PERIPHERAL NERVE SURGERY—TECHNICAL CONSIDERATIONS*

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IT IS ESTIMATED that 70 per cent of all battle casualties suffer from extremity wounds. It is further estimated that 15 per cent of the extremity wounds (i.e., 10.5 per cent of all casualties) are complicated by injuries to large nerve trunks. Peripheral nerve surgery, therefore, in point of numbers, is the most important military neurosurgical problem.

Every soldier with a serious injury to one of the major nerves is unfit for active combat duty for several months, and in many instances, forever. When anatomical continuity is disrupted, regeneration, under the most favorable circumstances, progresses at not more than 2 inches each month. As an example, a sciatic nerve, severed in the midthigh, requires a minimum of 15 months for regeneration of fibers to their distant terminations. After anatomical restoration of the nerves, comes the long period of reeducation and strengthening of muscles so necessary to full functional activity. Deformities can be prevented by properly applied braces, and, in many instances, the patient can do productive work during the convalescent period. However, care of the paralyzed muscles complicates the problem. It is useless to have nearly perfect regeneration of nerve fibers if the muscles are allowed to atrophy and fibrose so they are no longer capable of responding to motor stimuli. If soldiers with nerve injuries are to be salvaged for further military service and from veteran pension lists of the future, they must receive prolonged expert care under favorable conditions.

Since most nerve casualties will not be fit for combat duty again, the Army had three choices for their disposition: First, give them the best possible surgical repair of the lesion and then discharge them to veteran facilities for care. Second, keep them in Army hospitals under continuous physical and occupational therapy until maximum recovery has been achieved. Third, teach them the principles of physical therapy, especially the care of their muscles and joints, fit them with proper splints and appliances to prevent deformity, return them to a duty status commensurate with their disability, and require them to return for observation to the hospitals where they received surgical treatment at regular intervals not exceeding 90 days.

The Surgeon General of the United States Army, after careful consideration, has elected to pursue the third course. It is still too early to be sure of the wisdom of the decision. From the patient's point of view, it is the best

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solution, for it restores him to a productive status without seriously jeopardizing the perfection of his recovery.

GENERAL PRINCIPLES OF NERVE REPAIR

*The Wound.* Experience in our own Army, as well as in the Armies of our Allies, indicates that battle wounds should not be closed primarily even though débridement can be accomplished under favorable conditions. As a result of this policy, many peripheral nerve casualties arrive in the zone of the interior with open granulating wounds—most of them mildly infected. Before the days of chemotherapy, it was considered the best surgical practice to wait at least 3 months after healing before performing elective operations.

During this war considerable modification of these practices had slowly evolved. Now at the Walter Reed General Hospital, the mildly infected wound is closed by secondary suture as soon as the granulating surface is reasonably clean—sometimes a few days after admission. Two weeks after secondary suture, if healing has been satisfactory, repair of the nerve is attempted keeping the new incision as far removed as possible from the recently infected field. This practice is making possible repair of severed nerves earlier than ever attempted before in war time.

*Chemotherapy.* Sulfadiazine in sufficient amounts to produce a blood level of approximately 5 mgms. per cent is given to all patients with recently infected wounds for 48 hours prior to operation. This level is maintained for a minimum of 10 days postoperative. The operative wound is frosted lightly with sulfanilamide crystals, care being taken to prevent an accumulation of crystals around the nerve trunks. Not more than 5 grams of sulfanilamide are used in any case.

*Condition of Joints.* In all cases where end-to-end suture is contemplated, it is desirable to have complete mobility of contiguous joints, for it is only by positioning them that extensive defects can be overcome. A high percentage of extremity wounds with nerve injuries have also bone and joint injuries and, in most instances, casts will have been applied. A favorable position for the injured joint or bone may be an unfavorable one for nerve repair; therefore, before operation is attempted, joint mobilization by all means available should be undertaken.

*Hemostasis.* Careful hemostasis is especially important in peripheral nerve surgery. A wet field with the inevitable swelling that accompanies it is incompatible with consistently good results. It should be unnecessary to state that a tourniquet is seldom necessary or justifiable in operations upon peripheral nerves unless there is an associated lesion of one of the major blood vessels.

*Freedom from Tension.* When large gaps are to be overcome, excessive tension at the suture line is by far the most difficult problem; yet, to compromise with this principle means inevitable failure. Freedom from tension in many cases can be accomplished only by extensive dissection of the prox-
mal and distal ends of the severed nerve and by positioning contiguous joints
to shorten the course of the nerve. In other cases, transplantation of the
nerve may be necessary. In most major nerve trunks, gaps of from 3 to 4
inches can be overcome by correct dissection, transplantation and joint posi-
tioning and still leave the anastomosis free of tension.

When motor branches must be sacrificed in order to relieve tension, due
consideration should be given to the handicap produced and the possibility
of combating it at a later date by appropriate tendon surgery.

Electrical Stimulation of the Exposed Nerves. Electrical stimulation of the
exposed nerve trunk is valuable in determining its anatomical continuity.
Galvanic, faradic or sinusoidal current provides a satisfactory stimulus. The
minimal current is that which will produce a visible contracture of muscle
fibers when the electrodes are applied directly to them. The current should
be increased 4 or 5 times above this minimal level before deciding that there
are no functioning fibers passing through the involved segment.

If stimulation proximal to the scarred area causes contraction of muscles
normally innervated by the nerve distal to the scar, it may be assumed that
there is still anatomical and physiological continuity of the motor fibers.

If stimulation of the nerve proximal to the scar fails to elicit motor re-
sponses even with five times the minimal stimulus, it may be assumed that
anatomical continuity is lost, providing the nerve has been liberated from its
extrinsic scar prior to the test.

If the operation is conducted under local anesthesia and no procaine has
been infiltrated into the proximal segment of nerve, information of great
value can be obtained from the sensory responses. Stimulation of the scar or
neuroma is always painful, more so than stimulation of normal nerve above
the scar. Stimulation distal to the scar without sensory response indicates
disruption of the afferent fibers unless the amount of current is excessive and
overflows into the neuroma.

Sensory responses to electrical stimulation are valuable in cases of re-explora-
tion after suture. Not infrequently, physiologically active sensory fibers
can be demonstrated traversing the suture line before any motor fibers have
reached their appropriate end-plates.

The Anesthetic. Infiltration procaine anesthesia is the method most com-
monly used at the Walter Reed General Hospital in the peripheral nerve
cases. Where there have been extensive wounds with dense, widespread scar
formation, local infiltration anesthesia may not be completely satisfactory.
In these circumstances, either inhalation ether or continuous spinal anesthe-
sia is used.

Indications for Exploration. Preoperative clinical and laboratory studies
of motor, sensory and vasomotor functions will indicate usually the degree
of physiological disruption of a peripheral nerve. However, there can be
complete physiological loss of function without anatomical severance of the
nerve. This fact explains the frequency with which injured peripheral nerves
regenerate spontaneously. Because of the likelihood of spontaneous regene-
ration, some surgeons have recommended a waiting period of from 6 to 9 months before advising exploratory operations. However, most recent investigators believe that the degenerative changes which inevitably occur in the denervated muscles are progressive and that the best results are obtained in those cases where repair is accomplished early, therefore waiting for spontaneous regeneration is unjustifiable.

The policy presently followed in this clinic is to explore all cases of peripheral nerve palsies, complete or incomplete, unless there has been rapid, progressive improvement of symptoms. If the nerve has been severed, valuable time has been saved by early repair. If the nerve is anatomically intact, freeing it from the surrounding scar tissue will usually hasten recovery, and seldom retard it. It is believed that exploration of any major nerve trunk under proper conditions can be accomplished without risk to life or to function.

The policy of radical exploration, however, should always be combined with one of conservative treatment once the nerve is exposed. Unless actual anatomical division can be demonstrated, or unless the intrinsic scar is so dense that no motor or sensory impulses can be demonstrated to pass through the scar, only complete neurolysis should be done. Clinical experience and laboratory experiments have shown that regeneration through a crushed segment of nerve is often more nearly complete than can be obtained by end-to-end suture. If a nerve thus treated fails to show evidence of regeneration within 2 months, re-exploration is done, and if there are still no sensory impulses passing through the scarred area, resection with end-to-end suture is undertaken.

All cases of suture—or neurolysis for that matter—should be observed carefully week by week for evidence of new functional activity. If at any time satisfactory progress seems to have stopped, re-exploration should be recommended.

The value of the Tinel's sign in diagnosis has been discredited by many observers because of the frequency with which percussion impulses can be transmitted through scarred soft tissue to a distant neuroma. If the percussing stroke is heavy no doubt the jarring will invalidate it. The sign should be elicited by very gentle tapping with the finger tips along the course of the nerve, always working from below the lesion upward. At the point where tingling in the peripheral distribution is produced, functioning sensory fibers are believed to be present. The Tinel's sign when performed properly is a valuable one, especially in following the progress of regeneration after suture.

**OPERATIVE TREATMENT**

*The Acute Lesion.* The following quotation from a recent directive to all military surgeons from the Surgeon General's Office gives the present status of treatment of acute nerve injuries in the Army:

Primary nerve suture should be done when the nerve-ends are readily accessible and can be approximated without tension. If this is not possible, and the injured nerve-ends are
identified, a sling suture of fine stainless steel wire should be placed between them, or they should be anchored with similar suture material to the surrounding tissues in order to prevent retraction. The use of metal suture material here is desirable because it permits roentgenographic identification for subsequent repair. In view of the irreparable degenerative changes that occur in the end-plates of severed nerves, early repair of these nerves is absolutely essential. For this reason, it is of the utmost importance to evacuate these patients as soon as possible to the zone of the interior where operative repair and the necessary postoperative physical therapy can be instituted.

Probably the optimal time for the repair of a severed nerve is at the original débridement. Conditions of warfare make this impossible in the vast majority of instances. It is extremely important, however, that at the first débridement, the injured nerve be visualized and the anatomical situation with respect to it be noted on the record. Such information is invaluable to the surgeon who must undertake the repair at a later date.

Not infrequently, there is local contusion of the nerve trunk without actual severance, and in some cases an intrinsic hematoma forms at the site of contusion. Prompt evacuation of the hematoma through a slit in the perineurium in line with the nerve fibers may be followed by early restoration of function.

A recent dramatic example of such a lesion occurred at the Walter Reed General Hospital. The patient sustained severe contusions about the elbow in an automobile accident, and an immediate complete ulnar nerve palsy resulted. Exploration of the nerve 2 hours after injury demonstrated a large intrinsic hematoma. Immediately following evacuation of the clot, motor and sensory symptoms improved and within 24 hours, all functions had been restored to fully 50 per cent of normal. Had the hematoma not been evacuated, the nerve fibers might have been destroyed by pressure or by subsequent fibrosis within the perineurium.

The Subacute Lesion. Approximately 60 per cent of all peripheral nerve cases treated at this hospital also have bone or joint injuries. In those cases with compound fractures, appropriate treatment of the broken bone is of first importance. In those with extensive soft tissue loss, infection and the necessity for large pedicle skin grafts may delay the treatment of the nerve injury for several weeks or even months. Most of the cases, however, are ready for exploration 3 months after injury. Only rarely have operations been delayed longer than 6 months.

During the 12-month period, January 1, 1943 to January 1, 1944, there were 133 patients with peripheral nerve injuries operated upon by the neurosurgeons of the Walter Reed General Hospital. In this group there were 42 end-to-end sutures, 67 neurolyses with or without transplantation of the nerve, 5 nerve grafts (4 homogenous and 1 autogenous), 9 excisions of amputation neuromas and 10 explorations where no remedial pathological conditions were found.

The location of the injured nerves is interesting but perhaps not significant. The arm and shoulder were involved in 69 per cent and the lower extremity in 31 per cent of the cases.
The ulnar nerve was involved 39 times, the median 30 times and the radial but 15 times. This is in striking contrast to the statistics from the last war when all observers found the radial nerve to be more frequently injured than any other major nerve trunks.

In the lower extremity, common peroneal injuries predominated (16 cases), sciatic second (12 cases) and the posterior tibial third (11 cases).

In most penetrating wounds from missiles, particularly where there is a through-and-through wound, the resultant scar about the nerve binds it firmly to the muscles, fascia and bone. After the extrinsic scar has been dissected, the nerve may be found to be intact, even though the muscles in the distribution of the nerve are paralyzed. Sometimes the nerve is remarkably normal in appearance and to palpation, but more frequently it is harder than normal and the external surface is ragged. Electrical stimulation above and below the lesion provides valuable information in such cases and may clearly indicate whether or not the area should be resected and end-to-end suture attempted. If there is the slightest response to electrical stimulation, a conservative course has been followed, particularly if there is minimal intrinsic scarring without neuroma formation.

The practice of injecting normal saline solution into the nerve trunk above and below the lesion with the hope of separating and breaking up an intrinsic scar is a practice which is believed to be both futile and dangerous. The repeated introduction of a hypodermic needle destroys nerve fibers and often injures blood vessels. Furthermore, a scar sufficiently dense to strangulate nerve fibers cannot be destroyed by saline infiltration. Saline injection of the perineurium, however, may be a valuable aid in determining the limits of an intrinsic scar when resection is contemplated.

With both extrinsic and intrinsic scars, a dense firm perineurium is frequently encountered. This fibrous tissue sheath may actually constrict the nerve sufficiently to destroy function. Splitting the perineurium in line with the nerve fibers may have a decompressing effect, and when performed carefully is not harmful and may be of value.

Casts must be applied to all cases after end-to-end suture because the contiguous joints must be kept flexed to shorten the course of the nerve. Such casts are bivalved 24 to 48 hours after operation, or, in some instances, are applied and bivalved preoperatively. Immobilization of the joints is maintained strictly for 2 weeks, although gentle massage and heat are applied after the wound is healed, usually on the tenth postoperative day. Gradual extension of the joints is started after the second week, and full extension is completed by the fifth week.

The Technique of End-to-End Suture. For the past 15 months at the Walter Reed General Hospital, fine tantalum wire has been used to suture peripheral nerves, and the site of anastomosis has been wrapped in a cuff of tantalum foil. Extensive animal experimentations, as well as clinical observations, indicate that tantalum is, for all practical purposes, inert when buried in human tissue.\textsuperscript{11,12} Because of its inert qualities as well as its malle-
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ability and strength, it has become an important adjunct to peripheral nerve surgery. No other suture material, with the possible exception of human hair, is so free of adverse reactions.

The usual method of end-to-end repair of large nerves with only a series of sutures in the perineurium is open to certain criticisms. Correct apposition at the periphery of the union can be maintained, but the centrally placed tubular structures may separate, particularly if there is tension upon the loose tissues of the perineurium. A sling (traction) stitch placed through the center of the upper and lower trunks and tied with just enough tension so that the tubular structures meet, appears to be the answer to these criticisms (Fig. 1.A–E). The chief objection to the sling stitch in the past has been the inflammatory reaction occurring around the suture material. With fine tantalum wire this objection has been removed. When the sling stitch is tied, great care must be exercised so that the cuff surfaces of the proximal and distal stumps just touch each other. Too much tension on this stitch causes wrinkling of the tubes—too little leaves an undesirable dead space.

After the sling stitch is placed and tied, a series of fine interrupted sutures of .003 inch tantalum wire is placed in the perineurium. Tantalum wire sutures welded to fine curved needles are now available.

In making an end-to-end suture, it is desirable that no twisting of the proximal or distal trunks should occur. To prevent rotation an orientation suture should be placed in the perineurium above and below the lesion before dissection of the ends has been attempted.

To replace a carefully made nerve anastomosis into a bed of scar tissue has always been conceded to be undesirable. Surgeons have resorted to many materials—fat pads, fascial sheets, preserved membranes and excised segments of arteries and veins—in an effort to eliminate or diminish the extrinsic scar. Most of these materials have been abandoned because the resulting fibrosis was seldom diminished and often increased by the would-be protective substance. A cuff of thin tantalum foil (twelve ten-thousandths of an inch in thickness) wrapped around the nerve prevents scar tissue from infiltrating into the nerve trunk. It has been clearly demonstrated that a non-inflammatory membrane resembling peritoneum forms on either side of the tantalum foil. Also, movement within the cuff has been demonstrated in the human by measuring the position of the metallic sutures within the cuff on roentgenograms, after changing the position of the contiguous joints.

In applying the cuff, a number of precautions must be observed. First, the foil must be smooth and unbroken or fibrous tissue will grow through every little tear and fix the nerve firmly to the surrounding scar. The foil may be annealed by wrapping around an obturator, inserting the obturator with its covering of foil into the sheath and heating the whole assembly in a flame until the sheath just begins to glow. We have used a large ventricular needle with its stylet as an obturator for this purpose. Thus treated, the foil maintains a firm spring curl and is much easier to apply to the nerve without wrinkling. Second, the cuff is held in place by two circular ties of
Fig. 1-A. Line of incision used for exploration of axillary portion of brachial plexus. Note healed gunshot wound in anterior axillary fold.

Fig. 1-B. Brachial plexus exposed. Note dense scarring of plexus. The axillary artery had previously been ligated.
Fig. 1-C. Key explanatory sketch for Fig. 1-B.

Fig. 1-D. After resecting scar end-to-end sutures of the musculocutaneous and median nerves completed with sutures of fine tantalum wire. The sling stitch in the ulnar nerve has been placed.
00000 plain catgut. In the beginning, fine tantalum wire was used, but it was found undesirable because with the growth of fibers the cuff over the lower segment must be able to expand. The wire tie below the point of anastomosis was drawn too tightly in two cases and regeneration stopped at this point of construction and was resumed only after removing the wire tie.

The length of foil cuff is determined by the extent of the surrounding scar. On several occasions a cuff 4 inches in length has been used, although in most instances 2 inches will suffice.

It is very important that the central stump of the severed nerve should be trimmed until normal appearing nerve bundles appear. Likewise, the distal stump should be trimmed until well formed bundles of Schwann cell tubes are evident. There can be no compromise with these trimming procedures, for unless the anastomosis is made of tissue free of scar, the operation is doomed to failure.

Brisk bleeding from the stumps always occurs. It is best controlled by placing a hemostatic substance, either a bit of free muscle or a piece of human fibrinogen foam saturated with clotting thrombin, on the end of the nerve. These hemostatic substances must be removed before suture is attempted.

In many instances, it will be found necessary to transplant the ends of the severed nerve to a new anatomical environment in order that tension on
the suture line may be reduced. This is particularly true of the ulnar and radial nerves where transplantation is relatively simple and effectual.

Incomplete division of a nerve is not infrequently found. If the anatomically intact part contains functioning fibers then every effort should be made to save this part while repairing the divided part. It is often possible to separate the nerve into two parts by longitudinal dissection, making an end-to-end suture of the severed portion and leaving the intact portion coiled free in the tissues.

In certain cases where it is impossible to do a primary end-to-end suture without tension, the two-stage method may be effective. In the first stage, the neuroma and the pseudoneuroma are tied tightly together with .005 inch tantalum wire after the contiguous joints have been placed in extreme flexion. The extremity is immobilized in a cast, and after 2 weeks, gradual extension of the joints is started, thus automatically stretching the nerve. When full extension is reached, the wound is re-explored, the neuromas excised, and, again, tension relieved by flexing the joints, after which an end-to-end suture is performed in the usual manner. In most instances, this two-stage method is preferable to an immediate nerve graft, although there is considerable danger of widespread destruction of fibers in the central portion by over-stretching.\(^6,8,12\)

Nerve Grafting Procedures. Fortunately the number of cases of nerve injury with loss of tissue so extensive that end-to-end suture by one method or another is impossible, are relatively few. Yet, they do occur and some attempt to bridge the gap must be made. Some surgeons have recommended shortening the extremity by bone resections to permit end-to-end suture as a solution to the problem.\(^3\) However, there are relatively few injuries to major nerve trunks where such procedures are practical.

Recent experimental work\(^4,7,14,12\) indicates that in experimental animals autogenous nerve grafts of short length are not far inferior in results to end-to-end sutures. However, nerve grafting operations in humans have been most discouraging. This is particularly true of results reported from the last war.

The most brilliant clinical results of human nerve grafting have been achieved in the repair of the facial nerve and of the small nerves of the hand.\(^2\) Apparently, small nerves recover function much more completely after grafting than do the larger nerve trunks.

Autografts undoubtedly have given the best results, although homografts are not far inferior. It is always an easy matter to obtain autografts for small nerves, but to obtain an autograft for a large nerve trunk is seldom practical.

Alcohol or formalin fixed homografts have been tried repeatedly and some evidence has accumulated\(^9\) to indicate that there may be an occasional recovery. However, in the opinion of most observers, fixed grafts provide only a bridge for the growth of Schwann cell fibers, and the graft itself disappears by phagocytosis or becomes incorporated in scar tissue from the host.
Fig. 2-A. Area of soft tissue loss about the elbow repaired with pedicle skin graft. Note line of incision for nerve suture in relation to the skin graft.

Fig. 2-B. Drawing illustrating anatomical condition of ulnar and median nerves secondary to machine-gun fire.
FIG. 2-C. Key explanatory sketch for Fig. 2-B.

After resecting scarred nerves and neuromas gaps of three inches remained.

FIG. 2-D.
Fig. 2-E. Gaps in ulnar and median nerves repaired with homogenous grafts obtained from an amputation stump undergoing revision. Median nerve graft completed with tantalum foil cuffs in place. Ulnar nerve graft sutured and cuffs will be applied about suture lines.

After considering the problem from all angles, it has been elected to confine the nerve grafting operations at the Walter Reed General Hospital to fresh homografts, although there is no evidence at the present as to their success. One reason for this decision is the abundance of material available from the amputation service, where stumps are being revised in large numbers.

There have been five such operations performed during the past year. The suture technique employed has been similar to that used in end-to-end suture, namely, the anastomosis is made with fine tantalum wire and the site of anastomosis is surrounded by a small cuff of tantalum foil (Fig. 2, A–E).
NERVE IRRITATION—TRAUMATIC NEUROMAS

Many incomplete nerve injuries are associated with causalgic-like pain and may be relieved by dissection of the extrinsic scar or the removal of foreign bodies. Neurolysis in such cases is usually followed by slow progressive improvement of symptoms, and if the nerve must be replaced into a bed of scar tissue, a protective cuff of tantalum foil is used. Minor causalgias from nerve irritation should not be confused with other types of causalgia and phantom limb. These major cases form quite a different problem, and surgical procedures directed toward the peripheral nerves are seldom beneficial.

Painful amputation stumps are due frequently to neuromas on the ends of the severed nerves. With the guillotine type of amputation in particular, the nerves are often incorporated in the scar, and the whole mass is fixed to the end of the bone. The pain of traumatic neuromas is characteristic; it is produced only by pressure, and it radiates into the normal distribution of the nerve. It is relieved by novocain injection at the site of the neuroma.

Neuroma formation on the central end has generally been considered inevitable after sectioning a nerve trunk. There is considerable evidence, however, to indicate that under certain conditions, neuromas may be prevented. In an attempt to prevent neuroma formation, two types of procedure have been used. The first one consists of burying the central stump of the nerve into the medullary cavity of the most accessible long bone. Four such cases have been operated upon with satisfactory clinical results. The second procedure used consists of wrapping and fixing of the central stump of the nerve into a tantalum foil sleeve. Two cases have been operated upon by this method. One of them was re-operated upon after two and a half months and no evidence of neuroma formation could be demonstrated. The clinical results in these two cases have been completely satisfactory. However, insufficient time has elapsed to evaluate the effectiveness of either procedure.

REFERENCES


