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EXTENT AND PERMANENCE OF DENERVATION PRODUCED BY LUMBAR SYMPATHECTOMY

A QUANTITATIVE INVESTIGATION OF ITS EFFECTS ON SUDOMOTOR ACTIVITY

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Is the denervation produced by lumbar sympathectomy permanent? This is a controversial topic of obvious practical importance. This paper presents the results of a quantitative investigation into the early and late effects of operation on sudomotor activity, thermoregulatory sweating being a most sensitive index of recovery of sympathetic function. The very different results obtained in the proximal and distal dermatomes of the limb are illustrated, and their mechanism is discussed.

Sweating was determined by measurement of the electrical conductivity of the skin (Richter, 1929). Dry, non-sweating skin is a poor conductor of electricity, while damp sweating skin is a good conductor. As sweating depends on sympathetic sudomotor activity the skin-conductivity measurements can be used to determine the extent of residual sympathetic activity after operation.

Quantitative Sudomotor Test

Nineteen standard points, sited with due regard to the dermatomes, were marked with ink on each of the lower limbs (Fig. 1). The patient then lay on a couch for 20 minutes with the whole of the lower limbs exposed at a laboratory temperature of 22° C. Thereafter, the electrical conductivity of the skin was measured at each of the marked points, using a commercially made skin-conductivity meter (Light Laboratories). An electrical heat cage was then placed over the trunk and face, and

body-heating applied for 20 minutes or longer, till the patient was sweating profusely and his oral temperature had risen by at least 0.3° F. (0.17° C.). It is essential for the test that the stimulus to sudomotor activity is maximal. The skin conductivity was again measured at each of the 19 points. The examining electrode was then moved slowly up the limb from the toes towards the trunk until a sudden increase in conductivity occurred. This point, whose position was always quite precise, was marked, and indicated the junction of

LIMB	TOTAL CONDUCTIVITY IN MICRO-AMPS WITHIN THE SHADED AREA		CONDUCTIVITY [INCREASE IN MICRO-AMPS]
	BEFORE HEATING	AFTER HEATING	
SYMPATHECTOMIZED	8	10	2
NORMAL	133	312 +	179 +

FIG. 1.—A typical quantitative sudomotor test (see text). The current in microamperes at each of the points within the "denervated" (shaded) area is totalled before and after vigorous body-heating. A similar calculation is made within the corresponding area of the non-sympathectomized limb. The increase in conductivity after heating is a measure of sympathetic sudomotor activity.

normally innervated and denervated skin. By moving the electrode up the limb a number of times the points obtained could be linked up round the limb as a line separating the innervated and denervated parts.

The sudomotor test thus yielded information of two kinds: firstly, on the persisting area of partial or complete sympathetic sudomotor denervation below the line drawn round the limb; and, secondly, on the amount of sweating occurring before and after body-heating at a number of fixed points on the skin within this area. The sum of the readings in microamperes at each of the fixed points below the line of denervation gives a measure of sweating within this area. Comparison of sweating in corresponding areas of the sympathectomized and non-sympathectomized limbs

before and after body-heating indicates the extent of sudomotor recovery.

A typical sudomotor test result is illustrated in Fig. 1, and it shows well the method of calculation by which a quantitative measure of sweating is obtained. The patient had had a unilateral sympathectomy two years previously. Even before body-heating the difference in skin conductivity in the two limbs is striking, a total of only 8 μ A being recorded within the "denervated" area of the sympathectomized limb, while 133 μ A was recorded within the corresponding area of the non-sympathectomized limb. After body-heating, conductivity increased by only 2 μ A in the operated limb, but by 179+ μ A in the normal limb. (The microammeter of the apparatus measured only up to 50 μ A, and when the skin resistance was so low that the current exceeded this the reading was recorded as 50+.)

Clinical Material

Sudomotor activity was investigated in 77 patients, in whom there were 98 sympathectomized and 56 non-sympathectomized lower limbs. The latter, in patients with a unilateral sympathectomy, formed a control group. The early changes resulting from operation were investigated in a number of patients by tests carried out at intervals up to one year after operation. The long-term effects were investigated in 75 patients by tests carried out between one and seven years after operation.

To enable the cutaneous extent of denervation to be correlated with the vertebral level at which the sympathetic chain had been divided, silver clips were placed on the chain at operation just above the highest and below the lowest ganglion removed, and whole-spine radiographs were taken post-operatively. All the operations were performed by me or by one other surgeon, so that the operative technique was fairly uniform.

The area of sudomotor denervation produced by operation is discussed first, and then the evidence of partial recovery of sudomotor activity within this area.

Area of Cutaneous Denervation Produced by Operation

In spite of the fact that the second and lower lumbar ganglia, if not the first, had certainly been removed in all patients, the resulting areas of persisting sudomotor denervation in the 98 limbs, when tested between one and seven years after operation, indicated an apparently

FIG. 2.—The three main patterns of persisting sudomotor denervation present in 98 limbs one to seven years after lumbar sympathectomy, compared with the areas of the sensory and sympathetic dermatomes.

lower level of sympathectomy in them all. The line separating normally sweating from denervated skin lay, in the majority of the limbs, at one or other of three main levels, thus indicating three principal patterns or areas of persisting denervation, partial or complete, best seen on the anterior aspect of the limb (Fig. 2). In pattern 1 (17.5% of the limbs) the upper limit of denervation anteriorly was marked by a transverse or

FIG. 3.—Silver clips indicate upper and lower levels of section of sympathetic chain in relation to vertebral bodies. (Case 1.)

obliquely placed line lying somewhere in the lower third of the thigh. In only four patients, included in this group, did the upper limit of denervation lie above the lower third of the thigh. In pattern 2 (48%) the line lay transversely at the level of the knee-joint. In pattern 3 (27.5%) the upper limit of denervation was marked by a line passing from the lateral aspect of the knee down the subcutaneous border of the tibia to the region of the medial malleolus. In addition to these three main patterns of denervation, exhibited by 91% of the limbs, five limbs showed a pattern of denervation between 1 and 2, one limb was denervated only to the level of the ankle anteriorly, while one limb sweated so profusely all over that no area of denervation could be plotted.

When the three main areas of denervation are compared (Fig. 2) with the areas of the sensory and sympathetic dermatomes of Foerster and of Richter and Woodruff (1945), it is seen that the pattern 3 area of denervation corresponds only to a denervation of the fourth lumbar dermatome and below, pattern 2 to a denervation of the third lumbar dermatome and below, and pattern 1 to a denervation of the second lumbar dermatome and below. Of especial interest was

the fact that in only 4 of the 98 limbs did the area of denervation encroach on the first lumbar dermatome.

This anomaly between the segmental level of section of the sympathetic chain and the resulting area of sudomotor denervation is now well recognized, "escape" areas of persistent sweating in the last thoracic and upper one or more lumbar dermatomes originally having been observed after thoracolumbar sympathectomy (Ray and Console, 1948).

It is of some interest to investigate the changes in sudomotor activity within these upper lumbar dermatomes, which apparently are rarely denervated, at intervals after lumbar sympathectomy. The results in a typical patient are illustrated in Figs. 3 and 4. The upper silver clip (Fig. 3) indicates that the sympathetic chain was sectioned at the level of the upper border of the last thoracic vertebra, suggesting that the last thoracic ganglion was probably removed. Eleven days after operation the sudomotor test did in fact show a pattern of denervation extending into the lower abdomen, the area of the last thoracic dermatome (Fig. 4). However, two months after operation apparently normal sweating was found in the last thoracic and much of the first lumbar dermatome, while five months after operation the area of denervation extended only just above the knee, all the first lumbar dermatome now sweating freely. One year after operation the area of sudomotor denervation was unchanged.

In Table I are set out the results of similar tests in 11 patients, and certain conclusions can be drawn from them. (1) Even though the first lumbar ganglion is certainly removed, the first one, two, or three lumbar dermatomes later recover sweating. (2) The area of denervation produced corresponds well to the segmental level of sympathectomy only in the early post-operative period. (3) Recovery of sweating in these lower thoracic and upper lumbar dermatomes is not immediate, however, there being a variable delay. (4) Recovery is often as complete as it will be by eight weeks, and there is never any marked change between the test at about five months and a later test at one year. Recovery thus apparently goes so far and then stops. (5) Recovery seems to take place dermatome by dermatome from above downwards. (6) A "high" sympathectomy may produce a smaller final area of denervation than a lower one. (7) Within the areas of recovery sweating appeared to be normal as judged by skin-conductivity measurements. (8) The lumbar sudomotor dermatomes appear to correspond fairly well in position with the sensory dermatomes.

FIG. 4.—Changing area of sudomotor denervation after lumbar sympathectomy. (Case 1.)

Reason for Recovery of Sweating in Upper Part of Limb

There seems no doubt that the reason for the recovery of sweating in the last thoracic and upper lumbar dermatomes is due to the presence of residual sympathetic-nerve pathways which escaped damage at operation. These pathways, which pass via so-called intermediate ganglia lying outside the paravertebral

TABLE I.—Area of Sudomotor Denervation Present on Anterior Aspect of Leg at Intervals After Lumbar Sympathectomy of Varying Extent

Case No.	Vertebral Level of Upper Section of Sympathetic Chain	Highest Dermatome Showing Sudomotor Denervation at Intervals after Operation			
		1st Test	2nd Test	3rd Test	4th Test
1	Upper border T 12	11 days T 12	8½ weeks L 1/2	22 weeks L 2	1 year L 2
2	Upper border T 12	7 days T 12	11 weeks L 3		1 year L 3
3	Middle of T 12	4 days T 12	6 weeks L 4	17 weeks L 4	1 year L 4
4	Lower border T 12	12 days T 12	5 weeks L 3	16 weeks L 3	1 year L 3
5	Lower border T 12	6 days L 1	6 weeks L 3		
6	Junction of T 12/L 1	10 days L 1	5 weeks L 1	16 weeks L 3	1 year L 3
7	Junction of T 12/L 1	8 days L 1	5 weeks L 3		
8	Upper border L 1	4 days L 1	6 weeks L 1/2	17 weeks L 2/3	1 year L 3
9		7 days L 1	9 weeks L 1/2	20 weeks L 1/2	1 year L 1/2
10	Middle of L 1	8 days L 2	8 weeks L 3	20 weeks L 3	1 year L 3
11	Upper border L 2	7 days L 2	7 weeks L 3		

Note.—Where the dermatome is given as L 1/2, for example, this indicates that the upper limit of denervation was very low on the L 1 dermatome, almost down to the L 2 area.

sympathetic chain, have aroused much recent anatomical interest, fully reviewed by Boyd (1957). While the presence of the intermediate ganglia has long been known to anatomists, their functional significance was unrealized till Ray and Console (1948) attributed the escape areas of sudomotor denervation seen after thoracolumbar sympathectomy to their activity.

There are good grounds for believing that residual pathways rather than regeneration, as ordinarily understood, are responsible for the early segmental return of sudomotor activity in the lower limb after lumbar sympathectomy. (1) If chance regeneration was occurring, then recovery of sweating would certainly be scattered, and incomplete in any dermatome. (2) Neither would recovery cease so abruptly when a certain segmental level of reinnervation had been reached. (3) "High" sympathectomy may result in a lower final level of denervation than a lower sympathectomy, suggesting that the main factor determining the final level of denervation is the number of lumbar segments having residual pathways. (4) Also, as strong evidence for bilaterally symmetrical residual pathways, was the finding that in 20 patients who had had a bilateral sympathectomy, with an interval of up to several years between operations, the final area of denervation was the same in both limbs in 17. It is most unlikely that exactly the same amount of sympathetic chain was removed on the two sides of each of these patients. If chance regeneration was occurring, then the likelihood of a similar final pattern of denervation in the two limbs would be small.

The number of segments in which residual pathways are present varies in individuals, though they seem almost invariably to occur in the last thoracic and first lumbar segments, and often in the second and third lumbar segments also. This is well illustrated by the findings in the 98 limbs (Fig. 2). Residual pathways

are rarely present in segments lower than the third lumbar. As would be expected, they are bilaterally similar.

Mechanism by Which Residual Pathways Restore Sympathetic Innervation

While it might be that the residual pathways by themselves restore normal innervation, it seems likely that the process of reinnervation is a little more complicated. Of particular interest is the variable delay of several weeks to several months before recovery is complete. It is difficult to explain this delay in function in pathways which are already anatomically complete.

One possible explanation of a temporary delay in function in the residual pathways after operation is that degeneration in the post-ganglionic fibres of the extirpated paravertebral ganglia interferes temporarily with conduction in the post-ganglionic fibres of the intact intermediate ganglia running with them in the peripheral nerves. A somewhat similar phenomenon occurs in relation to taste, for example. If the semilunar ganglion of the fifth cranial nerve is destroyed the sense of taste is temporarily lost over the anterior two-thirds of the tongue, but is recovered after about two weeks (Wright, 1952). The fibres of the chorda tympani, responsible for carrying the sense of taste from this area, do not traverse the semilunar ganglion but pass as passengers in the lingual nerve, which has its cell bodies in this ganglion. When the fibres of the lingual nerve degenerate after damage to the ganglion, conduction is temporarily interfered with in the chorda tympani. This explanation of delay in functional activity in the residual pathways might also fit with the recovery of sweating in the lower limb dermatome by dermatome distally, degeneration going on for longer in the longer pathways and hence interfering for a greater period with conduction in the residual sympathetic fibres of these dermatomes.

However, while temporary interference with conduction in the residual pathways may well be the explanation of a delay in the beginning of recovery lasting up to two weeks, it is less easy to ascribe to it the longer delays which sometimes occur before recovery has reached its final extent. There is, in fact, a more likely explanation of the later complete recovery of innervation in the dermatomes supplied by the residual pathways.

Murray and Thompson (1957) demonstrated the occurrence of profuse collateral sprouting from the remaining fibres after partial section of a sympathetic-nerve trunk. These collateral sprouts grow down the distal part of the divided fibres to give complete reinnervation. It seems most probable that such sprouting occurs from the post-ganglionic fibres of the undamaged intermediate ganglia soon after sympathectomy, the sprouts establishing connexion with the decentralized post-ganglionic fibres of the excised paravertebral ganglion of the segment. In this way complete recovery of sweating occurs after a variable delay in every segment having residual pathways, but only in these segments, the most proximal dermatome concerned, as its pathway is shortest, recovering sweating first.

Clinical Implications of Recovery of Sudomotor Innervation in the Thigh

It has often been stated that removal of the first lumbar ganglion is essential to ensure denervation of the collateral vessels in the thigh, the common site of

arterial occlusions in obliterative vascular disease (Ratcliffe and Jepson, 1950). However, if the usual recovery of sympathetic sudomotor activity in the thigh is associated with a similar recovery of sympathetic vasomotor activity, it seems pointless to extend the dissection at sympathectomy to include the first lumbar ganglion. There is, in fact, no definite evidence that vasomotor recovery in the thigh does parallel sudomotor recovery, but Dornhorst and Sharpey-Schafer (1951) did find that lumbar sympathectomy produced only a transient reduction in collateral resistance round femoral-artery occlusions, resistance being back to its pre-operative level within about two weeks. It seems not unreasonable to suppose that if collateral sprouting leads to restoration of the sudomotor pathway it will equally lead to restoration of the vasomotor.

If no lasting vasomotor denervation in the thigh follows removal of the first lumbar ganglion, then leaving it *in situ* at operation may reduce the incidence of post-sympathectomy neuralgia in the thigh (De Bakey, Crawford, Cooley, and Morris, 1958) and the more nebulous risk of male sexual dysfunction after bilateral operations.

So much for the activity of the residual nerve pathways in the recovery of sudomotor activity in the upper lumbar segments after sympathectomy: the evidence for the occurrence of some partial recovery of sudomotor activity within the apparently denervated more distal parts of the limb is now presented.

Evidence of Partial Recovery of Sudomotor Activity Within Apparently Denervated Distal Parts of Limb

The sudomotor test was applied in 97 of the limbs sympathectomized between one and seven years previously. Of these limbs, 82% showed some increase in conductivity after body-heating, a figure which compares closely with Haxton's (1947) 83%, and might support the view that the lower limb is not immune to sympathetic recovery after the lumbar operation. However, the present quantitative investigation (Table II) shows that, even though most of the limbs showed some recovery of sweating, the extent of the recovery was very small, probably in most limbs being insignificant.

TABLE II.—Results of Skin-conductivity Test in 76 Patients

Type of Limb	No. of Limbs	Mean Conductivity before Heating (μA)	Mean Increase in Conductivity after Heating (μA)
Sympathectomized	97	7.9 (S.E. 0.97)	7.4 (S.E. 1.13)
Non-sympathectomized	53	58.2 (S.E. 6.33)	166.8 (S.E. 14.15)

Note.—The difference between the means in column three is significant at the 0.1% level, as is the difference between the means in column four.

For example, even before body-heating there was a highly significant difference (at the 0.1% level) in the mean conductivity of the sympathectomized and non-sympathectomized limbs—7.9 and 58.2 μA respectively—while after body-heating the mean increase in conductivity was only 7.4 μA in the sympathectomized limbs compared with 166.8 μA in the control limbs, this difference again being highly significant (at the 0.1% level). These figures can be further broken down: the increase, if any, in conductivity on body-heating in the sympathectomized limbs was less than 5 μA in 51 limbs, between 5 and 10 μA in 24 limbs, and in only one limb did it exceed 34 μA . These findings are to be

contrasted with those for the control limbs, in which the smallest increase was 34 μ A and the largest 515+ μ A, while in over two-thirds of these limbs it exceeded 100 μ A. In short, the mean increase in conductivity in the sympathectomized limbs after body-heating amounted to less than 5% of that in the normally innervated control limbs.

Mechanism of Scattered Peripheral Recovery of Sudomotor Activity

The mechanism by which this scattered return of sudomotor activity in the more distal parts of the leg occurs cannot at first sight so readily be explained by activity of the residual pathways, as these apparently are arranged on a strictly segmental basis and are present only in the upper dermatomes of the limb. However, it is likely that a few collateral sprouts from post-ganglionic fibres of the undamaged intermediate ganglia make chance contact with decentralized post-ganglionic fibres of the extirpated paravertebral ganglia of lower segments. Such scattered peripheral recovery of sudomotor activity as results may therefore be regarded as purely accidental. In favour of this view is the fact that there is seldom any significant degree

TABLE III.—Effect of Time on Partial Peripheral Recovery of Sudomotor Activity in Sympathectomized Limbs

Interval between Operation and Testing	No. of Limbs	Mean Skin-Conductivity Increase (μ A)	S.E. of Mean Conductivity Increase (μ A)
2 to 7 years	51	6.2	1.15
1, 2,	46	8.6	2.01

Note.—There is no significant difference in the mean conductivity increase in the two groups of limbs.

of recovery, and that this process of recovery is not a progressive one. For example, the mean increase in conductivity on body-heating in those limbs tested between two and seven years after operation was not significantly different from that in limbs tested between one and two years after operation (Table III).

The findings suggest that, apart from the effects of scattered accidental rerouting, lasting sympathetic denervation in the distal dermatomes of the lower limb is produced by lumbar sympathectomy.

Correlation Between Evidence of Recovery of Vasomotor and of Sudomotor Activity

In conclusion, it is of interest to note the "curious fact" reported by Barcroft and Hamilton (1948a, 1948b), amongst others, that after cervico-dorsal sympathectomy the sudomotor reflex, but not the vasomotor, may return in the hand. In the present work such a correlation between vasomotor and sudomotor recovery was sought in 26 lower limbs sympathectomized between one and seven years previously for non-obliterative disease. Blood-flows were measured by venous occlusion plethysmography before and after body-heating (Gillespie, 1960), and the sudomotor test was carried out as described above.

The results (Table IV) confirm those obtained in the upper limb—namely, that some sudomotor activity may be present even if vasomotor activity is not demonstrable. Slight sudomotor activity was present in 12 limbs in which vasomotor activity apparently was not, while the reverse occurred in only two limbs. This illustrates the greater sensitivity of the skin-conductivity test in detecting the presence of minimal sympathetic activity post-operatively.

TABLE IV.—Comparison of Recovery of Sympathetic Sudomotor and Vasomotor Activity in 26 Lower Limbs Sympathectomized for Non-obliterative Vascular Disease Between One and Seven Years Previously

	Sudomotor but Not Vasomotor	Vasomotor but Not Sudomotor	Sudomotor and Vasomotor	Neither Sudomotor nor Vasomotor
No. of legs ..	12	2	6	6

Summary

The effects of lumbar sympathectomy on sudomotor activity in the lower limb have been investigated in a quantitative manner in 77 patients.

Complete recovery of sympathetic sudomotor innervation is the rule in the last thoracic and first lumbar dermatomes, and is common in the second and third lumbar dermatomes. This recovery is usually as complete as it will be within a few weeks or months after operation. The evidence that it is almost certainly due to the activity of residual nerve pathways is discussed. The practical implication of this recovery is that nothing is gained by removing the lower thoracic and upper lumbar ganglia at operation.

Lumbar sympathectomy, apart from the effects of accidental rerouting, produces lasting sympathetic denervation of the more distal dermatomes. The amount of sweating in response to body-heating averages less than 5% of normal in these dermatomes.

Slight recovery of sudomotor activity is more often demonstrable than recovery of vasomotor activity in sympathectomized lower limbs.

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"In 1949 Newfoundland became the tenth province of Canada and came under Canada's immigration and taxation laws—with a corresponding increase in Federal money grants for social services. In the last ten years standards of health and welfare have been raised enormously. In "the hungry thirties," deficiency diseases and frank starvation were common in the fishing villages around the coasts, while tuberculosis was a great problem. These conditions are now comparatively rare. The tuberculosis mortality rate is nearly as low as Canada's and the sanatoria are half empty. Adequate medical care is available in all the large centres, although some of the outports have no doctors, and medical care is given through nursing stations." (Dr. J. S. Harley, Newfoundland, in *Chest and Heart Bulletin*, December, 1960.)