Brachial Plexus Injury: The London Experience with Supraclavicular Traction Lesions

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KEYWORDS
• Brachial plexus injuries • Neuropathic pain • Timing of repair

George Bonney introduced a policy of urgent repair of injuries to main nerves in the early 1960s at St Mary's Hospital, London. The case was considered an emergency if the nerve injury was complicated by a rupture of a main artery at the same site. This policy was extended to the closed supraclavicular lesion, and the first urgent repair was performed in 1962. Other repairs had been done earlier, in selected cases, at the Royal National Orthopaedic Hospital (**Fig. 1**). The results of grafting of the ruptured spinal nerves were generally poor, which, with the high incidence of preganglionic (avulsion) lesions, was disappointing. Several operations were performed for the purpose of establishing diagnosis alone. It was the work of his friend, Algimantas Narakas, of Lausanne, which stimulated Bonney to make a fresh start in 1974. The results in 1162 operations for supraclavicular injuries were outlined in 1998.[1] In all, repairs by one means or another have been performed in more than 1500 cases of the closed traction lesion in the adult since 1962.

Important advances have been made in methods of diagnosis and repair during this time. Myelography[2] was replaced at St Mary's Hospital by CT scan with contrast enhancement[3] and later by MRI. The early work of Bonney[4] and of Bonney and Gilliatt[5] was extended to the analysis of central conduction by Landi and colleagues[6] in 1980 at the Royal National Orthopaedic Hospital and this seminal work has become a central, essential component in the diagnosis of lesions exposed within a few days of injury.

New methods of repair were introduced. The free vascularized ulnar nerve graft was introduced by Jamieson with Bonney in 1975.[7] The first repair of the intradural lesion was carried out by Bonney and Jamieson in 1977 in one case operated within 24 hours of injury.

> *With the patient in the left lateral position, I exposed the brachial plexus above the clavicle; the plexus had, as was expected, been completely avulsed. I marked the 7th and 8th cervical nerves and their roots. I then exposed the posterior elements of the cervical spine through a posterior incision, and went onto expose the right side of the cervical dura by hemi laminectomy. I opened the dura to expose the right side of the spinal cord and to show the avulsion of the roots. Now, I passed fine forceps through the foramina between the 6th*

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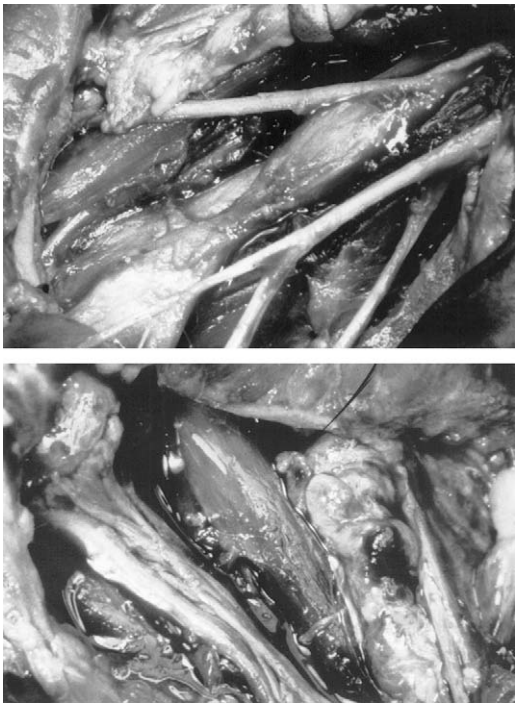

Fig. 1. Repair by graft of lesion of upper trunk of the brachial plexus using fibrin clot glue. (*From* George Bonney and Donal Brooks. Royal National Orthopaedic Hospital, 1952.)

> *and 7th and 7th and 8th vertebrae, and with these caught hold of sutures tied to the cuffs of dura at the junction of roots with peripheral nerves. With these sutures, the roots were drawn back into the spinal canal. Forceful traction was not needed; the roots lay easily in the canal, offering themselves for re-attachment.*[8]

The rupture had taken place just distal to the surface of the cord; little stumps of the rootlets were visible and Jamieson sutured the dorsal rootlets of the two nerves. I reviewed this patient 10 years later. He was well adjusted, in full-time work, and had no pain. He demonstrated remarkable recovery into pectoralis major and biceps muscles, which perhaps confirms Carlstedt's[9] view that the ventral neurone can find its way out to the periphery through a pathway between the spinal cord and the avulsed spinal nerve.

Advice and examples from such friends and colleagues as Aligimantas Narakas, Yves Allieu, Laurent Sedel, Christophe Oberlin, Alain Gilbert, and Akira Nagano led to the extensive use of nerve transfers from 1980.

The incidence of this injury was described by Goldie and Coates,[10] who wrote to every orthopedic surgeon and to other interested surgeons in the United Kingdom. Details of 328 cases of injuries to the supraclavicular plexus were analyzed. The lesion was complete in 22.8%. A wound existed in 5.1%. The subclavian artery was ruptured in 4.7% and no less than 43% of these patients had other major injuries. It seems that the severity of the lesion is declining (**Table 1**).

THE LESION

The level of lesion has been clarified. The observation of small stumps of the dorsal rootlets led to the idea that the preganglionic injury should be considered as either central to the transitional zone or peripheral to it. Schenker[11] examined the tips of the roots of avulsed spinal nerves and found that most of these were torn peripheral to the transitional zone.[12] Schenker[13] also confirmed that the ventral root in man contains myelinated afferent fibers. This fact may be relevant in the relief of pain by reinnervation of skeletal muscle and it may also underlie the absence of cocontraction, which is seen in many cases of selective reinnervation of the avulsed ventral root.

INDICATIONS FOR URGENT EXPLORATION

Magalon and colleagues[14] set out the case clearly: ''It is advisable because emergency nerve surgery is technically easier and because the overall results are better if combined vascular and nerve injuries are involved immediate emergency surgery is mandatory.'' These workers also provide good advice in situations where only the great vessels can be repaired: ''Positioning ruptured nerves away from the vascular bypass will greatly facilitate second stage repair.'' The biologic imperative for repair of ruptured nerves as soon as possible is established beyond any reasonable doubt and is supported by numerous clinical studies. The last 25 years have seen a growing appreciation of the central effects of proximal axonotomy.[15,16] The central response is swift and occurs within hours or minutes.[17,18] I have come to the view that repair in the closed traction lesion comes, in urgency, close behind reattachment of the amputated hand or repair of a great artery and a trunk nerve in the combined lesion, and it is a pleasing duty to acknowledge the clinical acumen of so many of our colleagues, mostly orthopedic surgeons, throughout the United Kingdom who have made it possible for us to do this work by virtue of their early recognition of the severity of the injury and by their appreciation that it may, in fact, be possible to do something useful for the patient.

DIAGNOSIS

The history is all important. The direction of application of force and some understanding of the

Table 1
The changing lesion displayed at operation: samples of 40 years of experience

Years	Total Number of Patients	Total Number of Spinal Nerves	Nerves Avulsed	Avulsion C5–T1	Arterial Injury
1966–1984	210	1100	690 (63%)	48 (23%)	26 (12%)
1989–1993	300 (consecutive)	1500	826 (55%)	52 (17%)	21 (7%)
2003–2006	320 (consecutive)	1600	730 (46%)	26 (8%)	16 (5%)

violence of that force comes first. Deep bruising indicates tearing of deep structures; ecchymosis or abrasions over the neck and the shoulder show the application of force. Sensory loss involving the cervical plexus suggests serious injury to the upper spinal nerves (**Fig. 2**). Two other features are important. The first is pain. Nearly one half of our patients have been seen within the first week or two of injury, and most describe immediate onset of pain, or its development, within 24 hours. The pain was eloquently described by Frazier and Skillern's[19] patient in 1911:

> *The pain is continuous, it does not stop for a minute either day or night. It is either burning or compressing… ….. in addition there is, every few minutes, a jerking sensation similar to that …… by clutching….. a Leyden jar. It is like a zig zag made in the sky by a stroke of lightening. The upper part of the arm is mostly free of pain; the lower part from a little above the elbow to the tips of the fingers, never.*[19]

It is all here. The pain is severe, it has two parts (one constant, the other intermittent), and it is worst in the hand and forearm. The lightning pain is usually expressed within the first 24 or 48 hours after injury and it is precisely distributed. If it radiates to the radial aspect of the forearm and the thumb, then avulsion of C6 is likely. If it radiates to the back of the hand, then a similar lesion is likely at C7. When it radiates down the inner side of the forearm and into the fingers, then the lowest nerves are similarly damaged.

The second factor is the presence or absence of the Tinel sign, which is detectable on the day of injury in postganglionic rupture, and the irradiation of pins and needles advises the clinician which spinal nerves have been ruptured.[20] For C5, irradiation is to the elbow; for C6, it is to the radial aspect of the forearm and the base of the thumb, and for C7, it is to the back of the hand. We have recently examined the validity of this finding in 300 consecutive operated cases and found that the prediction of rupture was confirmed in close to 90% of the spinal nerves so diagnosed.

Examination of the extent of paralysis is important, paying particular attention to serratus anterior and trapezius muscles and to the ipsilateral hemidiaphragm. The evidence provided by the history and by clinical examination should enable the clinician to make accurate diagnosis of the extent and depth of injury and to form a fairly clear idea of the level of lesion. That diagnosis is clarified by CT scan with contrast enhancement or by MRI and it is finally established at operation.

These injuries are high energy transfer injuries. In at least 15% of our patients, other potentially life-threatening injuries, which must take absolute priority, have enforced delay. Care must be taken to seek out occult injury to the spinal cord, the spinal column, the chest, and the abdominal viscera at the receiving hospital and again at the hospital to which that patient is transferred. The treatment of significant injuries to the head, to the spinal column and chest, and to the abdomen and pelvis come first.

INTRAOPERATIVE STUDY OF CONDUCTION

The study of somatosensory evoked potentials from the proximal stump of ruptured nerves enables recognition of the combined partial avulsion complicating distal rupture and it also points to selective injury to either the ventral or the dorsal root. Placing grafts onto a stump where central conduction is abnormal or absent is usually fruitless (**Fig. 3**). Analysis of distal conduction in urgent cases is informative; it is usually present for up to 80 hours after injury. In one case, distal conduction in the avulsed ventral root was present at 132 hours after injury.

The patient illustrated in **Fig. 4** came off his motorcycle at speed on the day before Christmas Eve. The referring surgeon diagnosed rupture of the subclavian artery, so providing the opportunity to deal with this at the same time as dealing with the nerve injury in a limb, which was not critically ischemic. Operation was undertaken at 60 hours. The clinical diagnosis was confirmed. Postganglionic rupture of C5 and of C6, with avulsion of

Fig. 2. Some examples of bruising, abrasion, and extensive sensory loss, which indicate extent and severity of injury.

C7, C8, and T1, was easily demonstrated. Stimulation of the avulsed ventral roots was followed by the appropriate response in distal muscles, which showed us three things. First, that critical ischemia of muscle or nerve had not occurred; next, that a second injury to any major nerve trunk had not occurred; and finally, that we could confine resection of the tips of the ventral roots to no more than a millimeter or two. This case illustrates the technical ease of early exposure and how easy it is to diminish the gap between the stumps. The avulsed spinal nerves had been pulled downwards to lie below the clavicle.

PRINCIPLES OF REPAIR

The closed traction lesion falls into one of two broad groups. In the first, which accounts for nearly one half of our cases, a lower nerve is intact or recovering and the upper nerves have been

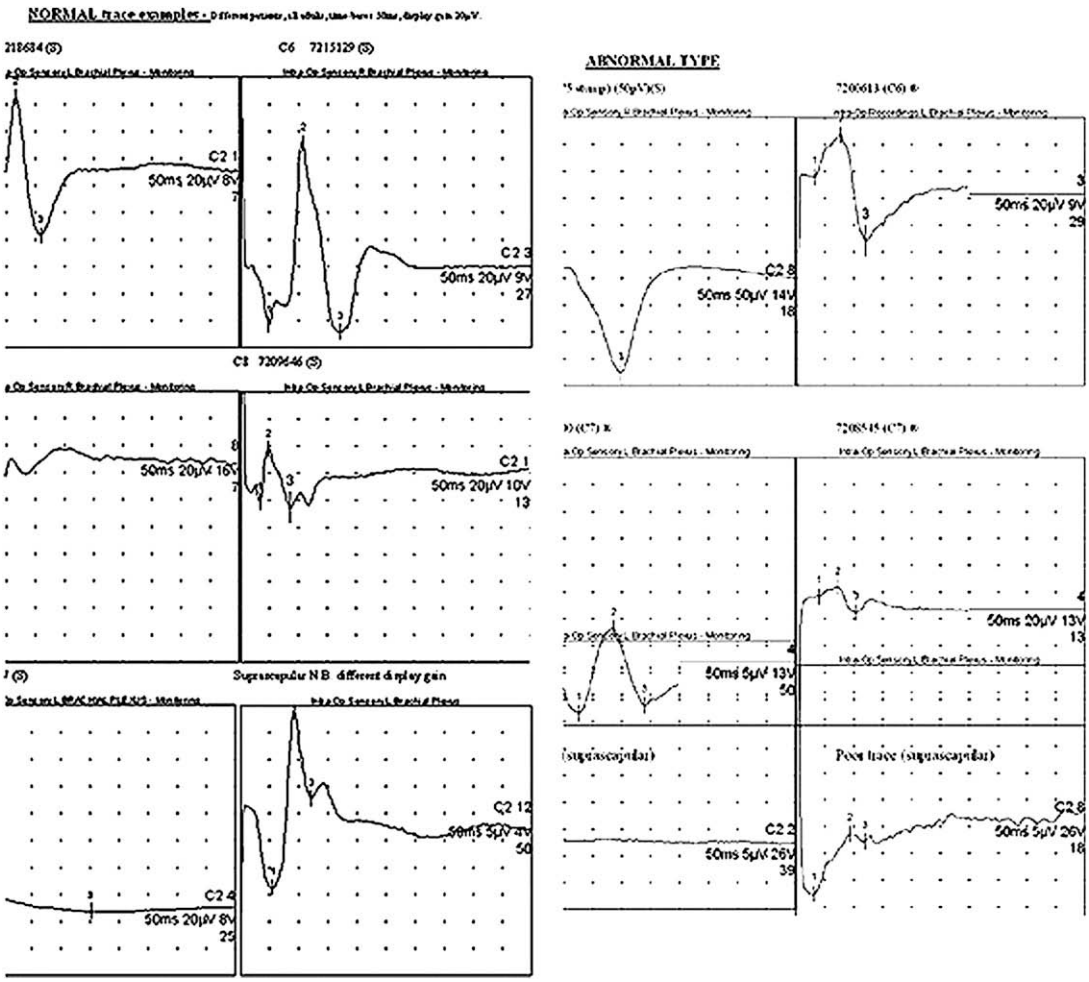

Fig. 3. (*Left*) Normal somatosensory evoked potential traces recorded from postganglionic ruptures. (*Right*) Abnormal traces recorded from postganglionic ruptures indicate an element of preganglionic injury.

damaged. The patient has the potential for hand function, and the object of restoration of function at shoulder and elbow can usually be achieved. It should be the rule that a useful and relatively pain-free limb is achieved by combining graft with specific nerve transfer, and by transfer of the spinal accessory nerve to either the suprascapular nerve or the avulsed ventral root, with timely musculotendinous transfer (**Fig. 5**).

In the complete lesion, every reasonable effort should be made to display postganglionic ruptures. The finding of even one rupture makes

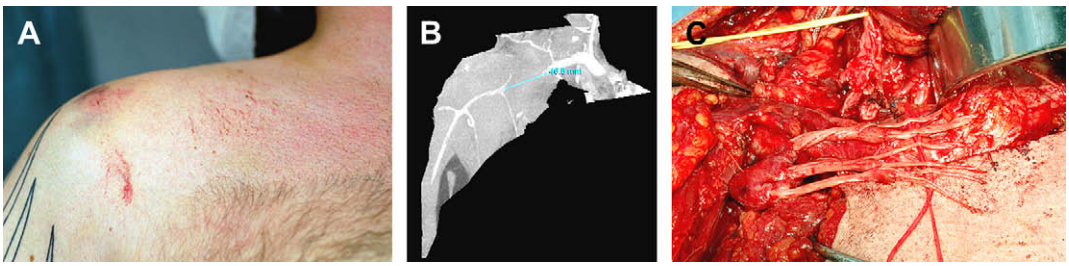

Fig. 4. (*A*) Soft tissue abrasions around the shoulder and neck with pain with percussion into the C5 and C6 distributions suggested postganglionic ruptures of these elements. (*B*) Conventional angiogram demonstrates subclavian artery occlusion. (*C*) Operative appearance of the preganglionic lesions to C7, C8, and T1.

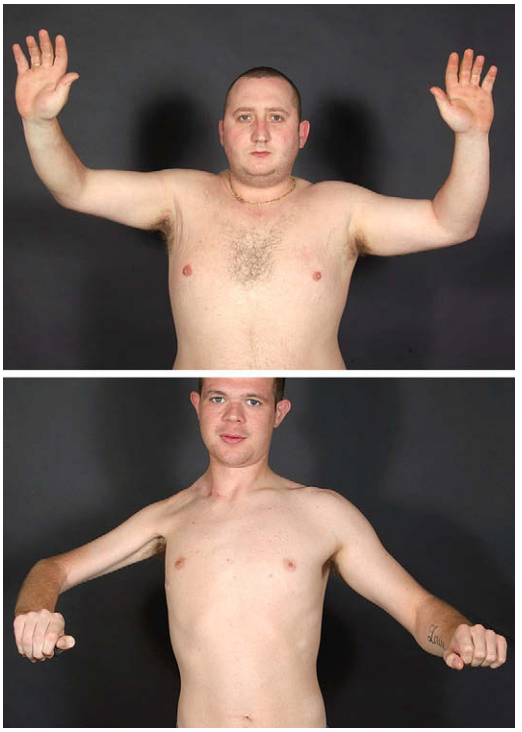

Fig. 5. (*Top*) A 23-year-old manual laborer who sustained rupture of C5 with avulsion of C6 and C7, with recovery for C8 and T1. Repair at 3 days was done by graft and nerve transfers. The spinal accessory nerve was transferred to the ventral root of C7. He considered function within his limb as normal at 24 months. In this case, reinnervation of the ventral root of C7 restored function in triceps and in the wrist extensor muscles (*Bottom*). A 24-year-old electrician who sustained rupture of C5, avulsion of C6, C7, C8, with recovery of T1. Repair was done by graft and by nerve transfers. The spinal accessory nerve was transferred to the ventral root of C6. The operation was done at 4 days after injury. At 9 months, a successful flexor-to-extensor transfer was done. His function was good enough for him to be able to return to his trade. In both patients, pain was severe for the first 9 months after operation. It resolved with return of muscle function.

Fig. 6. Elements of hand function were regained in both of these patients who sustained postganglionic rupture of C5, C6, and C7, with avulsion of C8 and T1. (*Top*) A 7-year-old child who was operated 8 weeks after injury at age 3. (*Bottom*) A 17-year-old woman 3 years after repair, which was done at 6 days from injury.

a great deal of difference. In earlier years, we hoped that the free vascularized ulnar nerve graft would not only regain elbow flexion but also restore hand function by reinnervation of the median nerve (**Fig. 6**).[1,7] Only 14 of 65 patients regained wrist and finger flexion to the Medical Research Council 3 or better, with sensory recovery to light touch, pin prick, and warm sense within the median territory. In 13 of these cases, the operation was done within 14 days of injury. Useful hand function was regained in only 3 patients. Pain persisted in some patients despite recovery of function. We abandoned the method about 15 years ago, preferring instead to repair the whole of the plexus in cases that involve two or three postganglionic ruptures with avulsion of the remainder.

Recovery after repair of the spinal nerves of the brachial plexus is determined by several factors. Among these, delay before repair and the severity of the injury come first. **Table 2** outlines the results of 37 spinal nerves repaired by either graft or nerve transfer in 153 cases operated in the years 1991 to 1993. One third of patients achieved no useful function. Forty-three cases achieved good function across two joints in the upper limb and, of these, 33 were operated within 14 days of injury. Four patients regained useful hand function following repair of the whole of the plexus. All four were operated within 14 days.

Table 2
Recovery by delay and severity of lesion: 367 spinal nerves repaired by graft or by transfer in 153 cases operated during 1991 to 1993

	Interval from Injury to Repair			
Recovery	**Within 14 Days**	**To 3 Months**	**To 6 Months**	**To 12 Months**
Partial lesion (at least one intact nerve, usually C8 or T1)				
Useful	75	83	16	11
Failure	11	25	3	11
Complete lesion (mixed rupture and avulsion C5–T1)				
Useful	43	15	3	7
Failure	22	17	6	19

These figures exclude repairs using the vascularized ulnar nerve graft and also intercostal transfers for pain relief, hand sensation, and medial cord function.

A more recent study comes from Kato,[21] who studied the effects of operative delay on the relief of neuropathic pain in 148 patients in whom at least one spinal nerve was avulsed. The average number of avulsed spinal nerves in this series was 3.2. In 80 patients, pain was apparent at the moment of injury or within 24 hours, and it developed within 2 weeks in 35 more. In 15 cases, intubation and ventilation was necessary for up to 3 weeks and for these, recollection of the onset of pain was difficult. All patients experienced severe pain that was slightly worse where the lower roots were avulsed. Kato divided his patients into four groups based on the interval between injury and exploration: group 1 (early), within 1 month of injury (n = 61); group 2 (delayed), 1 to 3 months after injury (n = 29); group 3 (late), 3 to 6 months after injury (n = 32); group 4 (neglected), more than 6 months after in jury (n = 26). Results were decisively better in the early group. Recovery of function and relief of pain were strongly correlated.

It is tempting to suggest that the improvement in pain so often seen with reinnervation of muscle is brought about by restoration of the deep afferent pathway from muscle.[22] However, late intercostal nerve transfer is sometimes effective for the relief of pain, even when functional recovery of skeletal muscle is not a realistic prospect.[23] Several explanations are possible. First, the transfer of healthy intercostal nerves into the trunk nerves of the upper limb may inhibit abnormal electric activity within the substantia gelatinosa. Second, relief from pain may purely be a nonspecific effect of operation, depending on the anesthetic used, the degree of postoperative pain, and the use of analgesics, or on suggestion alone. Third, relief may be produced by sectioning functioning axons of the posterior root system, impulses from which have, in some way, been reaching the central nervous system. However, as Kato[19] pointed out, a few of the patients in his series showed a dramatic improvement in their neuropathic pain immediately after operation, whereas others showed relief from pain shortly after their return to work, suggesting that psychologic factors are important.

THE COMPLETE PREGANGLIONIC INJURY: AVULSION C5 TO T1

Carlstedt has continued and expanded work towards reconnecting the spinal cord to avulsed spinal nerves and more than 30 cases have been done at the Royal National Orthopaedic Hospital since 1996. Some remarkable results have followed. That regeneration from the spinal cord into the peripheral nervous system does occur is no longer a question for debate: what is required is refinement in selection, in appreciation of risk, and improvement in technique. Flow through the anterior spinal artery is maintained by radicular vessels concentrated at the cervical and lumbar enlargements.[24,25] An incomplete Brown-Séquard syndrome is detectable in at least 10% of cases of complete avulsion. Diminution of flow through the anterior spinal artery caused by interruption of the radicular arteries is one possible explanation. Potential ischemia of the cervical cord overshadows attempts at reimplantation of avulsed spinal nerves. Direct access to the ruptured ventral root is an interesting possibility. In one of our cases, a small joint arthroscope introduced into the foramen of C8 revealed the ventral root floating around in the cerebrospinal fluid, and in three cases it was possible to graft onto the stump of the ventral root. Such cases offer a challenge for future development.

Fig. 7. "Distraction or destruction." This 44-year-old man sustained avulsion of C6, C7, C8 and T1, with severe lesion of C5. We repaired the subclavian artery on the day of injury but no repair of the nerves was possible. He had useful spontaneous recovery into the suprascapular nerve and a successful free muscle transfer (latissimus dorsi) restored elbow flexion. He returned to full-time work 3 months after his injury because it helped his pain. The motto is his.

SUMMARY

To the biologic imperative of urgency of repair in these severe injuries is added the technical ease of early exploration. We have dismal experience of operations in late cases, where fibrosis prevented full analysis of the lesion and restricted opportunities for repair. In some cases, fibrosis was so severe that the operation was abandoned, which was particularly true where undue delay occurred between emergency repair of subclavian artery and exploration of the nerve lesion. Some methods of repair are possible only in the early days after injury, and these include selective reinnervation of the ventral root and reattachment of the avulsed spinal nerves to the spinal cord. The gap between stumps can be greatly diminished and, often, the distal stumps lie deep to, or even below, the clavicle. Recording of central conduction is essential in the analysis of the lesion in early cases to ascertain the quality of the proximal stump.

The traction lesion of the supraclavicular brachial plexus is different from that seen involving the cords of the brachial plexus in a severe infraclavicular lesion where nerves may be greatly stretched but not ruptured, presenting a difficult problem for the operating surgeon. Instead, the injury to the spinal nerve in the posterior triangle is clearly one of avulsion, rupture, or recovery. Preparation of the stumps of the damaged nerves is much easier in the early cases, especially when peripheral conduction is still present. Resection back to a recognizable architecture usually coincides with return of conduction centrally and distally and it is remarkable how little we resect. I reject the idea that early repair will be compromised by fibrosis; the most difficult and the most fruitless cases that we have encountered have been sent to us late.

Associated injuries, and injuries to the spinal cord and the spinal column, can impose an absolute contraindication to urgent exploration of the brachial plexus in at least 15% of all of our cases. The risk for a gush of cerebrospinal fluid is also a factor in the early case. Although we have never experienced a case of coning, the clinician responsible must bear the possibility in mind, and sealing of the dural tear by absorbable sponge, fibrin clot glue, and plugs of muscle or fat is necessary.

The object of operation in the incomplete case, in those patients in whom C8 and T1 have survived, is to restore useful function to the upper limb by reinnervation of the shoulder and elbow. No muscle transfer at the shoulder girdle or elbow ever matches the results seen after a good nerve repair. Early improvement of hand function by musculotendinous transfer is facilitated by clear knowledge of the prognosis for the nerves.

In the complete lesion, the object of operation is to reinnervate two segments, or even more, within the limb, and one of the major aims of reinnervation is to ease pain. Complete avulsion is a terrible injury and much more work needs to be done to explore the opportunities for reconnection between the spinal cord and the peripheral nervous system set out by the pioneering work of George Bonney and Thomas Carlstedt. The clinician should never forget that the patient who has a complete lesion of the brachial plexus will endure misery and depression for many months. His/her livelihood is threatened. The operation is but the first step in rehabilitation. The first surgeon must actively engage in the whole process of rehabilitation, and must engage him/herself in active treatment of pain, in the mitigation of disability by provision of orthoses, and in actively supporting early return to work, return to work modified, early training for alternative work, or return to study. These patients need to be followed for many years and the later development of neurologic symptoms or worsening of pain requires thorough investigation.

Most of these patients are risk takers, and most demonstrate remarkable spirit and fortitude. Their loyal appreciation of efforts, which are all too often unavailing, is most rewarding (**Fig. 7**).

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