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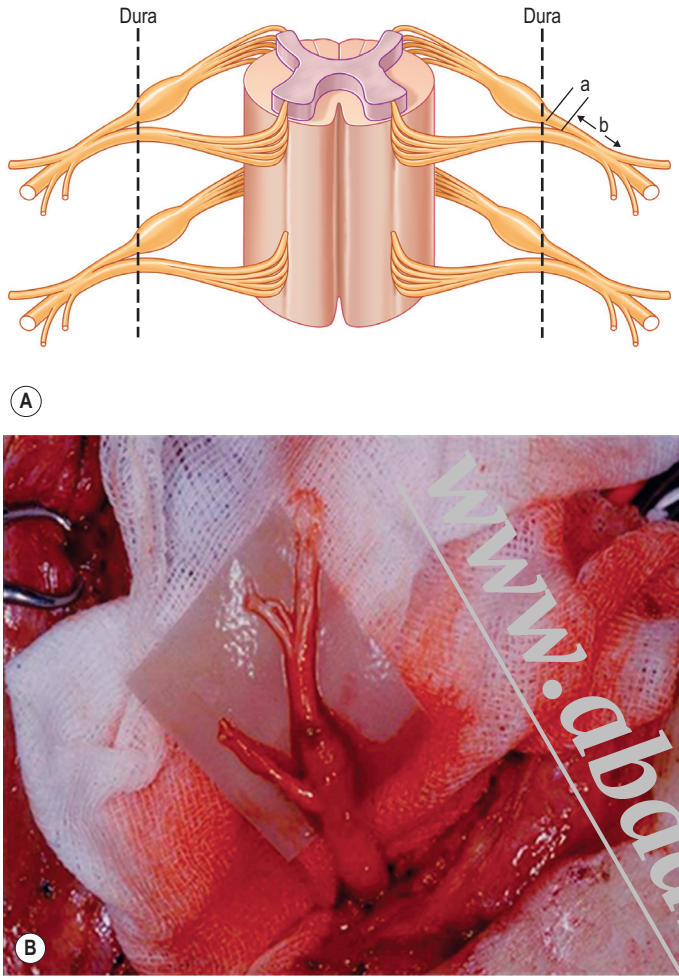


Figure 23.2 **(A)** The drawing shows that the postganglionic root is part "a"; the postganglionic spinal nerve is part "b" from the anatomy point of view; **(B)** an avulsion C7 (distal stump) during dissection.

Level II injury: inside the (scalene) muscle; it is postganglionic spinal nerve injury, located at the interscalene space proximal to the suprascapular nerve; pure level II injury is around 8%.

Level III injury: pre- and retroclavicular; it includes trunks and divisions; pure level III injury is about 5%.

Level IV injury: infraclavicular; including cords and terminal branches injury proximal to the axillary fossa; the second most commonly encountered injury, about 17%.

There are some relationships among the levels of injury:

1. An extended-level injury on the same nerve is frequently observed: for instance, C7 injury from the root level down to the interscalene space (level I and II injury).
2. A combined-level injury on different nerves is common: for instance, C5 and C6 spinal nerve rupture injury (level II) accompanied with C7–T1 root avulsion (level I).
3. A skip-level injury is rare: for instance, a longitudinal skip-level injury in which C5 and C7 are injured (avulsion or rupture) but C6 is intact; a horizontal skip-level injury in which level I and level III are injured, but level II is grossly intact.
4. Level IV injuries are usually isolated, and rarely show upward extension.

The term "supraclavicular BPI" will cover a large zone of injury, including level I, II, or III lesions.

Preoperative differentiation of supra- (level I–III) vs. infraclavicular (level IV) injury is important to avoid long incisions, unnecessary dissection and tissue damage, prolonged operative time, increased postoperative morbidity, and large scars [42] (Table 23.3). With the help of imaging studies and preoperative clinical evaluation, it is not difficult to diagnosis a level I lesion. However, when the injuries are incomplete, differential diagnosis becomes difficult.

Patterns of brachial plexus injury

There are two types of characteristic lesions seen in BPI: avulsion and rupture. Both are traction injuries but with different characteristics. Avulsion refers to the nerve being torn from its attachment (proximal avulsion occurs at the spinal cord, distal avulsion at the muscle or bone edge). Rupture is a nerve injury involving a traction force on an incompletely divided nerve, causing a complete division with irregular proximal and distal ends. In avulsion injury, only one disrupted end with a coiled spring-like appearance can be seen in the operative field in the acute stage (Figs. 23.3A & 23.4A), or a fusiform pattern (glioma) in the chronic stage (Figs. 23.3B & 23.4B). If a surgeon attempts to locate the other disrupted end, a second operative wound is usually required. However, in rupture injury the two nerve ends can be visualized in the same operative wound in the acute stage (Fig. 23.3C), or within a big neuroma noted in the chronic stage.

Root avulsion is very common in BPI due to its weak supporting structures consisting of dura and dentate ligaments. A novel approach of performing spinal cord implantation with or without nerve graft[43–45] showed unsatisfactory clinical results. This implies that in avulsion injury only one end (distal end) is available, while the other (proximal) end is absent or unsuitable for repair. "Root injury" is an obscure term which may mean avulsion from the cord (true avulsion), or rupture or stretch at rootlets or roots. Root avulsion in BPI is usually accompanied by dura tearing and a cerebrospinal fluid leak with cyst formation, called pseudomeningocele. However, in some cases the root can be avulsed at its origin with an intact dura cone (called "avulsion *in situ*"). The nerve root may remain inside the spinal canal or at the dural orifice, giving a grossly normal appearance or loosening with curvature of the spinal nerve at the time of surgical intervention despite established paralysis. Most often, however, the entire avulsed root, including ventral, dorsal roots, and ganglia, retracts and migrates downward to the interscalene or preclavicular region (Fig. 23.2B).

Pathophysiology and degree of nerve injury

Timing of nerve exploration is dependent upon the degree of nerve injury. The degree of peripheral nerve injury can be classified into neuropraxia, axonotmesis, and neurotmesis (Seddon classification[46]) or grade 1–5 injury (Sunderland classification[45]). Seddon's axonotmesis or Sunderland's second-degree injury starts to have wallerian degeneration

Table 23.3 Differentiatial diagnosis (DD) between supra- and infraclavicular BPI with incomplete paralysis of shoulder and elbow

Condition	Supraclavicular BPI	Infraclavicular BPI	DD
Isolated axillary nerve injury	Impossible	Yes	No need to DD
Isolated musculocutaneous nerve injury	Impossible	Yes	No need to DD
Shoulder dislocation		Yes	No need to DD
InfraclavicularTinel's sign (+)	+ (due to nerve regeneration)	+	**Need to DD**
Muscle strength examination			
(A) When supraspinatus (M0), serratus anterior (M0)	Yes	Impossible	No need to DD
(B) When supraspinatus (M>3), serratus anterior (M>3)	Impossible	Yes	No need to DD
(C) When supraspinatus (M<2), serratus anterior (M<2)	?	?	**Need to DD**
(C-1) when C-PM (M>3), teres major (M>3), LD (M>3)		Yes	**No need to DD**
(C-2) when C-PM (M<2), teres major (M>3), LD (M>3)	High possible level III		
(C-3) when C-PM (M<2), TM (M<2), LD (M<2)	High possible level II–III		
Condition			
Scapular fracture		Potential lesion	
Imaging studies	Important for level I	Not important	
EMG, NCV	important	important	

C-PM, Clavicular part of pectoralis major muscle; EMG, electromyography; LD, latissimus dorsi; NCV, nerve conduction velocity.

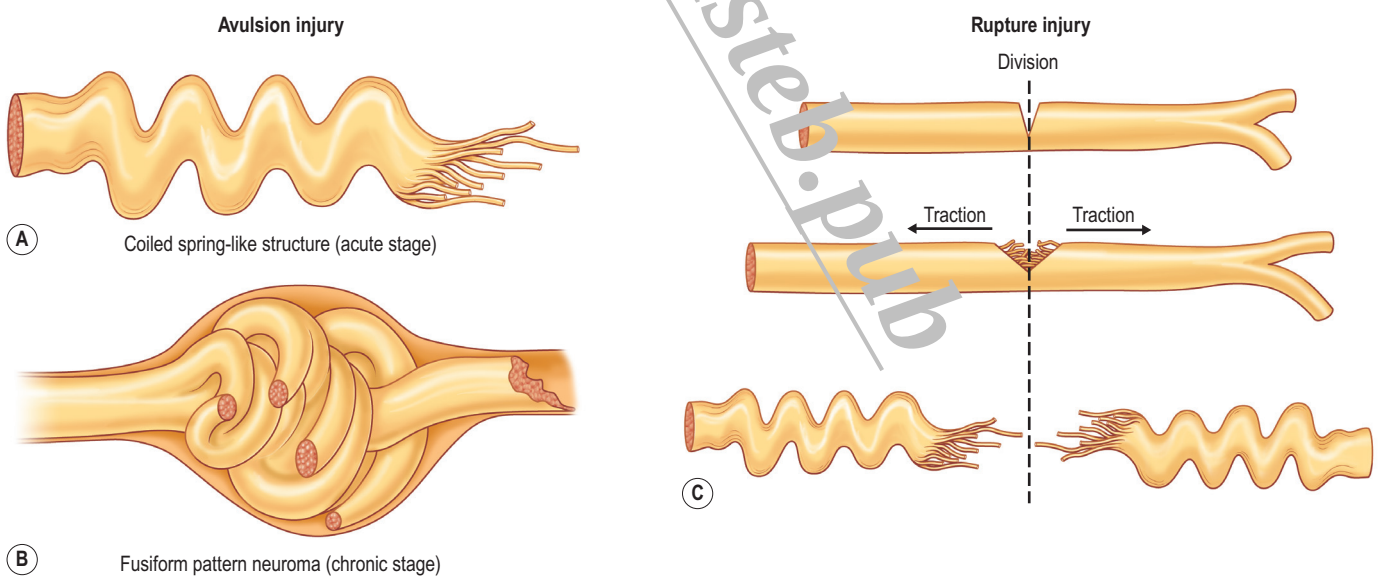


Figure 23.3 The drawing shows the mechanism of avulsion **(A,B)** vs. rupture **(C)** injury.

at proximal and distal stumps. Seddon's neurotmesis or Sunderland's third- to fifth-degree injury has the potential for aberrant reinnervation after nerve regeneration. In Sunderland's fourth- or fifth-degree injuries, only nerve repair can succeed in restoring continuity, but in first-, second- or third-degree injuries, spontaneous recovery, complete and incomplete, may occur.

Timing of brachial plexus exploration

There are five possible time points for brachial plexus exploration and repair:

1. Immediate repair or repair within days or weeks
2. Early repair within a month
3. Delayed early repair within 3–5 months

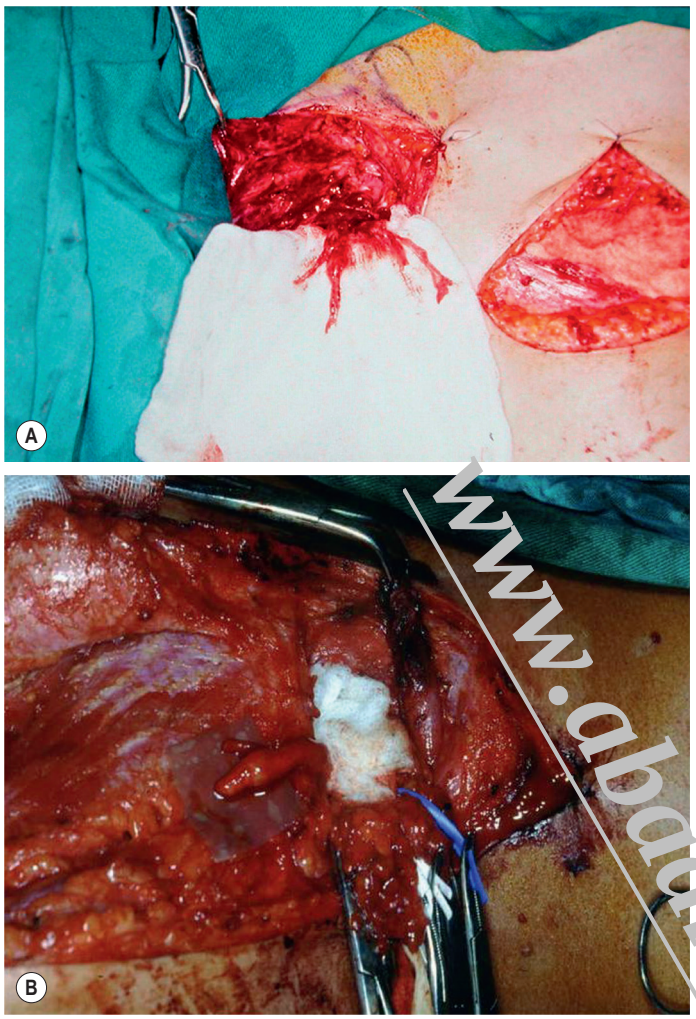


Figure 23.4 **(A)** Coiled spring-like structure with irregularity of stumps of C5 and C6 avulsion (acute stage); **(B)** fusiform pattern neuroma (or glioma) of the distal C7 stump (chronic stage) during dissection.

4. Late repair more than 6 months
5. Chronic repair more than one year

There is rarely an argument for immediate exploration after penetrating injury by sharp objects for direct nerve repair. Some surgeons also advocate exploration of the BPI as early as possible[47,48] for adult closed BPI for its advantages, including easy diagnosis of root avulsion and avoidance of difficult dissection through scarring. However, such early exploration is not recommended by most brachial plexus surgeons.[31,33,37] In cases of closed BPI, the degree and extent of injury are difficult to judge soon after injury and are often underestimated. The benefits of waiting usually outweigh the advantages of early surgery.[41]

Clinical evaluation

Etiology of adult brachial plexus injury

BPI may be caused by trauma (open or closed type), compression, tumor, infection, inflammation, toxins, and other etiologies.

Patient history

Patient history should include mechanism of injury, conscious level at the time of trauma, associated injury (such as head injury, fracture, open wound, chest injury, vascular injury), kinds of previous surgical intervention (such as chest intubation, cervical spine surgery), and characteristics of pain. This information helps to determine the degree and extent of injury and the need for surgical intervention. Mechanism of injury (e.g., upward or downward traction and with or without rotation) is not easily detected due to the patient's loss of consciousness or amnesia for the accident. A history of shoulder dislocation or glenoid fracture may have a high incidence of level IV injury, whereas a history of cervical spine injury or fracture may cause a level I root injury. Artery rupture and repair imply the site of nerve injury. For instance, arm traction by rolling machine or conveyor belt often causes an open wound in the axilla, extensive ecchymosis around the shoulder and chest (due to rupture of axillary vessels), and level IV BPI. Segmental thrombosis of the subclavian artery is usually associated with C8–T1 root injury. History of rib fracture and chest intubation may preclude intercostal nerve transfer because of a higher failure rate.[49] Extreme causalgia with or without a phantom limb is often seen in cases of root avulsion in lower-root (C8–T1) avulsion as they contain the richest sympathetic fibers. The pain character, like an electric shooting, continues for short duration for seconds, followed by spontaneous relief and recurrence. Extreme causalgia is also a major factor for poor outcome due to poor rehabilitation. Sometimes a partial Brown–Sequard syndrome (hemitransection of the spinal cord with ipsilateral upper motor neuron lesion below the level of lesion, and contralateral abnormal sensation to pain and temperature which may not be at the same level) is also noted in the level I injury.[50]

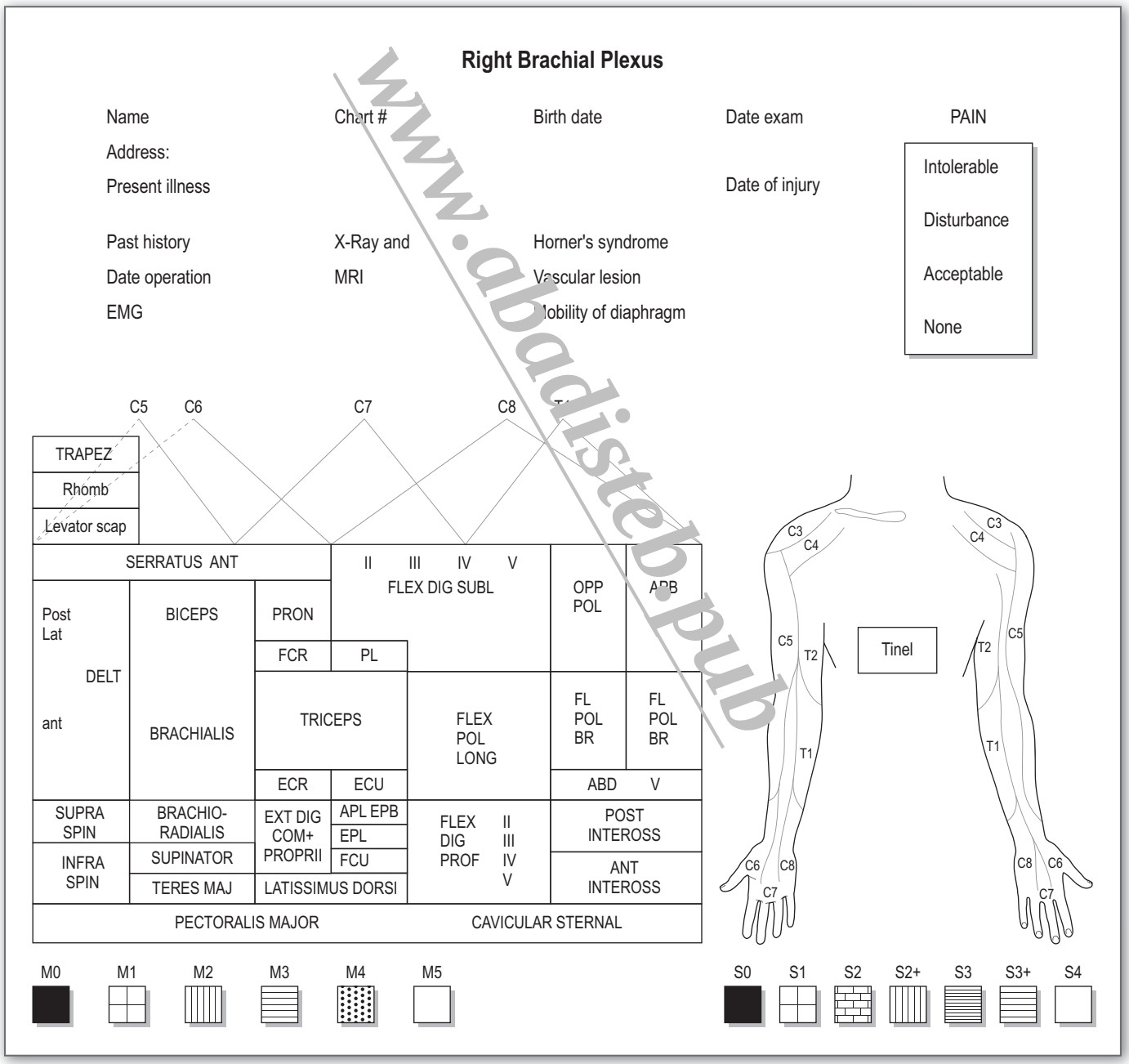
Preoperative evaluation and diagnosis

Most adult BPIs are closed injuries. Accurate assessment of the extent and severity of the injury in closed BPI is difficult. Clinical evaluation is still essential and is the most important step in establishing the diagnosis of site and degree of injury, and determining the treatment and prognosis. A brachial plexus chart (left and right formats, Fig. 23.5) outlining the possible injury should be completed before definite brachial plexus surgery. This chart is filled at the initial examination, usually performed at 2 months after injury. The chart is also useful for follow-up evaluations allowing comparison of clinical pictures.

Motor examination

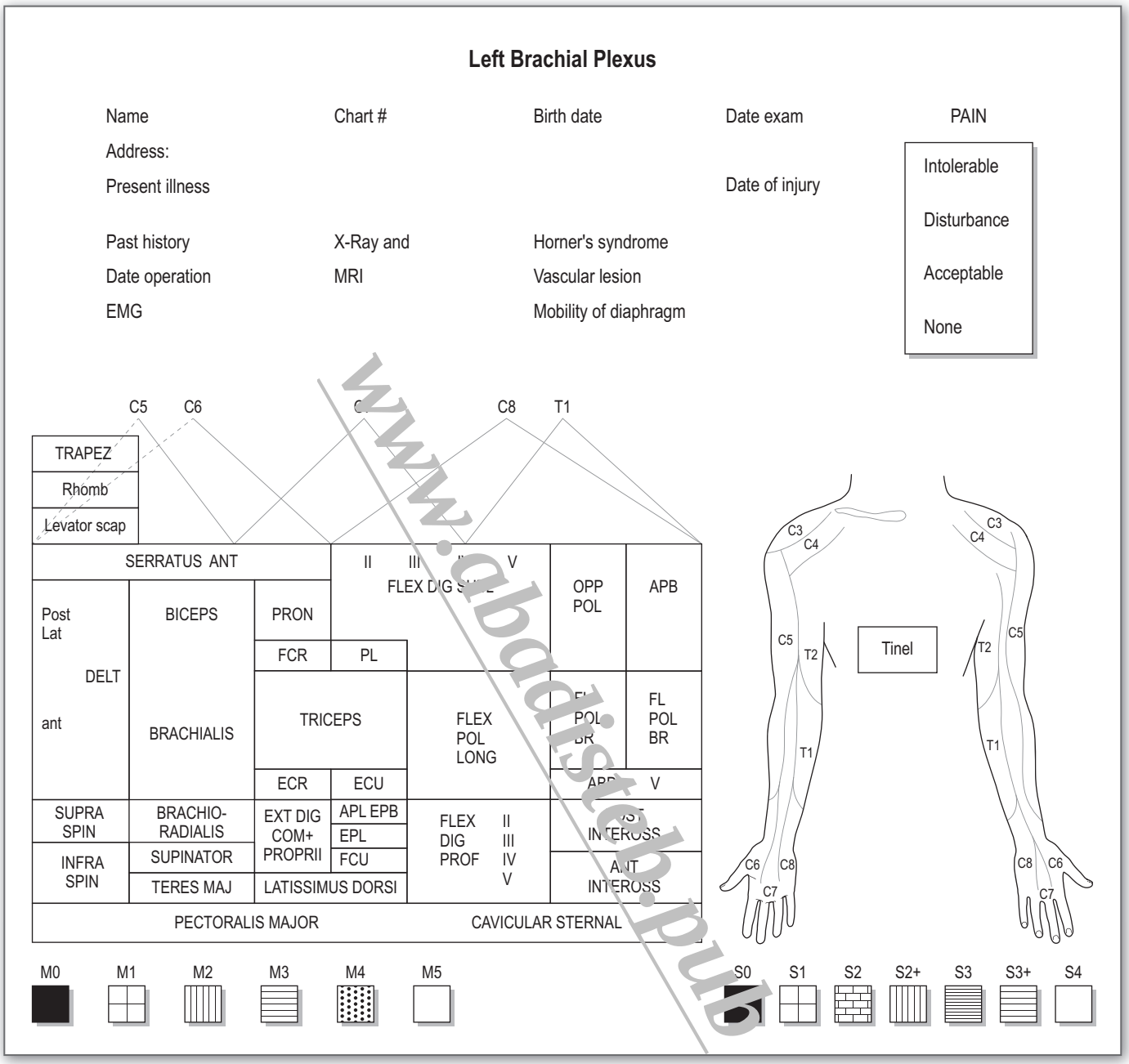
Muscle-by-muscle examination should be completed in a distal-to-proximal fashion and recorded, using the British Medical Research Council (MRC) scale (M0–5).[51] We have modified the motor evaluation system, adding more detailed differentiation: M5, strength against four fingers (examiner) resistance; M4, against one finger, resistance for longer than 30 seconds; and M3, against gravity (Table 23.4). M4 is recognized as useful muscle strength. The action of each muscle should be examined separately in relation to the movement of a single joint. Although there is no single muscle innervated by a single spinal nerve, some muscle palsy can give specific information related to the level of the injury. For instance:

1. Diaphragm palsy implies C4 and very proximal C5 (level I) injury.
2. The levator scapulae muscle lies anterior to the trapezius muscle in the neck, and can be more easily detected than the rhomboid muscles, which are covered by the trapezius muscle. Both levator scapulae and rhomboid muscles are innervated by the same nerve (dorsal scapular nerve, or C4 and C5). Preservation of its function in upper plexus or total plexus injury may imply C5 is a rupture injury (level II) with an available proximal stump.
3. Serratus anterior muscle: The long thoracic nerve has two portions: the upper portion originating from C5 and C6, and the lower portion from C7. The upper portion is responsible for scapular protraction, and the lower portion is important for scapular stabilization.[52] Positive anterior traction of the scapula (shoulder protraction test) shows that at least C5 is ruptured after branching to the long thoracic nerve, so the proximal C5 is available for transfer. Scapular winging is observed only when the lower portion is denervated, but isolated C7 root avulsion is rarely seen in adult BPI. In pure



(A)

Figure 23.5 Special charts for evaluation of the brachial plexus injured patient, **(A)** for the right and **(B)** for the left upper limb.



B

Figure 23.5 cont'd

C5–6 level I injury, the lower part of the muscle is still functional. The result of spinal accessory nerve transfer to the suprascapular nerve is much superior in the reconstruction of total root avulsion.

4. Clavicular and sternal portions of the pectoralis major muscle: The major pectoral muscle can be separated into two parts: clavicular and sternal parts. The clavicular part is innervated by upper and middle trunks or its divisions (lateral pectoral nerve), while the sternal part is innervated by the lower trunk (medial pectoral nerve). An incomplete or complete paralysis of the clavicular part of the pectoralis major muscle may imply at least level III or more proximal lesion.[42]

Sensory examination

Sensory evaluation should include sensory tests and elicitation of a Tinel's sign. Sensibility tests include pain and temperature appreciation, static and moving two-point discrimination, constant touch, and vibration. However,