THE SEGMENTAL INNERVATION OF THE LOWER LIMB MUSCLES IN MAN

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by

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THE SEGMENTAL NERVE supply of limb muscles has stimulated interest for almost a century. Ferrier and Yeo in 1881 reported the results of stimulation of nerve roots in the cat and Sherrington in 1892 results in the frog, rat, rabbit, cat, dog and monkey, a paper in which he propounded the concept of prefixed and postfixed plexuses. More recently Romanes (1951) showed how the muscles of the limbs are represented in the motor cell columns of the spinal cord in the cat. Useful though these and other animal investigations have been in providing a parallel for the study of human limb innervation, they cannot provide the whole answer for man.

Experimental study of the nervous tissues in life in man is, of necessity, subject to considerable limitations. The full picture can only be obtained by a combination of facts and inference obtained in several ways and amalgamated to give as accurate a picture as possible as will agree with all the findings. Four methods can be used:

1. Dissection of nerve plexuses and roots.
2. Stimulation of motor nerve roots.
3. Study of motor root lesions.
4. Analysis of the motor cell columns of the spinal cord.

DISSECTION OF THE LUMBO-SACRAL PLEXUS AND ITS ROOTS

Anatomical dissection of the lumbar and sacral roots and plexuses can only establish the general level of the segmental innervation of the peripheral musculature. The segmental supply, for instance, of each of the muscles supplied by the lateral popliteal nerve cannot be established by dissection alone; it can only be inferred that their innervation is likely to lie within the compass of the four roots from which the nerve takes origin. Even the fact that the inferior gluteal nerve, arising from the fifth lumbar and first and second sacral roots, supplies only one muscle and gives no cutaneous branches does not necessarily mean that the motor supply of the gluteus maximus derives from all three roots. A substantial proportion of a pure motor nerve contains afferent fibres and it may well be that rather more of these are passing in the fifth lumbar root and less in the first and second sacral roots.

Appreciation of the variability in the root origins of the lumbar and sacral plexuses is important in studying the effects of motor root stimulation or of motor root lesions. Prefixation and postfixation of the lumbo-sacral plexus is common in animals (Sherrington, 1892) and may be present in man, in whom the phenomenon is often shown by the position of the furcal nerve that splits to contribute to the lumbar plexus above and the sacral plexus below. Jefferson (1954) has shown that prefixation

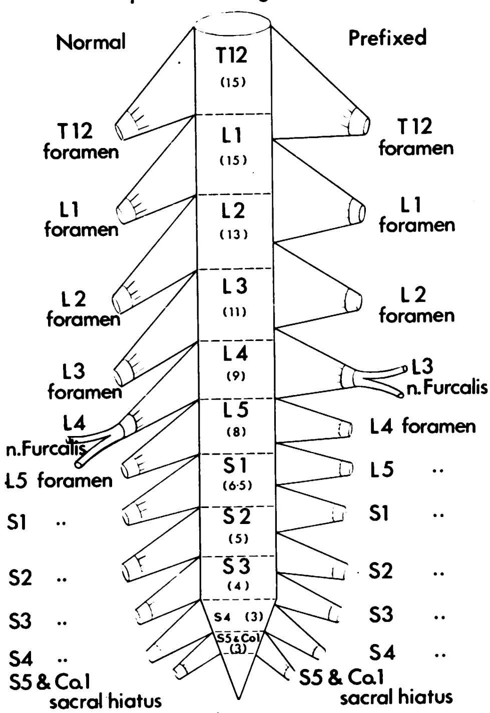


Fig. 1. Diagram to illustrate a theoretical mechanism to account for prefixation in the human lumbo-sacral plexus (after Jefferson). The numbers shown in each segment are the average length in millimetres of the segment.

and postfixation may be largely dependent on variations in root size rather than on an upward or downward shift of the spinal cord in relation to the intervertebral foramina or movement of the motor cell columns of the grey matter in relation to issuing rootlets. His results, and those of Romanes (1951), suggest that the cells of the motor columns of the spinal cord bear a constant relationship to the supply of individual peripheral muscles whatever the variations in the derivation of the individual roots from the spinal cord or of the plexuses beyond them.

Earlier studies (Sharrard, 1955, 1956) have shown that the same constant representation of the peripheral muscles in the motor cell columns of the spinal cord exists in man. Dissection of the rootlets of origin of lumbar and sacral motor roots in 15 normal human spinal cords has shown that variation in root size similar to that suggested by Jefferson is a common finding in man and, not infrequently, the size of the roots on the two sides of the same cord may differ. In spite of this, the vertical topography of the motor cell columns on the two sides rarely differs by more than half a millimetre. Figure 1, modified from that proposed by Jefferson (1954) for the cat, is put forward to indicate the arrangement of the neurological segments of the grey matter in relation to issuing roots in a normal and in a prefixed plexus in man. It demonstrates how, with a small increase in the size of lower thoracic and upper lumbar roots, it is possible for root fibres derived from the fourth neurological segment of the spinal cord to issue through the third lumbar intervertebral foramen so that this nerve becomes the nervus furcalis. A corresponding diminution in the size of the lower lumbar and sacral roots allows readjustment of root origin below this level. Variations as extreme as those represented on the left side of Figure 1 are, however, uncommon. A direct correspondence between the spinal neurological segments and the issuing motor roots exists in 80 per cent of spinal cords.

In Figure 1 is also shown an average figure in millimetres for the length of each spinal neurological segment. There is a steady diminution in length of the segments from the first lumbar downwards. The importance of this lies in the fact that a muscle such as the quadriceps receives its nerve supply from a length of more than 30 millimetres of spinal cord, whilst the biceps femoris, whose supply arises only from sacral segments, is represented in a length of only 13 millimetres of spinal cord. The number of segments that supply a muscle is not necessarily equivalent to its total neurological supply.

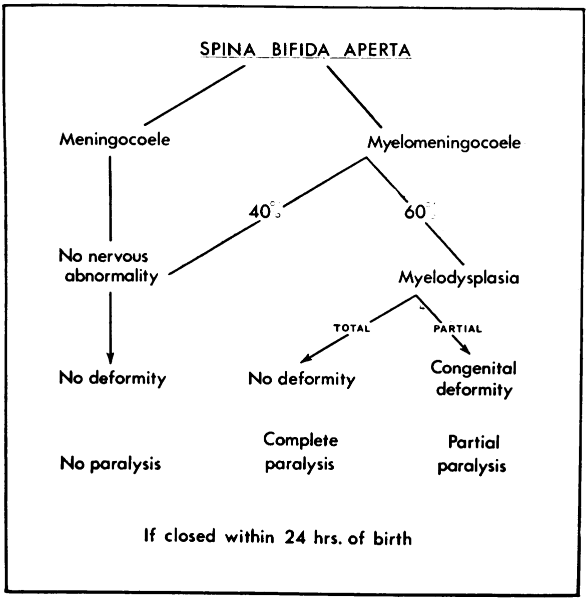
ROOT STIMULATION

The first adequate account of the findings of root stimulation in man were published by Bumke and Foerster (1929). Opportunities to investigate the effects of root stimulation of all the lumbar and sacral roots in the same individual at one time are rare. In the course of the investigation and treatment of children suffering from meningocele and myelomeningocele there has presented a unique opportunity to record the results of stimulation of lumbar and sacral nerve roots. Before presenting the results, some comment is required upon the selection of cases and the techniques involved.

Examination within 48 hours of birth of children suffering from myelomeningocele has shown that 20 per cent present with no paralysis of their lower limbs, 25 per cent with partial paralysis, 25 per cent with moderately severe paralysis and 30 per cent with complete paralysis. Failure to operate immediately results, at best, in no change and, at worst, in a considerable worsening of the paralytic state. Immediate operation results, at best, in considerable improvement in the paralytic state and, at worst, in no deterioration (Sharrard *et al.*, 1963). To investigate the causes underlying the differences between these two groups of patients, electrical stimulation of peripheral muscles, main nerve trunks and nerve roots was undertaken immediately before and during operation upon the spinal defect. The initial results have suggested that approximately 40 per cent of all children born with myelomeningocele have potentially

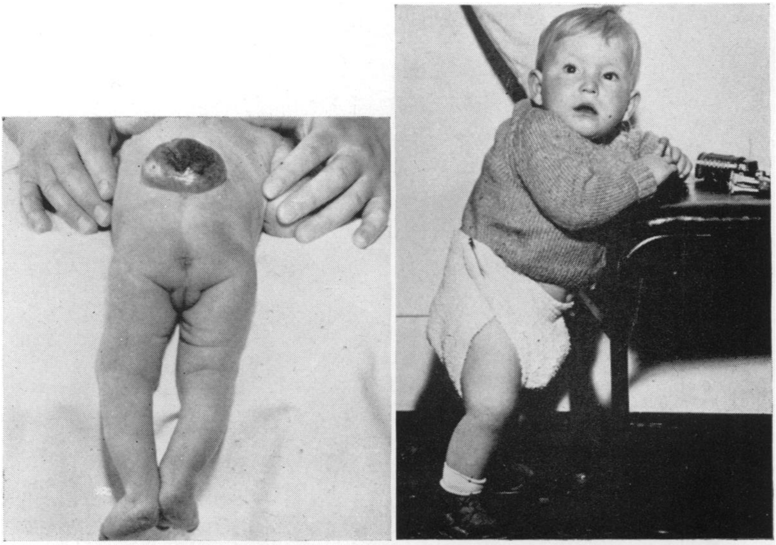
TABLE I

Paralysis and Deformity in Spina Bifida Aperta



normal innervation of the lower limbs as shown by evidence of a normal response to electrical stimulation in all the muscles of their lower limbs (Table I). This finding appears to be independent of the clinical state of paralysis of the lower limbs and of the size or site of the spinal lesion (Fig. 2*a*). Closure of the spinal defect, provided that it is done early enough, often results in improvement to normal or near normal in those apparently paralysed at birth (Fig. 2*b*) and in retention of muscle activity in those showing no clinical paralysis. In the remaining 60 per cent of cases, evidence from electrical stimulation and the progress of subsequent recovery suggest that they are suffering from myelomeningocele combined with myelodysplasia of the spinal cord and roots.

Forty-one infants suffering from myelomeningocele (Fig. 3) with normal or potentially normal innervation of the lower limbs have formed the material for the study of the effects of root stimulation. At operation, performed within 48 hours of birth, the membrane surrounding the plaque of nervous tissue that constitutes the opened-out spinal cord (Fig. 4) is incised. The nerve roots passing forward and laterally to the intervertebral foramina can be identified and displayed without difficulty (Fig. 5*a*). The motor nerve roots may be stimulated either immediately



(*a*) (*b*)

Fig. 2. (*a*) Lumbar myelomeningocele in an infant on the day of birth. There was, clinically, complete paralysis of both lower limbs, but all muscles responded normally to faradic stimulation. (*b*) The same child as in Figure 2 (*a*) aged 18 months. There is normal innervation in the lower limbs and the child is starting to walk.

before they pass through the dura or, at a later stage in the dissection (Fig. 5*b*), immediately outside the dura. The effects of motor root stimulation were felt and seen in the muscles of the lower limbs. Very weak interrupted single stimuli of about 0.1 milliseconds were used.

Because of the abnormally caudal situation of the lumbo-sacral spinal cord in most of the infants, the nerve roots were much more easily separated one from another than in the normal cauda equina. The identity of the roots was resolved by discovering the lowest root that gave a response in the lower abdominal muscles; this was designated the first lumbar root. Working caudally, the uppermost root that caused contraction of the perineal musculature was designated the second sacral root. By observation and palpation, contraction of any of the main muscle groups and many of the individual muscles in the lower limbs could be determined satisfactorily but, in some instances, particularly where individual tendons were not present as in some of the adductor muscles, it was not possible to determine, for certain, individual muscle action but only action of the whole group.

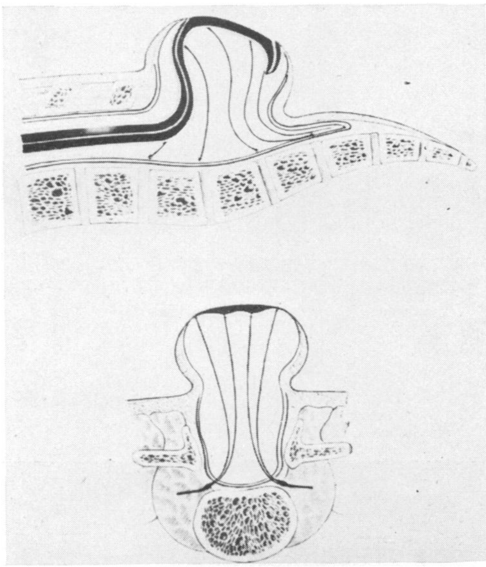


Fig. 3. Diagram of longitudinal and transverse sections of a lumbar myelomeningocele to show the position of the spinal cord and nerve roots. (After Barffaldi and Divano.)

The results to be given indicate those muscles that showed a contraction in at least three-quarters of the patients, though special mention will also be made of instances in which a muscle contracted in more than half but less than three-quarters of the patients.

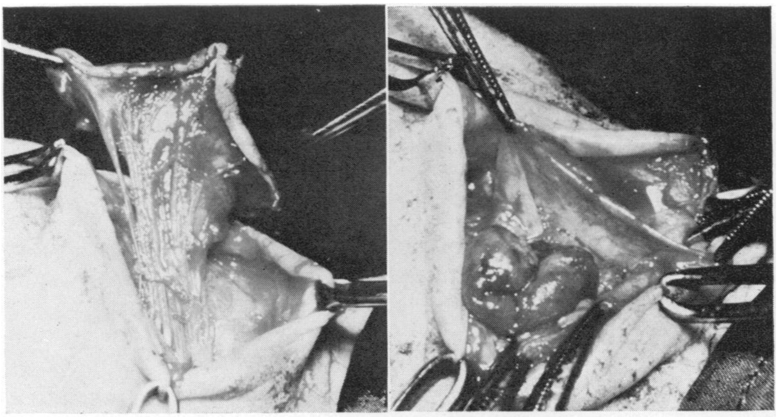
First lumbar root

Stimulation caused hip flexion by the iliopsoas and a slight contraction in the upper part of the sartorius. The cremaster and lower abdominal muscles also contracted.

Second lumbar root

Stimulation caused strong hip flexion and moderate hip adduction by illiopsoas, sartorius, pectineus, gracilis and adductores longus and brevis. There may have been slight action in the adductor magnus but this was

Fig. 4. Lumbo-sacral myelomeningocele eight hours after birth. The central plaque of opened-out spinal cord is surrounded by a membrane merging peripherally into normal skin.



(a) (b)

Fig. 5. (*a*) Lumbo-sacral myelomeningocele with plaque dissected up to show intradural nerve roots. (*b*) The nervous tissue has been allowed to sink into the spinal defect and a layer of dura has been dissected up from the walls of the spinal canal in preparation for closure.

not at all definite. The rectus femoris component of the quadriceps also showed a strong contraction, causing slight extension of the knee, but there was no activity in any of the remainder of the quadriceps muscle.

Third lumbar root

Stimulation caused strong hip adduction and knee extension. Some hip flexion, though not as strong as on stimulation of the first and second lumbar roots, was also present. All the adductor muscles and the whole of the quadriceps musculature contracted strongly. The hip flexion that was present arose partly as a result of contraction in the rectus femoris and partly from activity in the iliopsoas and pectineus muscles.

Fourth lumbar root

Stimulation of the fourth lumbar root again produced hip adduction and knee extension and, for the first time, activity below the knee in the form of dorsiflexion and inversion of the ankle and foot. The adductor muscles except gracilis, all the vasti, the tensor fasciae latae and tibialis anterior were the muscles responsible. In about half the cases, some anterior fibres of the gluteus medius were also felt to contract and some contraction could be felt in the semitendinosus and semimembranosus. Contraction in the tibialis posterior muscle could be identified in some but not all cases.

Fifth lumbar root

Stimulation produced strong abduction and lateral rotation of the hip, flexion of the knee and dorsiflexion of the foot. On the whole, eversion, particularly of the forefoot, was predominant over inversion. The muscles responsible included tensor fasciae latae, gluteus medius and minimus, some of the small lateral hip rotators (though it was not possible to identify exactly which), semimembranosus, semitendinosus, extensor hallucis longus, extensor digitorum longus, peroneus tertius, peroneus brevis and peroneus longus. There was palpable contraction, though not strongly, in both heads of the gastrocnemius, but such was the power of the combined action of all the dorsiflexors of the ankle that no plantarflexion of the ankle resulted. If there was any contraction in the gluteus maximus, it was difficult to determine and was inadequate to cause any extension of the hip.

First sacral root

Stimulation caused abduction, extension and lateral rotation at the hip, strong flexion of the knee, plantarflexion and eversion of the ankle and foot, flexion of the terminal phalanx of the great toe and extension of the lesser toes. The muscles concerned in these actions were all the glutei, the lateral hip rotators, semimembranosus, semitendinosus and biceps femoris, all the peronei, all the components of the triceps surae, flexor hallucis longus and extensor digitorum longus and brevis.

Second sacral root

Stimulation caused extension and lateral rotation of the hip, moderate flexion of the knee, plantarflexion of the ankle and foot and flexion of all the toes. The muscles concerned were gluteus maximus, the lateral hip rotators, biceps femoris, soleus, flexor hallucis longus and flexor digitorum longus. There was also palpable contraction in the intrinsic musculature of the sole of the foot, particularly in the short muscles to the great toe, but any contraction in the other intrinsic musculature of the foot was overpowered by the action in the long flexors of the toes. There was also contraction of the perineal musculature.

Fig. 6. Lumbar myelomeningocele three days after birth, for comparison with that in Figure 4. The membrane is bulging, due to the pressure of cerebro-spinal fluid, and the nervous plaque has been lifted up, causing traction on the nerve roots.

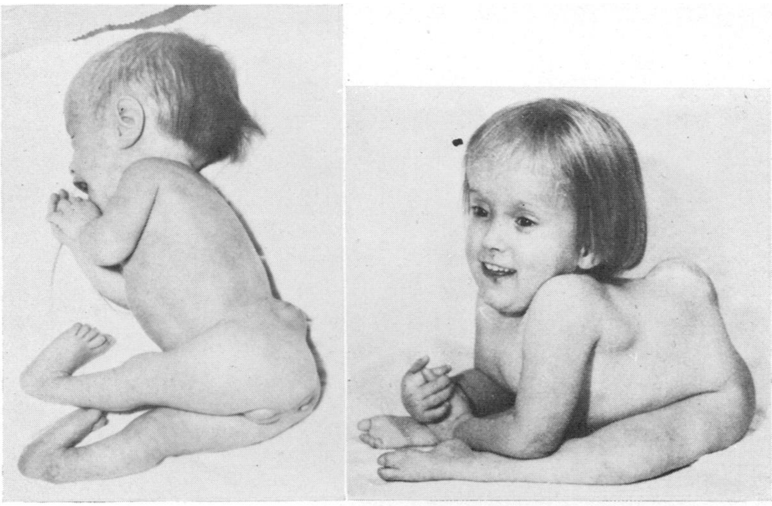
Third sacral root

Apart from action in the perineal and anal muscles, good contraction was found in the intrinsic muscles of the sole of the foot causing flexion of the metatarsophalangeal joints and extension of the interphalangeal joints of the toes. A slight palpable contraction in the biceps femoris and soleus could be found in about half the cases and there was a suspicion of some activity in the flexor digitorum longus muscle, though this was not easy to determine for certain in the presence of intrinsic action.

ROOT LESIONS

At least 50 per cent of the nerve supply to an individual muscle must be lost before clinical paralysis can be detected (Sharrard, 1955). Only when a muscle receives most of its nerve supply from one root, therefore, can loss of function in that root be detected. Lesions of the cauda equina in adult life are uncommon and, when they do occur, there is often difficulty in establishing the precise extent of root damage. In this series, children with myelomeningocele have, once again, provided the main material for the investigation of the effects of extensive root lesions.

Reference has already been made to the fact that infants born with myelomeningocele and treated conservatively are liable to remain paralysed or to become increasingly paralysed. Among the factors responsible for this deterioration may be traction exerted on the nerve roots passing



(*a*) (*b*)

Fig. 7. (*a*) Infant, aged three days, with lumbar myelomeningocele and myelodysplasia with paralysis below the fourth lumbar root. There is fixed flexion and adduction of both hips, which are dislocated, fixed extension of both knees and calcaneo-varus deformities of both feet. These are intra-uterine paralytic deformities. (*b*) Child, aged five, with lumbar myelomeningocele treated by conservative methods. There is paralysis below the first lumbar root and fixed flexion and lateral rotation of both hips due to solitary action of iliacus, psoas and sartorius.

from the plaque of spinal cord to the intervertebral foramina when the meningocele sac fills up with cerebrospinal fluid during the first week of life (Figs. 4 and 6) and the caudal roots tend to be more severely affected (Sharrard, 1963; Nash, 1963). Amongst 250 children, many of whom had not been treated operatively or who had been operated upon more than 48 hours after birth, many examples of cauda equina lesions at all levels of lumbar and sacral roots were available for study. In others, myelodysplasia in association with the myelomeningocele was responsible for partial root paralysis due to absent or abnormal development of a portion of the spinal cord and its roots (Table I) and it was characteristic of these infants that they are born with corresponding paralytic deformities (Fig. 7*a*). Additional evidence was also provided by three infants born with sacral agenesis in whom the fifth lumbar and all sacral roots were absent and who also presented at birth with paralytic deformities. The results will be presented in terms of paralysis of the cauda equina below each segmental level.

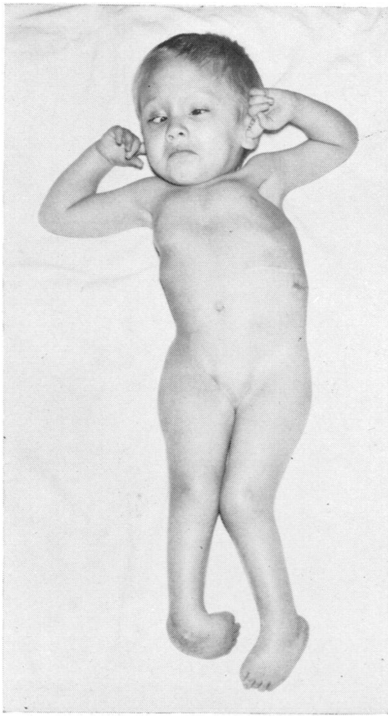


Fig. 8. Child with lumbar myelomeningocele following delayed operative repair. There is paralysis below the second lumbar root in the left lower limb and below the fourth lumbar root in the right lower limb with corresponding paralytic deformities.

Paralysis below the twelfth lumbar root (75 limbs)

There was complete paralysis in all muscles in the lower limb including the hip flexors.

Paralysis below the first lumbar root (38 limbs)

Weak to moderate hip flexor power was present and a palpable contraction could usually be found in the upper part of the sartorius. Partial innervation of iliacus, psoas and upper part of sartorius was confirmed in cases seen at necropsy. Figure 7*b* shows a child with paralysis at this level in both lower limbs. There is fixed flexion and lateral rotation of both hips and kyphosis of the lumbar spine, a feature of extensive spina bifida treated conservatively. In spite of the degree of paralysis, this child is now able to walk with the help of specially designed callipers and body corset.

Paralysis below the second lumbar root (32 limbs)

Strong hip flexion and moderately strong hip adduction were present. The muscles contributing to this were psoas, iliacus, sartorius, pectineus, gracilis, all the adductor muscles and the rectus femoris. Evidence at necropsy has shown that, in spite of the good power of hip flexion, approximately one-quarter of the psoas, iliacus, sartorius and pectineus muscles were denervated. The adductor gracilis was well innervated, the adductor longus and brevis moderately well innervated and the adductor magnus partially innervated. The rectus femoris showed moderate innervation. The left lower limb on the child in Figure 8 is innervated at this level and shows fixed flexion and adduction of the left hip.

Paralysis below the third lumbar root (43 limbs)

Hip flexor and adductor power were clinically normal and there was almost normal power in the quadriceps muscle. There was evidence of some denervation in part of the adductor magnus and quadriceps. Iliopsoas, sartorius, pectineus, gracilis, adductor longus and brevis all appeared to be normally innervated.

Paralysis below the fourth lumbar root (44 limbs)

Normal hip flexion and adduction and knee extension were present. Some ability to abduct the hip in flexion was also present due to partial innervation of the tensor fasciae latae. Dorsiflexion and inversion of the foot by the tibialis anterior was strong and there was also some action palpable to the tibialis posterior. In some patients, semitendinosus and semimembranosus showed weak action. In others there was evidence at operation of slight innervation of the gluteus medius and minimus, though insufficient to produce any active abduction on clinical examination. The severe imbalance of muscle action at the hip, knee and foot at this level resulted in severe deformities of the type shown in both lower limbs of the child in Figure 10 and in the right lower limb in the child in Figure 8. Gross fixed flexion, adduction and lateral rotation of the hip, fixed recurvatum of the knee and a calcaneo-varus foot arose as the result of unopposed action of muscles supplied by the first four lumbar segments.

Paralysis below the fifth lumbar root (27 limbs)

At the hip, in addition to normal hip flexion and adduction, moderately strong abduction was possible by tensor fasciae latae, gluteus medius and gluteus minimus. Active hip extension was absent. At the knee, normal extension and moderately strong flexion by the semimembranosus and semitendinosus was present. Normal power of inversion by the tibialis anterior and posterior and moderate power of eversion by the three peroneal muscles was present. Strong dorsiflexion of the ankle by normal tibialis anterior, extensor hallucis longus, extensor digitorum longus and peroneus tertius muscles was present, but active plantarflexion was virtually absent except for some palpable activity in the gastrocnemius muscles. The deformity that results is shown in the right lower limb in the child in Figure 9. The hip shows fixed flexion but no fixed adduction or abduction. The knee lies in semi-flexion but the foot is in gross calcaneus.

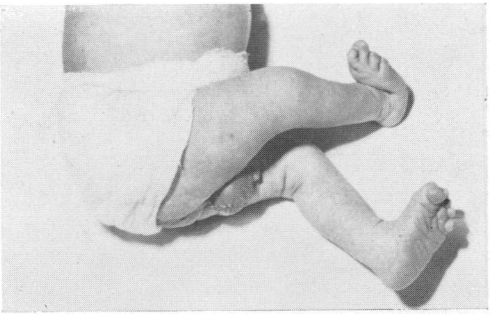


Fig. 9. Infant with lumbo-sacral myelomeningocele repaired on the first day of life. There is paralysis below the fifth lumbar root on the right side and below the first sacral root on the left side, with corresponding paralytic deformities.

Paralysis below the first sacral root (53 limbs)

In addition to normal hip flexion, adduction and abduction there was now moderate power of extension by the gluteus maximus. Flexion of the knee was strong, all the knee flexors being active with distinct weakness of the biceps femoris. Dorsiflexion, inversion and eversion of the ankle and foot were normal and plantarflexion was of moderate power, the gastrocnemius and soleus muscles being partially innervated. Extension of all the toes was normal, but flexor power was only present in the great toe by a strong flexor hallucis longus and weak activity in the flexor hallucis brevis. Medial and lateral rotation of the hip were both normal. The only muscles that were completely paralysed were the intrinsic muscles of the feet except for the abductor hallucis and flexor hallucis brevis. There was only weak activity in the flexor digitorum longus. The deformity that results is shown in the left lower limb in a child in Figure 9, which demonstrates the clawing of the toes and flattening of the skin of the sole of the foot.

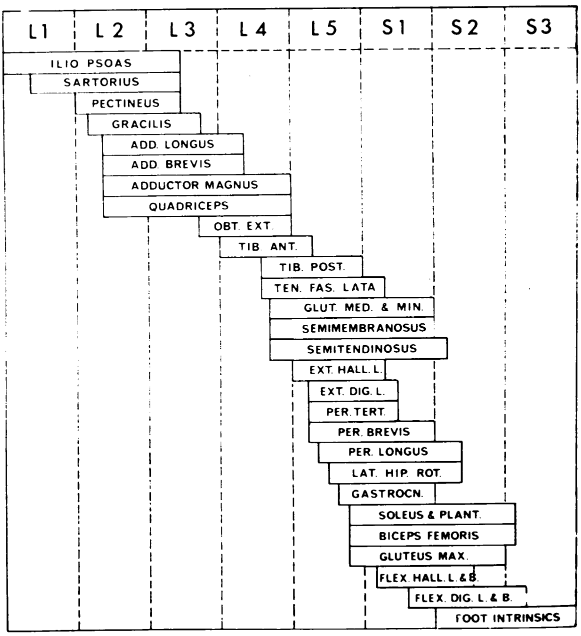
Paralysis below the second sacral segment (21 limbs)

At clinical examination it was difficult to detect any specific abnormality in these patients but, with growth, the development of clawing of the toes due to muscle imbalance arising from weakness of the intrinsic muscles of the sole of the foot became apparent. Biopsy of these muscles confirmed that they were only partially innervated.

Table II summarizes the results derived from observations of the effects of root stimulation and root loss.

TABLE II

THE INNERVATION OF THE LOWER LIMB MUSCLES



DISCUSSION

Except for some minor differences, mainly ones of emphasis on the predominant roots involved, the findings agree substantially with those described by Bumke and Foerster (1929). They also agree with the findings derived from a study of the motor cell columns of the spinal cord in the normal and in poliomyelitis (Sharrard, 1954, 1955, 1956). In contrast with the impression given in many anatomical textbooks, the majority of muscles in the lower limb are supplied mainly by one or two roots, though, from the functional point of view, a partial supply from a further root may often be sufficient to provide useful function when one root is paralysed. In relation to joint movements, anterior displacement of a segment of the limb—that is hip flexion, knee extension and ankle dorsiflexion—are innervated at a higher level than the corresponding posterior displacement—hip extension, knee flexion and ankle plantar-flexion. The description given by Last (1949) of the innervation of limb movements is also confirmed except for flexion and extension of the hip, whose main innervation would appear to be from the first and second lumbar and the first and second sacral roots respectively. Innervation of the sartorius muscle from the first lumbar root as well as the second and third suggests that this supply must have entered the femoral nerve through a communication between the first and second lumbar nerve roots immediately after they leave their intervertebral foramina. The superior gluteal nerve would appear to send most of its derivation from the fourth lumbar root to the supply of the tensor fasciae latae and very little to the gluteus medius and minimus. Similarly the inferior gluteal

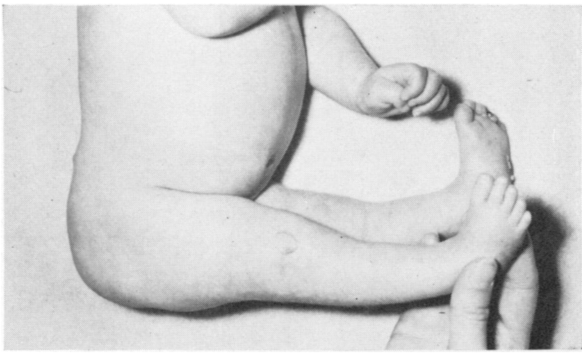


Fig. 10. Congenital paralytic deformities in a child with myelomeningocele and myelodysplasia. There is gross fixed flexion, adduction and lateral rotation of both hips, fixed recurvatum of both knees and calcaneo-varus of both feet.

nerve appears to send very little motor supply to the gluteus maximus from that part of it derived from the fifth lumbar root. All the investigations show conclusively that the third sacral segment is responsible for a substantial part of the supply to the intrinsic muscles of the sole of the foot, an opinion expressed by Bumke and Foerster (1929), from observations on stimulation of that root and my own observations on the spinal cord (Sharrard, 1954).

An anatomical point of great practical value in the assessment of root paralysis is that the root supply of the medial hamstring muscles and the gluteal abductors coincides as does the supply of the lateral hamstring (biceps femoris) and most of the triceps surae.

SURGICAL APPLICATIONS

In the fields where neurological medicine and surgery and orthopaedic surgery meet, a precise knowledge of the root innervation of the lower limb musculature is essential in diagnosis, assessment and treatment. Paralysis of a single root is a common feature of prolapsed intervertebral discs. Muscles supplied by more than one root are unlikely to show any clinical weakness, but muscles predominantly supplied by one root warrant specific examination. From Table II, it can be seen that paralysis of the fourth lumbar root is likely to lead to weakness of the tibialis anterior, of the fifth lumbar root to weakness of the extensor hallucis longus and of the first sacral root to weakness of the flexor hallucis longus.

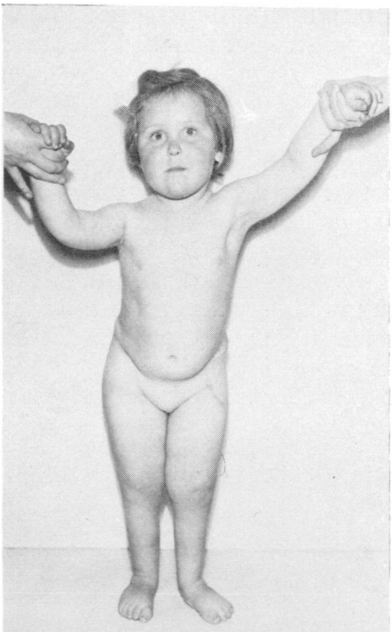


Fig. 11. Child similar to that shown in Figure 10 following operative correction of deformities and tendon transplantation.

In the management of patients suffering from traumatic paraplegia, particularly in injuries to the dorsilumbar vertebral junction, an accurate analysis of residual motor power should enable one to determine accurately the true level of cord and root damage described by Holdsworth and Hardy (1953).

In children suffering from myelomeningocele, appreciation of the segmental distribution of the paralysis and the various deformities that may result has enabled the orthopaedic management of the deformities to proceed on a rational basis of reconstruction (Sharrard, 1962). Elongation of shortened active muscles combined with tendon transplantation makes it possible for even the severely deformed child (Fig. 10) to become an independently active child without significant deformity (Fig. 11).

If nothing else, I hope I have been able to convince you of two things: that knowledge of the root innervation of the muscles of the lower limb is well worth having and that, to obtain results from research, it is not always necessary to resort to animal experiment. Much can be learned by the appropriate study of man himself.

> " Know then thyself, presume not God to scan;
> The proper study of mankind is man."
>
> —*Pope.*

ACKNOWLEDGEMENTS

The treatment of children suffering from myelomeningocele and hydrocephalus cannot be managed successfully other than by a team of surgical, medical and nursing staff devoted to the welfare of these unfortunate infants. To all those at the Children's Hospital, Sheffield, whose heart lies in this work, and in particular to Mr. R. B. Zachary and Dr. J. Lorber, I wish to offer my thanks for their help and co-operation. To my teachers, Professor Francis Davies, Mr. F. W. Holdsworth and and Sir Herbert Seddon, who inspired my interest in anatomy, neurology and orthopaedics, I owe a permanent debt of gratitude.

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APPOINTMENT OF FELLOWS AND MEMBERS TO CONSULTANT POSTS

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S. H. RICHARDS, F.R.C.S.	Consultant in Otolaryngology to the United Cardiff Hospitals.