larsen and Asanuma, 1979; Strick, 1973). This thalamic zone is capable of carrying short latency information to the motor cortex from the periphery (Asanuma, Larsen and Yumiya, 1979). A homologous zone may exist in the raccoon. There is a small cluster of large neurons in ventral VL which are labelled following and injection into the MI distal forepaw area. Whether this area corresponds to the cat VL/VBC border zone awaits further study. In view of the differences between primates and carnivores in the relative contribution of the dorsal column and spinothalamic tract to the motor cortical response from peripheral stimulation, it would be of value to examine the inputs from the periphery to motor cortex in the raccoon.

An alternative input site for the response to peripheral stimulation in motor cortex may be the intralaminar nuclei, particularly the central lateral nucleus (Hendry, Jones and Graham, 1979). Spinothalamic fibers terminated in the same region of CL that results in projections to the motor cortex in the cat (Itoh and Mizuno, 1977). The results of the present study indicate that CL is the major intralaminar projection to the motor cortex in the raccoon.

MII Thalamic Projections

In the present study, the thalamic projections of MII were shown to arise primarily from the lateral one third of the mediodorsal nucleus. Sparse labelling was also present in VA, dorsal VL and CM. Traditionally, MD projection cortex has been defined as prefrontal cortex (Rose and Woolsey, 1948). However, a relationship of lateral MD to motor structures has recently been established. MII and the premotor area are reciprocally connected with the lateral aspect of MD, the paralamellar portion, VA, VL, and the intralaminar group (Akert, Hartmann, VonMonakow and Kunzle, 1979; Kievit and Kuypers, 1977; Kunzle, 1978) in the macaque. Furthermore, a cytoarchitectonic subdivision of lateral MD, pars multiformis, maintains a reciprocal connection with the arcuate region, the frontal eye fields (LeGrosClark and Boggon, 1935; Rose and Woolsey, 1948). Paralamellar MD receives afferent input from the cerebellum, spinal cord and the superior colliculus (Leonard, 1972).

It is of interest to note that Jameson's (1968) electrophysiological map indicated a wide field in the rostral portion of MII that resulted in conjugate eye movements when stimulated. This field is shown to abut and partially overlap the zone that resulted in forelimb and hindlimb movements. Based on the thalamocortical connectivity of this MII region, it is possible that the frontal eye fields and MII partially overlap. However, the distribution of the collicular and cerebellar afferents to MD

remain to be determined in the raccoon.

The projections of MII have not been extensively studied among carnivores. Rinvik (1972) reported corticothalamic projections from presumptive MII in the cat using degeneration techniques. He reported terminal projections to VA, VBC, VL, lateral MD and the intralaminar group. In the dog, MII receives sparse projections from VA and VL while the premotor region, the region that occupies the medial one third of the anterior cruciate gyrus, receives predominantly MD projections (Weeks, Tanaka and Stanton, personal communication). The premotor projections in the dog are interesting in the light of the present results which may suggest maintenance of a topographic thalamocortical relation across these two carnivore species.

The localization of the primary thalamic source of MII to MD in the present study is in contrast to the MII projections reported in either the dog (Weeks, Tanaka and Stanton, personal communication) or cat (Rinvik, 1969) and appear to resemble the MII projections reported in primates (Kievit and Kuypers, 1977). The primate MII is hypothesized to be involved with the programming of complex motor sequences (Roland, Larsen, Lassen and Skinhøj, 1980). In particular, MII plays a role in modifying a sensory cued motor output (Tanji, Taniguchi and Saga, 1980). In view of the ability of the raccoon to skillfully use its forepaws and its complex behavioral repetoire, it is possible that the thalamic organization of MII projections in the raccoon and primate exhibit functional parallels.

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