Twenty Years In Brachial Plexus Surgery

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Brachial plexus surgery has been performed since the first half of our century, but initially the procedure was a rudimentary technique. Results were very poor, in fact, because of insufficient knowledge of the anatomy of the brachial plexus, of the pathophysiology of nerve regeneration and because of inadequate means of diagnosis and lack of modern sophisticated surgical equipment. Because of the poor results, a group of outstanding orthopedic surgeons wrote, in the sixties, an official agreement stating that brachial plexus surgery was useless and should be abandoned. Nevertheless, even though obstetrical palsies were on the decline due to the increase in Cesarean sections, the need for brachial plexus surgery was on the rise with the dramatic increase in the number of car and motorcycle accidents.

At the beginning of the seventies, development of microsurgical technique and equipment, along with an improved knowledge of neuroscience, led to a new brachial plexus surgery. (Narakas[1], Brunelli GA Brunelli GR and Monini[2], Bonnel[3].)

The new surgery did not suffer from limitations of time or of scope. It was important, after all, to clearly see the plexus and to recognize its lesions. It also took advantage of the new operating microscopes, intraoperating electrical stimulation apparatuses, bipolar coagulators, larger and safer anesthesia and more delicate instruments and suture materials. (Sugioca Nagano and Hana[4], Narakas[5], Millesi[6].)

We have been doing brachial plexus surgery since 1973. Our series includes more than 1,100 cases, 608 of which were operated on. Most of the cases were of different combined types and of different levels. One hundred thirty-eight had predominant lesions at root, 258 at trunk, and 212 at cord level. In terms of the type of brachial plexus lesion, 208 were upper plexus, 117 lower plexus, and 136 total plexus type. The other 157 were either intermediate type or mixed type.

At the beginning, despite careful preparation by means of cadaveric dissections, our experience was very poor, about what you would expect from other neophytes in the field. Operations were long, often lasting 10 or 12 hours. Such a protocol allowed us to examine the plexus thoroughly and to fully recognize the lesions. We received a great deal of information on topographic anatomy, anatomic variations, physiology, and lesion typesall of which had not been achieved by previous surgeons whose operating protocol covered a period of 2 hours, too short a time to permit a satisfying examination. The dissection of the scared tissue, which was practiced in the first operations, was time consuming, and in cases where the previous operation had been performed by vascular surgeons, bleeding was severe and transfusions necessary.

Over the past 20 years, our surgical procedure and philosophy have greatly changed due to greater surgical experience, improved knowledge of the plexus's internal anatomy, availability of more precise imaging techniques, lessons learned from previous cases as well as other minor factors.

In terms of the internal anatomy (i.e. the functional topography) of the brachial plexus, our ability to ascertain the anatomical lesions, which were related to the functional impairment and the intraoperative electrical stimulation of the uninjured elements, allowed us to draw a map of the internal anatomical and functional topography of the brachial plexus (Figure 1). This map enabled us to connect, with good approximation, fibers of the proximal stump to fibers of the distal stump (sensory with sensory fibers, motor with motor, extensor with extensor, and flexor with flexor). (Narakas[1], Brunelli GA Brunelli GR and Monini[2], Bergershaller and Mailander[7].) After all, mismatching fibers, such as when motor fibers are connected to sensory ones and vice versa, produces a total loss of function. In addition, it is difficult to reorganize the brain cortical pattern when motor fibers are sutured to other motor fibers of different function, such as flexor to extensor. We were also able to recognize the functional meaning of the decussation division, which occurs between trunks and cords.

In terms of the diagnosis, physical examination is much more important than it was 20 years ago. Clinical exam-

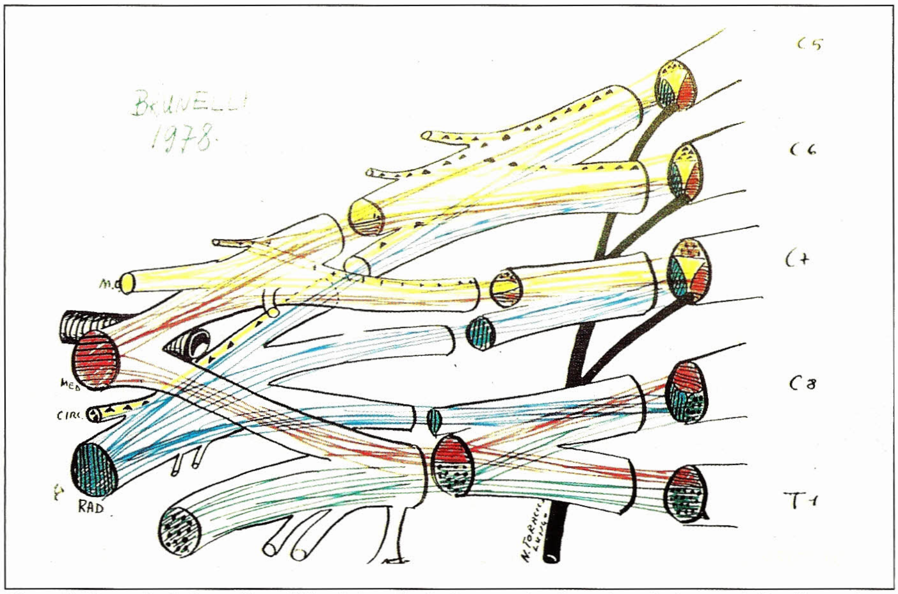

Figure 1. By surgical observation of the status of spinal nerves, trunks and cords, by correlating the anatomical findings to the paralyzed muscles and by stimulating the preserved nerves and recording the muscular response, in 1978 we were able to draw a map of the position inside trunks and cords of the different contingents which, coming from different roots constitute the different nerves. These maps are very important in order to obtain the better connection of the axons of the two stumps having the same function.

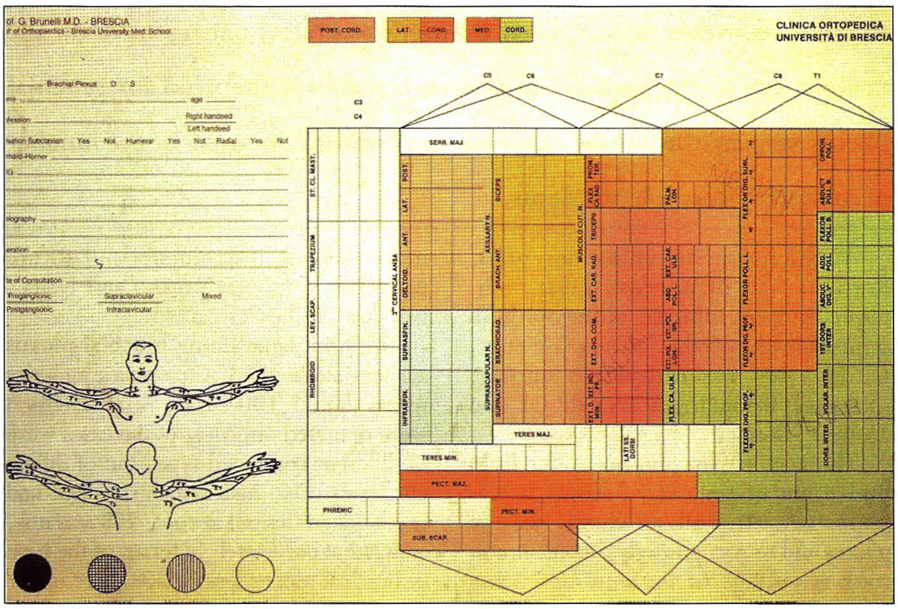

Figure 2. This chart has been divised in order to have at a glance the panorama of the plexus, to be able to say if the lesion is at the level of spinal nerves, trunks, cords or terminal nerves and to see if there is reinnervation (both before and after the operation). It is also very useful in deciding reconstructive surgery.

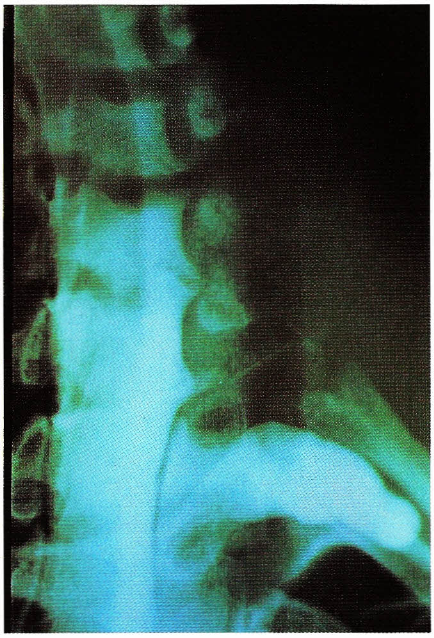

Figure 3. Example of myelography: big pseudomeningocele at the roots T1, absence of the negative image of the roots C8 with very small meningocele. The negative image of the roots C5 C6 C7 are present. Such an image means that the roots of C8 T1 are avulsed. C5 C6 C7 either are sound or there is rupture out of the vertebral canal.

ination of each single muscle is carefully done and recorded on a chart, which not only shows the function of the muscles but also variations of the score at different times and objective clinical follow-up. The latter is very useful in closed lesions, both to show a tendency for spontaneous regeneration, and postoperatively, to show reinnervation (Figure 2). This chart also enables us to see at a glance if we are dealing with a lesion of the spinal nerves or of the trunks, cords, or terminal nerves. Myelography remains the most reliable imaging technique to ascertain root avulsion, but because it is an invasive test, it has been replaced by CT scan and MRI, which is a noninvasive test (Figure 3). No more is EMG considered an important preoperative test. In traumatic lesions the analitic muscular test of all the muscles of the upper arm (see above chart) is much more indicative. Intraoperative evoked potentials to detect root avulsion is a very useful method, which unfortunately is often neglected because it is time consuming. Both the waiting list and the availability of the anesthesiologist prevent its routine use. Instead, it is limited to the very cases in which, under the operating microscope, the surgical observation of the proximal stump—stained with diluted metylen blue—indicates the presence of fibers and therefore excludes a root avulsion. The preoperatory physical examination, together with an EMG of the posterior muscle of the neck and the experience of the surgeon, can be enough to omit this exam. We have learned that even with a big pseudomeningocele of C8 Tl and a Bernard-Horner sign, the C8 Tl spinal nerves may be sound (we have even seen spontaneous repair in one case).

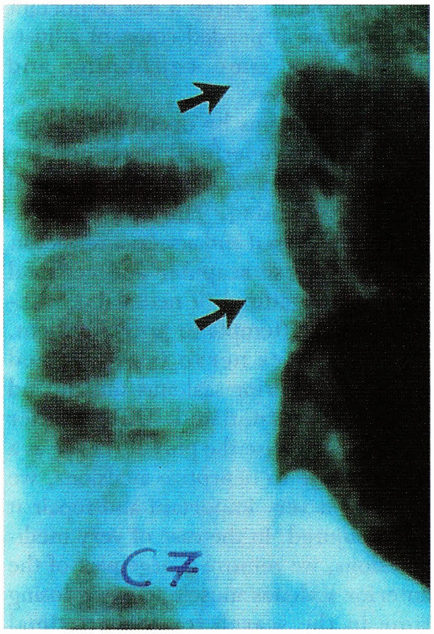

Figure 5. Intermediate lesion of the brachial plexus. Upper part of mielography of a case of avulsion of C7 with preservation of the roots C5 C6.

During these years we were also able to recognize and demonstrate a fourth type of brachial plexus lesion: the intermediate preminent lesion (C7) (Brunelli and Brunelli[8]). A downward trauma exerts its strength on the proximal elements of the brachial plexus, which are oblique from medial to lateral and from proximal to distal, producing an upper-plexus injury, while an upward trauma stretches and then breaks caudad elements, causing a lower-plexus injury. But an anterior-to-posterior trauma involves the first of the 7th cervical spinal nerve or roots (Figure 4). This type was well documented by means of myelography and published. (Figures 5, 6, 7).

In terms of the timing of surgery, we operate immediately if there is an open wound. The reconstruction of the brachial plexus should be immediate, even in the case of a subcutaneous rupture of the subclavian artery. Vascular surgeons, however, who generally treat this kind of lesion, often do not repair nerves and defer nerve surgery to a secondary (orthopedic) operation. In closed brachial plexus lesions, we try to ascertain as soon as possible if there is avulsion of the roots. If this is the case, immediate surgery is planned since spontaneous recovery is not possible and waiting is not productive. Early surgery, on the other hand, allows better treatment of those elements of the brachial plexus that are injured (and not avulsed) and allows earlier extraplexual neurotization of the avulsed nerves.

In the other cases, we start the rehabilitation program and wait. The initial rehabilitation program includes splinting the arm in abduction to avoid exhaustion of the fibers of the deltoid muscle which, if pulled down by the weight of the upper limb, degenerate. This not only leads to shoulder subluxation but also results in no more fibril-

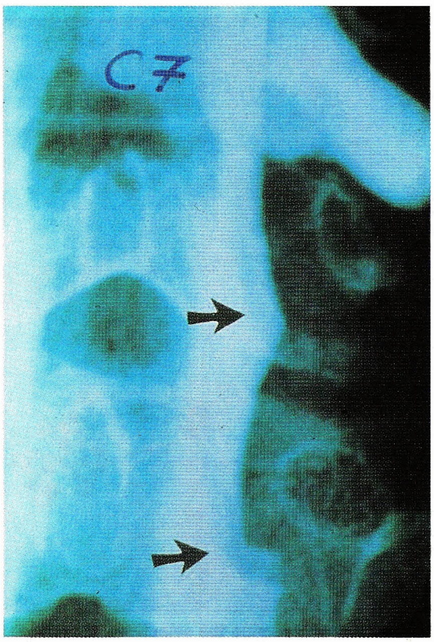

Figure 6. Lower part of mielography of the same case showing preservation of the roots C8 T1.

Figure 4. The mechanism of the rupture of avulsion of C7: while a trauma from cephalad to caudad gives an upper plexus lesion and one from caudad to cephalad a lower plexus injury, a trauma from anterior to posterior comes first the involvement of C7.

lation, which is commonly thought to be necessary for reinnervating a muscle. A program to maintain the trophism of muscles is immediately started by means of massages and exponential electrical stimulation. Also, at the beginning, the joints are moved to avoid stiffness, especially of the MPJ. In case of neuroapraxia, spontaneous recovery may be quick. In the case of axonotmesis, it will take some months to see if spontaneous recovery will occur.

We have learned that in brachial plexus surgery a single type of nerve lesion occurs only rarely (clean knife cuts excluded). Therefore, different types of surgery such as neurolysis, sutures, grafts, and neurotization typically must be done in combination. In total or upper-plexus lesions, the first muscle to be reinnervated is the supraspinatus. With an average of 1 mm a day of axon progression, nerve regeneration will take place within approximately 4 months. If reinnervation does not occur in that time, surgery is compulsory. Moreover, if the chronology of muscle reinnervation (according to the distance from the plexus) is not respected, surgical exploration is indicated as soon as one muscle reinnervation in the progression list is missing. This alteration of chronological progression means in fact that while the nerves of the reinnervated muscles have had axonotmetic lesion, the nerves of muscles not reinnervated have had neurotmetic lesion, which requires surgical repair. Patients often come late—presenting partial reinnervation patterns. In these cases a combined program of nerve and reconstructive surgery should be done on a case-by-case basis.

We have altered our surgical protocol, changing our Z-shape approach, which provoked severe keloid scars, to an angulated retrosternocleidomastoideous incision (3 to 4 angles) lengthened laterally with two opposite rectangular flaps above the clavicle (these flaps are respectively retracted upwards and downwards to give a large light to the operating field). The approach is continued with another angulated incision along the deltopectoralis crease. If it is necessary to prolong the approach on the arm, the skin incision crosses perpendicularly to the anterior arch of the axilla. In the axillary hollow, the incision deviates 90 degrees to continue on the medial aspect of the arm. This approach never gave us keloids.

Another small protocol change is the way we position the patient to obtain a more ergonomic operation. The operating table is slightly elevated, putting the patient in a semi-seated position, and the whole table is tilted towards the surgeon who keeps his forearms resting on sterile forearm supports to diminish the fatigue in these long-lasting operations. In addition, the operating microscopes have improved both in their optical and in their ergonomic performances. In fact, we were consultants in the preparation of a new operating microscope: the Leica M 680. This dramatically improves microsurgery by producing a much larger field, which allows the operator to see the instruments around the elements; by offering easy focus and zoom options by means of pedal control; by maintaining brightness even at maximum magnification; and by enabling the assistant to see perfectly what the operator is doing. The old operating microscope which has a tremendous depth of field (8cm), on the other hand, played a less important role because it needed constant adjustments, was time consuming and strained the eyes.

Surgery begins by opening the skin. The cervical superficial fascia and the superficial layer of the middle cervical fascia are divided. The omojoideous muscle is severed and acts as a retractor. The transverse scapular and cervical artery are ligatured (if necessary) without lengthy attempts to preserve them. The phrenices nerve is recognized above the anterior scalenus muscle and electrically stimulated. Unlike other surgeons who use the phrenic nerve as a donor nerve to neurotize avulsions, we consider it very important and repair it if it is injured. In the case of very medial lesions, we remove a large part of the anterior scalenus muscle to avoid losing time in the search for the proximal stumps of C5, C6, C7. This enables us to see the proximal stump of the spinal nerves if existent. If the elements of the

Figure 7. Operatory finding showing avulsion of C7 (the sensory ganglion is seen) and rupture of C5 C6 while C8 T1 are normal.

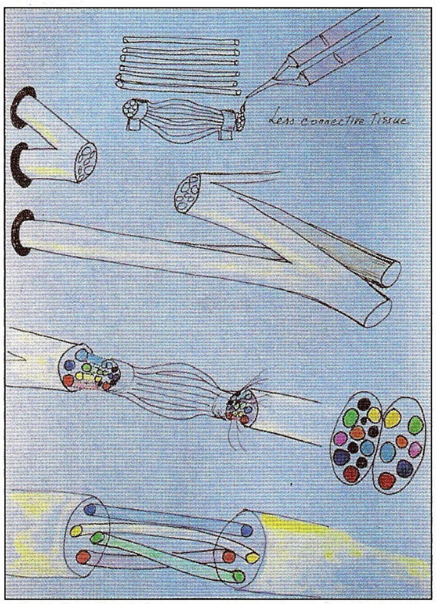

Figure 8. If we use glue the selective connection of sectors of the proximal and distal stump having the same function is not possible.

plexus are well recognizable, reconstruction is done by suturing (in case of a neat cut) or by grafting. Grafts are generally taken from the sural nerve of both legs by means of long approaches to prevent damage to the collateral branches or to anomalous constituents of the nerve as well as to avoid lesions of the graft like axonotmesis or partial neurotmesis. (It is illogical, after all, to repair any damaged engine with damaged spare parts.) Vascularized grafts are not used anymore except in case of C8 Tl avulsion. In this case the ulnar nerve, which will never recover, may be taken with its artery to reconstruct one or two trunks or cords or terminal branches. We no longer use glue to connect elements of the plexus with cables of sural nerve (Narakas[9]). In fact, we believe that grafts have to connect sectors of the proximal stump to other sectors of the distal stump, which are supposed to have an identical function (based on the map above). By gluing cables, this selective connection is not possible (Figure 8). We prefer to suture isolated segments of sural nerve to sectors of proximal and distal stumps or, even better, to the correspondent terminal branches. In case of severe and wide scars, we do not waste time dissecting the elements, which are severely damaged and useless and would be further damaged by dissection.

Plexus elements above and below the scar are recognized and sectioned at their entrance to the scar. Connection is done by means of grafts. In this way operating time and bleeding are dramatically reduced and results are better. We are inclined to connect the functional sectors of the proximal stumps to terminal branches, even if it means longer grafts, because it prevents the dispersion of axons inside trunks or cords and allows more dedicated reinnervation. (For example, one graft from the superior sector of the superior trunk to the suprascapularis nerve; two grafts from the supero lateral sector of C5 and C6 to the origin of the muscolocutaneous nerve.) If oné or more spinal nerves are not available due to roots avulsion, neurotization is done. We no longer perform intraplexual neurotization, because it is a severe autolimitation. In fact, there is no advantage in distributing nerve fibers of one spinal nerve to two or three such nerves. Results are poor due to dispersion and mismatching. It is much better to use thousands of fibers from extraplexual nerves. (For example, if C5 is avulsed and C6 ruptured, we prefer to reconstruct C6 with its elements and neurotize C5 with nerves external to plexus.) Extraplexual neurotization still has some controversial indications, such as the use of a nerve from the controlateral limb—a rare and experimental operation.

In addition, we do not favor the use of the intercostal nerves. Because they work together, the intercostal nerves may innervate only one function. If 2 different muscles are innervated by them, co-contractions will occur, and if the muscles are antagonistic, no hlnction will result. Furthermore, the activation of the intercostals is semiautomatic and the corticalization of their new function is difficult, requiring much time, and often cannot be separated by voluntary breathing (or tussing). Therefore, we use intercostal nerves only rarely (5 cases out of 608 operations). On the other hand, we have checked the anterior nerves of the third cervical ansa by anatomic dissections in cadavers and by histologic observation. Four of these nerves may supply about 4,000 motor fibers, which are able to voluntarily function separately (Figure 9). With the addition of the XItl- cranial nerve (2,000 motor fibers) and of about

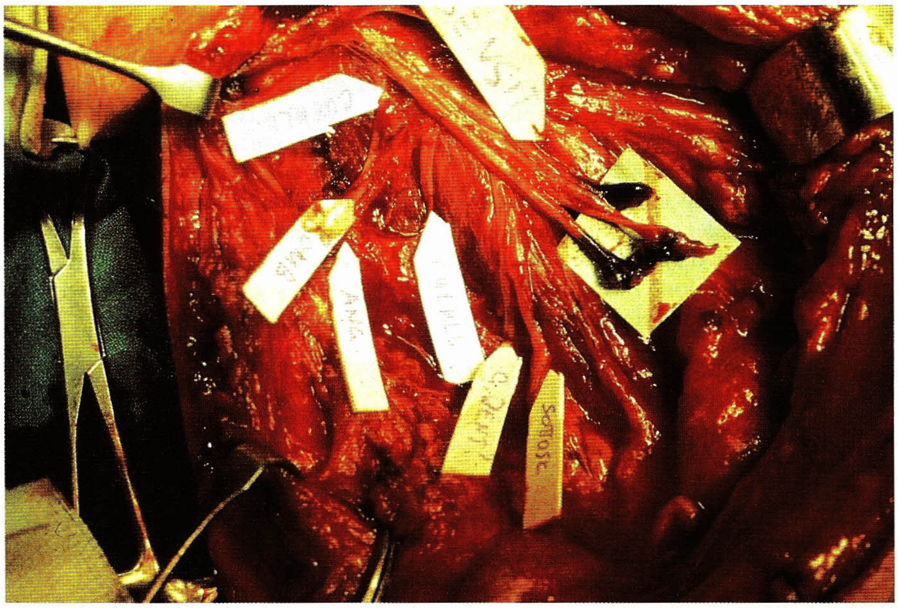

Figure 9. Anterior branches of the 3rd ansa of the cervical plexus. Four of them (stained in blu) are sensory and four are motor branches. All of them are individually voluntarily activated and may innervate different functions.

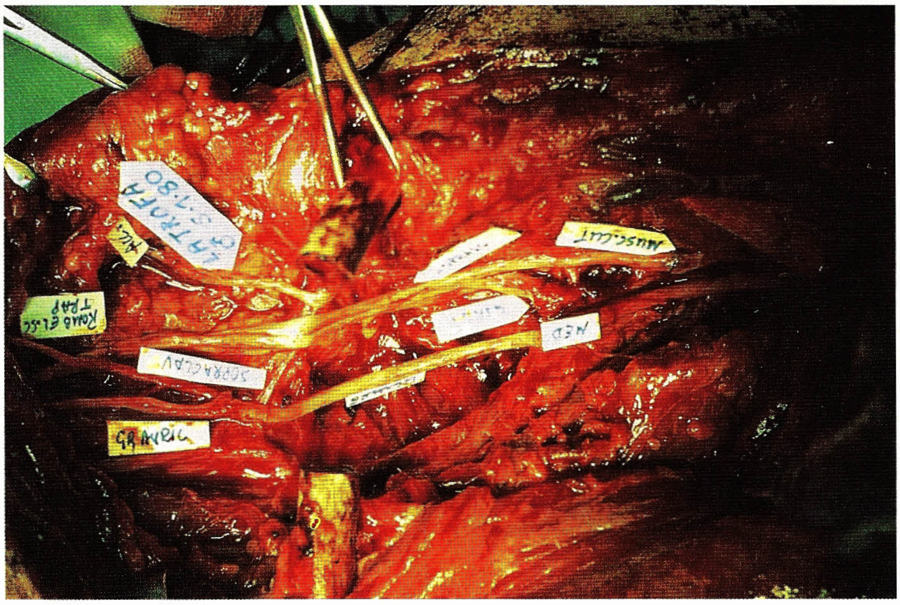

Figure 10. Example of connection of proximal stump to terminal branches by means of long grafts.

2,500 sensory fibers, we can neurotize 4 functions: (1) the flexion of the elbow (with the XIth) (2) the external rotation of the arm, which is more important than abduction—with the nerves to trapezium and to romboid (3) some abduction, with the nerve to levator scapulae and st. cl. mast. and (4) some sensation of the hand, which will occur three years later by connecting the sensory supraacromialis and supraclavearis nerves with the external contingent of the median nerve (Brunelli GA Monini and Brunelli GR 10).

To avoid axon dispersion and loss of function, connection of the donor nerves with the terminal branches is compulsory (Figure 10). In some cases of double level lesions, even direct muscular neurotization was done.

Over the years we have learned that every time we observe an ondulated cord or terminal nerve (Figure 11), we must suspect a double level lesion, which is often an avulsion from the muscle. If associated with a fracture of the humerus, an immediate exploration of the radial nerve is almost mandatory since, at the site of the fracture, there is frequently a second-level nerve lesion, which will complicate the recovery if not repaired.

In terms of the reconstructive surgery (palliative operations), our philosophy is to start doing such a procedure as soon as possible after the initial surgery, specifically after the calculated time for reinnervation from the lesion to the muscle (1 mm a day) has elapsed without recovery of that muscle. In this case, reconstructive surgery is done progressively from proximal to distal, unless a shoulder arthrodesis has been done. In this case the shoulder should be operated on last, because of the difficulty of operating on an elbow or a forearm with a shoulder blocked by a joint fusion. In case of C8 Tl avulsion, the distal reconstructive surgery may be done early by means of tendon transfer or wrist arthrodesis.

Great importance should be given to reeducating the motor and sensory functions. In order to maintain as much as possible the trophism of muscles, motor rehabilitation, from the beginning, should be done through massages and stretching. Passive movements must also be done every day to prevent joint stiffness, especially of the MPJ. In fact, no weak muscle, after recovery, will flex a stiff joint. Exponential electrotherapy also must be done from the beginning. Several fields of daily applications, each lasting about 30 minutes, are necessary. The parameters of the electrical wave depend on the state of the reinnervation of the muscle. Active reeducation should follow reinnervation and should be light at the beginning. Because of the unavoidable mismatching in proximal nerve surgery, the brain will have severe difficulties both in recognizing the sensory stimuli and in elaborating them up to gnosis (Brunelli Battiston and Lee Dellon 11). Therefore, sensory reeducation should not only follow reinnervation but also should be done with all the means at one's disposal.

Actinic plexopaties are caused by different kinds of iatrogenic radiation, such as found in women being treated for breast cancer and for men who have Hodgkin's disease. High-powered radiation induces a severe plexopaty, a pro-

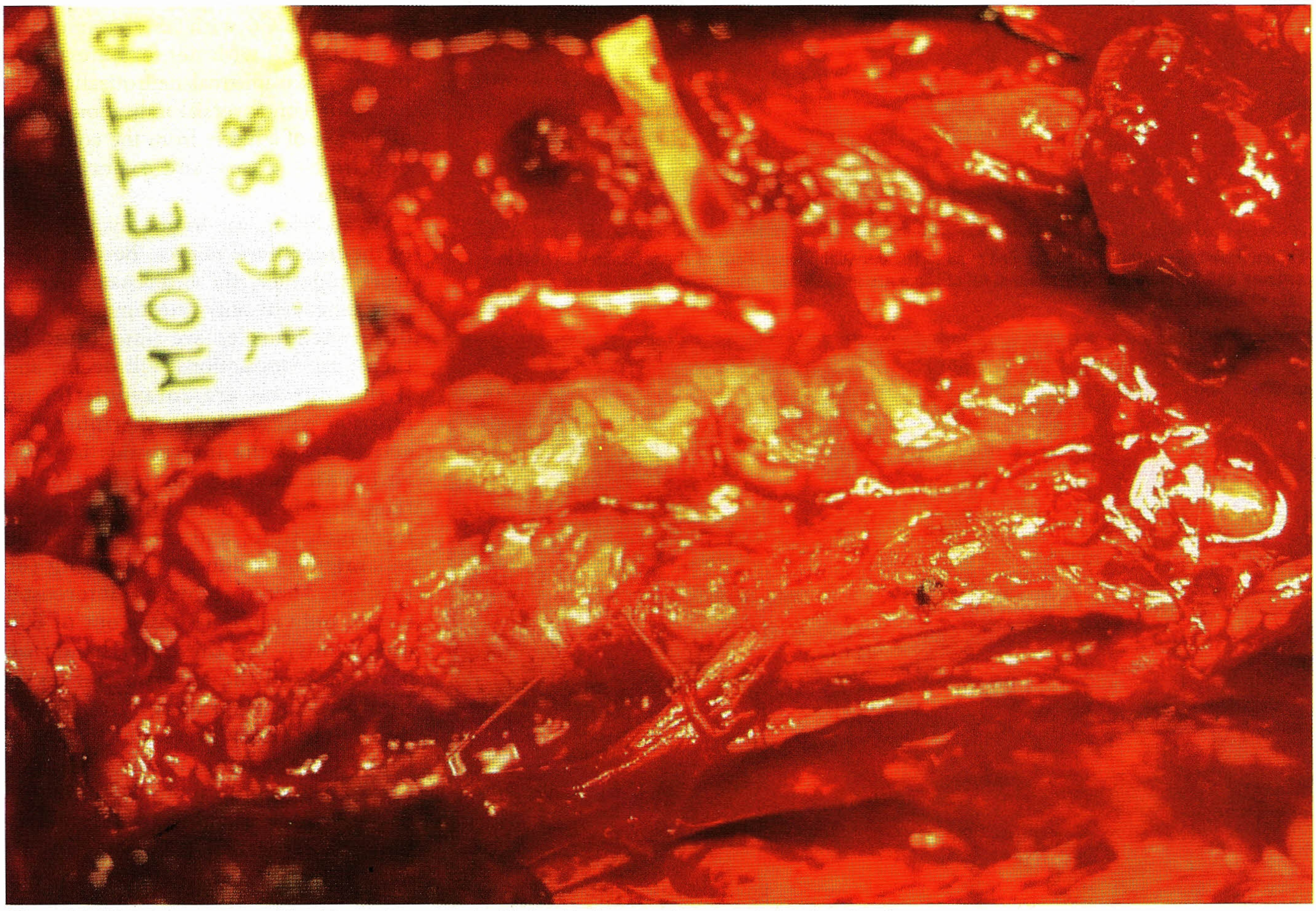

Figure 11. When an appearance like this one is seen, a double-level lesion must be suspected and explored.

gressive sensory and motor palsy. It occurs several years after the treatment and is often accompanied by pain. The pain, in fact, can be so excruciating that it can lead to suicide (two of our patients tried to commit suicide before coming to us). The cause of such a painful syndrome is the severe sclerosis of the brachial plexus and of all the connective tissue surrounding the plexus. Twenty years ago, we thought that the syndrome's progression could be stopped by means of a meticulous neurolysis of the plexus and by wrapping sound tissue around it. Our research on animals has demonstrated that the greater omentum is by far the best tissue for wrapping a nerve and to prevent scar formation. We have operated on 49 patients by means of neurolysis and omentum wrapping but no improvement in motor and sensory palsy has been obtained. However, the procedure successfully eliminated pain, which did not reoccur later. Today, we perform this operation only for pain.

In conclusion, our experiences gave us a good understanding of brachial plexus lesions and their treatment, and allowed us to change and improve the original operating protocol. In this way we reached three goals: to simplify and shorten the surgery, to obtain better results and to get the results in a shorter time. STI

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