

Functional Variation in Dermatomes in the Macaque Monkey Following Dorsal Root Lesions

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ABSTRACT Previous definitions of dermatomes, in various species, have revealed a characteristic pattern of serial overlapping root areas. Most investigators have used either the method of "remaining sensibility" or recordings of dorsal nerve root potentials, and have sectioned the dorsal nerve roots within the spinal canal, proximal to the dorsal root ganglia.

We have used the method of "remaining sensibility" in experiments in macaque monkeys. Section of the neighboring dorsal roots proximal to their ganglia produced dermatomes which resembled closely those isolated by Sherrington. However, we found consistently that when the neighboring spinal nerves were sectioned distal to their dorsal root ganglia, the isolated root areas on the trunk were approximately twice as large as before and now also showed persistent hyperesthesia. Re-sectioning of the dorsal roots of these nerves within the dura reduced the isolated root areas to their "classical" size, but usually only after a delay of three or four days. The injection of subconvulsive doses of strychnine sulfate solution produced an enormous expansion of an isolated dermatome, irrespective of whether the neighboring roots had been sectioned intradurally or beyond their ganglia; no change in area was observed after the injection of morphine sulfate solution. Conversely, the size of a dermatome which had been isolated by intradural section of three dorsal roots above and below was reduced by subsequent section of three additional roots above and below.

We have concluded that the observed size of an isolated dermatome is a variable quantity and can be taken as an index of the efficiency of sensory transmission within the same and neighboring segments of the spinal cord.

The first satisfactory delineations of dermatomes were made by Sherrington (1893, 1898) in acute experiments in the frog, cat and macaque monkey. Sherrington used the method of "remaining sensibility" to isolate the areas of innervation by one root from the overlapping of neighboring roots. He sectioned at least two dorsal spinal nerve roots cranial and two caudal to the nerve root under study to produce an insensitive area on either side of the isolated dermatome. He tested for sensitivity by observing reflex responses to pinching of the skin with fine pointed forceps, and found the trunk dermatomes to be serial bands extending between the dorsal and ventral midlines with a cranio-caudal overlap of approximately one-half. In the limbs the root areas overlapped more extensively, and some did not extend to the midlines of the trunk. Sherrington also noted that within each dermatome the intensity of responses lessened toward the boundaries of the root area.

A similar characteristic pattern of serial overlapping fields has been revealed in subsequent investigations. Other studies using the method of "remaining sensibility" include those in man (Foerster, '33), and the lizard (van Trigt, '17), pigeon (Kaiser, '24), dog (Ten Cate and Waterman, '32; Cardozo, '37; van Rijnberk and Ten Cate, '37), ox (Arnold and Kitchell, '57) and sheep (Kirk, '68). It appears that in these isolations the root sections have been made proximal to the dorsal root ganglia.

In monkeys (Kuhn, '53), sheep and goats (Linzell, '59), cats (Kuhn, '53; Hekmatpanah, '61; Pubols et al., '65), dogs (Fletcher and Kitchell, '66) and opossums (Oswaldo-Cruz et al., '66) dermatome charts have been assembled from electrophysiological recordings of dorsal root po-

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tentials. Other observations have also been utilized. Rossi ('10) charted sensory boundaries after spinal transections at various levels in dogs. Visceral pain in Head's study (1893) was often referred to skin areas similar to those involved in herpes zoster infections. Dusser de Barenne ('11) applied strychnine sulfate solution to spinal segments in dogs and mapped the resultant areas of cutaneous hyperesthesia: de Boer ('16), Cardozo ('37) used the same method in cats. The dermatomes defined by these means are of the same pattern as those defined by the method of "remaining sensibility". Keegan and Garrett ('48) recorded non-overlapping areas of diminished sensitivity in humans with intervertebral disc protrusions; their limb fields extended as regular bands from the dorsal midline of the body.

The charting of dorsal root filament potentials by Kuhn ('53) revealed a successive overlap between the area of skin innervation of the different filaments that make up each root. In addition this study confirmed the greater density of innervation in the central part of the root dermatome and filament areas, compared with their rostral and caudal edges. Root potentials also enabled the dermatome to be charted to purely tactile (hair) sensation. Neurologists, following Head, have noted that in the human patient the loss of sensation following multiple root lesions is commonly wider in extent to pin prick than to light contact. There is no confirmation of this difference in animal experiments. The finding by one of us (Denny-Brown, '65) that one type of hyperesthesia in human patients results from loss of light discriminative sensation at borders of sensory loss produced by peripheral nerve lesion led us to expect comparable changes following experimental root lesion. An observation that hyperesthesia followed root lesion in the macaque monkey (Denny-Brown and Kirk, '68) was the starting point of the present investigation. This hyperesthesia was found to have a different explanation.

METHOD

The animals used were immature (2-3 year old) macaque monkeys (*Macaca mu-*

latta) weighing 2-3 kg. Most were males. All operations were performed, with aseptic precautions, under pentobarbital ("Diabotal", Diamond Laboratories) anesthesia. As described in the text, in most animals the dorsal roots were either sectioned intradurally, through a longitudinal opening in the dura, or they were sectioned immediately distal to their dorsal root ganglia, the dura surrounding the spinal cord being left unopened. The accompanying ventral roots were divided along with the dorsal roots in section distal to the ganglia. In a third series of four animals, the dorsal root sections were made extradurally but immediately proximal to the ganglia, two with section of ventral roots, two with intact ventral roots. We usually sectioned three roots cranial and three caudal to the root to be isolated; the exceptions are specified in the text. Whenever possible, the root to be isolated was chosen so as to leave intact as many prominent blood vessels as possible, and vessels which accompanied a root to be sectioned were left intact when they were clearly separable from all the filaments of that root. It was found advantageous to leave a portion of a vertebral lamina over the isolated root(s) as a bridge in order to reduce post-operative compression of the spinal cord by dorsal scar tissue.

Sensitivity was usually tested by scratching the skin with a pin. The animals reacted by either reaching for the pin and pushing it away, or by scratching themselves: the responses are described in detail in the account of the various procedures. Pin prick was found a less reliable stimulus, and regular responses to touch or to cold were obtained only when the area of skin was hyperesthetic. Most of the dermatomes isolated were caudal thoracic or upper lumbar fields; the costal and abdominal reflexes could then be used as supplementary indices of sensitivity, and the monkeys retained some control of their lower limbs and bladder. Some hyperesthetic reactions were recorded on movie film.

Once the surgical wounds had healed, the monkeys were restrained in a chair by straps around the neck, thorax and pelvis (fig. 1). A board tied loosely around the

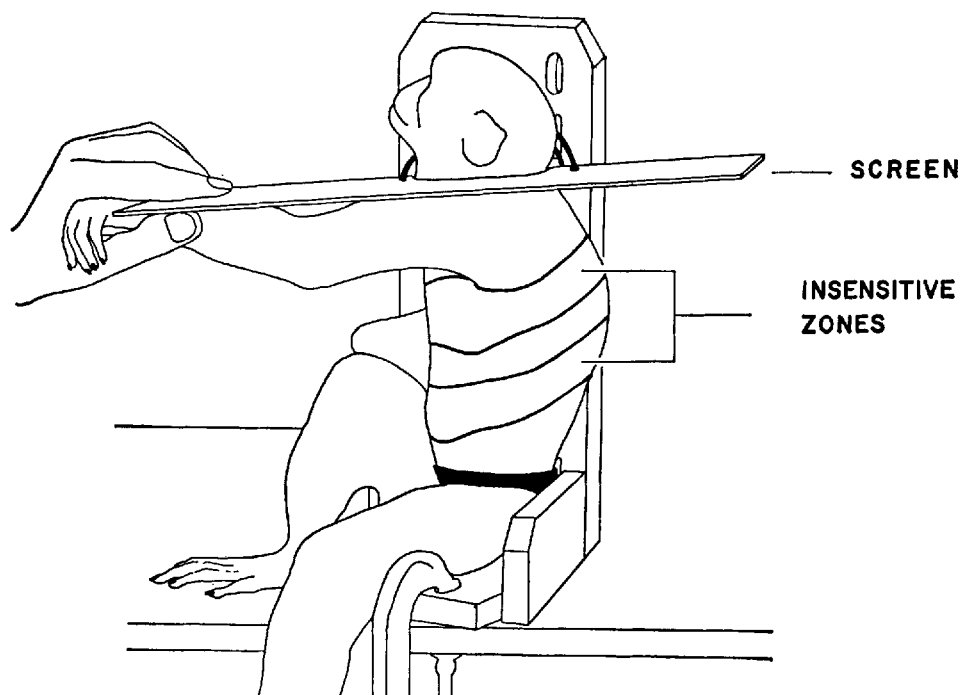


Fig. 1 Monkey in examination chair. The thoracic dermatome isolated by the method of "remaining sensibility" lies between the charted zones of insensitive skin. The loosely-tied screen prevents the animal from anticipating test-stimuli.

monkey's neck, or some other such shield, prevented it from anticipating a test-stimulus. The animals were generally examined daily during the first two weeks after surgery, and at longer intervals once the sensory areas had stabilized. The sensory borders were marked in the skin in inks of various colors, and photographed on 35 mm color film. Before a second operation was performed the existing (stabilized) borders were tattooed in the skin. The monkeys were usually kept for two to eight weeks after the dermatome areas had ceased to expand.

In all animals the dorsal root sections were checked at autopsy. The relations of the sensory borders to the vertebrae, rib cage, nipples, umbilicus, and tubera coxarum were recorded. The text-figures were prepared by inserting this information into standard figurines based on the measurements of representative monkeys. Details of the course of each border were transferred from the 35 mm slides.

RESULTS

(a) *Intradural section of neighboring dorsal roots proximal to their ganglia*

We first repeated some of Sherrington's isolations. The neighboring dorsal roots were exposed by a longitudinal opening in the dura, and each root to be sectioned was identified, raised on a small angled seeker and a segment some 3 to 7 mm in length excised.

We isolated the eighth and tenth thoracic dermatomes and the lumbar dermatomes unilaterally each in at least one animal. The extent of the stabilized lumbar fields is illustrated in figure 2; the eighth thoracic fields are shown in figure 3. These areas closely approximate those mapped by Sherrington (1893, 1898). In the course of subsequent experiments the separate borders on the trunk of the remaining thoracic dermatomes were charted and their positions were also found to correspond closely with Sherrington's descriptions.

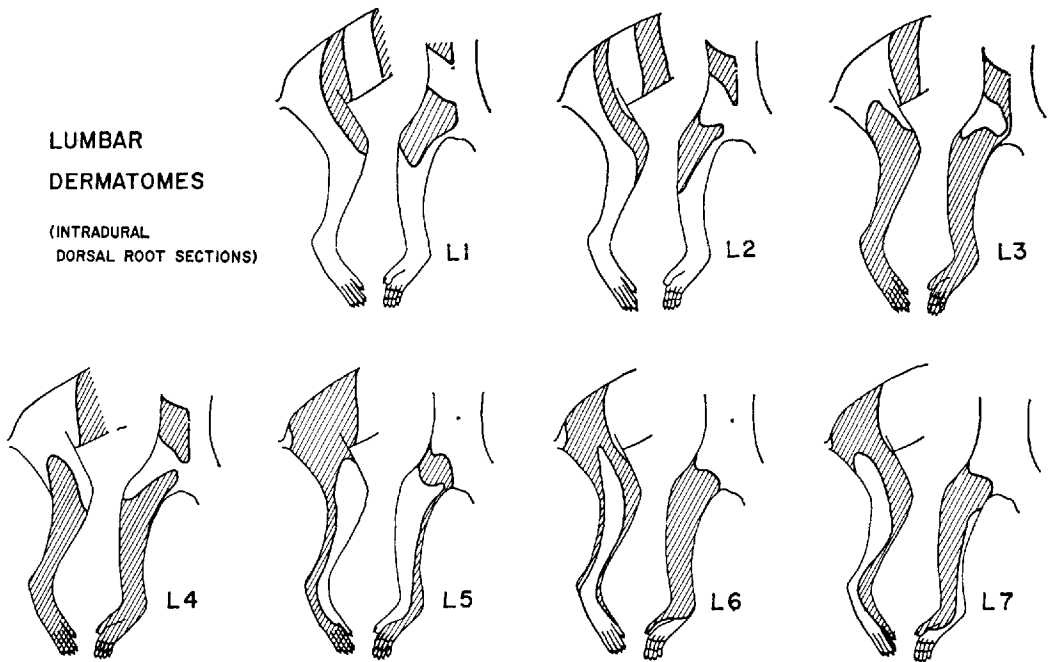


Fig. 2 Lumbar dermatomes in the macaque monkey isolated by intradural section of neighboring dorsal roots proximal to their ganglia. The sensitive areas remain unshaded. In isolating the L3 and L4 fields, five and four neighboring caudal roots were sectioned, respectively; three roots were divided above and below in each other instance.

The animals' responses to test stimuli were similar in each instance. In the first two or three days after surgery they were characterized by scratching and general restlessness. In this period the monkeys, when held with minimal restraint and with one arm free, would usually immediately scratch at the area of skin being stimulated by light pin strokes or pin pricks. They would frequently flex and abduct the ipsilateral elbow in order to reach the dorsolateral areas on the trunk. On the thorax and abdomen the scratching response could be obtained from the whole width of the isolated dermatome (except within 2-3 cm of the dorsal midline), but was more intense along its borders. In the caudal thoracic dermatomes scratching was most often seen along the upper borders, and in the caudal lumbar fields it appeared on the lateral and caudomedial aspects of the thigh, and over the knee. In many instances the monkey merely groped slowly in the general direction of the stimulating pin; at most it would scratch briefly (4-8 beats) with relatively

moderate intensity. These movements were characteristically unhurried and not accompanied by struggling or vocal protest. They were often difficult to fatigue, yet if the free arm was restrained the monkey did not give any visible response to continued stimulation.

General restlessness in response to stimuli usually arose when the sensitivity of the root area appeared to be temporarily depressed, or when the dermatome borders were not particularly prominent, and it gave the impression that the sensations being experienced were unpleasant but poorly localized.

Scratching responses and general restlessness usually disappeared after the second or third day, and did not reappear during the four weeks to eleven weeks for which the animals were observed. The axillary regions remained very sensitive; the groin, caudoventral abdominal wall and the medial aspect of the thigh poorly reactive. The extent of apparent conscious response was reduced when the bladder was distended, or the animal agitated or

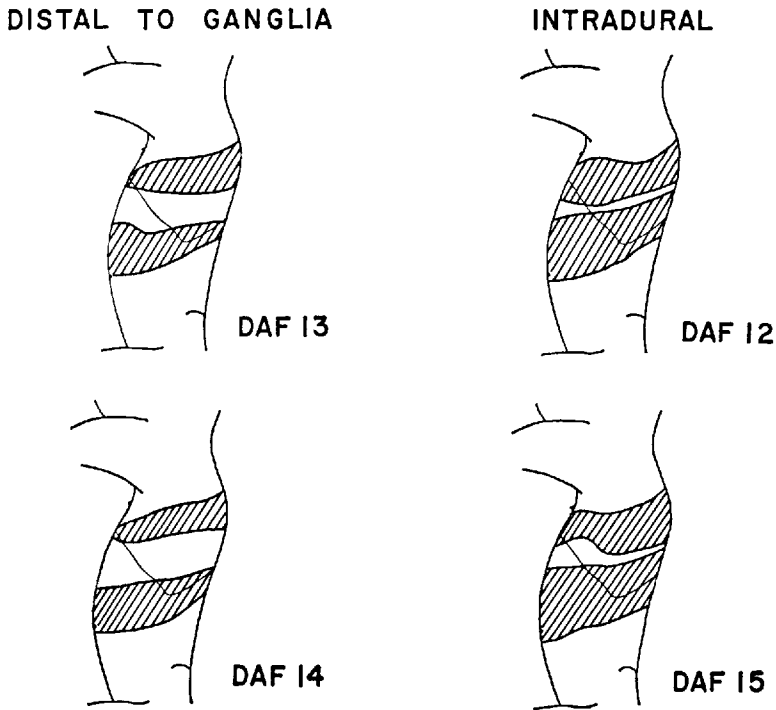


Fig. 3 The eighth thoracic dermatome isolated unilaterally in each of four animals. The insensitive (shaded) zones were narrower in the two animals shown on the left, in which the sections had been made distal to the dorsal root ganglia, than in the two shown on the right, in which the sections had been made intradurally proximal to the dorsal root ganglia.

closely restrained. Sensitivity was then greatest in the middle of each dermatome. As in the normal macaque monkey, several successive pin pricks in a sensitive area would be apparently ignored, yet one further stimulus could evoke vigorous struggling and even a vocal protest.

In the caudal lumbar fields the dorso-lateral pre-femoral and pre-tibial areas were usually the most reactive from the first day. However, it usually took up to two weeks for a limb dermatome to stabilize: the progressive changes in the position of a boundary being quite abrupt between one day and the next. It was usual for the monkey to then give strong scratch and/or struggle responses for the first two or three days when stimulated in these newly-reactive areas. The greatest extensions occurred on the lateral aspect of the thigh and on the dorsum of the foot. Those areas of the dermatome that appeared first continued to be the most reactive. Stimuli

were accurately localized: the monkey would occasionally pick up its leg and, if not obstructed by a shield, closely inspect the area stimulated and perhaps use the thumb and first finger to pluck at the site in a "grooming" action.

From the first day after surgery the local cutaneous reflex responses were enhanced, and it was usual for the area from which they could be elicited to be larger than the area from which conscious sensory responses could be obtained. The reflex area extended approximately 0.5 cm beyond the borders of the sensory dermatome. In the periphery these reflexes were often most readily elicited by light pin pricks. During the period in which the dermatome area was expanding, the appearance of reflex reactions from a localized area just outside the dermatome boundary was often a prelude to local extension of the sensory area within the following two days. Once the sensory area had stabilized, the re-

sponses to pin prick became quite variable, but the "reflex fringe" commonly remained.

Three monkeys continued to scratch at the upper parts of their legs for one or more weeks. These actions became quite stereotyped, their intensity was usually poorly correlated with the location or intensity of the applied stimulus, and they were only seen while the monkey was in the examination chair. We considered that these were conditioned responses distinguishable from those which we attributed to transient hyperesthesia. Again, these latter responses could also be differentiated from the grasping, biting behavior of small males and the clawing, clinging movements of many females.

After intradural section of neighboring roots it was most unusual for a monkey to protest when small blocks of ice were applied to its skin. In these animals, as in normal macaques, the ice was virtually ignored. The monkey would often momentarily stop the casual movements of its eyes as it gazed around the room, and would occasionally contract its eyebrows in a definite frown, but if it made any other movements at all, these were limited to an unhurried groping for the ice and perhaps an attempt to push the examiner's hand aside.

In addition, in four animals the neighboring dorsal roots were sectioned immediately proximal to their dorsal root ganglia. The eighth thoracic dermatome was isolated unilaterally in the first monkey and the ninth thoracic in the second, by section of dorsal roots alone. In the remaining two animals the accompanying ventral roots were also divided: the sixth thoracic root area being isolated unilaterally in one monkey and the first lumbar area in the other. In the last mentioned animal the contralateral first lumbar dermatome was also isolated, at the same operation, by the usual intradural section of the corresponding dorsal roots proximal to their ganglia. The monkeys were observed for 4, 28, 6 and 10 days respectively. These isolated root areas all closely resembled, in both size and sensitivity, those already described, and in the last-mentioned animal the first lumbar fields were symmetrical and of equal sensitivity.

(b) Section of neighboring dorsal roots distal to their ganglia

Having confirmed the classical pattern of the several thoracic and lumbar dermatomes when isolated by intradural section of the adjacent dorsal roots, we then isolated the eighth thoracic and fifth lumbar dermatomes unilaterally in two (DAF 13, 14) and three (DAF 5, 7, 10) monkeys, respectively, by sectioning the adjacent dorsal roots distal to their dorsal root ganglia.

From the first day after surgery the eighth thoracic fields were approximately twice the width of the same fields isolated by intradural root section (fig. 3), both the cranial and the caudal borders having expanded. Also, the uppermost and lowermost sensory borders lay approximately 1.0 cm closer to the isolated dermatome, further reducing the bands of sensory loss. The sensitive root areas continued to expand by several millimeters each day until they stabilized at the end of the first week.

The fifth lumbar dermatomes were also enlarged. They extended proximally onto the trunk to include much of the caudal abdominal and pelvic skin (fig. 4), though the borders distal to the knee did not differ from those seen after the intradural isolations.

The responses shown by each monkey to pin scratch or pin prick in these enlarged thoracic and lumbar areas were much more intense than any observed previously. The animals scratched themselves vigorously and persistently, and during each examination became increasingly restless. The scratching was usually poorly localized: the two monkeys in which a thoracic dermatome had been isolated scratched the skin over the ipsilateral costal margin, those with a lumbar isolation scratched the dorsolateral aspect of the ipsilateral thigh. It often appeared that the animals scratched in these areas because they were the most readily accessible: this was particularly noticeable in the lower limbs, where stimulation of the foot or pretibial skin often induced the scratching of the thigh.

The responses from the middle of each root area remained large and brisk, but in both the thoracic and the lumbar fields

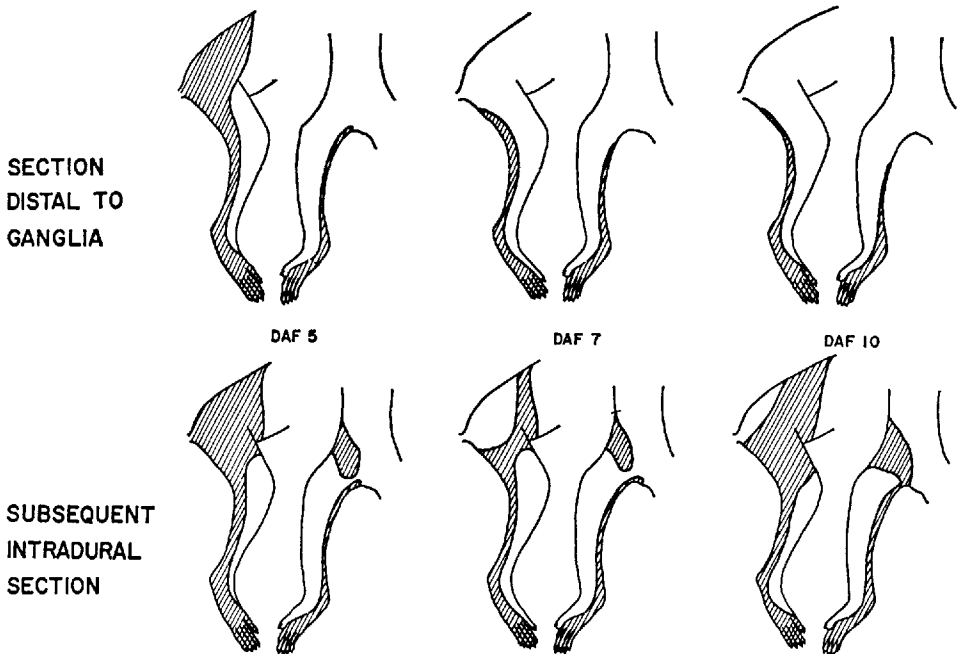


Fig. 4 Fifth lumbar dermatomes. Each upper diagram shows the extent of the sensitive cutaneous areas (unshaded) following sections distal to the dorsal root ganglia. In the first animal (DAF 5), five roots were sectioned caudally, instead of the usual three roots. The lower diagrams show the reduced areas of sensitive skin in these three animals following intradural re-section of the *same* neighboring dorsal roots proximal to their ganglia.

the border zones were much more reactive than before. The monkeys also now gave definite responses to pin scratch and pin prick to the skin adjacent to the ventral midline between the xiphoid and the groin, and on the medial aspect of the thigh: areas in which it is often difficult to elicit repeated responses from a normal macaque. Responses followed even extremely light pin strokes to the skin, but the animals did not react to movement of hairs of the skin in these areas. Local cutaneous reflexes were brisk and of increased magnitude. In the first two days brief micturition often followed each series of stimuli to the ventral sectors of the border zones on the thorax and cranial abdomen.

This increased reactivity persisted: even after eight weeks one animal would use a foot to scratch the eighth thoracic field when prevented from using his hands.

Responses to ice applied to the thorax were equivocal. An occasional vocal protest and grasping at the ice occurred; but these actions were not clearly distinguish-

able from general restlessness. However, the responses to the application of ice along the sensory borders on the legs, especially on the lateral and caudo-medial aspects of the thigh and on the medial surface of the hallux, were dramatic. After a brief delay the monkey would suddenly struggle violently, turns its head abruptly to look at its legs, bare its teeth, grasp strongly at the observer's hand and, in many instances, vocalize in apparent anger. If the observer continued to hold the ice in place the monkey would either tug its leg away or scratch the observer's hand severely with its fingernails in its attempts to remove the ice. These animals would give no such reaction when ice was applied to the central part of the isolated dermatome or to any other part of the body; nor would they respond when wet objects of various textures (wood, paper, plastic) and sizes were applied along the dermatome boundaries. It was consistently found that during any one examination a monkey would only once react violently to the ap-

plication of ice to a particular point along the dermatome boundary, yet would give an equally intense display when the ice was applied to an adjacent sector of the boundary.

In the first 3-4 days after surgery, hyperaemia of the skin was observed in these dermatomes isolated by section of roots distal to their ganglia. While this was increased in degree by stroking the skin with a pin, it was not limited to the site of the stimulation. It was observed on the medial and lateral aspects of the thigh in a region about 1-2 cm wide immediately within the sensory boundary.

After the lumbar fields had remained stable for two or five weeks, we operated for a second time (at 21, 43 and 42 days, respectively, after the initial operation) and sectioned the same dorsal roots again, but this time intradurally, i.e. proximal to the dorsal root ganglia. Each dermatome

then contracted to the size and shape characteristic of an intradural isolation (fig. 4): there being no detected change in the boundaries distal to the knee. However, in the first two of these three monkeys there was no immediate reduction in the root area: the change occurred quite abruptly between the third and fourth days after the second operation. In these two animals reactions from the skin which was to become unresponsive could be readily obtained by moving the point of a pin lightly across the (clipped or shaved) skin so that it made minimal contact with the skin surface.

After the reduction in area the responses from the residual dermatome were indistinguishable from those following a primary intradural isolation. The peripheral sensitivity had diminished, the monkeys did not protest the application of ice and no hyperaemia was observed.

DAF 15

T8 ISOLATION
INTRADURAL
PATTERN: 2nd-5th WEEK

(0.25 MG/KILO)

ON 22nd DAY

▨ - AT 7 MINUTES

■ - AT 15 MIN (MAXIMUM)

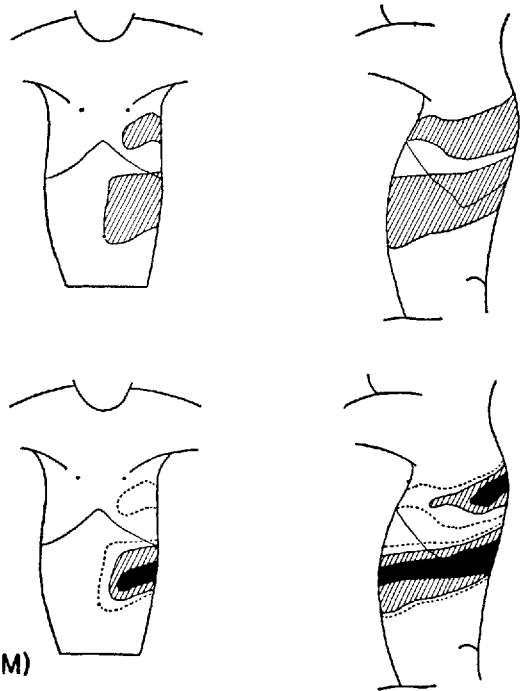


Fig. 5a Effect of strychnine. The upper diagrams show the pattern (between the second and fifth weeks) of an eighth thoracic dermatome isolated by intradural section of neighboring sensory roots proximal to their ganglia. The insensitive areas are shaded. The lower diagrams show the reduced size of the insensitive zones following the injection of strychnine sulfate (0.25 mg/Kg) on day 22: the shading represents the insensitive zones after seven minutes, the solid black the (minimum) zones after 15 minutes.

(c) *The effect of strychnine and of morphine*

As noted above, in two of the monkeys in which the neighboring dorsal roots had been sectioned distal to their ganglia and then, at a second operation, re-sectioned intradurally, there was a delay of three to four days before the abrupt reduction in the size of the isolated root area. This delay was indicative of a functional rather than an anatomical change. We accordingly investigated the effect of injecting strychnine, a drug which has been found to abolish spinal inhibition (Bradley and Eccles, '53). We tested five monkeys between 11 and 45 days after dermatome isolation. In two animals the eighth thoracic dermatome had been isolated by intradural root sections, in two others it had been isolated by section of roots beyond their ganglia, and in the fifth animal the ninth thoracic dermatome had been isolated by section of roots between the dura mater and their ganglia.

Following the subcutaneous injection of strychnine sulfate solution (Mallinckdrodt

Chemical Works), at 0.25-0.5 mgm/kg, a progressive contraction of both insensitive zones was apparent in each monkey (fig. 5). The effect was greater in the upper insensitive zone, so that at the stage of maximal effect (15 minutes after injection) only a small area of dorsal skin remained unreactive. All the monkeys gave very definite reaction to stimuli in the newly extended areas: struggling briefly and, less often, reaching for the pin or the site of stimulation. The animals with roots sectioned distal to the ganglia showed and even greater final reduction of the areas of sensory loss. The final degree of increase in sensitivity was comparable in all five animals.

In view of this remarkable effect of a subconvulsive dose of strychnine on the dermatome pattern it was of interest to examine the effect of morphine. We used a 2.9 kilo macaque monkey with the first lumbar dermatome isolated on both sides 17 days earlier by intradural section of three dorsal roots above and three below. This animal had small lesions in the dorso-

DAF 14

T8 ISOLATION
DISTAL TO GANGLIA
PATTERN: 2nd-6th WEEK

(0.5 MG/KILO)
ON 31st DAY
▨ - AT 7 MINUTES
■ - AT 15 MIN (MAXIMUM)

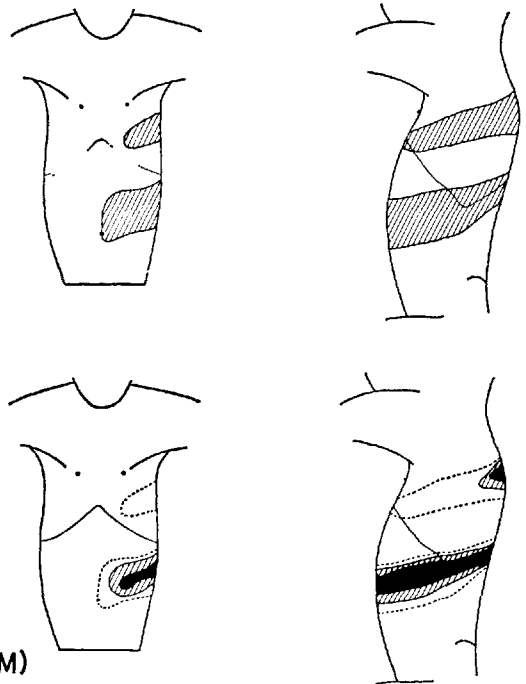


Fig. 5b A similar reduction in the same dermatome isolated in another animal by section of the neighboring dorsal roots distal to their ganglia. The strychnine sulfate was injected, at 0.5 mg/Kg, on day 31.

lateral column of one side at the level of L1 segment in addition as part of an investigation of Lissauer's tract to be reported later (Denny-Brown, Kirk and Yanagisawa, '70). Crystalline morphine sulfate was dissolved in distilled water to a strength of 5 mg/ml. Beginning with a dosage of 0.5 mg, further increments of 0.5, 0.5, 0.1, 0.1, 0.2, 0.2, and 0.2 mg were injected subcutaneously at intervals varying from 12 to 32 minutes, during which the dermatome borders and reactions were repeatedly charted. The general response of the animal became gradually more difficult to elicit, though local reflexes remained brisk throughout. After a total dosage of 9.5 mg (3.3 mg per kilo) in two hours it required several repetitions of severe pin scratch to elicit a feeble general protest, yet the borders of the reflex and general responses did not change. No pupillary change was induced. It is evident that morphine acts at some different point than strychnine. The dissociation between general and reflex response induced by morphine has been noted by Wikler ('50).

(d) The effect of section of additional dorsal roots

In order to isolate dermatomes for study in chronic preparations we, like previous investigators, were obliged to use the method of "remaining sensibility". The size of the dermatome obtained appeared to depend in some way on the nature of the ablation of the neighboring spinal roots. It seemed possible that the necessary section of the adjacent dorsal roots was, in itself, producing restriction of the root areas, and that section of additional dorsal roots cranially and caudally might therefore further reduce the size of an isolated dermatome.

We accordingly made a unilateral isolation of the eighth thoracic dermatome in one monkey (DAF 17) and of the tenth thoracic in another (DAF 25) by sectioning, as usual, the three adjacent dorsal roots above and below. At a second operation on the first animal 16 days later we sectioned three more dorsal roots above and below without re-opening the central portion of the initial incision (i.e. we had now sectioned T2-T7 and T9-L2 on one

side). When examined the following day, both borders of the eighth thoracic root area had contracted by 0.75 to 1.0 cm. The cranial border remained at its new level until the second week and then shifted progressively craniad until at day 23 it coincided with the initial (tattooed) level. Section of yet another four dorsal roots cranially at a third operation on day 76 of the experiment was not followed by any further change in the upper border within the subsequent 28 days. Throughout this time the caudal border of the dermatome showed virtually no change from its position on day 17 of the experiment. The contralateral sensory reaction did not change.

In the second animal three additional adjacent dorsal roots above the initial isolation were sectioned on day 28. Next day the upper border of the isolated tenth thoracic field lay 1.5 cm further caudad: the lower border had not changed (fig. 6). The upper border was still at this new caudad level 29 days later, at which time three more roots were sectioned below the initial isolation. The caudal border of the dermatome was found the next day to have shifted 0.5-0.1 cm craniad: the upper border had not changed (fig. 6). During the third week after this third operation both dermatome borders returned to their initial (tattooed) positions, and in the subsequent week extended several millimeters beyond the tattoos.

The first animal exhibited a narrow band of hyperesthesia immediately above the upper insensitive zone for three days after the second operation. Apart from this the section of additional roots was not followed by hyperesthetic reactions. There was on the contrary a marked decrease in reactivity both within the isolated root area and in the zones adjacent to the new uppermost and lowermost sensory borders. In both animals the latter border was particularly difficult to define even when a pinwheel was used to provide summation of stimuli. Facilitation from the contralateral axillary region was often necessary before definite replies were obtained on the thorax. After each successive operation the adjacent dermatome boundary shifted approximately 1.0 cm. Outside the

DAF 25 T10 DERMATOME

INTRADURAL DORSAL ROOT SECTIONS

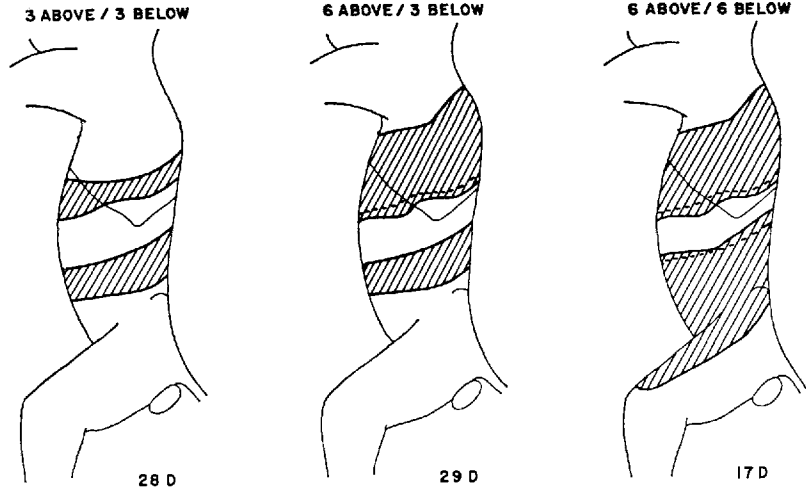


Fig. 6 Reduction in dermatome size following section of additional dorsal roots. The diagram on the left shows the extent of the tenth thoracic dermatome 28 days after unilateral intradural section of three neighboring dorsal roots above and below. This dermatome is typically much wider than the eighth thoracic dermatome isolated in the same manner. (c.f. fig. 3). The insensitive areas are shaded. The center diagram shows the contraction of the upper border still present 29 days after section of three additional roots above; the dotted line represents the original level of the dermatome boundary. The diagram on the right shows a similar contraction of the caudal border of the dermatome, as seen 17 days after subsequent section of the next three roots below.

newly insensitive zone was a 0.5–1.0 cm fringe zone from which sensory and reflex responses were very variable; this persistent transition zone contrasted with the usual sharply defined boundaries varying by only a few millimeters from day to day.

The expansion of sensory areas after injecting strychnine indicated that in an unresponsive zone there are still some afferent fibers capable of conducting impulses into the spinal cord. One possibility would be that some very diffuse fiber system in the skin could traverse the insensitive zones from above and below. We found, however, that where a caudal thoracic or upper lumbar dermatome had been isolated intradurally, linear section of the skin along the center of the upper and lower insensitive zones from across the dorsal midline around to and across the ventral midline did not produce any apparent change in the position of any of the sensory boundaries or in the sensory and segmental reflex responses.

DISCUSSION

The experiments we have described have demonstrated that the extent of the cutaneous area from which sensory reactions may be obtained after the isolation of a single sensory nerve is a variable quantity, dependent in some way upon the integrity of neighboring sensory spinal nerve roots. Following intradural section of the three neighboring dorsal roots above and below, the dermatome area, as defined by the reactions of the animals to pin scratch, increased progressively in the first week and then remained stable for the remainder of the observation period (more than 3 months). Though the degree of responsiveness varied greatly with fatigue, satiety or distension of the urinary bladder, there was little fluctuation in the size of the reactive area. Responses were most easily elicited from the middle of a sensory root field, where the density of intact nerve endings is presumed to be greatest. When the animals were poorly reactive, responses could at first be obtained only in the cen-

tral area, but be extended by facilitation to the borders of the field.

It was therefore surprising to find that the dermatome area was enlarged after the neighboring spinal nerves had been sectioned distal to their dorsal root ganglia. The increase in area was found to be a consistent phenomenon and reversed by subsequent section of the dorsal roots of these nerves proximal to their ganglia. At first we were inclined to attribute the difference in area and reactivity to the presence of recurrent sensory fibers of the type which Claude Bernard demonstrated to extend proximally from their dorsal root ganglion cells to enter the meninges. In the cat one of us (D. Denny-Brown) had found bundles of up to six to ten such fibers re-entering the meninges along one dorsal root and, after running a short distance in the pia, joining a bundle of the emerging fibers of an adjacent sensory root. Section of neighboring dorsal roots distal to their ganglia leaves intact the recurrent fibers which originate in these ganglia and join the isolated sensory root. It is possible that these fibers have a more extensive cutaneous distribution than those originating within the isolated root itself. However, in the monkey we rarely found recurrent dorsal root fibers, and then only in groups of two or three fibers in some lumbar roots, and in one animal, in a cervical dorsal root. Examination of silver-stained spreads of the pia surrounding the dorsal root entry zones of sectioned thoracic spinal nerves in five animals failed to disclose any residual recurrent fibers in this situation.

Following section of a peripheral nerve, particularly in the distal parts of the human limb, unpleasant and prolonged hyperesthesia becomes prominent in zones bordering complete sensory loss. There is some evidence that this hyperesthesia, which is particularly increased by cold, is produced by impulses in slowly-conducting fibers acting in the absence of the normal restraint of more highly differentiated sensation (Denny-Brown, '65). The occurrence of hyperesthesia at the borders of the enlarged dermatome area following section of the neighboring roots distal to their ganglia suggested the possibility that the larger area was produced by widely branch-

ing, slow-conducting nerve fibers which mediated poorly differentiated sensation. We have, however, no evidence to support such a possibility. The sensory responses we have observed, and their reflex accompaniment, have been nociceptive in type but any increased responsiveness to cold in the expanded root areas has been accompanied by a comparable increase in segmental reflex response to non-noxious stimuli such as stroking the skin with a blunt object. Our present data suggests that the observed hyperesthesia reflects an increased effectiveness in every aspect of sensation.

The delay in the reduction in the size of the dermatome after the neighboring nerve roots, initially sectioned distal to their ganglia, were sectioned proximal to these ganglia indicated the operation of some physiological factor. Opening of the dura *per se* did not account for the change. Damage to blood vessels accompanying the sectioned nerve roots was not likely to have been important. Indeed, section of both the dorsal and the ventral roots distal to the dorsal root ganglia should deprive the spinal cord of more of its blood supply than intradural section of dorsal roots alone.

The smaller dermatome following intradural root sections proximal to the dorsal root ganglia could result from the presence of some suppressor effect, or, conversely, from the absence of some facilitating effect within the spinal cord. The first possibility is supported by the effect of a subconvulsive dose of strychnine in greatly expanding the dermatome. Strychnine not only reverses postsynaptic inhibition (Bradley and Eccles, '53) but can also abolish some types of presynaptic inhibition (Eccles, '64). Kuhn's ('53) recordings of dorsal root potentials reveal more extensive hind-limb dermatomes in the monkey than those charted by Sherrington (1893, 1898) or seen in the present study after intradural root sections. It is possible that the more extensive overlapping of cutaneous areas described by Kuhn and other investigators using dorsal root potentials (Hekmatpanah, '61; Pubols et al., '65; Fletcher and Kitchell, '66; Oswaldo-Cruz et al., '66) results from the lack of suppression of these afferent potentials by regulating me-

chanisms in the spinal cord such as those suggested by Wall ('64) and Melzack and Wall ('65).

Even the largest dermatomes outlined by section of neighboring roots distal to their ganglia could be still further enlarged by the affect of strychnine indicating the constant pressure of such a central "gating" mechanism. On the other hand, we have found that the extent of a dermatome is in some degree dependent on facilitation mediated by intact neighboring sensory roots. This was shown by the effect of sectioning three additional roots above and below the isolated root. The effect is regional, being limited to adjacent spinal segments, for section of still further roots had minimal effect. There did not appear to be any apparent contralateral effect produced by the dorsal root sections, for bilaterally-isolated dermatomes were comparable with the same fields isolated unilaterally.

The size of an isolated dermatome is therefore within limits dependent on the efficiency of some level of convergence of sensory input in neighboring segments of the spinal cord. It reflects the state of an equilibrium between inhibitory and facilitatory mechanisms. The lack of effect of morphine on the extent of the dermatome is in strong contrast with the facilitatory effects from neighboring roots and from the action of strychnine. This difference and the absence of change in local reflexes following injection of morphine suggests that its effect in depressing sensory response was due to action of the drug at some higher level of sensory integration.

The observed differences resulting from root sections distal or proximal to the dorsal root ganglia indicate in the former case some continued facilitatory effect from the intact ganglion cells. The observations we have made appear to exclude the possibility of other peripheral anatomical possibilities. Either these primary afferent neurones continue to produce a background discharge even though cut off from their receptors, or their central processes, by their anatomical persistence, maintain some facilitatory effects at convergent synapses in the dorsal horn. To examine these possibilities we have observed the effects of differential sections

of Lissauer's tract and the dorsal column, which will be reported in a subsequent paper (Denny-Brown, Kirk and Yanagisawa, '70).

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