The crossing of the spinothalamic tract

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Summary

The question whether the spinothalamic and spinoreticular fibres cross the cord transversely or diagonally was investigated in cases of anterolateral cordotomy and in a case of thrombosis of the anterior spinal artery. The pattern of sensory loss following transection of the anterolateral quadrant of the cord consists of a narrow area of decreased nociception and thermalgesia at the level of the incision; it extends for 1–2 segments cranial and caudal to the incision. This area is immediately cranial to the area of total loss of these modalities. This pattern of sensory loss is explained as follows. The cordotomy incision transects two groups of fibres: those that are already within the anterior and anterolateral funiculi and those that are crossing the cord. The area of total thermalgesia and analgesia is due to transection of fibres that are already within this region.

The area of partial sensory loss is due to transection of the fibres that are crossing the cord at that level. Owing to the craniocaudal extent of the branches of the dorsal roots, there is an overlap of their collaterals that results in every spinothalamic neurone receiving an input from several dorsal roots. The narrow cordotomy incision thus divides the few fibres crossing at that level, causing diminished noxious and thermal sensibility over a few segments above and below the incision. These facts can be accounted for only on the assumption that these spinothalamic fibres are crossing the cord transversely. This evidence of transverse crossing was found in the cervical, thoracic and lumbar segments. There were three of 63 cordotomies for which this explanation of the partial sensory loss could not be maintained. Although no explanation has been suggested, this is unlikely to be due to the fibres crossing the cord diagonally.

Keywords: anatomy of spinal cord; anterolateral cordotomy

Introduction

This paper is a clinicopathological study of the manner in which the spinothalamic tract crosses the cord from its cells of origin to the opposite anterior and anterolateral funiculi.

The introduction of anterolateral cordotomy led to much discussion of the manner in which the spinothalamic tract crosses the cord. There are two views: one is that the fibres cross transversely; the other is that they cross diagonally, taking several segments to cross. In this paper we present the evidence that the fibres cross transversely and also theoretical reasons why they cannot be crossing diagonally.

The first investigator to make use of anterolateral cordotomy to study the anatomy of the spinal cord was Foerster (Foerster, 1927a, b). He wrote that he had had seven cases with a sensory level at the segment below the incision (Foerster, 1927b). He concluded that the fibres cross the cord within one to one-and-a-half segments above their cell bodies and that when this result is not obtained the incision has not been deep enough. Later, Foerster and Gagel published a series of cases in which there were nine autopsies (Foerster and Gagel, 1932). But they did not make use of this histological material, stating that their conclusions were based on clinical observation and not on ‘anatomical proof’.

Babtchine, working in Leningrad, obtained analgesia and thermalgesia up to the level of the incised segment and confirmed Foerster’s view (Babtchine, 1936).

Kuru, who studied with Foerster, had detailed histological material from 10 cases of cordotomy (Kuru, 1938, 1940). His conclusions supported Foerster and Gagel.

White and colleagues found that an analgesic level to within one segment of the incision was rarely obtained and they concluded that this was due to the diagonal crossing of the fibres (White et al., 1950). They therefore wrote that their opinion differed from ‘that of Foerster and Gagel but conforms with most other observers’. With further evidence, White modified his view, stating that ‘the number of segments required for decussation for the pain fibres varies from one individual to another, the fibres requiring only one to two segments to cross in some and at least six in others’ (White, 1951). He reported a case in which the incisions into the cord were at T4 or T5 with hypoalgesia at T5 level. In 1954
he reported 20 cases of cordotomy carried out at C2; the analgesia was up to the territory of the fifth cranial nerve in two of them.

One of the best papers on this subject is that published by White and colleagues in 1956. In this paper, as in many others, the reader needs to distinguish the level of sensory loss obtained immediately after the operation from levels seen when some return of sensibility had taken place. Their paper reported a study of 300 upper thoracic cordotomies, in 18 of which there was histological examination of the cord. They concluded that ‘the more extensive transections of white matter have resulted in higher and more consistent levels of analgesia’ (White et al., 1956).

Bohm reported that, in 28 of 35 cases of unilateral cervical cordotomy, there was complete analgesia extending to one segment below the incision (Bohm, 1960). In 10 of these patients the incision was at C1–2 and in 12 it was between C3 and C4. Šourek concluded from his experience of anterolateral cordotomy that the fibres ‘take one to three segments to cross the cord’ (Šourek, 1977).

On reading the literature, one finds that adequate attention has not been given to the relationship between the surgical incision and the fibres passing from the anterior commissure and through the anterior horn. Yet this relationship provides an important clue showing that the fibres cross the cord transversely.

A note on terminology
The relevant fibres of the anterolateral funiculus are often referred to as the ‘spinothalamic tract’, although most of the fibres do not terminate in the thalamus. Present knowledge of the different terminations of the fibres of the anterior and anterolateral funiculi makes this name unsatisfactory. Therefore, as in our previous papers, we refer to all these fibres and tracts, including the spinoreticular fibres that cross the cord, as the spinothalamic complex. This complex does not include the spinocerebellar tracts or propriospinal fibres.

Material and methods

Material
Spinal cords were available from 63 patients who had had anterolateral cordotomy for severe pain due to cancer. The operations were performed at every segment from C1 to C6 and from T1 to T9, and at L1 and L2. There was one case of thrombosis of the anterior spinal artery and one case in which no autopsy was obtained. The case numbers are the same throughout the papers by Nathan and Smith.

Methods

Clinical examination
Sensory examination was carried out in almost all patients before the cordotomy and repeatedly after the operation until a few days before death. As the sensory state tends to change over months, conclusions are based mainly on the state between 2 days and 2 months after the operation.

For rapid determination of any change in cutaneous sensibility, the pinprick was used. Care was taken to see that the patient was reporting pain and not a difference between blunt and sharp. Further examination was by needles fixed to graded springs. Springs equivalent to 60 and 140 g were mainly used; a 60 g spring gives a moderately painful stimulus and stimulation with a 140 g spring is very painful.

In some cases that were on the border of normal cutaneous sensibility and partial loss of cutaneous pain, the number of pinpricks per square centimetre was recorded. Cutaneous pain was also examined with the instrument designed by Bishop (Bishop, 1943) and modified by Nathan (Nathan, 1958). This instrument delivers a small spark to the skin from a distance of 1–2 mm. Where there was cutaneous analgesia, the spark was felt either as a slight touch or was not felt at all. In normally innervated skin, it is felt as a small burning prick. When it is repeated rapidly, the burning sensation becomes more intense. The advantage of this instrument is that it can cause pain without mechanical deformation of the skin. This instrument is referred to as the sparker.

Very hot stimuli were also used to examine pain. Either a tuning fork that had been immersed in water at 80–100°C or a brass cylinder containing water at 80°C was held against the skin. The pain sensibility of muscles and other tissues beneath the skin was tested by the actual algometer used by Head and described by Head and Thompson (Head and Thompson, 1906). Deep pain was also examined by the injection of 0.5 ml of 6% saline into muscles. The pain sensibility of the periosteum was examined by scratching with a needle. The pain sensibility of the deep tissues of the lower limbs was also tested by occlusion of the blood supply with a sphygmonanometer cuff while the limb was placed in water at 0–4°C. This is a most painful stimulus.

Thermal sensibility was tested with brass cylinders containing water: the highest temperature was 50°C and the lowest was 25°C. Warmth was also tested with radiant heat stimuli and cold with a refrigerant spray and an ice cube.

Spatial and temporal summation were also used to determine the segmental level of loss of the pain of pinprick. When the border below which pinprick caused no pain was determined, moderately strong pinpricks were applied repeatedly from this border caudally at a rate of 2 Hz. As this stimulus was applied further caudally, at first only touch was felt but as the stimulus was repeated it became painful. This manner of stimulation was then repeated further caudally until a new border was found below which no cutaneous pain could be induced.

Spatial summation was also used in the examination of thermal sensibility. The lower limbs were put in buckets of hot or cold water. This increase in the area of stimulation always lowered the segmental level of thermal sensibility so that it was present in about two segments below the
dermatome where it had previously been found with a localized thermal stimulus.

**Histology**
The spinal cords were fixed in formol saline. Each segment was identified and cut transversely immediately cranial to the insertion of the most cranial nerve roots. This plane is taken to indicate the cranial limit of each segment. In all cases, sections were made throughout the craniocaudal extent of the incision. The photographs shown in the figures show the maximum area of the incision. The segments were mostly divided into several blocks, which were processed for different staining methods. Most blocks were embedded in celloidin, others in wax; frozen sections were also prepared. The Marchi method was mainly used, owing to its good photographic properties. Staining was also done with the Weigert Pal method and the Loyez method. In Marchi preparations, degenerating fibres stain black; in Weigert Pal and Loyez preparations they remain unstained and are demonstrated by pallor.

**Results**

**Cases establishing the location of the spinothalamic complex**
Four cases are first presented to show the location of the spinothalamic complex. Conclusions regarding the mode of crossing of these fibres cannot be reached unless it is certain that the tract has been transected completely. Of these four cases, three show the medial extent and one shows the posterior extent of these fibres.

**Case 39 (Fig. 1)**
A unilateral cordotomy was carried out on the left side of the cord at C2–3. Forty-eight hours after the operation, on the right side of the body all noxious stimuli were felt as painful above the clavicle at C3. Light pinprick caused no pain below C4 and pinprick of 140 g was not felt below C5, just above the nipple.

The incision extended to a line drawn between the mesial angle of the anterior horn and the anterior surface of the cord.

**Case 4 (Fig. 2)**
A bilateral cordotomy was carried out, the right incision at T4 and the left at T5. Three hours after the operation there was total loss of pain to pinprick from just below the nipples at T4–5 bilaterally. On the next day, no painful stimuli were felt below T6 and cold stimuli felt warm. Between T4 and T6 light pinprick was not felt but stronger pinprick caused pain. Below T5 there was loss of pain with the algometer at a pressure of 40 lb. The level of loss of pain sensibility did not change throughout the rest of the patient’s life, which was 22 months.

Only the left incision is considered, as it is relevant to the location of the spinothalamic complex. This incision reached the anteromedian fissure. In Case 39 (Fig. 1), the region between the anteromedian fissure and the mesial angle of the anterior horn was not involved and in Case 4 (Fig. 2) it was. In both cases the clinical state showed that the spinothalamic complex had been divided completely. It is concluded that no sensory fibres of this complex ascend in this part of the anterior funiculus. This conclusion is supported by the next case.

**Case 94 (Fig. 3)**
A unilateral cordotomy was carried out on the right side at T2. The relevance of this case is that the incision extended across the midline to involve the left anterior funiculus. But transection of these fibres produced no sensory changes. There were three other cases with a similar incision of the
Case 13 (Fig. 4)
A bilateral cordotomy was carried out at T9. Only the left incision is considered here. Immediately after the operation the pain in the pelvis, the right lower limb and the right inguinal region had gone. There was no pain to pinprick of 90 g at the level of the umbilicus (T10) and none to pinprick of 140 g at T12. No pain could be induced below the iliac crests with 40 lb pressure with the algometer. Water at 50°C caused no sensation of warmth below T10. The left incision extended slightly posterior to the attachment of the denticulate ligament.

It is concluded from these cases that the spinothalamic complex is located within the area shaded in Fig. 5.

Cases with division of the entire spinothalamic complex: typical sensory loss (54 incisions)
If the fibres of the spinothalamic complex are crossing the cord transversely, there will be a pattern of sensory loss
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having the following features: (i) at the level of the incision there will be a narrow area of partial loss of noxious and thermal sensibility; (ii) the area of partial loss will be immediately cranial to the area of total loss of noxious and thermal sensibility; (iii) the cranial level of sensory loss will be the same for the various sensory modalities. This pattern of sensory loss will be referred to as the typical sensory loss. It is suggested that the area of partial loss is due to transection of the fibres that are in the course of crossing the cord and the area of complete loss is due to transection of the fibres that are already within the anterior and anterolateral funiculi.

At every segment the collaterals of the branches of the dorsal root fibres enter the posterior horn of that segment and also the posterior horns of the neighbouring cranial and caudal segments. Thus, neurones whose fibres are in the process of crossing the cord have received their input not only from the dorsal roots of the segment incised but also from the dorsal roots of the adjacent caudal and cranial segments. There is so much overlap of the branches and collaterals that the narrow surgical incision does not transect enough crossing fibres to cause total loss of noxious and thermal sensibility at the level of incision.

That the collaterals of descending branches of dorsal roots above the segment of the incision synapse with neurones of the spinothalamic complex at the level of the incision is shown most clearly by cordotomies at C1, C2 and C3. In such cases the area of partial sensory loss extended up to the border of the fifth cranial nerve territory. An example is shown in the next case.

Case 80 (Fig. 6)
A left unilateral cordotomy was carried out in the caudal part of segment C2, transecting the whole of the spinothalamic complex.

Thirty hours after the operation the border between decreased and normal sensibility was where the cervical dermatomes meet the cutaneous territory of the fifth cranial nerve. In the dermatomes supplied by cervical nerves, there was slight diminution in the pain of light pinprick and sensation of warmth with water at 42°C. Below C4, water at 48°C caused no sensation of warmth, and pinprick of 60 g and repeated pinprick caused no pain.

Comment. The typical pattern of sensory loss occurred in this case, in which the incision was made in the more caudal part of C2. The total loss of noxious and thermal sensibility below C4 indicates that the whole tract was transected. The partial loss between the territory of cranial N5 and C4 indicates that the relevant fibres are crossing between the lower part of C2 and C4, thus transversely.

There were three similar cases with an adequate incision at C1–C2 and two cases in which it was at C3. In these five cases the area of partial sensory loss extended up to the territory of cranial N5.

Figure 7 illustrates the overlap of the collaterals of the descending and ascending branches of the dorsal roots in simplified diagrams. The finest afferent fibres divide in Lissauer’s tract; the larger fibres divide in the dorsal columns. All neurones of the spinothalamic complex receive an input from several adjacent roots. (The labelling of the laminae is derived from work on species other than man, as the data in man are incomplete.)

A case of anterior spinal artery thrombosis
Further evidence of the transverse crossing of the fibres comes from a case of thrombosis of the anterior spinal artery at lower thoracic and lumbar levels that was reported previously (Nathan et al., 1986).

Mrs W., aged 53 years, had a two-stage bilateral thoracolumbar sympathectomy for hypertension carried out at another hospital. During the second operation, performed 1 month after the first, the patient went into cardiovascular shock. When she recovered from the anaesthetic, it was apparent that thrombosis of the anterior spinal artery had occurred within the lumbar region. The patient survived 216 days after the second operation.

The post-mortem findings confirmed the clinical diagnosis. The gliosis of the cord extended from T9 to T10 caudally. Although it appears in the photograph (Fig. 8) that the anterior half of the cord had been replaced by gliosis, measurement actually showed that the anterior two-thirds had been destroyed. Along the periphery of the infarct, neural tissue stained normally, because it is supplied by the pial arterial plexus.

The sensory state was similar to that of a bilateral
Fig. 7 Diagrams illustrating the overlap of collaterals of ascending and descending branches of dorsal roots. (a) Terminations of unmyelinated and fine Aδ fibres in laminae I, IIo and V. (Adapted from Crosby et al., 1962.) (b) Termination of Aδ fibres and unmyelinated fibres of visceral origin in laminae V, VI, VII and X. Intermediate stages involving interneurones between the dorsal roots and neurones of the spinothalamic complex have been omitted.

cordotomy (Fig. 8), with the slight difference of an indefinite boundary between normal and abnormal sensibility. The patient was first seen 2 months after the second operation. Sensibility was normal in all respects above a segmental level of T10. Pain, cold and warmth were not felt below L2. Between L2 and T9, pinprick of 140 g was painful at some spots. There was also some thermal sensibility. Water at 40°, 50° and 70°C felt warm but stimuli at 70°C caused no pain. No abnormalities were found in position sense, tactile sensibility, two-point discrimination or graphaesthesia.

Over the next few months, aching pains developed in the lower limbs, most severe in the groin. Pinpricks were felt at isolated points in the lower limbs but there was no return of warmth and cold sensibility.

Comment. Figure 9 shows diagrammatically the putative course of ascending fibres in relation to the cranial end of the infarct. Below T9, ascending fibres within the anterior half of the cord were blocked. Yet warmth, cold and cutaneous pain were felt, though to a diminished degree, between T10 and L1. The transmission of the input from dorsal fibres to the spinothalamic complex occurs in laminae I, IIo, V, VI, VII and X. Laminae I and IIo were intact; laminae V, VI, VII and X were within the infarcted area. It would therefore
Fig. 8 Mrs W. Thrombosis of the anterior spinal artery. Transverse section of the cord at the cranial end of the infarcted area. Upper panel: shading indicates total thermanalgesia and analgesia; cross-hatching indicates partial loss of noxious and thermal sensibility (see text). Lower panel: Loyez and neutral red preparation.

be expected that some, but not all, of the noxious and thermal input would be transmitted. This is what was found.

The ascending branches of the dorsal roots from L1 to T8 must have synapsed with neurones of the spinothalamic complex above the level of the infarct. The fibres of the spinothalamic complex must then have crossed the cord transversely at the cranial end of the infarct.

Cases of unilateral cordotomy with a band of sensory loss at the level of and ipsilateral to the incision

In some cases the incision divided the anterior commissure in the midline; an example is shown in Fig. 3. Such an incision would be expected to cause partial loss of noxious and thermal sensibility at the level of the incision not only contralaterally but also ipsilaterally. Although this did occur, it was uncommon. The following case showed this sensory loss; no autopsy was obtained.

Mrs D. had an amputation of the left lower limb for a sarcoma of the thigh. A unilateral right upper thoracic cordotomy was carried out for the severe stump pain and painful phantom limb. On the following day all pain had gone; but the phantom limb persisted, though it had become painless and ‘rather vague’.

On the left side of the body strong pinprick, warmth and cold from ice and the refrigerant spray evoked no sensation below T6. On both sides of the body there was a band of analgesia in T5–6 dermatomes: pinprick of 60 g, water at

45°C and radiant heat caused no sensation and the maximal stimulus from the sparker caused only a sensation of touch (Fig. 10).

Comment. The expected band of sensory loss ipsilateral to the cordotomy, as illustrated above, was rarely seen. A possible reason is that the incision did not divide enough fibres to cause an obvious clinical loss of sensibility.

Cases with incomplete division of the spinothalamic complex: atypical sensory loss

In various kinds of incomplete incision, the sensory loss differs from the typical sensory loss; this will be referred to as an atypical sensory loss.

In the cases in which the entire complex was not transected, the changes in sensibility did not extend as high as the level of the incision. In these cases there was an area of decreased sensibility which varied for different sensory modalities. This area of decreased sensibility extended throughout more segments than the narrow area immediately above an area
of total analgesia that is found with total transections of the anterior and anterolateral funiculi.

The following case is an example of an incision that was not deep enough to transect all fibres of the anterior and anterolateral funiculi on one side of the cord, whereas it did so on the other side.

**Case 11 (Fig. 11)**

In this case a bilateral cordotomy was carried out at T8. The right incision was complete; the left did not divide the entire spinothalamic complex as it extended insufficiently anteromedially and was too superficial.

In the first week after operation, there was on the left side of the body a decrease in sensation of light pinprick in T8 and total loss of response to heavy pinprick below T9. There was a decrease in sensation of warmth at 50°C in T8 and no thermal sensibility below T10. On the right side there was hypoalgesia to light pinprick between T10 and T12 and total loss of response to heavier pinprick below L2. Intramuscular injection of 6% saline caused no sensation in segments L5 and S1. Between T10 and L4, water at 50°C felt warm, not hot, and lacked any element of pain. Cold sensation was normal down to the knee and there was no thermal sensibility below the knee.

Two months after the operation, the levels of sensory loss on the left were unaltered. But on the right the cranial extent of sensory loss had receded. Pinprick of 140 g was felt normally in L1–2. Pressure pain had a normal threshold down as far as the knee (15 lb). The threshold below the knee was still raised, 20–25 lb being painful.

**Comment.** On the left side of the body, opposite the complete incision, there was a narrow belt of partial sensory loss above the area of total loss. On the right side there was no abnormality in sensibility for three segments below the incision. Partial sensory loss occurred a few segments below the level of the incision and gradually increasing loss of sensibility further caudally. This superficial incision did not involve the more cranially lying fibres of the spinothalamic complex or the crossing fibres.

**Cases with division of the entire spinothalamic complex: atypical sensory loss (three incisions)**

There were three cases in which the entire complex was transected and yet the type of sensory loss was atypical. The case presented to illustrate this is even more exceptional as there was the typical sensory loss on one side of the body and an atypical loss on the other.

**Case 38 (Fig. 12)**

The right cordotomy was performed 140 days before death at T5 and the left 87 days before death at T9. The right incision produced the atypical sensory loss and the left the typical sensory loss.

Following the right cordotomy at T5, there was a decrease in sensibility on the left extending up to the level of the incision. Water at 55°C caused no thermal sensation below T5–6 but ice felt cold between T6 and T10. There was no thermal sensation of any sort below T12. The response to pinprick was diminished below T6, but stronger pinprick of.
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Fig. 12 Case 38. Bilateral anterolateral cordotomy at T5 (right) and T9 (left). Shading indicates total thermanaesthesia and analgesia. Large dots indicate no pain felt with 90 g pinprick but pain felt with 140 g pinprick; small dots indicate light pinprick diminished but pain felt with 90 g pinprick. Marchi preparation.

90 g was painful between T5 and T10 and pinprick of 140 g was painful down to the inguinal ligament and the superior iliac crest. With repetitive pinprick this level was brought down to the L2 dermatome. Pressure with the algometer caused no pain below T12, as for the 140 g pinprick. Injection of 6% saline into the deep tissues of the left lower limb caused no pain.

Seven weeks after the operation, water at 60°C caused a sensation of warmth down to T11. Other forms of sensibility showed no change in levels throughout the rest of the patient’s life.

Thus, on the patient’s left side there were large differences within each modality between levels of total loss and degrees of loss. Also, the upper levels of sensory loss showed different levels for different modalities.

Following the left cordotomy at T9, on the right side of the body there was a decrease in thermal and noxious sensibility up to the level of the incision. Water at 60°C caused no thermal sensation below T9; ice and the refrigerant spray caused no thermal sensation below T11. Pinprick of 90 g caused no pain below T9; pinprick of 140 g was painful between T9 and L1 but caused no pain further caudally. Repeated pinprick brought the level down to L2. Thus, on the right side of the body the upper levels of sensory loss for different modalities and degrees of stimulation were all within two or three segments of the incision.

Comment. This case is presented because both incisions transected the whole spinothalamic complex and yet the two different types of sensory loss occurred, one on each side of the body. One cannot propose that the fibres cross the cord diagonally in all cases.

Conclusions
Before drawing conclusions from the material we have presented, we will consider the pattern of sensory loss that would occur if the fibres were crossing diagonally.

Fig. 13 Diagram illustrating sensory changes that might result from a unilateral cordotomy at T3 if the fibres of the spinothalamic complex were crossing the cord diagonally. All the fibres shown crossing the cord on the left convey impulses subserving noxious and thermal input. Fibres labelled 'a', immediately caudal to the incision, are not transected and so there is no sensory loss down to, say, T6; fibres labelled 'b' bypass the incision, but 'c' fibres do not. This causes partial loss of these modalities between, say, T6 and T10. All 'd' fibres are transected. This results in total analgesia and thermanaesthesia below T10. Shading indicates total thermanaesthesia and analgesia; dots indicate partial loss of thermal and noxious sensibility (see text).

The large incision on the right went across the midline and involved the opposite anterior funiculus. It must also have transected the commissures and the anterior horn. The left incision went up to the border of the anterior horn and would have transected the crossing fibres emerging from the horn. The area of degeneration in the right posterolateral funiculus was due to the knife inadvertently damaging this region as it was withdrawn from the cord. The same damage to this area can be seen in Fig. 3.

Conclusions
Before drawing conclusions from the material we have presented, we will consider the pattern of sensory loss that would occur if the fibres were crossing diagonally.

Figure 13 illustrates a possible incision dividing the
antrolateral quadrant at T3. As some of the fibres bypass the incision, there will be no sensory loss at that level or above the incision. Below the level of the incision, some but not all fibres will have been transected and so there will be an area of partial sensory loss, starting at, say, T6. Total loss of thermal and noxious input would occur a few segments further caudally, say T10, because of transection of all the diagonally crossing fibres. Furthermore, it is likely that the fibres subserving different sensory modalities do not all form the same angle with the long axis of the cord as they cross the cord. This difference in the angle of slope would lead to different levels of sensory loss for different modalities, as well as to wider areas of partial loss within each modality.

Sheehan concluded his study of dorsal roots with this sentence: ‘The fact that ascending and descending fibres may terminate around cells many segments above or below their point of entry into the cord is frequently overlooked in physiological interpretations of clinical observations.’ (Sheehan, 1935). Our conclusion is that the overlap of the ascending and descending branches of the dorsal roots is the anatomical basis of the partial sensory loss at the level of the incision. The incision cuts off some of the input to the neurones of this complex at the level of the incision and also that of the neurones of the neighbouring segments. But, owing to the overlap, it does not cut off the total input from the dorsal root of any one segment.

The area of decreased sensibility cranial to the incision is most obvious in the cases in which the incision was at C2 or C3, for in these cases the area of decreased sensibility extended to the border of the fifth cranial nerve. Hyndman and Wolkin also stated that sensory loss extended above the level of the incision and concluded that the primary afferent fibres of the dorsal roots synapse with neurones of the spinothalamic complex that are two or three segments above the incision (Hyndman and Wolkin, 1943).

We conclude that, wherever there is sensory loss up to the level of the incision or, more strikingly, above the level of the incision, the fibres must be crossing the cord transversely. As this pattern of sensory loss was found throughout the cervical cord, from T1 to T9 and at L1 and L2, transverse crossing of the fibres takes place throughout the spinal cord. Further evidence is provided by the case of anterior spinal artery thrombosis, in which warmth, cold and pain were felt below the cranial level of the infarct.

It is apparent that the crossing fibres emerging from the anterior horn go straight into the most medial part of the spinothalamic complex.

All neurosurgical evidence has shown that at every level the most cranial fibres of the complex lie most medially and the sacral fibres most posterolaterally. When this anatomical arrangement became known, surgeons tried to limit the extent of the section of the tract so as not to render large areas of the body analgesic unnecessarily and to avoid complications. These operations were usually unsuccessful. It then appeared advisable to transect the whole complex wherever the incision was made.

In addition to the basic topographical organization, there is also a large amount of scattering of the fibres from different segments throughout the area of the spinothalamic complex. These two features of the anatomy imply, in our opinion, that there are two types of operation likely to be successful. In the upper cervical cord the incision does not have to transect the entire anterolateral quadrant; it should leave the posterior fibres of the anterolateral funiculus intact. This operation will produce sensory loss extending from the level of the incision to the midthoracic region. In the thoracic cord, the operation has to transect the entire anterolateral quadrant to obtain analgesia throughout the body below the level of the incision.

Discussion
The reports of some of the surgeons who first carried out anterolateral cordotomies indicate that the entire spinothalamic complex was not always transected. If many of the crossing fibres escaped the incision, the typical sensory loss would not have been obtained and the conclusion that the fibres were crossing diagonally appeared to be justified.

It has not always been realized that the sensory changes are related not only to the extent and location of the lesion made in the anterior and anterolateral funiculi but also to the extent and exact location of the lesion made in the anterior commissure and the anterior horn.

The type of sensory loss seen following total traumatic division of the spinal cord is similar to that seen in successful anterolateral cordotomies. There is a narrow area of partial loss immediately above the level of total loss of sensibility. In this case the neurones of the spinothalamic complex immediately cranial to the lesion have not received an input from the dorsal roots immediately below the incision.

Discussions about different levels of the loss of deep and superficial pain are usually discussions about anatomy. But in addition to anatomy there are psychophysical problems. It is impossible to compare the degrees of two quite different kinds of pain. How is one to compare the pain of pinprick or excessive heat applied to the skin with the pain of pressure on bone or tendon and the pain from the injection of concentrated saline into deep tissues? How can a patient regard these different sorts of pain as equal or equivalent?

We have been unable to account for the findings in the three cases in which the whole spinothalamic complex was transected and yet there was no narrow area of partial loss of sensibility at the level of the incision and the type of sensory loss was what we have called atypical, i.e. the segmental levels of the loss of warm, cold and noxious sensibility were widely separated, as were the levels of the different degrees of loss of these forms of sensibility.

In many cases, even when the incision has transected the entire anterolateral quadrant, there is some return of thermal and noxious sensibility over a period of months. As sensibility returns, it does so with the pattern of atypical sensory loss, there being large segmental differences between slight and
total loss. These long-term changes in sensibility can be accounted for only by changes throughout the spinal cord and brain that come under the heading of plasticity.

Anatomical variations
Surgical incisions into the cord reveal anatomical variations that would not otherwise have been suspected. Cases have been reported in which the spinothalamic tract was uncrossed. Such were the cases of French and Peyton (French and Peyton, 1948), Voris (Voris, 1951), White and Sweet (White and Sweet, 1955) and Brenner and Pendl (Brenner and Pendl, 1966). Moffie reported two cases in which the tract was mainly posterior to the denticulate ligament (Moffie, 1975). No account of anatomical variation as shown by the operation of cordotomy would be complete without mentioning the paper by Osácar and colleagues. They reported a case of a bilateral cordotomy in which there was ‘no relief of pain and no detectable loss of touch, cutaneous pain or temperature sensibility’ and yet histological examination of the spinal cord showed that there was transection of both spinothalamic complexes, though it was incomplete (Osácar et al., 1961).

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