Operation.—A few days later an oblique incision was made over the external abdominal ring and the tunica vaginalis exposed. It was found to be large, and extended from the external ring downwards. On opening it, about 2 drachms of clear yellowish fluid escaped. The testicle and cord hung free in this cavity from the external abdominal ring, and were covered by visceral tunica vaginalis. There was a broad arrangement of the cord, with separation of the vas deferens from the vessels, and the testicle itself hung almost horizontal. The parietal tunica vaginalis was removed, and a strip of the visceral investment was separated with difficulty from the free aspect of the testicle. Catgut sutures were inserted, uniting the fresh surface of the testicle and the scrotal wall.

The after-history was uneventful, and two years later the patient reported that he was in the best of health.

CASE III.

A. W., aged 16, was seen in the out-patient department of the Edinburgh Royal Infirmary in February, 1902. For three years he had been suffering from sudden attacks of severe pain in the left testicle. Strain apparently brought on the attack, which varied in severity and duration. The pain was always sudden in onset, and got very severe in character. It was accompanied by vomiting, in a little time swelling appeared on the affected side, and at a variable time sudden relief would be obtained. As the attacks incapacitated him from work he applied for treatment. On examination there did not appear to be anything abnormal about the testicle, nor could the characteristic pain be induced by endeavours to twist the cord. Operation was recommended, and Professor Annandale, whose receiving day it was, operated later.

Operation.—The testicle, considerably atrophied and soft, was found lying free and horizontal in a large tunica vaginalis, which contained two to three drachms of clear fluid. The cremaster muscle was hypertrophied. The testicle and cord were covered by visceral tunica vaginalis, and the cord was broad, with separation of the vas deferens from the vessels. The tunica vaginalis was evaginated and stitched in this position, the testicle and cord lying in apposition to the fresh internal aspect of the scrotum, to which it was fixed by catgut sutures. As far as could be followed there was no recurrence of the previous symptoms.

CASE IV.

W. G., aged 24, seen at the Royal Infirmary, Edinburgh, in September, 1902, when in charge of Mr. Cathcart's wards. A year ago he had a bicycle accident and injured his left testicle, which remained painful for three weeks. Three weeks previous to admission there was a sudden onset of pain in the left testicle, sickening in character, and this remained for four to five hours, swelling gradually taking place and the pain subsiding. There was no vomiting. Altogether there had been three attacks of a similar nature. On examination there was a slight varicocele, the testicle lay somewhat horizontal and could not be twisted so as to produce a recurrence of the symptoms. Operation was advised and carried out later. The testicle lay free and almost horizontal in a large tunica vaginalis, and with the epididymis and part of the cord was covered completely by visceral tunica vaginalis. There was free fluid present in the tunica, and the cord contained a slight varicocele and was broad in its arrangement. The varicocele was excised and the cut ends united, the tunica vaginalis clipped away, and the testicle anchored by catgut sutures to the raw scrotal surface. Except for some slight superficial suppuration the case did well, but no after-history could be obtained.

CASE V.

R. C., aged 13, was seen in the out-patient department of the Edinburgh Royal Infirmary in July, 1903. There was a history of recurring attacks of pain in the right testicle from the age of 3. These attacks usually began in the early morning, waking him from sleep. The pain was sudden in onset, sickening in character, and quickly followed by vomiting. He could not bear any handling of the part, the pain was so severe. In two to three hours from the onset swelling began, and disappeared in twenty-four hours after relief had been obtained. The severity of the attacks varied in duration and degree but always passed off suddenly. He noticed that crossing the left leg over the right tended to induce an attack. The right testicle was smaller than the left; it lay horizontal, and was markedly raised compared to the other. The characteristic pain could be induced by rotation of the testicle outwards. He had been treated with a truss for supposed hernia but no sign of one could be found. Operation was advised.

Operation.—Mr. Cathcart, into whose wards he was admitted, operated, and found the testicle considerably atrophied and soft. It was lying horizontal in a large tunica vaginalis, which contained clear fluid. The testicle and cord were covered completely by visceral tunica vaginalis, and the veins and vessels of the cord were enlarged. The cremaster muscle was hypertrophied. The tunica vaginalis was clipped away and the testicle sewn to the scrotum. Recovery was uneventful.

REFERENCES.

- ¹ Perry, *Birmingham Med. Review*, vol. xliii, May, 1893, p. 270. ² Lapointe, *La Torsion du Cord Spermat. et l'Infarct. Hémorrhag. du Test.*, Maloine, Paris, 3. ³ Vanverit, *Annales des Malad. des Org. Génito-Urinaires*, vol. xxii, 1904, p. 401. ⁴ Van der Poel, *Med. Record*, New York, June 15th, 1895, p. 737. ⁵ Gifford Nash, *BRITISH MEDICAL JOURNAL*, April, 1893, p. 724. ⁶ Dowden, *Scot. Med. and Surg. Journ.*, vol. ix, p. 229. ⁷ Lauenstein, *Sammlung klinisch. Vorträge*, No. 92, 1894. ⁸ Kocher, *Die Krank. des männlich. Geschlechtsorgane*, Stuttgart, 1887. ⁹ Curling, *Dis. of Testis*, 4th edition, p. 20. ¹⁰ Nicoladoni, *Archiv f. klinisch. Chirurg.*, 31, p. 182, 1885. ¹¹ Macalaine et Vanverit, *Bull. de la Soc. Anatom.*, p. 267, 1898. ¹² Pearce Gould, *Clin. Soc. Trans.*, vol. xiv, p. 80. ¹³ Davies-Colley, *BRITISH MEDICAL JOURNAL*, p. 811, April 16th, 1892. ¹⁴ Spencer, *Trans. Lond. Path. Soc.*, vol. xlii, p. 51, 1892. ¹⁵ Johnston, *Annals of Surgery*, vol. xix, p. 530. ¹⁶ Hutchinson, jun.,

- Fascic. x, *Patholog. Atlas*, New Sydenham Society, 1895. ¹⁷ Barker, *Lancet*, vol. i, p. 792, 1893. ¹⁸ Whipple and Nash, *BRITISH MEDICAL JOURNAL*, June 6th, 1891. ¹⁹ Odierne and Simmons, *Annals of Surgery*, 1904, p. 962. ²⁰ Englisch, *Wiener klinisch. Woch.*, p. 603, 1893. ²¹ Stanton and Shaw, *Albany Med. Annals*, August, 1904. ²² Golding, *New York Medical Record*, January 21st, 1905, p. 98. ²³ Lexer, *Arch. für klinisch. Chirurg.*, vol. xlviii, p. 201, 1894. ²⁴ Manson, *Bulletin Med.*, p. 562, 1902. ²⁵ Legueu, *Presse Méd.*, p. 289, 1896. ²⁶ Niemann, *Ueber Hodennekrose*, *Breslauer Artz. Zeitsch.*, p. 13, 1884. ²⁷ Griffiths, *Journ. of Anat. and Physiol.*, vol. xxx, p. 81, 1896.

AN INVESTIGATION ON THE REGENERATION OF NERVES,

WITH A VIEW TO THE SURGICAL TREATMENT OF CERTAIN PARALYSES.

By BASIL KILVINGTON, M.S., M.D.MELB.,
Demonstrator of Anatomy, Melbourne University.

[PART I.]

THE various nerve fibres which run in a nerve trunk may in the present stage of our knowledge be classified under the following groups:

1. Motor nerves proceeding direct from the central nervous system to skeletal muscles.
2. Preganglionic fibres arising in the central nervous system and ending in nerve cells placed peripherally (sympathetic ganglion cells, mesenteric ganglion cells, and those of the heart, salivary glands, etc.).
3. Post-ganglionic fibres arising in these peripheral ganglia and ending in smooth muscle and glandular tissue.
4. Afferent fibres arising in the peripheral sensory apparatus, and proceeding to the central nervous system, and having their cells stationed in ganglion close to but not included in the central nervous system; with these must be classified for the present the vaso-dilator nerves.

In investigating the results of nerve crossing, we have to bear in mind the fact that the particular nerves used may contain any or all of these groups. Sensory phenomena are extremely difficult to determine in animals; and in such nerves as those of the limbs the preganglionic fibres are absent. Thus the motor fibres attract our chief attention as they give results which are the most striking and easy to interpret.

The startling results obtained from nerve crossing have opened a very fascinating field in surgery. The earliest experiment in this direction was apparently performed by Fleurens¹ in 1824. This observer divided the two chief nerves from the brachial plexus in a cock; one nerve supplies the muscle of the superior and the other those of the inferior surface of the wing. They were both divided, and the proximal end of one joined to the distal end of the other and vice versa. After a time co-ordinated movement was observed in the limb. Since then many other observers have used different nerves for crossing. These nerves may have a similar or different function. Schwann² made some experiments on the sciatic nerve in the frog, to see if sensory fibres could establish a functional connexion with motor fibres. His results were against any such union. These have been confirmed by many other observers, including Bidder and Gluge and Thiersnesse,³ who crossed the hypoglossal and lingual nerves. It seems that any such functional union is very unlikely. In all this class of experiment there is a considerable risk of all the nerves uniting in a common catatrix, which of course vitiates any result obtained. To avoid this, Rawa⁴ used only one crossing, and excised a considerable length of the other nerves. Such a procedure, of course, results in permanent loss of power in one set of muscles antagonistic to those innervated by the crossed nerve. Such a condition is unsatisfactory and not very easy to interpret, owing to the contracture developing in the innervated muscles. Rawa crossed the peroneal and posterior tibial nerves, and describes a contraction occurring in the muscles normally supplied by the posterior tibial, when the peroneal which has been crossed is stimulated and vice versa. This observer also crossed the vagus and hypoglossal, widely excising one set, and in the animals which survived the function of the vagus or hypoglossal was apparently carried on by the crossed nerve. After six months' interval in the animal the central end of whose vagus was sutured to the distal end of the hypoglossal, rhythmical movements were present in the corresponding half of the tongue. These had a definite relation to the movements of respiration. The conclusions drawn from this were that the central end deter-

mined the nature, and the distal end the position, of the movements.

Langley⁵ united the proximal end of the vagus to the distal end of the cervical sympathetic, and found the vagus had acquired an influence over all the structures innervated by the sympathetic. He had taken precautions to prevent the corresponding nerve joining in a common cicatrix, and he assumed that the "autonomic" motor fibres of the vagus to the oesophagus, stomach, lungs, and heart established this function. After a time the animal lost the dilated pupil and dilatation of the vessels to the ear seen after section of the sympathetic. It seemed that the vagus was exercising the tonic action on those structures which the sympathetic normally innervates. He also got return of most of the sympathetic functions when the distal end of this nerve was joined on to the proximal end of the lingual. This was presumably brought about by the vaso-dilator fibres in the chorda tympani branch.

Many experiments have now been done in nerve crossing where both pairs of nerves are kept, and some method of preventing union between the central and peripheral ends of the same nerve adopted. These confirm the original one of Fleurens, and are so interesting from their surgical possibilities that they may be briefly described. The fore limb of the dog was the part used. Stefani⁶ crossed the median and musculo-spiral nerves, and after 202 days good co-ordinated and voluntary movements were restored. Two out of three of his experiments were vitiated by some of the central fibres joining on to the distal ones in the same nerve. Cunningham⁷ successfully combated this tendency by wrapping round the nerves at the point of suture a layer of fascia. His experiments are also more conclusive, as he crossed the musculo-spiral with the whole of the nerves supplying the flexor muscles. After seventeen months electrical stimulation showed that the central end of the musculo-spiral had united with the peripheral end of the median and ulnar, and resulted in flexion of the limbs. At the same time volitional movements were far from satisfactory. In another set of experiments he crossed the median and ulnar nerves and found very good results following, but in these cases the immediate loss of power was not very noticeable. He concludes that after crossing two motor nerves the co-ordination was good, provided these nerves have a synergic function. When the nerves supply antagonistic muscle, however, the functional result is unsatisfactory.

Kennedy⁸ made some very complete experiments in crossing the musculo-spiral with the median, musculo-cutaneous, and ulnar—that is, the nerve supply of the whole of the flexors and extensors was interchanged.

This procedure maintained the balance of opposing action and prevented the development of contractures. Precautions were taken to avoid confluent union in a common cicatrix by interposing the internal anconeus muscle between the two sets of nerves. Co-ordinated voluntary movements were very completely restored, and a subsequent dissection showed no confluent union. Stimulation of musculo-spiral above the line of suture resulted in flexion, and vice versa. Thus, as Kennedy remarks, for restoration of function it is not at all necessary that the old paths for nervous impulses should be restored. Probably the same thing holds after simple division and suture of a nerve. The exact axis of the trunk is altered, and it is extremely likely that many of the peripheral fibres do not unite with the central ends of those with which they were formerly continuous. This means that in some cases the motor cells of the spinal cord supply different muscle fibres to those which they originally innervated. After cutting a nerve it apparently unites equally well as regards function whether the axis of the trunk be maintained or the lower piece be given a half twist round. Thus a considerable amount of co-ordination has to be developed, and I believe this accounts for the fact that the very delicate movements are with great difficulty—if ever—regained, after division of a nerve. This also agrees with the fact that when divided nerves are joined in their old position, function does not return any earlier than when they are crossed, though co-ordination may do so to some degree. Probably age plays a prominent part in this result, for the younger the animal the easier is it for fresh paths to be opened up.

In connexion with this subject, the state of the cortical centres after nerve crossing is of great interest. Stefani, in the work previously referred to, investigated the condition of these centres. He states that there is a loss of irritability in them. Cunningham finds the cortical representation is

changed after nerve crossing, but stimulation of any particular area gives rise to inco-ordinate movements. Kennedy finds the cortical areas for flexion and extension are interchanged after nerve crossing, and produce co-ordinate muscular action.

The next class of nerve crossing consists in suturing the central end of one to the peripheral end of two or more nerves. This has been used to treat certain cases of paralysis, and has been almost exclusively practised on the facial and spinal accessory nerve. The central end of the spinal accessory is sutured to its own peripheral end, also to the peripheral end of the facial which supplies the muscles. Some of the fibres of the spinal accessory unite with their own peripheral ends, and others with the peripheral fibres of the facial. This operation was first performed in man by Faure and Furet⁹ in a case of facial paralysis due to a bullet penetrating the ear. The lesion was of eighteen months' standing, so no functional result took place. Kennedy, in the paper previously referred to, reports fully the case of a woman on whom the operation was performed. She suffered from facial tic, and so of course the muscles had not undergone any atrophy at the time of the operation. A good result was obtained. It was interesting to note that when she voluntarily raised the arm on the side operated on, the same side of the face contracted. This was due to the nerve impulse passing along the spinal accessory to the trapezius muscle, as well as along the facial nerves. Bréavoine¹⁰ in his paper gives a drawing of the point of union of the spinal accessory and facial nerves. It is stained by Weigert's method, and shows some of the fibres of the central end of the spinal accessory going down the distal part of both spinal accessory and facial nerves. A similar result is obtained by crossing other nerves, such as the hypoglossal and facial. I have a dog at present whose left facial muscles are innervated by part of the twelfth nerve; nothing unusual is noticed when the animal laps. These experiments show that the muscles supplied by two nerves can be innervated by suturing these to the central end of one of them. The nerve fibres of this central branch effect a junction with the nerve fibres in both peripheral branches. I have emphasized that a raw surface is necessary. It seems that no junction occurs if a nerve is implanted laterally on to the side of a second when the latter is intact. Desprès¹¹ performed this experiment in the case of the median and ulnar nerves; and Nungebauer¹² with the peroneal and tibial nerves, and in both cases without any successful result.

In a recent communication Langley and Anderson¹³ have made very extensive observations on the union of different kinds of nerves. They conclude that (1) the central end of an efferent fibre can make functional connexion with the peripheral end of any other efferent fibre of the same class, whatever be the normal actions produced by the two nerve fibres; (2) functional union is not possible between efferent fibres proceeding from the spinal cord and post-ganglionic nerve fibres, that is, fibres arising in peripheral ganglia, and ending in smooth muscle and glandular tissue; (3) afferent fibres cannot unite with efferent or post-ganglionic fibres, to give a motor effect, though they may possibly join anatomically.

It has long been known that conductivity can be restored in a divided nerve if the cut ends be sutured together. This can take place even though the suturing be performed a considerable time after section of the nerve, if the ends be freshened and brought into apposition. Until very recently it was believed, chiefly from the work of Ballance and Purves Stewart,¹⁴ which agrees with the older experiments of Howell and Huber, that a considerable amount of regeneration takes place in the distal end of a cut nerve which remains unsutured to its central end. Complete regeneration, however, can only take place when the continuity of the nerve is restored. This is known as the "autogenetic" theory of regeneration. Langley and Anderson's¹⁵ experiments cast some doubt upon this theory. These observers are inclined to the old belief that the fibres from the central end grow down into and along the peripheral end, and that no regeneration at all takes place in the latter unless it is connected with its own central end or the central end of other nerves. They question the technique of the supporters of the "autogenetic" theory, which usually consisted in excising a considerable length of nerve or twisting the central end up and fixing it to the skin. Langley and Anderson explain the result so obtained by the fact that the peripheral end of a cut nerve, when sewn into the skin or left lying among muscles, may make connexion with the central nervous system by means of the nerves of the surrounding cut tissues, though it makes no connexion with its own central end.

Head and Ham¹⁶ removed a considerable length of the radial and sciatic nerves in cats, and found no medullated fibres present in the peripheral trunk in 249 and 100 to 150 days respectively. These experiments also are against the "auto-genetic" theory.

On the other hand, many cases are reported of some return in sensation in a few days after secondary suture of nerves which have been previously divided. It is obvious that this time is too short for any fibres to have grown down from the central end of the nerve, along to the sensory end organs. But the areas of distribution of sensory nerves are somewhat variable, and what is more important, they considerably overlap. Thus, these cases of supposed early return of sensation after union of nerves which have been a long time divided are not conclusive.

At the present time we cannot say definitely whether any regeneration at all takes place in the peripheral end of the cut nerve if it remains unconnected with its central end (provided, of course, that it does not establish more or less union with other nerves).

My own experiments were directed on the same line as the crossing of facial and spinal accessory, but two nerves which supplied antagonistic muscles were used. The hind limb of the dog was the part experimented upon in all cases, for though this does not give a good indication of the return of delicate movements, it is very easy to deal with the whole of opposing muscles. As the animals were not kept alive more than five months, the sensory phenomena were disregarded. Probably, as in man, sensory fibres regenerate earlier than motor ones. In fact, volitional co-ordination is impossible without sensory impressions; but a quiet dog will not evince any discomfort on being pricked, even in health. Thus it is impossible to estimate the early stages of restoration of sensation. The nerves were divided in the popliteal space, and were reached by means of a straight incision and retraction of the hamstring muscles. The sciatic nerve bifurcates deep down almost on the femur, but at a very variable height, into the two popliteals. With an unusually low point of division manipulation of the nerves is difficult. A considerable quantity of fatty tissue fills the space, and this with some lymphatic glands is best removed, as with traumatism it is very liable to suppurate. Thin chromicized catgut was used for suturing, as it is absorbed, though not too rapidly. As few sutures as possible were passed through the nerve substance. Any attempt to get an efficient hold by means of the nerve sheath in the small nerves of the dog failed. Cases which suppurated were rejected, but one animal in which the skin wound separated, but without any sepsis, was allowed to continue. An impervious suture, like silkworm gut, was used to unite the skin wound. After trying many appliances for protecting the wound, such as plaster-of-paris and collodion, I rejected all, and merely powdered the area of the wound with boracic powder. Dressings of any kind seemed to irritate the animal and caused it to bite and rub the wound.

The following is a list of the animals experimented upon. They were all anaesthetized with a mixture of equal parts of ether and chloroform after having morphine given them:

Dog I. Operated on January 20th, 1903. Both the internal and external popliteal nerves were cut completely across on the left hind leg. The central end of the internal popliteal was sutured to the peripheral end of both the internal and external popliteal by a single suture of chromicized catgut. As much as possible (about $\frac{1}{2}$ in.) of the central end of the external popliteal was excised. No attempt was made to interpose any muscle or fascial tissue between the central and peripheral ends of the external popliteal. After recovery from the anaesthetic, and when the wound was healed, the animal walked with the foot doubled over on the dorsal surface.

February 27th, 1903. The animal only occasionally treads on the dorsum of the foot, any attempt to scratch with the limb is ineffectual, and the movements lack co-ordination. At the same time the ankle joint is loose, and permits of flexion and extension to an abnormal degree. No ulcer has formed on the dorsal surface of the foot; sensation, as far as can be made out, does not differ in the two legs.

June 8th, 1903 (139 days). Function by this time has very much improved, and the animal does not go over on the dorsal surface of the foot at all. It runs and walks about almost like a healthy dog. The animal was anaesthetized and the popliteal space opened up; a slight swelling was present where the three nerves were sutured together. The central end of the external popliteal had a bulbous termination, but no fibrous strand extended down to the line of suture. Stimulation of the internal popliteal at A (above the point of suture) caused contraction of both flexor and extensor muscles, but the flexors of the toes predominated. After cutting through the internal popliteal at B (below the line of suture) stimulation of the internal popliteal at A resulted in forcible contraction of the extensor muscles of the toes. Thus the nerve impulse travelled from the central end of the interior popliteal,

along both the distal end of the interior and exterior popliteal to the muscles.

Dog II. Right leg operated on August 7th, 1903. A similar operation was performed as in Dog I, but the central end of the external popliteal was sutured to the peripheral ends of both internal and external popliteal. About $\frac{1}{2}$ in. of the central end of the internal popliteal was excised.

August 22nd, 1903. The animal usually holds the leg off the ground in walking, but when it is used the foot always comes down on the dorsal surface. The skin wound is gaping slightly, but no deep suppuration has occurred.

September 15th, 1903. Two ulcers which formed on the dorsal surface of the foot, have almost healed. The wound in the popliteal space has perfectly united. Animal walks fairly well, but still goes over very often on the dorsal surface.

November 15th, 1903. The ulcers have completely healed, and the animal walks much better, the foot only occasionally doubling over. The right leg is weaker than its fellow; this is well seen when an attempt is made to stand on the hind legs, for the right one often gives way. Co-ordination is not perfect, as the animal is somewhat awkward in scratching itself with the injured limb, and the foot is rather loose at the ankle joint.

Fig. 1.

Fig. 2.

November 25th, 1903 (110 days). The popliteal space was opened up and the nerves subjected to electrical stimulation. The central end of the internal popliteal had formed a bulb, but there was no fibrous strand growing down from this to the line of suture. A slight swelling had formed where the three ends had been sutured together. Stimulation of the external popliteal at A (considerably above the line of suture) results in contraction of both flexor and extensor muscles of the toes, but the latter, though usually the weaker set, now predominate. After cutting the external popliteal at B (below the line of suture) stimulation gives rise to vigorous contraction of the flexor muscles. This shows that some of the fibres of the central end have joined on to others in the distal end of internal popliteal. The nerves were removed, pinned out in a stretched condition on a sheet of cork, and hardened in Muller's fluid. Pieces of each were embedded in collodion and cut as nearly as possible transversely to their long axis. This was effected by placing small lengths of the nerve upright in a block of liver tissue. They were stained by Weigert's method, and the fibres counted under the microscope with the aid of an ocular micrometer. The numbers of fibres in the central portion of external popliteal was 4,435, and in the distal part of external popliteal 2,786. In the distal portion of internal popliteal there were 7,196 fibres.

Dog III. The left hind leg was operated on on October 29th, 1903. About $\frac{1}{2}$ in. of external popliteal was excised. A cut was made transversely in internal popliteal nearly half way through its entire thickness. Into this gap the peripheral end of external popliteal was drawn and fixed as accurately as possible by a single suture. The wound healed by first intention. Immediately after the operation the animal, when walking, held the injured leg off the ground, the toes were fully flexed, and when the foot was placed on the ground it was always on the dorsal surface.

November 14th, 1903. Animal constantly uses left leg in walking, and the plantar surface is placed on the ground, though very rarely the dorsal is used.

February 12th, 1904. Function is almost perfect, the animal never walks on the dorsum of the foot, the only difference between the hind legs is seen in the finer movements, such as in scratching a particular spot; but even here close observation is necessary. Sometimes, too, in jumping off the hind legs, it appears as if the left leg were a little weaker than its fellow. On asking a stranger to look at the dog, he stated that he could detect nothing peculiar when the animal was running about. The amount of recovery was about the same as in Dog I; 136 days after operation the dog was anaesthetized and electrical stimulation used. On stimulating internal popliteal above the point of junction with external popliteal, flexion of the toes and partial extension of the foot took place. The tendons in the front of the leg could be felt actively contracting; on cutting internal popliteal below at B stimulation resulted in vigorous flexion of the foot, and considerable, though less powerful, extension of the toes. The central end of external popliteal ended in a bulb and from this a thread of fibrous tissue tapered off towards the point of suture of external popliteal to internal popliteal. I was anxious to make certain that none of the fibres of the central end had joined

those in the peripheral end of external popliteal, so sections of the end of the bulb and fibrous thread were cut and stained by Weigert's method. These showed the nerve fibres extending a short distance down the thread, but they stopped quite $\frac{1}{2}$ in. above the junction of external popliteal to internal popliteal. They had the irregular curling distribution usually seen in the bulbous end of a cut nerve. Before stimulation, this bulb and thread was separated from internal popliteal, so the results obtained could not have been in any degree caused by the two ends of the external popliteal joining on to one another. Counting of the individual fibres showed there were 7,740 in internal popliteal above the point of junction with external popliteal, below this point there were 7,275 fibres. In the peripheral end of external popliteal there were 2,435 fibres. This experiment differed from the former two in that the majority of the fibres of one nerve, the internal popliteal, were not divided and so had no chance of joining with those of the peripheral part of external popliteal. Consequently a portion of the antagonistic muscle to the extensors was never paralysed.

Dog IV. The left leg operated on May 11th, 1904. Both external and internal popliteal were divided completely across as low as possible, and the central end of external popliteal was sutured to the peripheral ends of both external and internal popliteal. A suture was passed through the cut end of the central part of internal popliteal, which was doubled back and attached to the sheath of the inner side of the sciatic nerve. The wound healed by first intention.

Fig. 3.

Fig. 4.

May 20th, 1904. The dog usually keeps the leg well up, but when placed on the ground the dorsal surface of the foot is always downwards.

August 3rd, 1904. The dog walks fairly well, but the foot is often placed with the dorsal surface on the ground; the muscles of the left leg are distinctly smaller than those of the right. The left leg is decidedly weaker than its fellow, and this is easily seen when the dog jumps. Two small ulcers have formed on the dorsum of the foot.

September 3rd, 1904. These ulcers have extended and the outer one has now exposed the extensor tendon, and has spread round the nail to the plantar surface of the foot.

September 14th, 1904. Up to this time the ulcer did not cause any pain, but now the animal avoids using the limb by holding it off the ground. It has extended into the joint of one toe, and has an unhealthy appearance; the corresponding nail has dropped off.

September 25th, 1904 (after 137 days), the animal was anaesthetized and the nerve stimulated. The curled-up central end of internal popliteal was seen as a large bulb about 2 in. above the line of suture. No fibrous prolongation extended down from it, and no fibres could possibly have grown down to the line of suture. The external popliteal nerve was cut at A and B (above and below the point of suture). Stimulation at A caused vigorous contraction of the muscles at the back of the limb. Stimulating the proximal cut end of the external popliteal at B also resulted in the same contraction. This is an axon reflex, and the impulse travels up the external popliteal to the line of suture and then down the internal popliteal to the muscles. The tendo Achillis was detached from the os calcis and fixed to a lever, and it was found that the smallest stimulus capable of producing a contraction when applied at A would do so when given at B. The left leg below the os calcis was put in an oncometer, and the animal was curarized and artificial restoration kept up. Stimulation at A gave no alteration in the volume of the limb. Curare does not paralyse the vasomotor nerves. This proved that the vasomotor nerves had not regenerated. Similarly no axon reflex was obtained with the vasomotor nerves. This absence of vasomotor regeneration is interesting in connexion with the "trophic" ulcers. The counting of the nerve fibres gave 5,826 in the central end of the external popliteal; in the lower end of the external popliteal there were 1,880; in the peripheral end of the internal popliteal 6,808.

RESULTS OBTAINED.

1. When the peripheral ends of two nerves supplying antagonist muscles are sutured to the central end of one

of them—the other being thrown out of action—the fibres of this central end join on to those of both peripheral nerves and establish a functional result. Regarding this from the point of view of the motor cells of the anterior horn of the spinal cord, we see that it is possible to throw out of action those innervating one of two opposing groups of muscles, and to allow the remaining cells which previously set one group only in action to extend their sphere of innervation, and thus supply both groups. The fact that the central end of one nerve may innervate muscles through the peripheral end of two nerves has been shown by several observers in the case of the spinal accessory and facial nerves, but never before, so far as I am aware, with a nerve supplying antagonistic muscles.

2. As the animal has good co-ordination, it evidently has the power of using each group of muscles separately, and when using them together it can adjust their action so as to give accurate or fairly accurate movements. This is interesting in connexion with the axon reflex, and I shall discuss this relation later on. It is evidently due to a re-education of co-ordination, and would probably be more easily and thoroughly effected in young animals than in old ones. In Kennedy's interesting case, where the facial nerve was implanted in the spinal accessory, at the moment of rising the arm on that side the corresponding half of the face contracted. This latter "speedily passes away, although the arm is kept up." Possibly it will not occur at all when the co-ordination has been further improved. Whether the very delicate movements, such as are necessary in playing a violin or to give touch to the piano, would return after nerve crossing, or even after simple nerve division and immediate suture, is doubtful. Bowlby¹⁷ thinks this would not return in the latter case.

3. When a large nerve can be used to innervate two or more nerves, a better functional result is obtained than when a small one is used. This probably depends on the number of fibres (or motor cells) available in the two cases; the results in my own experiments were certainly much better when the central end of the internal popliteal was used, compared with the smaller external popliteal. Probably a limit will soon be reached, when the central end of a small nerve would cease to produce any useful movement.

4. When using one nerve to innervate two peripheral nerves, the muscles supplied formerly by the central nerve tend to predominate on stimulation, even if they are normally the weaker set. This happened in Dogs II and III, but I am doubtful if these are sufficient data on which to base the conclusion. A good deal may depend on the relative areas of the cut end of the central nerve which are in contact with the cut peripheral nerve. With comparatively small nerves, as in the dog, this is difficult to estimate. Langley and Anderson show that the peripheral end of cut nerve fibres exert a chemiotactic influence on their own central end, and this is greatest amongst the similar members of the same class; probably it holds to a lesser degree in different nerves of the same class. But this chemiotactic attraction may not be sufficient to counteract the purely physical one of having a large area of the cut face of two nerves in contact.

In Dogs II and IV the distal end of the internal popliteal contained about three times the number of fibres than the distal end of the external popliteal had. In these cases the central end of the external popliteal was used. In Dog II the flexor muscles of the ankle were apparently the more powerful.

5. The counting results and the axon reflex obtained in Dog IV show that when the central end of one nerve is joined on to the peripheral ends of two nerves, there are considerably more fibres in the lower set than in the upper—that is, a single nerve fibre in the central nerve may divide into two or more fibres which go to the peripheral nerve. The following is a tabulated list of the countings:

No. of Animal.	Upper Set.	Lower Set.
Dog II	E. P. 4,435	9,982 { E. P. 2,786 I. P. 7,196
Dog III	*I. P. 7,740	9,706 { E. P. 2,435 I. P. 7,275
Dog IV	E. P. 5,826	8,868 { E. P. 1,880 I. P. 6,808

*I. P. not completely divided at operation.

At first I thought that one fibre usually divided into two in the peripheral nerves (the discrepancy being due to unavoidable errors in counting), but the count in Dog IV, and the fact that the same animal proved no regeneration took place in the vasomotor nerves, negatived this idea. The count in the upper set of nerves thus included the vasomotor fibres, which were unregenerated in the lower set. This

makes the difference between the upper and lower counts more marked. As the nerves included both sensory and motor fibre, we cannot say more than that either or both of these two classes may divide into several branches after suture. Professor Osborne suggested I should try and get the axon reflex, which we were successful in obtaining in Dog IV on September 25th, 1904.

This shows that a single fibre from a ganglion cell may divide into two or more fibres and supply antagonistic muscles. On September 27th, 1904, that is two days later, the *Journal of Physiology* arrived, giving an account of the same experiment,

Fig. 5.

Fig. 6.

performed by Langley and Anderson, but Dr. Osborne's idea was obviously an independent one. These observers apparently consider that the axon reflex, or division of fibre as shown in the figure, accounts for the whole of the contraction occurring in the antagonistic muscles. I cannot conceive how the co-ordinated useful movement would be possible if every fibre divided to supply antagonistic muscles, and am at present trying to show that only some of the fibres do this. These experiments are not yet complete. It is quite likely that every fibre divides, but in most cases all the branches go to one set of muscles. The fact that in Dog II the peripheral external popliteal contained 2,786, and the peripheral internal popliteal 7,196 fibres, and in Dog IV the peripheral external popliteal 1,880, and the peripheral internal popliteal 6,808 fibres, excludes the fact of every fibre dividing into two branches of which one goes to each of the two antagonistic sets of muscles (or if more than two branches, an equal number going down either nerve). But it is still compatible with the theory that a fibre in the proximal nerve may divide into several branches, the majority of which go down one nerve. Even this hypothesis would result in a considerable waste of nervous and muscular energy, and would probably be incompatible with any accurate co-ordination of movement.

The counting shows that after suturing two nerves into one, the number of fibres in the peripheral nerves is not as great as it is normally (at the end of four and a half months). But at this time vasomotor regeneration has not taken place, and these fibres may possibly make up the deficiency. I intend to investigate this point later, but at present I cannot say that any diminution in number will ultimately be found. Thus there may be no wasting of muscles after nerve crossing, and all the muscle fibres may be innervated by "branch fibres," if I may so call them, but my experiment with the external popliteal show that a limit is soon reached in this direction, and possibly, too, to the number of branches into which a single fibre can divide.

The microscopical examination of the nerves after crossing shows some interesting facts. Most of the main muscular branches which come off the internal popliteal below the line of section were stained and examined. In every case except one, the muscular trunk contained some nerve fibres. The exception was found in a small muscle twig coming from the internal popliteal at the lower limit of the popliteal space in Dog III. This was possibly due to the mechanical effect of the interposition of the external popliteal in the gap in the internal popliteal proving too much for the chemiotactic attraction of the fibres from X into A (see Fig. 6).

The nerve fibres in the peripheral nerve often have a wavy course; this was shown in longitudinal section, and accounts for the fact that in transverse sections some of the fibres appear round and others oval, or occasionally spindle shaped. This factor adds considerably to the difficulty of counting.

The arrangement of the peripheral nerve into fasciculi is altered after division and union. The large fasciculi are broken up into numerous smaller ones, which, however, suggest the original outline of the former bundle. Thus the normal external popliteal in a dog consists, as shown in the figure, of a single large oval group of nerve fibres, surrounded by a thick connective-tissue sheath.

Fig. 7.—Normal external popliteal nerve magnified.

Fig. 8.—Peripheral end of external popliteal after suture.

In the peripheral external popliteal, after suture, six or seven small groups are seen, in which an evident relationship to the single oval group is apparent. These groups are separated by connective-tissue partitions. The normal internal popliteal consists of eight bundles, but in one case, after suture (Dog IV), the peripheral internal popliteal contained thirty-three small groups. At the same time, in all my cases the size of the peripheral nerve was much smaller than that of its corresponding central end.

APPLICATION OF THE RESULTS TO SURGERY.

In infantile paralysis we have a loss of power in certain muscles as the result of destruction of a certain number of motor ganglion cells in the anterior horn of the spinal cord. The foregoing experiments show that a certain number of these motor cells can be dispensed with and yet all the functions of the limb be efficiently retained. This suggests the idea that it is probable a good result could be obtained by suturing the nerve supplying the paralysed muscles on to the cut surface of the proximal end of an adjacent healthy nerve. The healthy nerve may be cut partly across and the paralysed one fixed in the gap so formed (as in Dog III). This has the advantage that some of the muscles are never cut off from their nerve supply, but the healthy nerve may be cut completely across, and its own peripheral end, as well as the peripheral end of the paralysed nerve, sutured to the central end. This has several advantages; in the first place, it gives all the fibres in the proximal nerve the chance of branching (for this seems impossible without dividing a fibre) and supplying a greater number of muscle cells. In the second place, the innervated muscles are liable to shorten and develop a contracture before regeneration in the divided nerves has taken place. Lastly, it is possible, as in Dog III, that the mechanical interposition of the paralysed nerve may prevent some of the branches of the peripheral end of the healthy nerve receiving any fibres. I think nerve crossing would be specially applicable in the common form of infantile paralysis where the extensors of the toes and the peronei are affected. The external popliteal being small compared with the internal nerve, experience with the dog would lead us to expect a good functional result. Where the calf muscles are affected, Dogs II and IV would lead us to expect a useful though not so strong a limb as in the former case. There are two classes of cases, where it is probable that this procedure would be useless. First, in those cases where a large amount of recovery takes place with a limb fairly useful, but still not so strong as its fellow; it is very doubtful if we could hope for a better result from nerve suture than would occur naturally. A great many cases of infantile paralysis go on to almost complete recovery in the course of time. Secondly, in very severe cases, where only a small group of muscles remains intact (as, for example, a case where the peronei alone retain their function), it is very questionable if the fibres of the musculo-cutaneous nerve could innervate at all efficiently the muscles supplied by the anterior tibial and large internal popliteal. Several objections may be raised against this procedure. It is impossible to tell for a considerable time how much recovery will take place naturally, and during this delay fatty degeneration and atrophy of the muscle fibres is going on. It is known that when a muscle has been cut off from its nerve for some time (about two years), little or no recovery follows suture of the separated ends of the nerve. It should, I think, be possible to come to an opinion as to whether the particular case merits trial of nerve crossing, in about six months at the outside limit, and very

often in a much shorter time. Meanwhile the nutrition of the muscles should be kept up by electricity and massage, so that if suture be performed, undegenerated muscle fibres should be ready to respond to the nerve stimulus. Ballance and Purves Stewart's experiments show that degeneration occurs in the distal end of a cut nerve whether sutured or not, and regeneration of the peripheral fibres goes on to a certain point without any stimulus from the central end, thus leading to the production of protoplasmic threads from the nuclei of the primitive sheath. These are the "embryonic fibres" of Howell and Huber. Thus, if the autogenetic theory be correct, it does not matter for the first few weeks whether the ends are united or not, as far as ultimate regeneration and function are concerned. In some cases, when an early decision can be made, it may be possible to perform the crossing within the first three weeks, which is as good as the immediate union I have made in the dog.

In many cases a muscle is not completely paralysed, a few of its motor cells having recovered. If the nerves are crossed, as in my experiment, the proximal end of the damaged nerve not being used, some healthy and useful horn cells are wasted. It would be best to stitch the cut surfaces of the four nerves in apposition (as in the figure),

Fig. 9.

and give the few healthy fibres which remain in the damaged nerve a chance to join on to some in the distal end. Of course I could not perform this experiment in animals, as there is no easy means of destroying a certain number of motor horn cells to produce a condition analogous to anterior poliomyelitis. A third objection may be raised against this procedure in that all the nerves of the limb being divided, "trophic" troubles would be very liable to occur before union of the nerves took place.

I believe the so-called "trophic" ulcers are really due to absence of the sensation of pain in the part, as well as the absence for a considerable time of regeneration of the vaso-motor nerves. The animal consequently does not trouble to rest the limb or protect it from injury. It is just as liable to occur after simple division and immediate suture of a nerve. I have a dog at present whose left sciatic nerve was divided and at once joined. An ulcer formed which led to loss of one of the toes, but the ulcer has now healed up and the leg recovered its function. After dividing the nerves in man such troubles could be prevented by avoiding prolonged pressure on any part of the limb. In infantile paralysis sensation is unaltered, so the purely sensory nerves need not be divided at all—for example, the external popliteal of the nerve in man gives off the nervus communicans fibularis, and the internal popliteal the communicans tibialis. These two join to form the external saphenous nerve, which gives sensation to a large part of the foot. These two communicantes nerves can easily be left. Sometimes they arise too low down in the space to allow of the external being brought into contact with the internal popliteal. In this case the fasciculus can be separated some distance up from the main trunks, and thus allow the latter to be drawn aside. In the same way, if only the peronei muscles were affected, it would probably be unwise to cut across the external popliteal nerve. If this nerve be followed to the

neck of the fibula it will be found to divide, and the nerve supplying the flexors of the ankle can be separated from the musculo-cutaneous right up to the popliteal space, by merely splitting the external popliteal. In this case it would be preferable to suture the separated musculo-cutaneous to the large internal popliteal rather than to the small anterior tibial. By these means a good many nerves can be preserved intact, and this, combined with proper care, should prevent any troublesome pressure sores and "trophic" ulcers. Contrasting this procedure with Nicoladoni's operation, it may be said that it would probably be an improvement on it in some cases. Nerve crossing would restore some of the power in the paralysed muscles, while tendon implantation merely utilizes the tendons of insertion of the useless muscle to which portions of vigorous and healthy muscles are sutured. At the same time, it must be acknowledged that no possible benefit could accrue by nerve crossing in long-standing paralysis; here the muscle fibres have atrophied and disappeared, and are beyond the stage of regeneration, when nerve stimuli are re-established.

I have not had an opportunity of trying this operation in a living subject, but it is easy to perform on the cadaver. A slightly curved incision is made in the centre of the popliteal space, and a very short flap of skin and subcutaneous tissue raised. Immediately under the strong deep fascia the popliteal nerves are met. If the external popliteal be the one whose motor cells are destroyed, it is cut completely across after splitting off the sensory nervus communicans fibularis and tibialis. The internal popliteal is cut, and the two peripheral ends sutured to the central end of the internal popliteal. At the same time, the central end of the external popliteal should be sutured to the junction to utilize any remaining fibres it may contain. Catgut or tendon sutures which are absorbed, and leave little scar tissue, should be used. These should take hold principally of the nerve sheath, so as to avoid breaking up the nerve fibres.

SUMMARY.

1. It is possible to functionate two opposing groups of muscles by a single nerve, which previously supplied one group only; or, to put it in another way, it is possible to innervate fairly completely muscles with a much smaller number of motor horn cells than usually bring about this effect.

2. When the central end of one nerve is joined to the peripheral ends of two nerves there are many more fibres in the peripheral nerves than in the central nerves, so that the nerve fibres in the proximal trunk divide on going to the distal trunks.

3. In some cases at least some of the branches from one nerve fibre go to supply one set, and others the opposing set of muscles. This may prevent very delicate movement being restored.

4. After this form of suturing the arrangement of the nerve-fasciculi in the peripheral nerves is considerably altered.

Though these experiments are incomplete, as they have not been performed on the human subject, I think sufficient has been done to justify the clinical trial of the method. It seems it would be likely to improve some of those distressing cases of infantile paralysis for which so little can at present be done. It may be applicable, too, in some injuries with loss of some of the length of the nerves, tumours of nerves, etc.

In conclusion, I should like to express my thanks to Professors Osborne and Martin for the help in this work, and also Mr. Mattheson, who assisted me in most of the operations.

REFERENCES.

- ¹ *Recherches Expérimentales sur les Propriétés et les Fonctions du Système Nerveux dans les Animaux Vertébrés.* ² Müller's *Elements of Physiology*, vol. 1, 1838. ³ F. Bidder: *Versuche über die Möglichkeit des Zusammenwachsens funktionell Verschiedenen Nervenfasern.* Gluge et A. Thierssen: *Bulletins de l'Académie Royale de Belgique*, vol. 7. ⁴ *Über das Zusammenwachsen der Nerven verschiedener Bestimmungen und verschiedener Funktionen.* ⁵ *Proceedings of the Royal Society*, vol. 62. ⁶ *Journal of Phys.*, vol. 23, No. 3. ⁷ *Archiv für Anat. und Physiol.*, 1886. ⁸ *Amer. Jour. of Phys.*, vol. 1, 1898. ⁹ *Restoration of Co-ordinated Movements after Nerve Crossing with Interchange of Function of Cerebral Cortical Centres.* ¹⁰ *Gazette des Hôpitaux*, Mars 8th, 1898. ¹¹ *Traité de Chirurgie de la Paralyse Faciale d'Origine Traumatique*, 1901. ¹² *Gaz. Hebdomad.*, 1876. ¹³ *Bruns. Beiträge zur klin. Chirurgie*, Bd. xv. ¹⁴ *Journal of Phys.*, vol. 31, No. 5. ¹⁵ Ballance and Purves Stewart: *Healing of Nerves*, 1901. ¹⁶ *Autogenetic Regeneration of Nerves.* *Journal of Phys.*, vol. 31, No. 5. ¹⁷ *Journal of Phys.*, vol. 29, *Lancet*, July 26th, 1902.

MR. FRANCIS J. LOVEDAY, M.R.C.S., L.R.C.P., has been elected People's Churchwarden of St. Barnabas' Church, Pimlico, for the ensuing year.