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SURGICAL PROBLEMS IN THE RECONSTRUCTION OF PERIPHERAL NERVE INJURIES *

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IN SO FAR as concerns the injured of the American Expeditionary Forces, the surgical treatment of peripheral nerve injuries did not begin, with few exceptions, until the soldier became a patient in one of the General Hospitals on this side of the Atlantic. That the management of peripheral nerve injuries was a problem distinct from other surgical problems was recognized by the Surgeon General by the following: Under his direction twelve hospitals were designated as peripheral nerve centres to which all patients with these lesions were ordered transferred from the ports of debarkation. To each of these centres was assigned an officer, experienced in neurological surgery, and a consulting neurologist, and for each, a uniform equipment for the examination and treatment of nerve injuries was provided. As further evidence of the importance of the peripheral nerve problem, the Surgeon General appointed a Consultant in neuro-surgery and a Peripheral Nerve Commission.

In order that the results of the examinations, the methods of recording the clinical findings, and the clinical records themselves should be as nearly uniform as possible, æsthesiometers were designed for the various centres with which to test sensory disturbances and to record them in terms of grammes, and a special Peripheral Nerve Register was prepared and distributed with instructions as to how the various clinical findings should be recorded. With this preparation, the Peripheral Nerve Commission will be provided with the records of all peripheral nerve cases, which, from the standpoint of uniformity and completeness, should be as nearly perfect as is possible under the widely variant conditions in the different hospitals. While many examinations by competent neurologists were made on the other side, with few exceptions none of the records accompanied the patient to his destination on this side.

Up to the present time it is estimated that there are over three thousand peripheral nerve cases in the peripheral nerve centres. Of this

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number, the largest collection, 550, has been admitted to General Hospital No. 11, which has been my headquarters, and my remarks on the surgical treatment will be based on my experience with this group. Of this number up to date 275 have been discharged, as recovered, to convalescent centres, 75 have already begun to recover function spontaneously, 150 have been or will be operated upon, and the remainder are under observation.

At the Second Annual Meeting of the Inter-Allied Conference, held in London, May 20, 1918, Professor G. Verga presented a report of 1000 cases in which only 160, or 16 per cent., had been operated upon. Comparative statistics are not of much value, since there may be wide variation in the character of cases in different centres, but I should regard 25 to 30 per cent. as a reasonably conservative estimate of the proportion of cases in which operation is justifiable.

Only to those who have been burdened with the responsibility of conducting a peripheral nerve clinic will the magnitude and multiplicity of problems present themselves in their true proportion. The technic of examinations, the proper interpretation of the clinical findings, their proper evaluation, the decision for or against operation, the direction of treatment during the period of observation or recovery, apart from the difficulties of the operations themselves, these are all matters requiring time, experience and judgment.

It would not be possible in the allotted time even to mention many phases of scientific and practical interest, the peculiar sensory and motor phenomena in relation to partial and complete lesions and to recovery, the consideration of muscle tone and Tinel's sign, the trophic disturbances, the pathology of peripheral nerve lesions and the question of regeneration, so that I will restrict my discussion to those matters which relate solely to the surgical problems involved.

The first question for consideration is the time of operation. How long should one wait for evidence of spontaneous recovery? It has been my practice to wait at least until three months have elapsed from the date when the wound was healed, and in most instances, by observing this general rule, it is found that at least six months have passed since the injury was sustained. If at this time there are no signs of spontaneous recovery, on the one hand, and there is substantial evidence of a complete nerve interruption, whether or not this is interpreted as an anatomical division or a central neuroma, there are no grounds for further delay. One must not be deceived by the action of supplemental muscles which may compensate for the paralyzed muscle, as in one instance I recall when the ward surgeon reported to me six months after the injury that a patient with a complete median and ulnar paralysis could flex the wrist, and asked to have the operation postponed. An examination revealed the fact that the patient had learned how to flex the wrist with the short extensors of the thumb.

PERIPHERAL NERVE INJURIES

Assuming, however, that the wound heals promptly, as in wounds from machine-gun bullets, should an operation be advised, no matter how early, providing there is evidence of a complete nerve block? Captain Alexander, at the Alder Hey Military Hospital, Liverpool, maintained that cases sutured within four months of the injury do not do as well as those sutured after the sixth month, probably because degeneration was not complete in the peripheral segment. Whether this be true or not, the mere fact that many cases do not show signs of spontaneous degeneration until about the sixth month, is, I believe, sufficient justification for deferring the operation at least that long. I am quite aware of the fact that the results of primary suture are better than those of delayed suture, *ergo*, the sooner the operation, the better, but I also know that it is quite impossible to distinguish with absolute certainty by any single clinical sign or syndrome between a complete but transitory physiological block and a complete anatomical division. If the general dictum, as advocated by some, were observed, namely, to operate as soon as the wound permits, with evidence of complete physiological division, many a case would be explored which eventually would have recovered spontaneously, and resection and suture would not only have postponed the time of eventual recovery, but might have been totally unsuccessful.

As to matters purely technical, certain general principles should be observed. The tourniquet should not be used routinely, but in the exceptional case with massive cicatrization of the tissues, much time may be saved in the preliminary dissection if hemorrhage is controlled with a tourniquet. This should be removed before resection or suture; in the interval all bleeding is controlled. Liberal incisions are essential, as the nerve must be exposed and often liberated far above and below the lesion. Traumatism to the healthy portion of the nerve is to be avoided, and to this end I have found it advantageous to operate under a constant spray of saline solution, which keeps the field clear, and if sponging be necessary, use small, moist, cotton pledgets. The preliminary dissection is the most tedious of surgical procedures. It may be carried out with a small, sharp scalpel, or, as I prefer, when the nerve is embedded in scar tissue, with small curved eye tenotomy scissors and fine fixation forceps. Unless one begins well above and below the lesion, the identification of the different nerve trunks, from one another or from thrombosed vessels, particularly in the upper third of the arm, may be quite impossible. Only with continuous scrutiny will one avoid severance of important rami.

While the preliminary dissection or disentanglement of the lesion is tedious and time-consuming, it is the choice of procedure and the method of dealing with the lesion where experience and judgment count. This brings me to the consideration of the various operative procedures, neurolysis or liberation, resection and suture, and the various suggestions for dealing with large defects.

As the least complicated, neurolysis will first be considered. In proportion to the total number of operations, we have performed a neurolysis in 20 per cent. The figures correspond to the experience of other clinics, although in some, as in a series recorded by Verga, there were 80 neurolyses in 160 operations, or 50 per cent., and in the series of Delangi re (*Bull. et Mem. Soc. de Chir. de Paris*, 1918, xliv, 522) there were 113 liberations in 245 operations. It is not always easy to make a decision in favor of neurolysis as against suture. When there is a constricting band, with grooving of the nerve, or when there is compression and a narrowing of the lumen over a greater distance, when there is evident pressure from callus, a spicule of bone or aneurism, there admits of little doubt. Neurolysis is clearly indicated (and one should always give the nerve the benefit of the doubt) when it responds promptly to faradic stimulation. But in a number of cases, and I have often found this the case with the musculospiral, in addition to compression from external causes, there is an associated sclerosis or fibrosis of the nerve, which of itself may inhibit regeneration.

It has become almost a routine practice to recommend resection and suture in the presence of a spindle-shaped neuroma. However, bearing in mind clearly the pathology of the neuroma, it must be acknowledged that the neuroma *per se* is not an absolute barrier to the growth of neuraxes. It represents, to be sure, an effort by Nature towards regeneration against difficulties, but not always ineffectually. The development of a neuroma in cases undergoing spontaneous recovery is not uncommon, and it is not infrequent after suture or transplantation. Huber found in a neuroma, resected in this clinic from the sciatic nerve, such an active growth of neuraxes that he considered spontaneous recovery in this instance would not have been out of the question. If the presence of a neuroma cannot be the indisputable criterion, the final decision must rest upon the time which has elapsed between the injury and the operation and upon whether the nerve responds to faradism. The decision will in all cases be more or less arbitrary. If there are signs of total loss of function at the expiration of six months, resection and suture are justifiable. Joyce (*British Journal of Surgery*, vol. xx, No. 23, 1918) takes exception to this recommendation; the resection of a spindle-shaped neuroma is not justifiable, he says, unless failure has resulted from a neurolysis capsulectomy at which the thickened portion of the sheath has been removed. In this conclusion I cannot concur.

The technic of neurolysis should include the freedom of the nerve from the cause of compression, the cicatricial band or the more extensive scar tissue, dissecting the nerve free from the callus in which it is engaged, such as one often finds in musculospiral palsies. We sometimes find massive fibrous infiltrations of the sheath itself, and an attempt should be made to remove as much of this thickened portion of the sheath as possible, but not to the point of laying bare the fasciculi. In the reconstruc-

PERIPHERAL NERVE INJURIES

tion of the wound, the ideal and natural bed is an intermuscular plane or a plane between a muscle sheath and the deep fascia. To surround the nerve with flaps taken from adjacent muscles is not good surgery, since the reparative process in the healing of the muscle wound is attended with such cicatrization as of itself to threaten compression of the nerve. At least, this is the conclusion to which I have been led from observations I have made at secondary operations. I believe it entirely justifiable, too, in selected cases, and I refer to those of massive cicatrization in the arm, to transfer the nerve to a plane between the deep and superficial fascia; by this procedure the nerve is totally isolated from a field of connective tissue, which may inhibit the reparative process.

The great problem of peripheral nerve surgery is that involved in resection and the bridging of defects. The bringing into apposition of the divided segments with appropriate sutures is a matter of minor consideration if one observes certain accepted principles of nerve suture, but in gunshot wounds resection is a matter of necessity and to such an extent usually that approximation cannot be effected without resort to one method or another of bridging the defect. These methods now to be reviewed include posture, nerve stretching, nerve flaps, suture à distance, tubulization, lateral anastomosis, implantation-suture, transposition; some of these may, I think, be discarded with a few words, because, whatever evidence there may be from the experimental laboratory, the clinical evidence does not justify their adoption as acceptable procedures.

The so-called *flap-operation* as proposed by Letievant is not deserving of consideration, since, when the central and peripheral flaps are reflected, the ends of the respective flaps would not be in alignment and this would interfere with the down growth of neuraxes. The modification of this flap operation in which a flap is taken from a healthy nerve is objectionable chiefly because it involves sacrificing a portion of a normal nerve. The operation would be practicable only when two large trunks were in proximity, as in the upper arm. But one would hesitate in a case of ulnar paralysis, where the disability will often not affect deleteriously the patient's earning capacity, to sacrifice either the median or musculospiral.

As Huber says, *suture à distance* is more of academic than practical interest. In his laboratory experiments, success was attained in two out of three instances by interposing bundles of coarse catgut between the divided ends, but I know of no successful attempts in human surgery.

Tubulization, as a means of bridging defects, has been used extensively both in the laboratory and in the clinic, but there have been so many clinical failures that I have scrupulously avoided it. With Prussian pertinacity the Germans clung to this method in the early stages of the war. The so-called Edinger's tube, the formalized calf artery, was repeatedly employed, sometimes filled with blood serum, sometimes with agar-agar, but always, and I have seen the reports of 100 cases, with failure. Not only was there no evidence of regeneration, but on later

examination the gap had increased and bulbous formations were found on either end of the divided nerve.

In this connection a word may be said as to the use of protective sheaths both in neurolysis and nerve suture. I have refrained from any protection to the liberated or sutured nerve with fascia, fat, calf arteries or any other material, since there is every reason to believe that devitalized tissues, such as the foregoing, will stimulate connective tissue formation and thus militate against, rather than facilitate, nerve regeneration at the line of suture. A pedicle flap of muscle, fascia, or fat might overcome the objection to the use of these so-called protectives, but it has been my belief that the nerve sheath itself, if carefully approximated with suturés, offers adequate protection from the invasion of connective tissue.

Lateral anastomosis, as practiced by Hofmeister (*Beiträge zur Klin. Chir.*, 1915, 96, 329), has no merit whatsoever. In his report, which contained the notes of 24 operations, the results of the operations were not included. It is merely assumed that a neighboring healthy nerve serves as a favorable and convenient medium for the down-growth of neuraxes. If the terms lateral anastomosis and lateral implantation are synonymous, I quite agree with the wholesale condemnation this method has received; Tinel speaks of it as always useless and often mischievous; Moynihan, as to be sharply condemned, and Benisty, as illogical.

In order to avoid confusion, we must, I think, coin another term for an operation, similar to lateral anastomosis, in that the central or peripheral stump alone or combined are sutured into an adjacent nerve, but differing in this essential respect, namely, that a portion of this adjacent nerve is sacrificed. This is virtually a nerve suture and the term I would suggest as appropriate would be "implantation-suture."

I believe this operation has a field, limited though it may be, chiefly in the arm with large defects in the ulnar or musculospiral, not only because a healthy nerve is accessible, but because certain portions of the median may be sacrificed with only slight and transitory sensory loss. While on physiological and anatomical grounds I have regarded this so-called implantation-suture as justifiable in selected cases, I have not yet had a case in my clinic for which I thought it was appropriate. But looking over the literature, I found several instances in which it had been practiced with success. Thus in one of Joyce's cases, an ulnar lesion (*British Journal of Surgery*, January, 1919, p. 426), while almost one-third of the circumference of the median nerve had been sacrificed, the sensory loss was entirely recovered in course of time, and in twenty-four months there was partial sensory and motor recovery in the ulnar area. Souttar (*British Journal of Surgery*, October, 1918) employed the method in two cases (Case 54 and Case 56); in one, he implanted the lower segment of the musculospiral nerve which was attached to the centre of the front of the median, the fibres of which were divided. Ten

PERIPHERAL NERVE INJURIES

months later there was faradic response in the extensors of the wrist. In the second case there was strong synergic action of the extensors of the wrist twelve months after the operation. It was noteworthy that Joyce cut the inner third of the median nerve and Souttar the external anterior fibres, and in both instances there was only transitory sensory disturbance.

On two occasions, one with a defect in two nerves, another with a defect in three, I have resected five centimetres of the humerus. This is a radical procedure and should be a court of last resort. When practiced, the operation should be divided into two stages, at the first liberating the nerves and resecting the humerus. This necessitates an incision on both the inner and outer aspects of the arm and after connecting the neuromata of the several nerves with strands of silk for later identification the wounds are closed, and the second stage is not undertaken until one is assured of uncomplicated wound repair. In one of the two cases, because of the time required at the first sitting in disentangling the injured nerves, the ulnar, median and internal cutaneous, the bone was not resected until a second sitting and the nerve finally sutured at a third.

The susceptibility of nerve trunks to stretching offers a valuable auxiliary measure for dealing with defects. Weir Mitchell in his classical monograph called attention to the tolerance of nerves to forcible stretching, and we know that, without the risk of rupturing its fibres, two to four centimetres of a defect may readily be made up. Nerve stretching with posture will often suffice to secure apposition in a defect of 7 to 8 cm. There are two ways of stretching the nerve. One as just described in the course of the operation, the other over a more extended period. The latter will be called for only in exceptional instances, and I do it in this way: If, after the nerve is liberated, it is evident that the defect cannot be bridged except with a graft, I pass heavy silk sutures through the bulbs and draw them as closely together as possible with the forearm or leg flexed. During the succeeding four weeks the limb is gradually brought into a position of extension and by this process the nerve is stretched. At a second operation, by bringing the limb again into flexion, approximation of the segments after resection is possible. This technic is particularly serviceable for injuries of the arm where two or more nerves are involved.

Nerve transposition as an aid to bridging defects is most helpful and is applicable to the ulnar and musculospiral, the former more frequently than the latter. The course of the musculospiral I have shortened by passing the peripheral segment between the biceps and brachial anticus and uniting it with the central segment on the inner aspect of the arm. The ulnar is isolated from its normal location and transposed to the flexor aspect of the forearm. I can see no advantage in following Stiles' recommendation to tunnel beneath the pronator radii teres and there are many disadvantages. In the first place, the deeper course is the longer when the forearm is in flexion, as it usually is when the nerve is sutured,

CHARLES H. FRAZIER

and secondly, the branches to the flexor carpi ulnaris and flexor profundus digitorum are sacrificed. These rami may both be conserved providing one slits them up as far as may be necessary beyond the point at which they join the parent trunk. Even though it may be more important to restore function to the intrinsic muscles of the hand, it need not be done at the expense of the ulnar flexor supply. The third situation in which transposition may be of service is the knee. Here in large defects of the external popliteal the distance from the bifurcation of the sciatic to the head of the fibula may be shortened by transposing the nerve to a plane superficial to the ham-string tendon with the limb in flexion.

With large defects advantage must unquestionably be taken of favorable positions to secure apposition without tension, such as flexion of the forearm or knee, adduction of the arm, inclination of the head toward the affected side.

As a last resort only should one resort to a transplant, not that there is not enough clinical evidence at hand to warrant the procedure, but the percentage of successful sutures is greater with direct suture than with the graft. In dealing with 150 nerve lesions at General Hospital No. 11, we have used a graft to repair the defect on seven occasions, as follows:

1	musculospiral	.....defect	7 cm.....	Transplant; musculocutaneous (leg)
1	brachial plexus	.....defect	7 cm.....	Transplant; musculocutaneous (leg)
1	ulnar	.....defect	5 cm.....	} Transplant; musculocutaneous (leg) } Transplant; dorsal branch of ulnar
1	ulnar	.....defect	14 cm.....	
1	external popliteal	.....defect	8 cm.....	Transplant; musculocutaneous (leg)
1	median	.....defect	8 cm.....	Transplant; musculocutaneous (leg)
1	brachial plexus	.....defect	5 cm.....	Transplant; musculocutaneous (leg)

It is too soon to report ultimate results, but in two of the seven there is already evidence of regeneration. In a brachial plexus lesion the fifth cervical nerve was replaced with a transplant of 7 cm. from the musculocutaneous of the leg and already there is a faradic response in the deltoid muscle. In a second case, a 5 cm. defect from the level of the wrist and upwards, there is tingling on pressure over the graft, 3 cm. below the upper line of suture. In every instance an auto-graft has been used and usually the musculocutaneous, although according to one's convenience, the sural, the radial, or, with a defect in the nerves above the elbow, the internal cutaneous may be used. Two to four cables, according to the size of the nerve, should be used, and the sutures should be introduced in either end of the transplant at the proper interval before it is severed from its connection. According to Huber, whose investigations during the past two years have been most illuminating, the fascial cuff should not be used and we have observed this injunction. Huber believes the auto-transplant should always be given preference, but in a recent communication he writes that he has obtained favorable results with homo-transplants stored in vaseline and in liquid

PERIPHERAL NERVE INJURIES

petrolatum. In his experiments with homo-transplants, stored in 50 per cent. alcohol, the neuraxes have grown 3 cm. into the distal segment.

In reckoning how much of the nerve is to be resected, as many fasciculi as possible should be spared. By palpation, inspection, and with the clinical notes, one can determine whether the entire trunk or but a part need be sacrificed, but when in doubt electrical excitation is helpful, stimulating first the various aspects of the nerve through the sheath and, if still in doubt, after the sheath has been opened. By this means I have been able to conserve healthy fasciculi which otherwise would have been sacrificed.

For the ultimate success of suture, the most essential factor is the presence of healthy fasciculi, free from the grasp of cicatricial tissue. Granted this, the prognosis may be good in spite of a clumsy suture. One is always tempted to keep the defect within reasonable limits, fearing the difficulty in securing apposition. But if after the preliminary sections, distal and central, the cut section does not present healthy fasciculi without scar tissue, slice after slice should be removed until the desired picture is obtained. One soon learns to recognize these conditions; when, upon section, the ends of the fasciculi project a little beyond the cut surface, one is reasonably sure that the section has been made above and below the invasion of scar tissue. *Per contra*, if the cut section is smooth, and the fasciculi do not project, it is because they are engaged in scar tissue and a higher or lower level must be inspected. Successive sections should not be made at greater intervals than 2.5 mm., since at this distance the whole picture may change. I have found a safety-razor blade preferable to either a scalpel or ordinary razor blade. The sheath of the nerve must be grasped on either side to steady the nerve while the section is being made.

One tension suture of chromic catgut, through the entire thickness of the nerve, one centimetre from the free end, with four to eight epineural sutures of the finest silk, suffices to keep the sheath in apposition. The tension suture should not be tied until the epineural sutures are in place and then just fast enough to bring the fasciculi in contact; if too tight, the fasciculi will be crushed, if too loose, a blood clot may form in the interspace. Second in importance only to the necessity of securing a healthy segment for suture is the avoidance of undue tension. Every resource must be availed of to enable one to bring the segments into apposition without undue tension.

We have dealt in but fragmentary fashion with the problems of nerve reconstruction. There are many minor points in technic, as affecting individual nerves, that are deserving of consideration. Enough has been said, however, to emphasize the complexity of the problem and the important part played by judgment and experience. Nothing has been said of tendon transplantation for those cases in which nerve suture has failed or is difficult, or where spontaneous regeneration has been arrested. The

CHARLES H. FRAZIER

two situations in which tendon transplantation is particularly adaptable are (1) in the residual paralysis of the extensor longus digitorum, when the patient has recovered full power in all the muscles supplied by the musculospiral, with the exception of the common extensors to the fingers; and (2) in the residual paralysis of the anterior tibial with foot-drop. Tendon transplantation should be resorted to in both these lesions and no patient should be discharged until an attempt has been made in this way to supplement the paralyzed muscle.

The after-treatment is a matter of vital consideration; massage, galvanism and later faradism, properly selected exercises, these must be continued faithfully and persistently until voluntary movement has returned. Secondary operations in some instances will be inevitable.

The Surgeon General has given every consideration to this branch of reconstructive surgery. Within two months practically all cases requiring surgical treatment will have been operated upon. Recovery of function is a slow process and it remains to be determined how long after the operation the patients will be retained in government hospitals.

The final chapter of peripheral nerve surgery cannot be written until two years hence, at least, so far as concerns the wounded of the American forces. The final test of superiority claimed for one method or another must be based upon the end results. As one of the most important functions, it remains for the Peripheral Nerve Commission, acting under the direction of the Surgeon General, to follow up all cases that have or will be discharged from the General Hospitals and prepare a final report based upon the end results.