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Upper Extremity Arterial Disease: Amputation

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Upper extremity amputation remains infrequent in today's vascular surgery practice. Loss of a portion of the arm and hand is usually a devastating and life-altering event, with surgery representing only the beginning of a life full of challenges for these individuals. Rehabilitative, social, financial, and psychological considerations are important and may be different from those patients who have suffered lower extremity loss.

EPIDEMIOLOGY

In 2005, there were approximately 1.6 million amputees living in the United States, with upper extremity amputations accounting for one-third of these.¹ Approximately 185,000 patients undergo amputation each year in the United States, with an estimated 10% to 25% of these involving the arm and hand.^{1,2} As the number of amputations is projected to double

over the next four decades, the relative proportion of upper extremity amputations is expected to remain stable. Most amputations in the upper extremity (93%) involve minor amputations at the wrist or within the digits.

Etiology

The majority of upper extremity amputations are the result of trauma (80%–90%), and thus these patients are generally younger (average age 20–40 years old) and predominately male.^{1,2} However, other etiologies exist and include vascular disease and tumors, representing 7% and 0.6% of upper extremity amputations, respectively. Other less frequent causes include infection, congenital anomalies, and iatrogenic complications from catheterization, vasopressor administration, or vascular access.^{1,2} This overall distribution differs from lower

extremity amputation, where vascular disease is the inciting etiology in nearly 80% of cases^{1,2} (see Ch. 114, Lower Extremity Amputations: Epidemiology, Procedure Selection, and Rehabilitation Outcome).

Ischemia as the cause of upper extremity amputation usually results from trauma. Atherosclerosis is less common in the arteries of the arm and is a rare form of peripheral arterial disease.³ Even in more chronic scenarios, the most frequent reason for upper extremity revascularization is traumatic injury, followed by embolization from more proximal atherosclerotic or cardiac origins as opposed to chronic occlusive disease.^{4–6} Such trauma may include vibration-induced white finger, hypothenar hammer syndrome, and athletic-associated conditions such as quadrilateral space syndrome and arterial thoracic outlet compression resulting in subclavian aneurysm. Arterial trauma or embolization related to drug use may also be responsible. Apart from atherosclerosis, a variety of arterial disorders leading to extremity arterial insufficiency may affect the arm, including vasospastic disorders (e.g., Raynaud disease), vasculitides, small-vessel diseases (e.g., Buerger disease), and radiation-induced arteritis.

Trauma and Military Injuries

The long-standing experiences from Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF, Afghanistan) have provided continued insight into traumatic vascular injury of the upper extremity and upper extremity amputation. Stansbury and colleagues characterized the amputations that occurred in 8000 United States troops after injuries to extremities during the first 5 years of OIF/OEF, finding that 7.4% of major limb injuries required amputation and that nearly 18% of amputees required multiple limb amputations.⁷ Interestingly, the experience in the upper extremity is somewhat different from that in the lower extremity. With nearly 3400 major upper extremity injuries recorded, the arm amputation rate was 3.1%, which is in contrast to the 8.5% lower extremity amputation rate in almost 4000 major lower extremity injuries, despite a similar incidence of neurovascular injury (15%) in the two groups.

Nevertheless, experience in Iraq clearly depicts the seriousness of arterial injury in the upper extremity during OIF.^{8,9} At the 332nd Expeditionary Medical Support Group (EMDG), Air Force Theater Hospital in Balad, Iraq, almost 10% of patients with upper extremity arterial injury who underwent initial attempts at arm salvage ultimately required amputation during the early period. However, if revascularization is successful among those sustaining upper extremity arterial trauma, the prospect of limb salvage into the later phases of treatment and rehabilitation is excellent.¹⁰ This reaffirms a small body of literature indicating that even in those with significant neurovascular, bony, and soft tissue upper extremity injury, aggressive limb salvage attempts are often successful.^{11–20} Moreover, even though disability after upper limb salvage is expected, intensive therapy can lead to improvement over the longer term and thus, unless absolutely clear from a destructive or systemic indication, early amputation should be avoided. Even in cases of traumatic upper extremity amputation, reimplantation,

as opposed to revision amputation and rehabilitation with a prosthesis, has been associated with improved patient-reported outcomes, with the majority of patients retaining function of the extremity.^{21–24}

The visibility of upper extremity amputation from OIF/OEF troops has led to an appreciation by society and produced an increasingly supportive environment. Our ability to address, improve, and provide newer prosthetic technologies, broadened therapeutic applications, and rehabilitative principles has been advanced for those missing a segment of an arm or hand. However, even with these advances, upper extremity amputees are unlikely to be found “fit for duty.” In a series of 1315 service members that sustained 1631 amputations, 173 service members were found to have an upper extremity amputation, none were found fit for duty, and only 12 were allowed continuation on active duty. In addition, upper extremity amputees were more likely to have a disability from posttraumatic stress disorder (PTSD) versus the general amputee population. These findings underscore the complexity of patients suffering an upper extremity amputation.²⁵

Nontraumatic Disease

When the cause of upper extremity limb threat is nontraumatic vascular disease, initial treatment should be directed at correcting the underlying condition. This may be relatively simple and systemic, such as cessation of smoking in those with Buerger disease; operatively straightforward, as with thromboembolectomy and anticoagulation; or more complex and infrequent, such as sympathectomy for vasospastic diseases and bypasses, with or without thrombolytic therapy, for occlusive disease. Unfortunately, all of these may proceed to a final pathway that requires some form of amputation, in which case the principle of conservatism and conservation of parts is critical, as aggressive surgical procedures may both aggravate the ischemic process and impede eventual function. Initial management of upper extremity ischemia, after revascularization, includes allowing adequate time for demarcation of the ischemic tissue, as this may allow a lesser level of amputation. Further avoidance of vasoconstrictors, such as nicotine and caffeine, may facilitate some healing and decrease the need for surgical intervention.

GENERAL CONSIDERATIONS

Initial Management

Amputations secondary to trauma are generally managed in a staged fashion to preserve as much of the arm as possible, based on principles dating back to the care of battlefield injuries during World War II.²⁶ As opposed to the lower extremity, which requires only adequate soft tissue coverage in anticipation of a functional prosthesis, an upper extremity amputation must be both functional and cosmetically acceptable, and thus definitive decisions on the level and length of amputation should not be made in the acute setting. Sequential stepwise debridement and later definitive closure are key to ensuring technical and functional success. In recent years, advancements in wound care and wound bed preparation prior to definitive closure, including the

use of negative pressure therapy to promote tissue granulation, has allowed for this staged approach to become the mainstay of therapy, even in the modern battlefield.²⁷ Additionally, emotional and functional rehabilitation has dramatically improved, with advancements in prosthesis design and functionality allowing these patients to return to meaningful positions in today's society. Factors that play major roles in individualizing the surgical strategy for upper extremity amputation include etiology, age, handedness, occupation, associated injuries and physiologic state, accessibility to state-of-the-art occupational and physical therapies, and cultural settings.

Arterial Assessment

For all indications, the level of upper extremity amputation depends on adequate arterial perfusion. The use of physical examination in conjunction with noninvasive studies, such as duplex ultrasound, segmental pressure measurement, pulse volume recording, infrared photoplethysmography, laser Doppler techniques, transcutaneous oxygen tension ($tcPo_2$) measurement, and arteriography can ensure that no ischemic component of the injury will prevent healing. Although the use of these tools in selecting the appropriate level in upper extremity amputations is less well described than for lower extremity amputation, the same principles can be applied. Generally, healing will occur at the hand level when digital pressure exceeds 40 mm Hg and wrist Doppler pressure exceeds 60 mm Hg, while healing is unlikely for digit pressures less than 20 mm Hg. At the forearm and arm levels, healing will almost always occur when wrist or brachial pressure exceeds 60 mm Hg, or when $tcPo_2$ is 40 mm Hg or greater. Healing is less predictable when $tcPo_2$ is between 20 and 40 mm Hg, and wrist or brachial Doppler pressure is less than 50 mm Hg. Pulse volume recordings may provide evidence of collateralization and suggest a higher likelihood of success, although they remain nonspecific when blunted. Once the level for amputation is chosen, simple ligation of blood vessels during the procedure is usually sufficient, provided that tissue coverage of these structures can be obtained.

Preservation of Length

Although preservation of length is a fundamental principle of amputation surgery, length does not always correlate directly with function, depending on the type of prosthetic application contemplated. However, in general, it is important to retain and salvage as much residual stump as possible to maximize the ultimate functional outcome. To this end, several reconstructive techniques have been described to salvage stump length,^{28–33} including plastic and orthopedic surgery techniques such as bone and free tissue transfer. These techniques have been applied selectively and may be helpful in certain instances, particularly in elective procedures. Moreover, selective reimplantation methods and even hand transplantation have been suggested in an attempt to maintain viable, functional tissue and length for the upper extremity, and should be given consideration in certain

circumstances.^{23,24,34} Length preservation techniques may have a more limited role when vascular insufficiency raises concern for viability of grafted tissue, with longer length correlating with poorer healing. The level of the acute amputation must balance the chance of healing with function, as shorter lengths result in decreased function. In addition, the elbow joint should be retained, if at all possible, to facilitate later prosthetic function.

Soft Tissue Coverage

Historically, length depended on local soft tissue coverage, and if tissue coverage was not adequate, one merely shortened the extremity until closure could be achieved. Skin grafts, free flaps, and composite tissue transfer have, however, dramatically changed this approach. Skin grafts are applicable when the underlying soft tissue bed is acceptable, but one must be sensitive to the ultimate functional needs of the amputation site; in some cases, skin grafts may not be durable enough to tolerate therapy and the use of prostheses. Local flaps are also an option for providing soft-tissue coverage (see below), but their applicability is limited by the anatomy at more proximal amputation sites. Pedicled flaps (regional or distal) have a long, productive history in hand surgery; however, they have been increasingly replaced by free tissue transfers. This change is based on: (1) better matching of the tissue transferred (in terms of thickness and ultimate functional performance); (2) avoidance of additional surgery (whether for division or thinning of the flap); and (3) lack of the joint limitations that result from the immobility that is typically necessary with pedicled flaps. Free tissue transfer is increasingly being accomplished at sites proximal to the hand to achieve more satisfactory results.

Nerves

Prevention of neuroma is the most difficult problem in upper extremity amputation. Distal ligation, proximal ligation, coagulation, chemical ablation of the end, simple division, traction and division, nerve repair to other divided nerves, and immediate burial of the transected nerve end have all been attempted with varying degrees of success. A divided nerve always attempts to regenerate and, in so doing, produces a neuroma of variable clinical significance. Thus, the goal is not to prevent the formation of a neuroma altogether, but rather to reduce the pain or dysesthesias from the neuroma that will predictably develop. In general, locating the divided, free nerve end as far from external stimuli as possible and placing it in a healthy, unscarred bed of tissue are the best preventive measures. Early postoperative therapy (desensitization or sensory re-education) is also an extremely important determinant of the patient's ability to tolerate the dysesthesias that result from an amputation. Other techniques that can be performed in an elective scenario include centrocentral nerve union, in which severed nerve ends are connected to form a loop, and targeted reinnervation by way of nerve transfer techniques, which improve residual muscle and sensory function at the stump.^{35,36}

Bone and Cartilage

Bony prominences must be optimally contoured, as irregularities lead to aesthetic abnormalities and difficulty in obtaining optimally fitting prostheses. Inadequate debridement of traumatized tissue and displaced bony fragments, improper initial contouring of bone, or failure to identify bone-producing periosteum, which must also be contoured, are the sources of such difficulties. Visual identification of the periosteum is easiest during initial management of the injury, and achievement of a natural bone contour is greatly assisted by palpating the end of the bone through the skin before closure. This is even more important in amputations through joints, where natural anatomic flares of the bone produce aesthetically unnatural contours and interfere with prosthetic fitting.

Tendons

The hand represents a very delicate balance between extensor and flexor forces. It is extremely difficult to duplicate the balance of these forces through myodesic methods (i.e., suturing of tendons or muscles to bones) or myoplastic techniques (i.e., suturing of tendons or muscles to tendons or muscles of the opposite functional group; for example, suturing an extensor tendon directly to a flexor tendon over a bony amputation site). In general, such techniques are not used distally in the fingers and hand because they often add to the functional deficit. However, they do have value proximally, where the balance is not as critical, and re-education and adaptation are easier.

SPECIFIC AMPUTATIONS

Fingertip Amputations

Distal finger amputations are extremely common, and are most commonly the result of a crushing blow, such as from a closing door. Although many people arrive at the emergency department with the tip of the finger available for reattachment, the injury is usually too distal for microsurgical reattachment. Many surgeons have attempted composite reattachment (i.e., reattachment without specific revascularization), however given the poor results, these are not indicated except in young children.³⁷ Most composite grafts fail because: (1) the amount of tissue is generally more than can survive the ischemia until new circulation develops; and (2) the zone of injury is greater than the area of amputation (i.e., the tip is usually damaged and thus is not capable of surviving as a composite graft).

Technique

If the proximal portion of the distal phalanx is not severely injured so the insertions of the flexor digitorum profundus and extensor tendons are intact, preservation of that portion of bone is indicated for functional length. Otherwise, disarticulation through the distal interphalangeal joint is indicated. The flexor digitorum profundus tendon should never be sutured over the tip or to the extensor tendon because this can weaken grip in the hand (the quadriga effect).³⁸ The bone of the distal phalanx

should be of adequate length to support the nail bed and nail growth.³⁹ Generally, these amputations occur through a portion of the nail bed – if enough proximal nail bed ($\approx 50\%$) is present to provide a functional nail, the bed should be repaired under optical magnification with absorbable 6-0 or 7-0 suture.

The distal phalanx is usually rongeured back so the end of the bone is not exposed. The digital nerves are identified, distracted distally, and divided so they will be at least 1 cm from the fingertip stump to avoid neuroma formation. If the final cutaneous defect is then less than 1 cm^2 , simply allowing the wound to close by secondary intention is acceptable. Other wound closure techniques have been attempted; however, given that flap closures are frequently insensate and do not reduce healing time, ultimate functional recovery appears to be better after secondary healing.

Skin Grafts

If the cutaneous defect is greater than 1 cm^2 , the amount of time needed for closure and the ultimate functional result may not warrant healing by secondary intention. If there is no exposed bone, a skin graft is possible. Although the temptation is to use the amputated part as a donor source for the skin graft, this practice should be avoided, as the amputated portion has been traumatized and the overall success of such skin grafts is disappointing. However, one advantage of these grafts is that they may serve as temporary biologic dressings while awaiting definitive closure, even if they do not survive.

Nontraumatized skin graft donor sites that may be considered are:

- The ulnar border of the palm (within the operative field and a good color match)
- The forearm (the medial portion of the forearm or the elbow crease, although hypertrophic scarring can lead to some cosmetic deformity)
- The groin (a well-hidden donor area, although the color match is poor and some unwanted hair may be transferred).

Local Flap Closure

As mentioned previously, many alternative flaps are often useful for cutaneous defects of the fingertip. Some of the more common local flaps include:

- The Kutler flap,⁴⁰ a lateral V-Y flap for closure of a central tip defect
- The Atasoy flap,⁴¹ a palmar V-Y flap
- The palmar flap,⁴² based on both digital neurovascular bundles in which the entire soft tissue coverage of the digit above the tendon sheath is elevated and advanced to cover the tip of the finger
- Radius- or ulna-based local flaps, which preserve cutaneous innervation on the appropriate digital nerve,⁴³ with skin grafting of the donor site as necessary.

In addition to these local flaps, numerous regional flaps can be used, such as dorsal skin cross-finger flaps, palmar skin cross-finger flaps, and thenar flaps. Although it is sometimes necessary to use these regional pedicled flaps, they carry significant additional morbidity by creating joint stiffness because of the obligatory period of immobility needed for attachment of the flap.

Digital-Level Amputations

Mid-Finger Amputations

Amputations that leave more than half the proximal phalanx can be functional. These amputations represent variations of fingertip amputations. First, the bone is rongeured back a short distance to allow soft tissue coverage. Tendons that have been separated from their bony insertions by the amputation are placed on traction, divided, and allowed to retract into the palm. Digital nerves are a potentially more difficult problem. While it is preferable to divide them under mild traction and allow them to retract beneath healthy vascularized tissue to avoid neuroma formation, excessive traction may denervate the new tip of the digit. The associated soft tissue defect is managed in the same manner as a fingertip amputation.

Proximal Phalanx

Amputation proximal to the midportion of the proximal phalanx is typically non-functional, and while it may be possible for patients to wear a cosmetic prosthesis that allows for some functional restoration if enough digits remain, most patients find the remaining digit a nuisance (Fig. 122.1). The effects of proximal digital amputation vary with the finger involved. For example, an index finger, which is second in importance

to the thumb, when amputated proximally can prevent the use of the middle finger for writing. With middle or ring finger amputations, small objects fall through the opening left by the remaining short digit. The small fingers play a role in gripping objects, and if the finger becomes immobile, it may become caught on objects. Because of these issues, patients frequently choose to undergo secondary ray amputation; however, regardless of the certainty of this denouement, ray amputation should not be offered to the patient at the time of initial wound closure. Instead, deciding to proceed with elective resection of the remaining portion of the digit is a decision that each patient should reach by experience.

Ray Amputation

Ray amputation, which includes removal of the injured finger to the metacarpal base, often provides a far more cosmetically acceptable hand, especially with an index ray amputation. This technique usually involves a dorsal longitudinal incision over the index metacarpal, along with a palmar skin incision over the proximal phalangeal level. Alternatively, a circumferential racket incision may be used. Minimal digital nerve neurolysis should be done to prevent pain. Attention to myodesic and myoplastic techniques is critical because improper attachment of the remaining muscle and tendons to the lumbrical

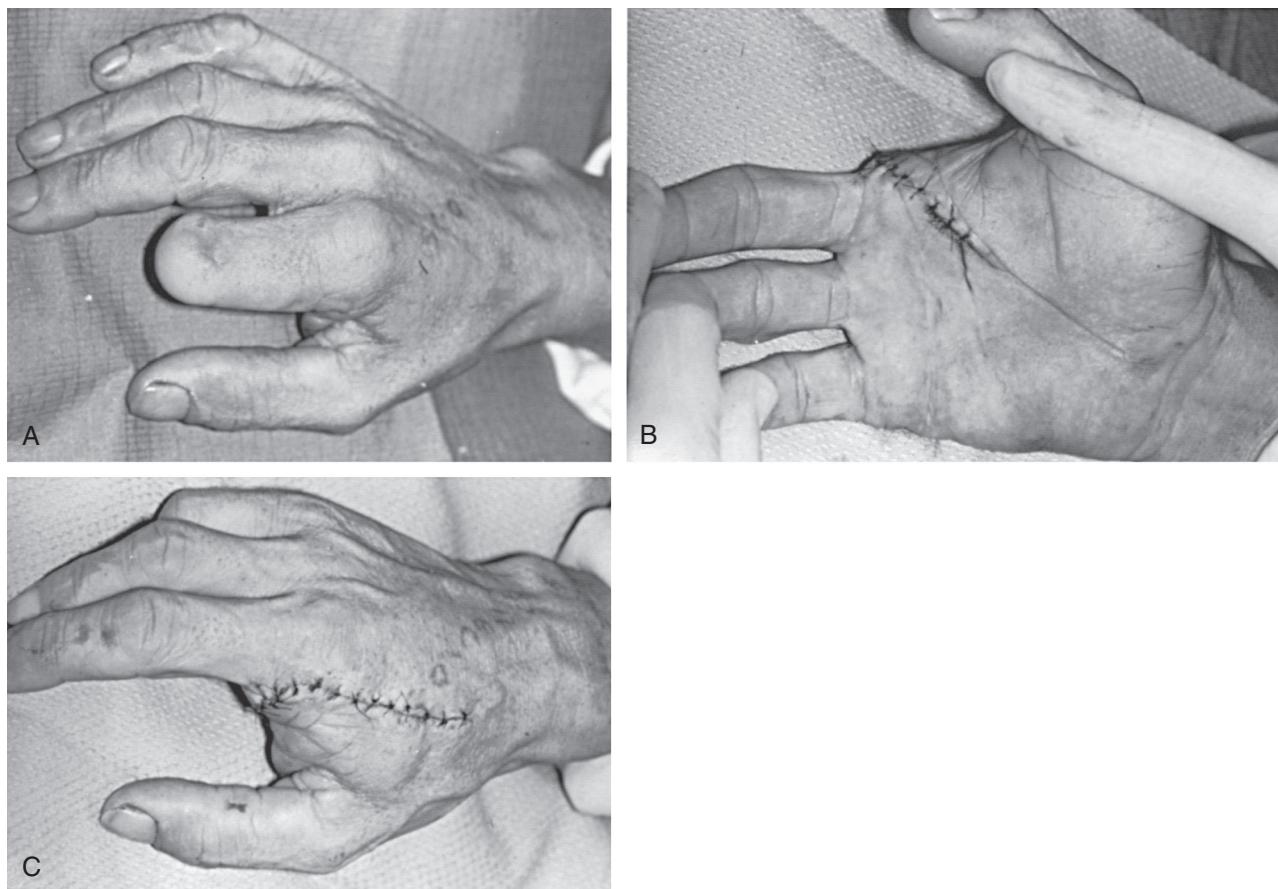


Figure 122.1 (A) Loss of the index finger at the proximal interphalangeal joint. The patient does not effectively use the index remnant but instead bypasses it to use his long digit. He requested elective ray resection because he thought that the remnant was in the way and unsightly. (B,C) Successful ray amputation is shown with a more natural hand contour.

and interosseous muscle or nearby periosteum can significantly downgrade intrinsic hand function. In addition, care should be taken when performing a fifth ray amputation because the extensor carpi ulnaris inserts at its base and wrist function can be affected.

In most cases, the appearance of a three-fingered hand with normal border contours is so natural that it goes unnoticed. Nevertheless, the operation is not without its own set of risks. First, the procedure narrows the palm by 20% to 25%, which reduces the hand's ability to stabilize objects. Second, the operation is a more extensive procedure that produces more proximal postoperative pain, edema, and stiffness than that caused by the original injury to the digit. Despite these limitations, ray amputation is very functional and cosmetically appealing, and there are few dissatisfied patients.

Thumb Amputation

Because it accounts for 40% of hand function, the thumb deserves special attention. Clearly, the major emphasis is on reattachment, and the current standard of care is to attempt reimplantation of the thumb whenever possible, with encouraging results being achieved even after avulsion injuries.⁴⁴ Non-reimplantable amputations at the level of the interphalangeal joint are functional, and most patients do not request or require additional reconstruction, as these stumps still provide the opposition function for the fingers. Revision of thumb amputations proximally to allow closure should not be performed as in the other fingers, and thought should be given to rotational, advancement, and free flaps.⁴⁵ More proximal thumb amputations can be reconstructed by pollicization (using a remaining finger, usually the index finger, and myodesic techniques to create a thumb), osteoplasty, bone-lengthening techniques, or toe-to-thumb transfer (great toe, second toe, or toe wraparound).

Hand–Wrist Amputations

Any tissue that can be preserved during hand amputation should be salvaged. A hand with a short palm may seem dysfunctional, but as an assist hand it may be preferable to a prosthesis. A transcarpal amputation allows for supination/pronation of the forearm and flexion/extension of the wrist, and can be fit for a prosthesis. Wrist disarticulation is preferred to more proximal forearm amputation because it has the same advantages of a transcarpal amputation, except that wrist flexion and extension are lost. Wrist disarticulation is performed by creating a long palmar and short dorsal flap; ligating the radial and ulnar arteries proximal to the wrist; identifying the median, radial, and ulnar nerves and distracting and dividing them; dividing all tendons; disarticulating the joint; and resecting the tips of the radial and ulnar styloid processes. The resultant smooth contour can easily be fitted for a prosthesis.

The radial, ulnar, and median nerves can present difficulties during hand–wrist amputation. The ulnar and median nerves are frequently avulsed at a more proximal level with these traumatic amputations – if they are apparent in the

wound, they can be severed with mild traction and allowed to retract. The sensory branch of the radial nerve, however, is quite superficial throughout its course in the forearm, covered only by the brachioradialis muscle, and neuromas from this nerve are not uncommon. Division of the nerve in the proximal part of the forearm may be considered at the time of the initial amputation. Sensation of the forearm skin is not directly determined by these nerves but instead is controlled by the brachial cutaneous nerves, and improper management of the brachial cutaneous nerves can cause difficulties similar to those that occur with the superficial branch of the radial nerve. However, it is preferable not to divide these nerves far proximally because sensation of the forearm skin will be sacrificed.

Forearm Amputations

The optimal level for a forearm amputation is the junction of the middle and distal third of the forearm. The issue with the distal third of the forearm is the relative paucity of padding in this area because of the thin skin and subcutaneous tissue. This factor can be more evident in patients with ischemia, as this area is notably prone to skin breakdown. So important is the elbow that the use of free-flap soft tissue coverage to preserve length or even distraction osteogenesis (Ilizarov technique)³⁰ is a viable consideration in the case of very short below-elbow amputations. However, with the exception of these very special cases, heroic efforts at preserving length are not usually indicated. In light of this, the surgeon can trim the bony tissues adequately to permit soft tissue closure. Equal anterior and posterior skin flaps are then created, followed by ligation of the radial and ulnar arteries; distraction and division of the medial, radial, and ulnar nerves; transection of the muscle bellies; and division of the radius and ulna. The deep fascia and overlying skin is then closed (Fig. 122.2). Reconstruction of the amputation is generally accomplished by means of a fitted prosthesis. However, as described by Tubiana, bilateral upper extremity amputations can be functionally improved with the Krukenberg procedure, in which a sensate pincer is created between the radius and ulna (Fig. 122.3).⁴⁶ The pincer is motorized by the pronator teres muscle, and this procedure allows preservation of proprioception and stereognosis. Although the cosmetic result is far from desirable, the functional improvement is great, and the procedure should be given serious consideration in the rare instances of bilateral injuries, in blind individuals, or when prosthetic reconstruction is not practical.⁴⁷

Elbow Disarticulation

If the elbow joint is not salvageable, elbow disarticulation is preferred over distal humeral transection. In addition to maintaining length, humeral rotation can be transmitted to the elbow, and the broad flare of the condyles makes for a good prosthetic fit. When compared with the forearm, which has two bones with a functional noncircular cross-section and thin soft tissue coverage that allows transmission of

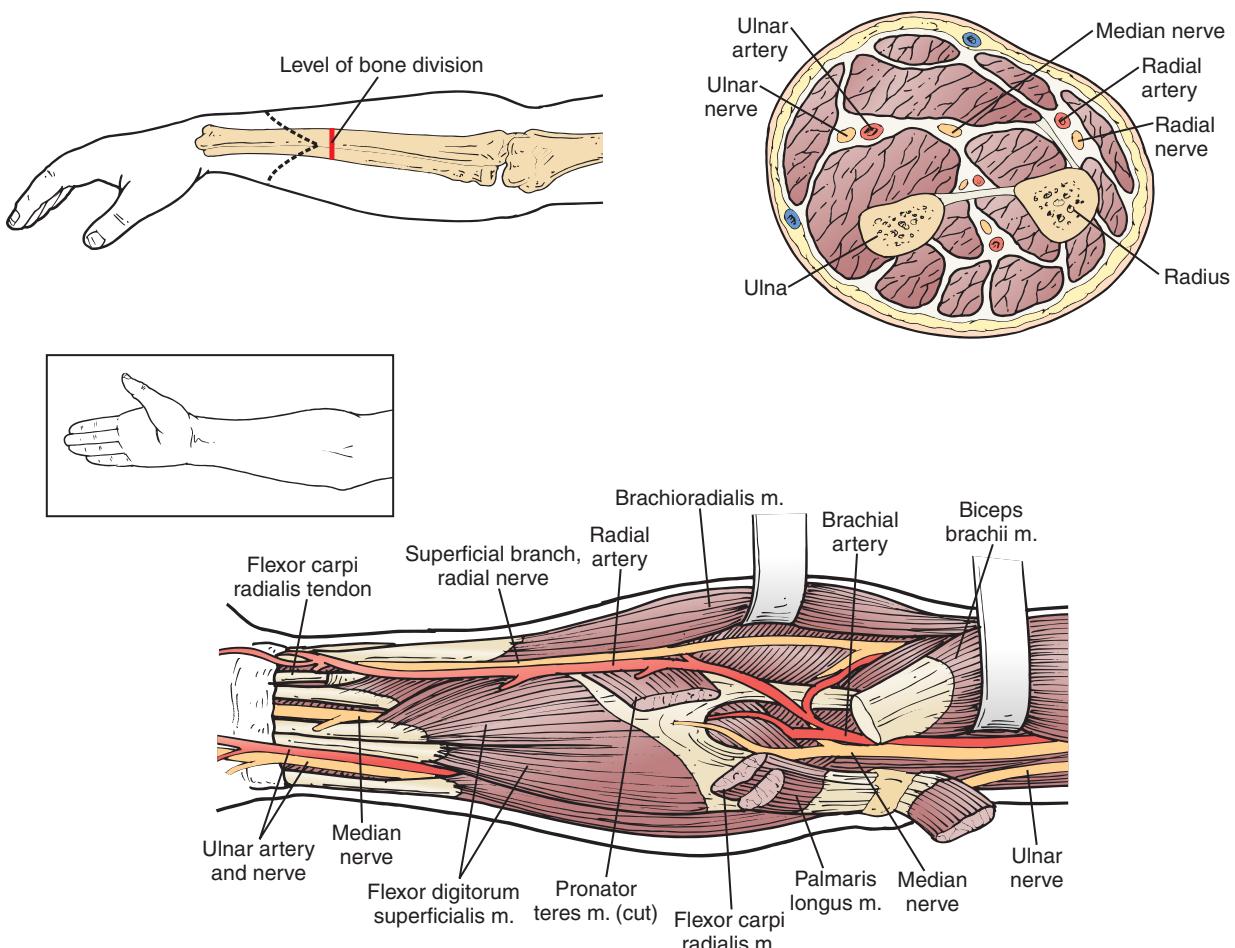


Figure 122.2 Forearm amputation is relatively straightforward: division of soft tissue at the junction of the distal third and proximal two-thirds of the forearm and several centimeters distal to the level of the bony division. Proper muscle coverage is achieved with myofascial closure. (Adapted with permission from Maxwell MC. Amputations in trauma. In: Thal ER, Weigelt JA, Carrico CJ, eds. *Operative Trauma Management: An Atlas*, 2nd ed. New York: McGraw-Hill; 2002:449.)

rotational forces (pronation and supination), the upper part of the arm has a single bone with a relatively circular cross-section and less rotational stability because of its thicker soft tissue. The amputation technique is similar to that described earlier in that anterior and posterior skin flaps are created; the brachial artery is ligated; the median, ulnar, and radial nerves are distracted and divided; the joint capsule is opened and the forearm removed; and a muscle flap (brachialis or triceps) is then used to cover the humerus (Fig. 122.4). As noted, there has been an emphasis on retaining all of the humerus if possible. However, in this case, the upper part of the arm may appear longer than the normal (unamputated) arm when fitted with an internal elbow joint prosthesis. While it is possible to use an external elbow joint option, these are substantially less durable. Another approach to this problem involves construction of an artificial asymmetry by means of angulation osteotomy, in which bone is resected yet epicondylar stability is retained.⁴⁸ This method has gained popularity in Europe but is not routinely practiced in the United States because of the obvious cosmetic deformity in the proximal remaining stump.

Upper Arm Amputations

Surgical considerations for above-elbow amputations are essentially the same as those for forearm amputations with respect to the treatment of bone, muscles, tendons, nerves, and skin. A transcondylar amputation functions essentially the same as an elbow disarticulation. More proximal amputations must include an elbow lock mechanism to stabilize the musculature and future prosthetic joint in full extension or flexion, and a turntable mechanism that will serve as humeral rotation. Considering the location of the elbow lock, which extends 4 cm from the distal amputation site, the transthumeral amputation should be made 4 cm proximal to the elbow (see Fig. 122.4).⁴⁹

Reimplantation remains a viable option, and Wood and Cooney have reported that reimplantation should be considered even with high amputations.²⁴ A multidisciplinary approach is required and involves early arterial and venous shunting followed by bony fixation, definitive vascular repair with attention to maximizing venous outflow, and finally nerve and soft tissue reconstruction. Functional recovery of the hand may not occur, yet it may be possible to convert

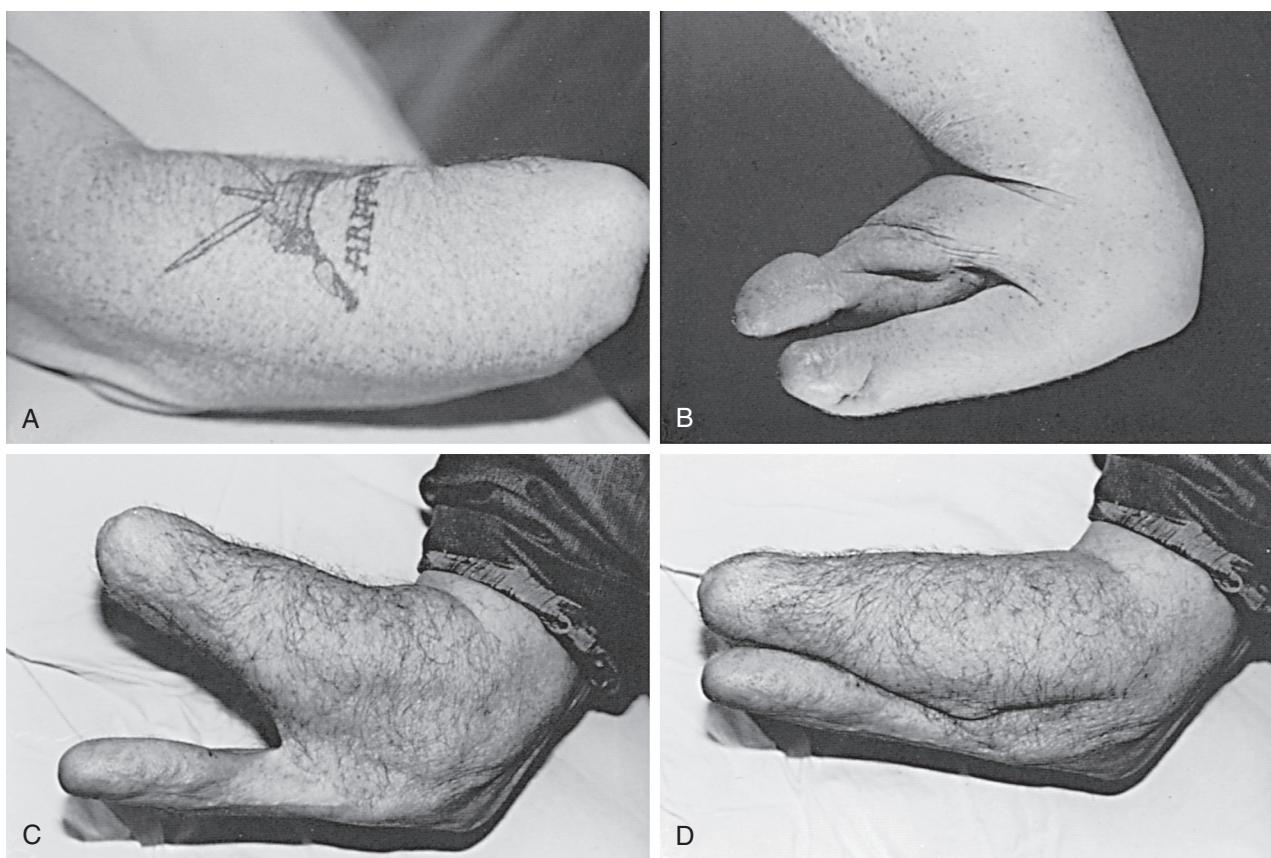


Figure 122.3 Classically, in a double-arm or blind amputee, the Krukenberg procedure has been performed. (A) A typical below-elbow stump. (B) The initial separation of the ulna and radius. (C) The open and (D) closed pincer grasp mechanism is preserved and controlled by the pronator teres muscle.

an obvious above-elbow amputation to a below-elbow amputation, which is far more functional. The shorter the remaining stump, the more difficult the prosthetic fit and the less functional the prosthesis will be. As a result, several new techniques have been developed to facilitate this type of reconstruction. The use of free flaps can provide additional soft tissue and bone length for a short upper arm amputation. Functional restoration of the glenohumeral joint may be accomplished with a free fibular transfer. The proximal humerus can be replaced with the fibula and its proximal joint with reattachment of the muscular insertions.^{28,29} Particularly in patients with malignant tumors, limbs that would otherwise have to be sacrificed can now be salvaged. Fibular flaps can also be used in conjunction with soft tissue coverage from a latissimus dorsi flap (pedicled or free) to provide acceptable upper arm length for fitting a prosthesis.

One final technique used to achieve adequate bony length is distraction osteogenesis, as mentioned previously.^{30–32} Although this technique was developed in the 1960s by Ilizarov, it did not become widely recognized and used worldwide until the 1990s. Limited reports of this method of treatment have been encouraging. As previously indicated, every effort should be made to avoid high amputations. Even when the amputation will be a functional shoulder disarticulation (amputation proximal to the insertions of the deltoid and pectoralis major muscles), maximal proximal length of

the humerus should be sought for either prosthetic fitting or potential reconstruction by these complex plastic and orthopedic techniques.

Shoulder Disarticulation and Forequarter Amputations

Shoulder disarticulation and forequarter, or scapulothoracic, amputation are the most complex and difficult procedures from a prosthetic and functional standpoint. Considerations are: (1) loss of potential motor units as drivers of the prosthetic device; and (2) difficulty fitting the prosthesis to contours. The shoulder disarticulation (after rounding off any bony prominences that may cause wear) leaves a contour adequate to provide a snug fit for the prosthesis (Fig. 122.5). In addition, scapular function is retained and can be used (with some difficulty) as a motor unit for the prosthetic device. However, a forequarter amputation (which is done almost exclusively for malignant processes), offers little hope for functional restoration of the limb, and prosthetic application is challenging.⁵⁰

The surgical techniques for these amputations are well described in the literature. The shoulder disarticulation may be modified by retention of the humeral head to assist in contouring or may be a true disarticulation with complete removal of the humerus. Regardless, the deltoid and pectoral muscles, along with their overlying myofasciocutaneous tissue, provide

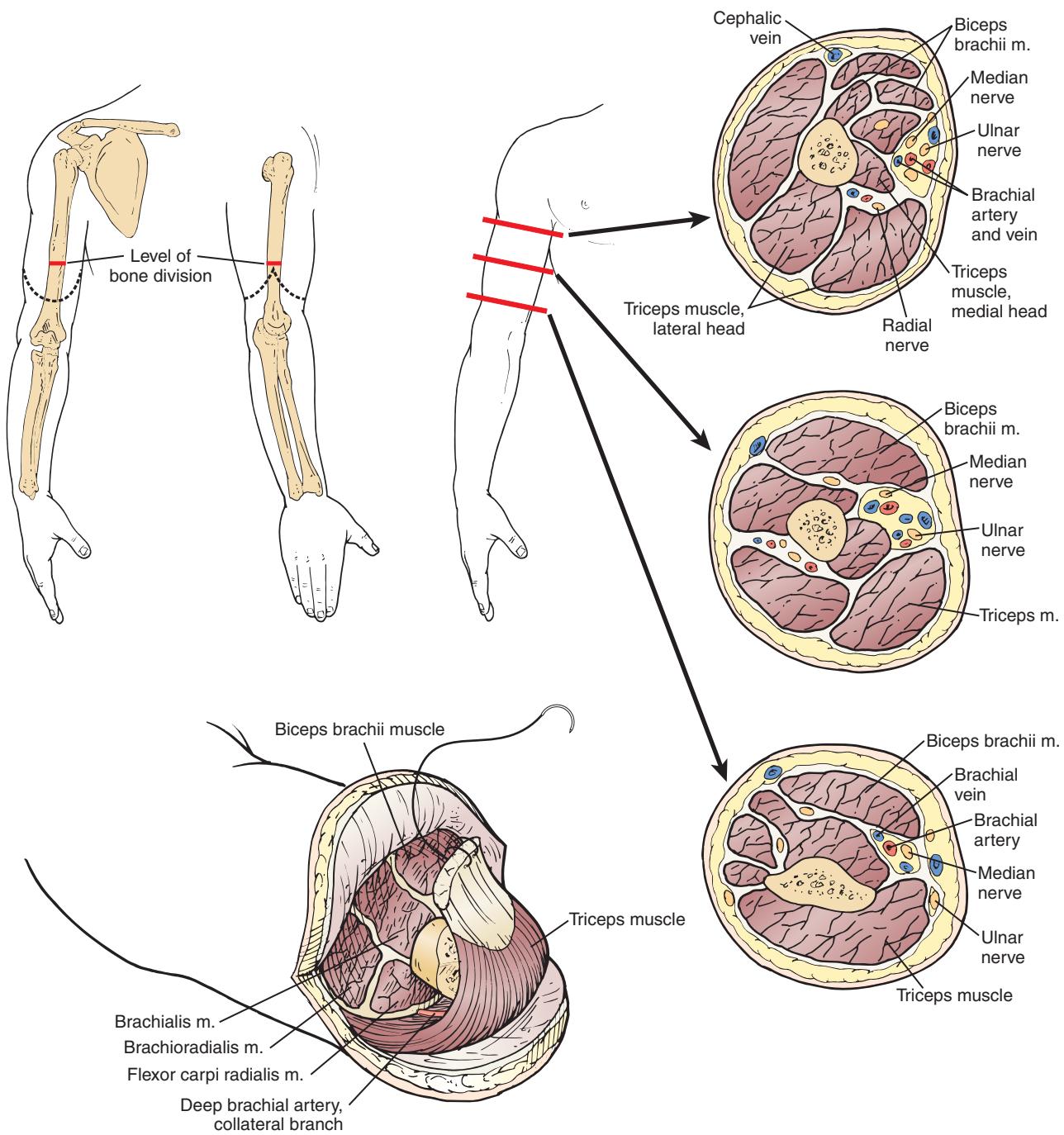


Figure 122.4 Upper arm amputation can be performed at several levels. The initial operation should be focused on maintaining as much humeral length as possible and the epicondyles, if salvageable. (Adapted with permission from Maxwell MC. Amputations in trauma. In: Thal ER, Weigelt JA, Carrico CJ, eds. *Operative Trauma Management: An Atlas*, 2nd ed. New York: McGraw-Hill; 2002:451.)

the flap coverage. Occasionally, if the deltoid is not available, an inferior axillary fasciocutaneous flap may be necessary. The latissimus dorsi and pectoralis major are reattached to either the glenoid capsule or the humeral head remnant. The tendinous components of the rotator cuff are also attached to the glenoid capsule. In a modified technique, their insertions are undisturbed, which reduces movement and, thus, pain in the joint area. It also stabilizes the muscles for future myoelectric control points.

There are two approaches to forequarter amputation. The anterior approach, described by Berger,⁵¹ and the posterior approach, described by Littlewood,⁵² differ only in exposure of the vascular structures hidden behind the clavicle. Both approaches are well accepted. Any available remaining myofascial components are used to provide closure. The same principles that were previously described apply in this situation. Specifically, removing the bony prominences, treating the nerves and muscles, and providing adequate soft tissue coverage.

POSTOPERATIVE MANAGEMENT AND COMPLICATIONS

Wound Treatment

Aside from standard postoperative wound and post-traumatic injury care, the principles of postoperative management after upper extremity amputation are supportive. There should be a low threshold for the use of drains in areas of potential space, as hematoma and seroma formation is common and cannot only delay rehabilitation and prosthetic placement, but also risks tissue viability and increases the potential for infection. Drain removal as soon as possible is encouraged to reduce infection risk. Early physical activity and rehabilitation are encouraged.

Compressive dressings are used immediately. The full range-of-motion exercises of the elbow and shoulder should be initiated immediately when these structures are preserved. Local amputation site concerns include infection, wound healing, and the viability of specialized reconstructive methods, such as free flaps. Infection is rare, and, even when trauma is the indication for amputation, should generally occur in less than 5% of cases. Failure of complex tissue transfers, if performed, occurs in 3% to 8% of upper extremity reconstructions early, and becomes even rarer in later evaluation.⁵³

Although poor wound healing and concerns of flap ischemia and stump necrosis are rare in comparison to lower extremity amputation, these must be recognized if they do occur. Potential systemic complications of upper extremity amputation

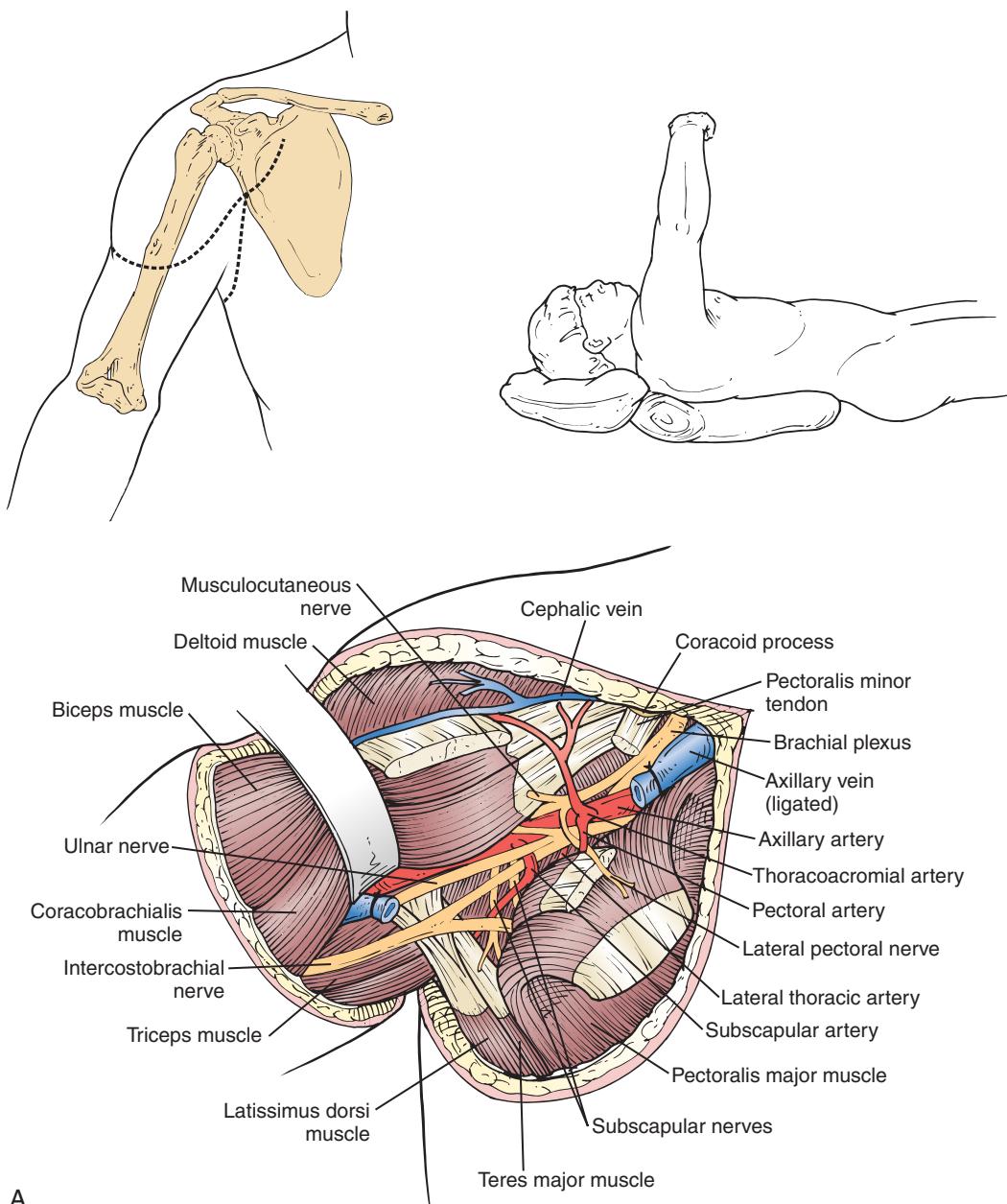


Figure 122.5 Shoulder disarticulation as classically described. (A) Skin incision and initial anterior approach with division of the anterior attachments, brachial plexus, and subclavian vessels.

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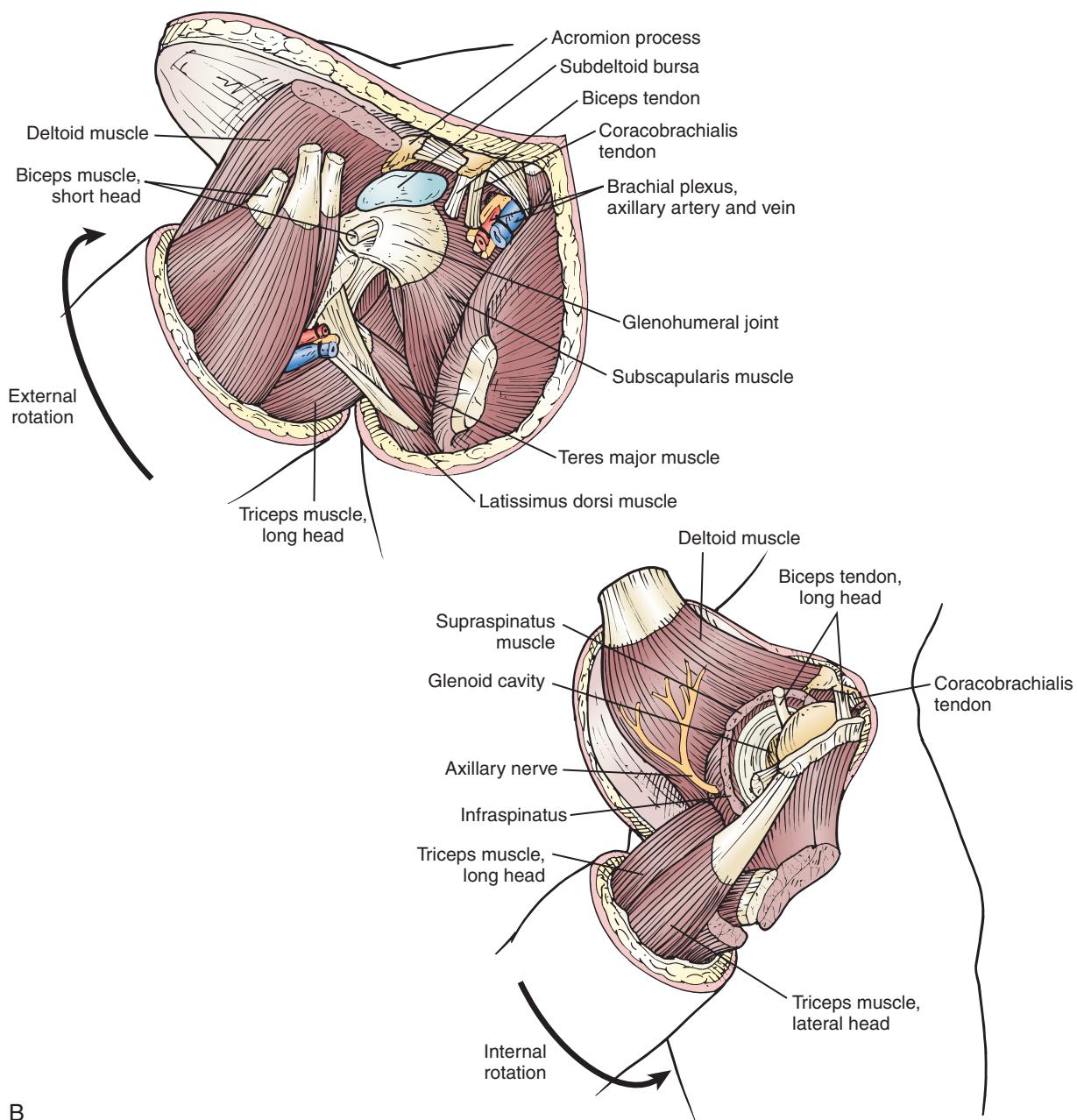


Figure 122.5, cont'd. (B) Completion of all anterior and posterior attachment transections.

Continued

include septic events, associated traumatic injuries, or systemic consequences of either a global vascular process or an organ system comorbidity. As with treatment of any ischemic injury, patients are at risk of rhabdomyolysis and myoglobinuria after upper extremity amputation, although the threat of this problem is usually less than in the lower extremity because of smaller muscle mass and shorter arm length.

Revision

Because the majority of upper extremity amputations are secondary to trauma, reoperations for residual limb revision are often required. Recently, in a study describing a cohort of soldiers involved in OIF/OEF including 100 major upper extremity

amputations, 42% required repeat surgical procedures. Interestingly, patients undergoing transradial amputation were 4.7 times more likely to have phantom pain. Revisions of these amputations resulted in an increase in prosthetic use from 19% preoperatively to 87% post-revision. Obviously, this underscores both the improved understanding and treatment of this complex patient population, as well as the complex and intensive care required to provide a reasonable endpoint for these patients.⁵⁴

Phantom Pain

Phantom sensations occur over time in the majority of patients undergoing upper extremity amputation. Long-term phantom pain, in varying degrees, occurs in 40% to 80% of

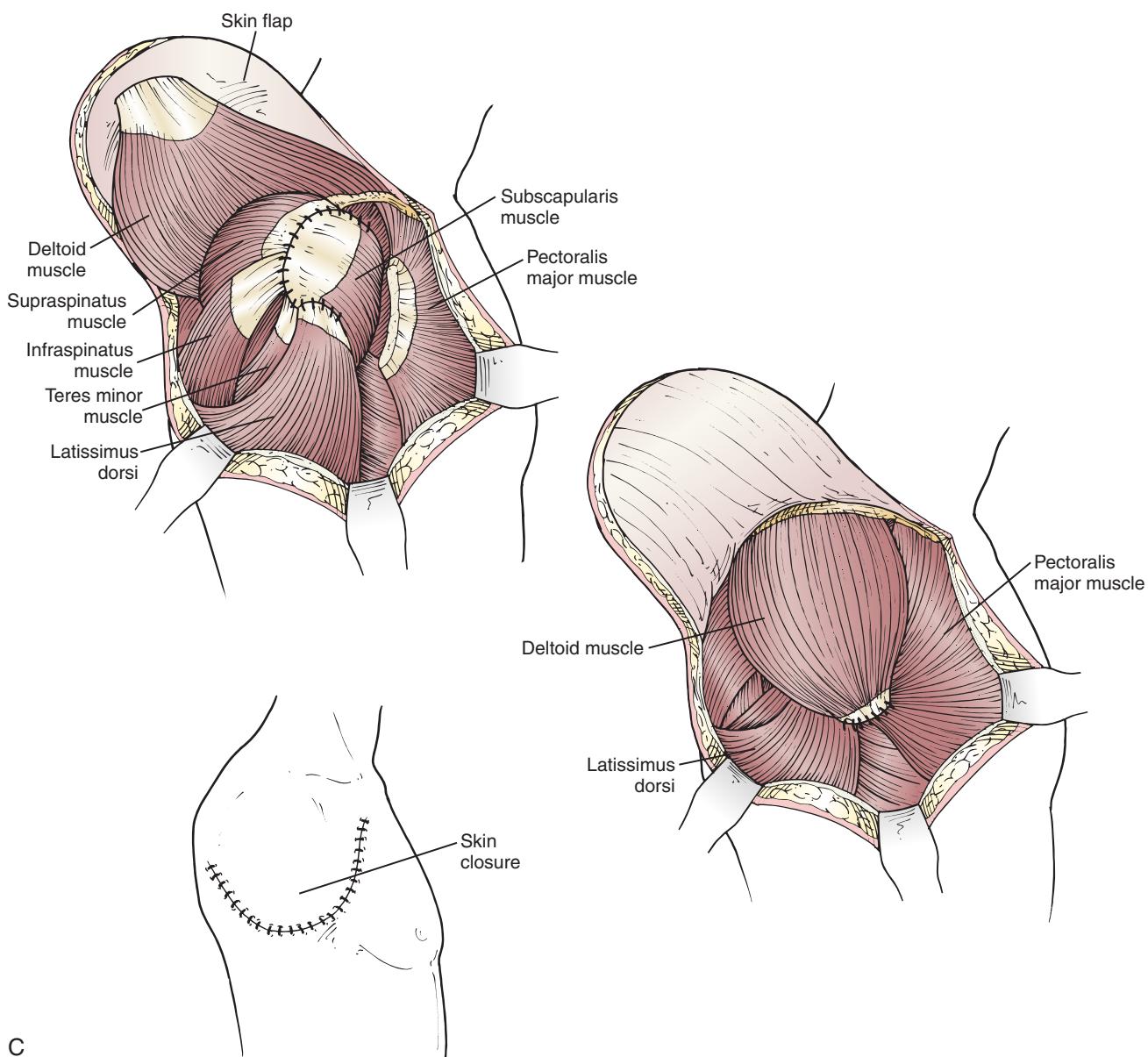


Figure 122.5, cont'd (C) Sequential closure over the glenoid of the scapularis muscle, other rotator cuff components, latissimus dorsi muscle, pectoral muscle, and deltoid muscle. (Adapted with permission from Maxwell MC. Amputations in trauma. In: Thal ER, Weigelt JA, Carrico CJ, eds. *Operative Trauma Management: An Atlas*, 2nd ed. New York: McGraw-Hill; 2002:452–457.)

patients.^{55,56} Treatment methods for phantom pain are numerous and usually multidimensional, but can be categorized as pharmacologic, surgical, psychological, and neurostimulatory. Newer evaluations of motor cortical changes and alterations in hemispheric function after upper extremity amputation may in the near future lead to novel therapeutic methods to treat post-amputation pain syndromes.⁵⁷ It has been suggested that loss of the dominant hand is an independent predictor for the development of more significant phantom limb pain.⁵⁸

Psychosocial Rehabilitation

When compared with lower extremity amputees, upper extremity amputees experience a higher rate of psychological disorders, such as depression, anxiety, and PTSD. Although poorly studied,

it appears that approximately 30% to 40% of upper extremity amputees will require psychological care, with studies noting a 28.3% prevalence of significant depressive symptoms.^{59,60}

Physical Rehabilitation

Rehabilitation for those with upper extremity amputation is complex and, to date, the technology and functionality of upper extremity prosthetics have lagged behind those of the lower extremity. Clearly, replicating the intricate movements and fine sensorimotor function of the native arm and hand has been difficult. The rehabilitative principles used for upper extremity amputees are not unique and encompass residual limb soft tissue shrinkage and shaping, desensitization, maximization of range of motion, skin health and mobility, muscle strength,



Figure 122.6 Aesthetic forearm and hand silicone prosthesis.

augmentation of self-reliance and daily activities, and exploration of prosthetic options.⁶¹ These key features are focused on reducing post-amputation pain and maximizing the potential for meaningful prosthetic use.

Prostheses

Prostheses used in the upper extremity fall into three categories: purely aesthetic, body powered, and myoelectrically powered.^{62,63}

Aesthetic prostheses usually consist of silicone and are fabricated to produce a lifelike appearance so the amputee can have a relatively normal body habitus (Fig. 122.6). They have very minimal function. Body-powered prostheses are simple mechanical devices that are controlled by residual body motion and function (Fig. 122.7). In general, these are the most durable prostheses and are used for most significant physical activity by amputees. Myoelectrically controlled prostheses convert the electrical stimulation of residual muscle groups into a current used to power the prosthesis. This has made movements, such as wrist rotation and finger movement, a reality, and many terminal devices may be attached to the prosthesis to allow various functions (Fig. 122.8). Although they permit greater degrees of freedom, these prostheses are much more complex, more expensive, and less durable for hard physical activity. Progress in myoelectric technologies continues at a rapid pace, and the Defense Advanced Research Projects Agency, in affiliation with Johns Hopkins University, is now developing and testing an upper extremity prosthesis that is myoelectrically controlled with nearly all the degrees of freedom of a human arm (Fig. 122.9).⁶⁴ The residual muscles are surgically reinnervated, with or without splitting, for the maintenance of cortical functioning to enable muscle contraction and, thus, application of the myoelectric prosthesis. This technique of targeted reinnervation has improved the prosthetic function in a small number of patients, and is allowing patients to simultaneously open and close the hand while flexing and extending the elbow.^{35,65,66} Another complex, contemporary method of neural control of biomechanical upper extremity prostheses involves the placement of electrodes directly on the cerebral cortex.⁶⁷ As this technique continues to undergo study and improvement, integration of direct cortical signaling into mechanical endpoints is proving to be intricate.



Figure 122.7 (A) Body-powered left arm prosthesis in a young soldier after transhumeral amputation. Note the pincer terminal device, cable powered by proximal movements at the shoulder girdle harness. (B) Forearm sleeve body-powered golf prosthesis with a terminal device for the club handle.

Hand Transplantation

The first hand transplant was performed in 1964, although it failed secondary to acute rejection. Since that time, over 70 transplantations have been performed.⁶⁸ The improvement in surgical technique and decreasing rejection with better immunosuppressive medications has led to success in hand transplantation. In a review of five bilateral hand transplant patients

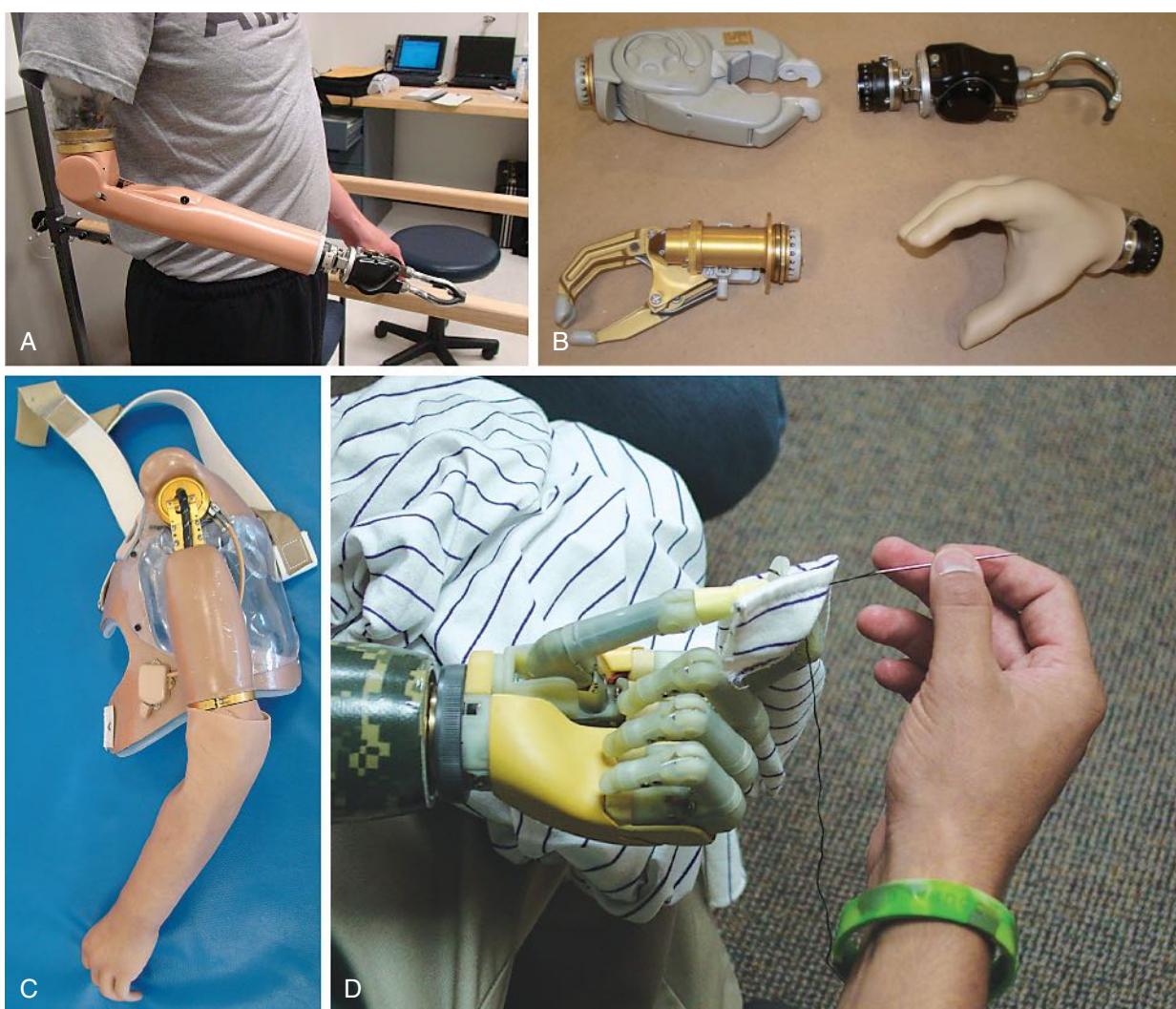


Figure 122.8 (A) Contemporary myoelectric arm prosthesis with a classic pincer terminal device. (B) Various detachable terminal devices used on myoelectric upper extremity prostheses for differing needs. (C) Shoulder girdle-mounted myoelectric arm prosthesis with a silicone aesthetic cover. (D) The i-LIMB hand (Hangar Orthopedic Group, Inc., Bethesda, MD) is a new hand prosthesis with myoelectric control that is able to simulate nearly normal hand motion.

with a mean follow-up of 7.6 years, Bernardon et al. found that although the physical results achieved were considered “fair” and the functional results were considered “good,” the procedure is demanding for patients and rehabilitation teams, and carries the risk of chronic rejection.⁶⁹ Alolabi studied the health utility of hand transplantation in the general public and a group of hand amputee patients, and found that their results did not support a clear benefit of hand transplantation.⁶⁸ As this technique grows and more long-term studies are performed, we will identify whether it is a viable solution for patients with hand amputations.

LONG-TERM OUTCOMES

There are few reports of late outcomes after upper extremity amputation. Meaningful comparative data is difficult to obtain because of differing causes, levels of amputation, and amputee age, in addition to many other variables. The rate of late stump revision remains poorly defined for similar reasons, but late

revision is not uncommon and is influenced by both disease and either prosthesis-induced or prosthetic technology-specific concerns. Such concerns may include late skin and musculoskeletal changes, and complications necessitating revision, such as ulcers, stump necrosis, dermatitis, infection, or disease recurrence in the stump, as with malignancy and vasculitis. In addition, revision of the bony and soft tissue stump components to allow the fitting and use of more modern prostheses may be chosen.

In general, attitudes toward prosthesis use in proximal upper extremity amputees are poor, and currently as many as 40% of these patients would rather not use prostheses.⁷⁰ Even those with hand-based amputations can find the return to activities of daily living and job performance challenging,⁷¹ though return to employment has a positive effect on prosthesis use.⁷² The potential for these long-term physical, socioeconomic, and psychological problems again reinforces the need for upper extremity amputees to have access to a multidisciplinary institution, regardless of whether they choose to seek contemporary rehabilitation and prosthetic options.



Figure 122.9 Complex myoelectric upper extremity prosthesis developed at Johns Hopkins in conjunction with the Defense Advanced Research Project Agency. Note the color-coded electrodes, which are placed on certain muscle groups for myoelectric control, or on various aspects of muscles after targeted reinnervation surgery, to allow areas of each muscle to independently transmit current.

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Thoracic Outlet Syndrome: Pathophysiology and Diagnostic Evaluation

HOLLY GRUNEBACH and YING WEI LUM

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INTRODUCTION

Thoracic outlet syndrome (TOS) is a condition resulting from compression of the neurovascular structures traversing the thoracic outlet.¹ The syndrome is divided into three types based on the symptoms and signs of neurovascular compression. Neurogenic TOS (nTOS) results from brachial plexus compression (see Ch. 124, Thoracic Outlet Syndrome: Neurogenic), venous TOS (vTOS) results from subclavian vein compression (see Ch. 126, Thoracic Outlet Syndrome: Venous), and arterial TOS (aTOS) results from subclavian artery compression (see Ch. 125, Thoracic Outlet Syndrome: Arterial). The distinct symptoms and signs of each of these syndromes are described in Table 123.1.

Most patients with TOS are 20 to 50 years of age. Fewer than 5% are teenagers, whereas 10% are older than 50 years. Seldom is any form of TOS seen in patients older than 65 and 70% are female. There is no explanation for the female predominance, but perhaps it is related to the observation that 70% of cervical ribs also occur in females. The exception to this is the subset of patients diagnosed with vTOS, as there is a 2:1 male predominance in this condition.

TOS is uncommon, but its true incidence is unknown because many people with upper extremity pain and paresthesias could have escaped diagnosis by healthcare providers who may have failed to recognize the diagnosis. Of the TOS subtypes, nTOS is by far the most common form, accounting

TABLE 123.1 Comparison of the Three Subtypes of Thoracic Outlet Syndrome

	Neurogenic	Venous	Arterial
Incidence	95%+	3%	1%
Etiology	Neck trauma (i.e., auto accident with whiplash), RSI at work, falls on the floor or ice	Repetitive overhead shoulder movements and/or coagulopathy	Cervical rib or anomalous first rib; rarely, congenital band
Predisposing factors	Cervical rib, congenital band, scalene triangle muscle variations	Congenital narrowing of the costoclavicular space by the costoclavicular ligament or the subclavian tendon compressing the subclavian vein	Cervical rib or anomalous first rib eliminating space under the artery
Pathology	Scalene muscle fibrosis; occasionally anomalous first rib or cervical rib	Subclavian vein stenosis with or without thrombosis	Subclavian artery stenosis, thrombosis or aneurysm formation with mural thrombus and emboli
Symptoms	Extremity pain, paresthesia, weakness plus neck pain and occipital headache, Raynaud phenomenon, chest pain for pectoralis minor syndrome	Swelling of the whole arm, cyanosis, pain	Pain, paresthesia, pallor, coldness; digital ischemia; arm claudication; seldom are there neck or shoulder symptoms
Physical examination	Positive response to provocative maneuvers; tenderness over the scalenes, pectoralis minor	Arm swelling, cyanosis, pain	Those with arterial occlusion: decreased pulses at rest, perhaps color changes and ischemic fingertips, distal emboli
Diagnostic tests	Duplex scan, scalene muscle block, MRI to rule out other conditions, pectoralis minor block, EMG/NCV, MAC measurement ¹	Duplex scan, venogram	Neck radiograph, duplex scan, arteriogram, digital pressures and waveforms, arteriography

EMG, electromyography; MAC, medial antebrachial cutaneous nerve; MRI, magnetic resonance imaging; NCV, nerve conduction velocity; PTA, percutaneous transluminal angioplasty; RSI, repetitive strain injury; Rx, treatment.

for more than 95% of all TOS patients; vTOS occurs in 2% to 3%; whereas aTOS comprises fewer than 1% of patients.

These syndromes result from a combination of developmental and anatomic anomalies in the thoracic outlet combined with physical activities and life events that predispose individuals to become symptomatic. A common initiating event is neck trauma, which causes symptoms in patients who may be anatomically predisposed to the development of compression in the thoracic outlet. In this chapter we describe the relevant anatomy, elaborate on the pathophysiology of each type of TOS, and follow up with a discussion of the diagnostic evaluation of TOS.

RELEVANT ANATOMY

There are three anatomic spaces that pertain to the thoracic outlet – the scalene triangle, the costoclavicular space, and the pectoralis minor (PM) space (Fig. 123.1). The costoclavicular space is traversed by the subclavian vein and is the most common site of subclavian vein compression (Figs. 123.1 and 123.2). The subclavian artery and brachial plexus traverse the thoracic outlet between the anterior and middle scalene muscles, also referred to as the scalene triangle (see Figs. 123.1 and 123.2). The scalene triangle is the most common site of brachial plexus compression. When present, cervical ribs and anomalous first ribs also compress the plexus in this location (Fig. 123.3).

Nerves

In addition to the brachial plexus, the phrenic and long thoracic nerves are seen during supraclavicular dissections. Very close to the area but rarely seen are the dorsal scapular nerve and cervical sympathetic chain.

Brachial Plexus

The brachial plexus arises from nerve roots C5 to T1. In the scalene triangle area the five nerve roots become three trunks. The anterior and posterior divisions and cords of the plexus are usually formed proximal to the PM space, so it is the branches of the plexus that lie under the PM muscle, along with the axillary artery and vein.

Phrenic Nerve

Arising primarily from C4, the phrenic nerve usually receives branches from C3 and C5. It is single in 87% and double or triple in 13% of individuals. The phrenic nerve descends 84% of the time from the lateral to the medial side of the anterior scalene muscle. In the other 16% of individuals, the phrenic nerve remains on the lateral side.²

Long Thoracic Nerve

The long thoracic nerve arises primarily from C6 and usually receives contributions from C5 and C7. The C5 and C6 branches run through the muscle belly of the middle scalene muscle, where they usually join. The C7 branch arises from the

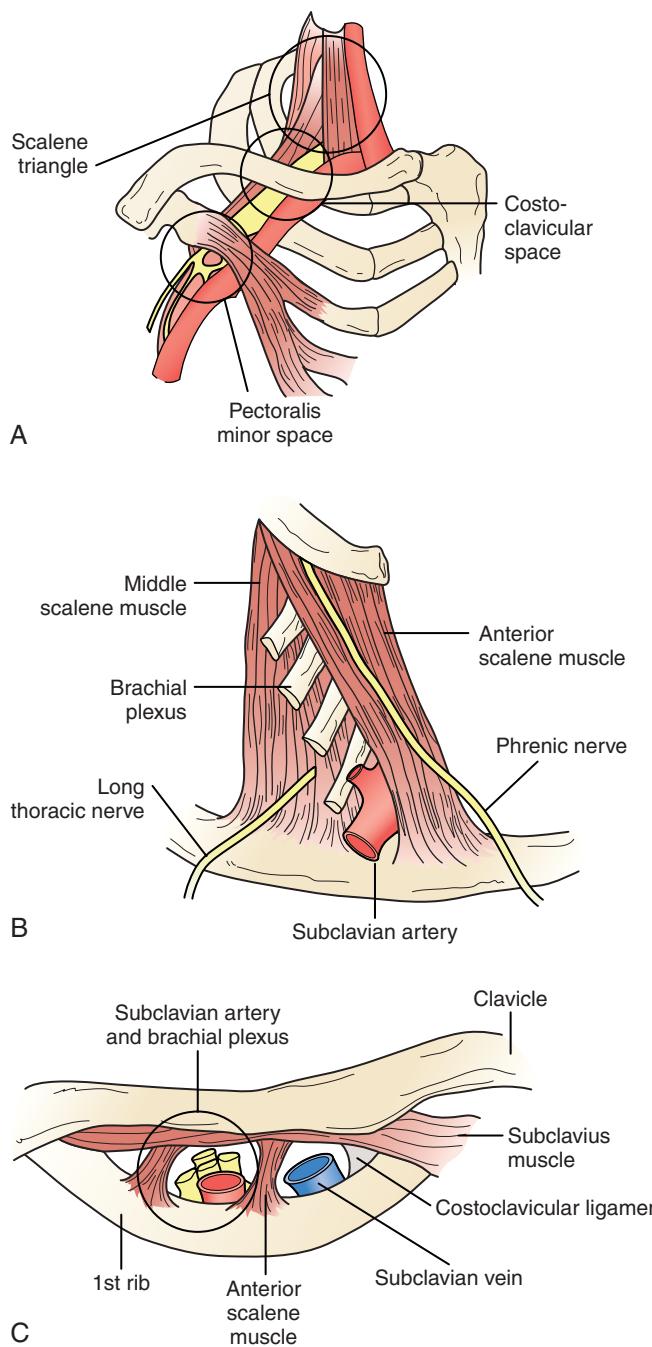


Figure 123.1 (A) Anatomy of the thoracic outlet with respect to the three major spaces. (B) Scalene triangle with the phrenic and long thoracic nerves located in the most common positions. (C) Costoclavicular space revealing the subclavian vein being separated by the anterior scalene muscle from the subclavian artery and brachial plexus.

posterior aspect of the nerve root and often descends below the middle scalene before joining the other two branches.

Dorsal Scapular Nerve

The dorsal scapular nerve, the first branch of C5, courses through the cephalic portion of the middle scalene muscle and then descends lateral to the muscle. However, it may course very close to the area of dissection in supraclavicular approaches to thoracic outlet decompression.

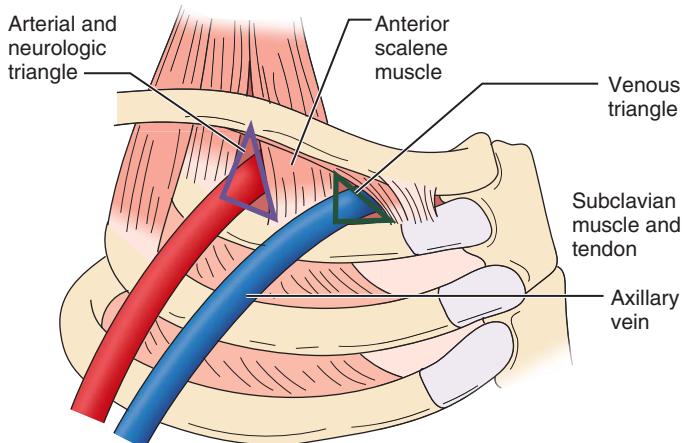


Figure 123.2 Anatomic triangles of the thoracic outlet highlighting the location of the neurovascular structures. The subclavian artery and brachial plexus traverse the thoracic outlet through the scalene triangle. The subclavian vein traverses the thoracic outlet anterior to this through the costoclavicular space. (Adapted from Moore R, Lum YW. Venous thoracic outlet syndrome. *Vasc Med*. 2015;20:182–189.)

Cervical Sympathetic Chain

Though not usually in the operative field of supraclavicular procedures, the cervical sympathetic chain lies over the transverse processes of the cervical vertebrae and is therefore very close to the origin of the anterior and middle scalene muscles. As a result, when cautery is used to excise the scalene muscles at their transverse process origins, the current may reach and damage the cervical sympathetic chain. This is the probable explanation for the occasional case of Horner syndrome observed after supraclavicular scalenectomy.

Variations of the Scalene Muscle

A significant number of anatomic variations in scalene muscles have been observed both in the normal population and in patients with nTOS. They are too common to be called anomalies. These variations might be regarded as anatomic and developmental variations predisposing to TOS, but are not regarded as causes.

Splitting of the anterior scalene around C5 and C6. Such splitting was noted in 45% of cadavers and in only 21% of nTOS patients.³

Scalene minimus muscle. This muscle arises from the transverse processes of the lower cervical vertebrae, runs in front of C8 and T1 and behind the subclavian artery, and inserts on the first rib or Sibson fascia. Its incidence is 25% to 55%.⁴

Interdigitating muscle fibers. Such fibers commonly run between the anterior and middle scalene muscles. They were noted in 75% of nTOS patients and in only 40% of cadavers.

Scalene triangle width. The width of the scalene triangle varies from very narrow to quite wide, with the distance between the two scalene muscles at their insertion on the first rib ranging from 0.3 to 2.0 cm. The nerve roots emerge lower in a wide triangle compared with their pathway in a narrow triangle (Fig. 123.4). Observations during surgery have revealed that most nTOS patients have the narrower type of triangle.²

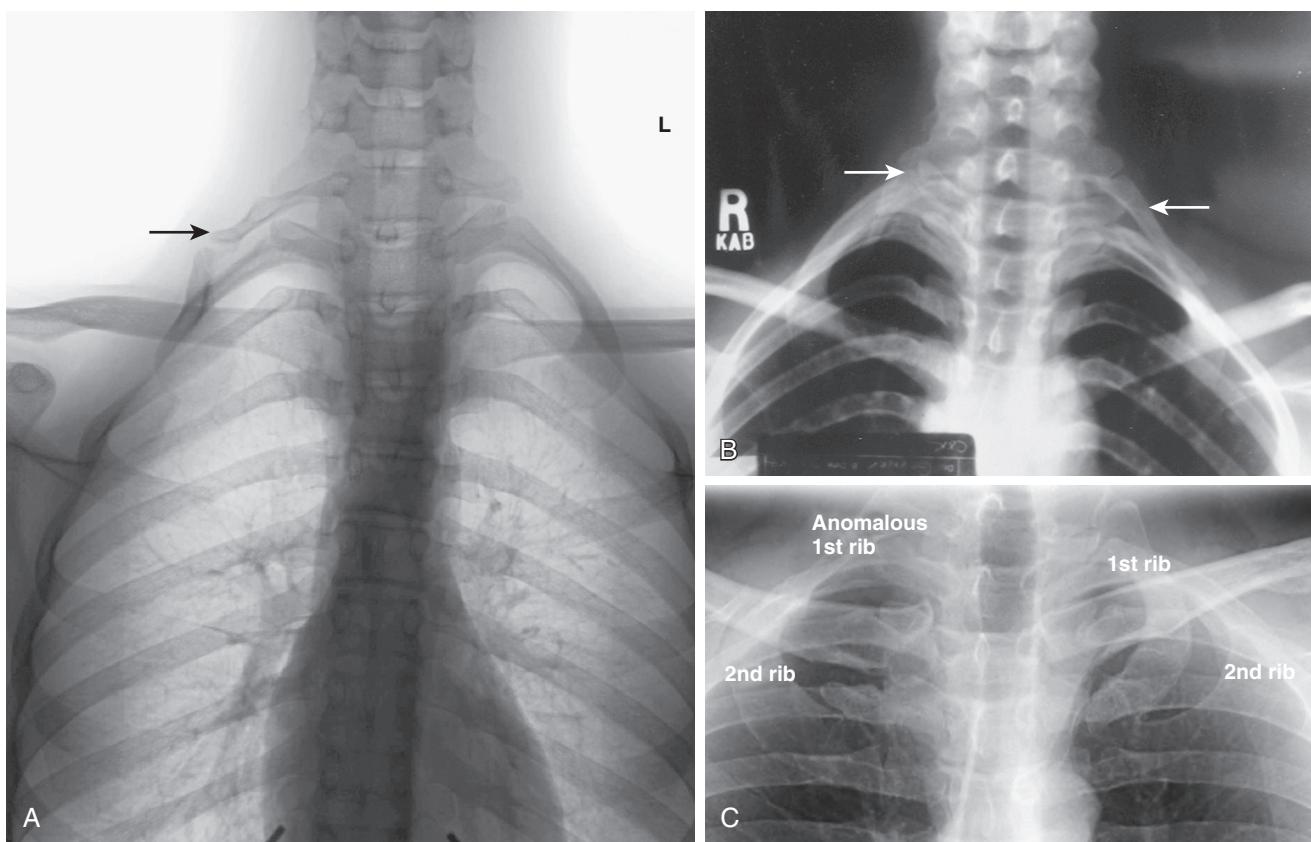


Figure 123.3 (A) Right complete cervical rib with a true joint between the cervical rib and a small process arising from the top of the first rib. (B) Bilateral cervical ribs, incomplete on the right and complete on the left. (C) Anomalous first rib.

Congenital bands and ligaments. These structures are frequently observed in the normal population, with an incidence as high as 63%.⁵ Although bands have been observed in almost every area of the scalene triangle and have been nicely classified,⁶ their role is as a predisposing factor rather than a direct cause.

Relationship of the subclavian vein to the phrenic nerve. The phrenic nerve usually runs posterior to the subclavian vein. However, in 5% to 7% of individuals, the phrenic nerve runs anterior to the vein and in this position can be a rare cause of subclavian vein obstruction.⁷

Relationship of the subclavian vein and costoclavicular ligament. The subclavian vein passes cephalad to the first rib just before it is joined by the jugular vein. It is bounded medially by the costoclavicular ligament and superiorly by the subclavius tendon. A variation in the position of the vein is its position more medially on the first rib so that it is partially compressed by the costoclavicular ligament. Variations in the thickness of the subclavius tendon can also result in compression of the vein from above. These variations in position between the three structures predispose to the development of subclavian vein obstruction. Obstruction is then caused by excessive abduction of the upper extremity, which results in compression of the vein against the dynamic outlet created by the costoclavicular ligament, subclavius tendon, and the first rib.

Skeletal Abnormalities

As many as 29% of patients with TOS have been reported to have skeletal anomalies, including cervical ribs, clavicular anomalies, and isolated first rib abnormalities; the majority of which are congenital.⁸ Anomalous or rudimentary first ribs are often overlooked on routine chest radiographs. In one study conducted in 1939, 5000 chest radiographs were reviewed. It was found that the incidence of anomalous first ribs and cervical ribs in these subjects was 0.76% and 0.74%, respectively. Anomalous ribs occurred equally in women and men. In contrast, the female–male ratio of cervical ribs was found to be 7:3.⁹ Cervical ribs and anomalous first ribs are both narrower and are positioned more cephalad than a normal first rib. The only difference between the two is that a cervical rib arises from the transverse process of C7, whereas an anomalous first rib arises from the transverse process of T1 (see Fig. 123.3).

About 30% of cervical ribs are complete ribs fused to the first rib by a true joint or a fibrous attachment. The other 70% are incomplete cervical ribs with no direct attachment to the first rib. However, most of these incomplete ribs have a tight fascial band extending from the tip of the cervical rib to the first rib.⁶ The cervical rib and attached band lie within the middle scalene muscle, thereby narrowing the space within the scalene triangle through which the nerve roots of

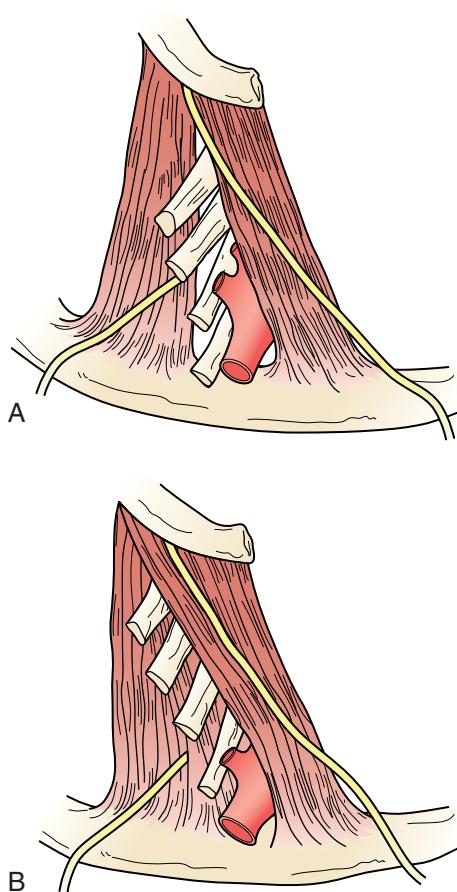


Figure 123.4 Scalene Triangle Variations. (A) The usual relationship found in cadavers. The triangle is wider and the nerves emerge lower in the triangle than in most patients with neurogenic thoracic outlet syndrome. There is minimal contact between nerve and muscle. (B) Narrow scalene triangle in which the nerves emerge high and are touching the muscles as they emerge. Contact between nerve and muscle is more significant compared with A. (Adapted from Sanders RJ, Roos DB. The surgical anatomy of the scalene triangle. *Contemp Surg*. 1989;35:11–16.)

the brachial plexus course. Thus an incomplete cervical rib with associated band can behave like a complete rib. Cervical and anomalous first ribs can compress the subclavian artery and cause stenosis with or without poststenotic aneurysm formation. More commonly, these anomalous ribs compress the lower trunk of the brachial plexus and cause neuropathy. However, most cervical and anomalous first ribs remain asymptomatic throughout life.

When symptoms do develop, they are usually neurogenic. In a recent review of 47 nTOS operations involving abnormal ribs, 15% were performed in the setting of anomalous first ribs and 85% were performed in the setting of cervical ribs. Spontaneous onset of symptoms occurred in 50% of patients with complete cervical ribs versus only 20% with incomplete ribs. Neck trauma preceded the onset of symptoms in the other 80% with incomplete ribs and in the 50% with complete ribs.¹⁰ All patients with cervical ribs are predisposed to the development of some form of TOS, most commonly nTOS. Cervical ribs or anomalous first ribs are almost always present in patients with aTOS. On the other hand, symptomatic cervical ribs are more likely to produce symptoms of

nTOS than aTOS. Over a 28-year period during which more than 1000 nTOS operations were performed, there were 39 cervical ribs and 7 anomalous first ribs treated in this group of patients, with an incidence of 4%. Among the same group of TOS patients there were only nine with aTOS, five with complete cervical ribs and four with anomalous first ribs, with an incidence of less than 1%.¹⁰

Contributions of the Pectoralis Minor

The PM can also cause compression of the structures of the thoracic outlet, leading to nTOS, vTOS, and aTOS in rare circumstances. Pectoralis minor syndrome (PMS) results when this muscle causes compressive symptoms in the subcoracoid or PM space. The PM space is actually outside the thoracic outlet area, but compression of the upper extremity neurovascular bundle can occur in this space between the PM muscle and ribs of the chest wall. Although this might better be termed “axillary compression syndrome,” it is appropriate to consider the PM space as an extension of the thoracic outlet area, because compression here is common and the axillary and the thoracic outlet neurovascular bundles contain the same elements (see Fig. 123.1). The PM syndrome results from excessive trauma or exercise of the shoulder girdle caused by hyperabduction. The PM muscle becomes tight and hypertrophied and can compress the brachial plexus, axillary vein, and rarely the axillary artery. PMS is frequently responsible for recurrent nTOS after thoracic outlet decompression, being responsible for up to 75% of cases of recurrent nTOS.¹¹ It is this PM space that should be evaluated more carefully, particularly in patients with recurrent or persistent symptoms, after initial operation for nTOS.

NEUROGENIC THORACIC OUTLET SYNDROME

There are no established diagnostic criteria or reference standards for the diagnosis of nTOS.¹² Unlike the diagnostic algorithm for aTOS and vTOS, the diagnostic criteria for nTOS are highly disputed. Such extensive debate exists regarding nTOS being a nebulous diagnosis that there are even classifications by which nTOS is classified as “true” nTOS (with objective changes such as muscle atrophy) or “disputed” nTOS.¹³ Regardless, a standardized approach in the diagnosis and work-up of nTOS patients selects a group of individuals who have an excellent chance of symptomatic relief from thoracic outlet decompression.

Pathogenesis

In nTOS, predisposing factors include scalene muscle anomalies, narrow scalene triangles, congenital ligaments or bands, roots of the plexus arising high near the apex of the scalene triangle, and cervical ribs. A common cause of nTOS is neck trauma that involves a hyperextension neck injury. Whiplash in a motor vehicle accident is the most common injury. Other

frequent causes are repetitive stress injuries in the workplace and falls on slippery floors or icy walkways. The presence of a cervical rib predisposes to the development of nTOS. In such patients, neck trauma may precipitate symptoms, but in some patients with no history of trauma, activities of daily living can also cause nTOS when the anatomic relationships between the rib and arm cause nerve compression.

Pathology

The common pathologic findings in most patients with nTOS are: (1) developmental anomalies of the thoracic outlet and fibrosis of the scalene muscle and (2) conversion of muscle fibers from fast twitch to slow twitch.^{14,15} The fact that transaxillary first rib resection for the treatment of nTOS has become popular since its introduction by Roos in 1966 has led some to believe that the first rib is the underlying cause of the pathology.¹⁶ This is not universally believed to be true. Many think that the attachments to the first rib are the more likely cause of nTOS. Support for this theory is that there are reports demonstrating that the results of anterior and middle scalenectomy without first rib resection are similar to those of scalenectomy with first rib resection.¹⁵

Pathophysiology

Although the pathophysiology of nTOS may vary depending on the specific predisposing and causative factors, it is usually associated with a narrowed scalene triangle. These patients are asymptomatic until neck trauma stretches and tears some of the anterior and middle scalene muscle fibers. This mechanism explains the neck pain that usually appears within the first 24 hours of a neck injury. Over the next few days, swelling of the muscles from bleeding or inflammation, or both, results in compression against the nerve roots of the brachial plexus. This compression then causes upper extremity pain and paresthesias, the onset of which is usually delayed a few days or weeks after the initial trauma. As the muscle injury heals and the swelling subsides, scar tissue replaces the blood that collected within the muscle, which accounts in part for muscular fibrosis. The upper extremity neurologic symptoms persist due to compression of the nerves by scar tissue. This may manifest as persistent neck pain resulting from scalene fibrosis and occipital headaches may occur as referred pain from scalene muscle spasm. When nerve compression involves the C8 and T1 branches of the lower trunk of the brachial plexus, the sympathetic nerve fibers supplying the extremity may also become irritated or compressed where they associate with the lower trunk of the brachial plexus traversing the scalene triangle. This may result in the development of a unilateral Raynaud phenomenon that manifests as intermittent subjective coolness and color change.¹⁷

Data supporting the scalene muscles as the site of pathology include: (1) histologic studies of the scalene muscles that demonstrate an average of three times more scar tissue in the scalene muscles of nTOS patients compared with control patients; (2) the

strong correlation between positive responses to scalene muscle blockade and positive responses to surgery; and (3) the fact that the rate of improvement after surgery for nTOS is the same as that for scalenectomy with or without first rib resection.

History

Obtaining a history of some type of neck trauma preceding the onset of symptoms is helpful for all types of TOS but particularly when considering a diagnosis of nTOS. Although nTOS may occur spontaneously, more than 80% of patients have a history of some type of neck trauma, the most common being whiplash injuries from motor vehicle accidents. Other common types of trauma include history of clavicular fracture, falls on slippery surfaces or down stairs, and repetitive stress injury from occupational related activities including hours on keyboards or assembly lines. However, the absence of such a history should not exclude the diagnosis of nTOS.

The patient should be asked specifically about occipital headache and pain over the trapezius, neck, chest, and shoulder girdle. A patient who has symptoms confined to the forearm and hand is more likely to have carpal or cubital tunnel syndrome and not nTOS. A history of other interventions related to the musculoskeletal system associated with the cervical spine, shoulder, and upper extremity should also be documented in the medical history. Last, patients with nTOS should be asked about subjective coldness and color changes consistent with the Raynaud phenomenon, which may develop as a result of sympathetic nerve compression.¹⁷

Physical Examination

The standard neurologic examination often fails to detect nTOS. In addition to tenderness over the scalene muscles and reduced sensation to very light touch in the fingers, an examination for nTOS should include eliciting symptoms by a variety of provocative maneuvers. The three notable provocative maneuvers that should be executed and documented in patients with TOS, particularly nTOS, are as follows:

Adson test. The examiner palpates the radial pulse and then moves the patient's upper extremity into an extended, abducted, and externally rotated position. The patient is then asked to rotate and laterally flex the neck to both the ipsilateral and contralateral sides while inhaling deeply. A positive test results in reduction in the amplitude or complete obliteration of the radial pulse.

Elevated arm stress test (EAST or Roos test). The patient is seated with arms abducted at 90 degrees in external rotation, with elbows flexed to 90 degrees and the head in neutral position. The patient is asked to open and close the hands for 3 minutes or until pain/paresthesia sets in and the patient is unable to continue. This test has a high negative predictive value for nTOS if the patient is able to perform the maneuver for 3 minutes.¹⁸

Modified upper limb tension test (Elvey test). The patient is asked to abduct both arms to 90 degrees with the elbows

extended. The patient is then progressively asked to dorsiflex both wrists. The test is considered positive if symptoms are elicited on the ipsilateral side. A subsequent maneuver is carried out by having the patient laterally flex the head on each side. The test is then considered positive if symptoms are elicited on the contralateral side.

Some authors believe that the most effective provocative test is the upper limb tension test of Elvey.^{17,19} This test is analogous to the straight-leg raise test in the lower extremity for sciatica and is worth incorporating into every examination for upper extremity symptoms.¹⁷ A positive response indicates compression of either the cervical nerve roots or brachial plexus at the level of the spine, thoracic outlet, or PM space. A negative response is usually adequate to rule out the diagnosis of nTOS.

The Adson test, however, is the most widely recognized of these maneuvers. In Adson's original description of his test, he noted "A decrease or obliteration of the radial pulse or blood pressure is a pathognomonic sign of scalenus anticus syndrome (this is one of the syndromes included in TOS)."^{20,21} However, in 1947, the same year of Adson's last report, Gage and Parnell noted that 50% of normal individuals had a positive Adson test.²² Subsequently others have demonstrated similar high rates of positive Adson tests in healthy volunteers.^{1,3,18,23–25} Therefore the Adson test is unable to rule in or rule out a diagnosis of nTOS.¹⁷ Despite the abundant evidence indicating its unreliability, the Adson test is still currently popular among many clinicians, probably because it is the only objective test available on physical examination.

These provocative maneuvers, while occasionally helpful in establishing the diagnosis of thoracic outlet compression, are neither highly sensitive nor specific for identification of thoracic outlet syndrome and are not reliable for identifying a specific anatomic region of pathology.^{3,17} Indeed, positive findings on these maneuvers frequently lead to an erroneous diagnosis of vTOS or aTOS in patients whose symptoms and physical findings are typical of nTOS without symptoms or physical findings of aTOS or vTOS.

Diagnostic Evaluation

Many patients undergo electromyography (EMG) and nerve conduction velocity (NCV) tests in the course of workup for nTOS. These tests usually have normal or nonspecific results and are useful in the diagnostic evaluation for nTOS because they help exclude other compressive neuropathic syndromes.¹⁷

Similarly, X-rays or magnetic resonance imaging (MRI) of the cervical spine are also important to exclude other causes of radicular pain.

Quite frequently, patients undergo noninvasive vascular lab photoplethysmography (PPG) which is not particularly useful due to the previously mentioned falsely-positive provocative maneuvers that can be completely incidental. Vascular lab testing with limited arterial duplex of the subclavian artery can, however, sometimes detect occult post-stenotic dilations.

Anterior Scalene Muscle Block

As elaborated previously, the diagnosis of nTOS can be challenging based on history and physical examination alone. The anterior scalene muscle block (ASMB) is a useful adjunct in the diagnostic evaluation of this syndrome, and we have incorporated it into the diagnostic evaluation for nTOS.^{17,26,27} ASMB involves injection of the anterior scalene muscle with 1% lidocaine.¹² The subsequent relaxation in the scalene muscle results in a change in configuration of the costoclavicular space, with a subsequent decompression of the thoracic outlet and relief of neurologic symptoms caused by neurovascular compression.¹² Symptomatic suppression subsequent to performing ASMB offers information that is helpful in localizing a pathologic process to a specific inciting anatomic site in the thoracic outlet that responds well to surgical decompression. Thus, performing ASMB selects patients who have a high likelihood of responding to surgical management. In our practice, we rarely select patients for surgical thoracic outlet decompression for nTOS unless they have symptomatically improved following ASMB.

VENOUS THORACIC OUTLET SYNDROME

vTOS is defined by the presence of compression and subsequent thrombosis of the axillosubclavian vein (see Ch. 126, Thoracic Outlet Syndrome: Venous). This condition is synonymous with Paget–Schroetter syndrome and "effort thrombosis," an older term originating before the pathogenesis of vTOS was understood. Primary effort thrombosis of the axillosubclavian vein, also known as Paget–Schroetter syndrome, was first described by Paget in 1875²⁸ and subsequently by Von Schroetter in 1884.²⁹ There exists a further subset of patients who have symptoms characteristic of vTOS but without the presence of venous thrombosis; it is a condition termed intermittent obstruction or McCleery syndrome.³⁰

Pathogenesis

Venous TOS is most often the result of developmental anomalies of the costoclavicular space and repetitive arm activities such as throwing, swimming, or working with the arms overhead for long periods. In vTOS, the predisposition is the relationship of the subclavian vein to the subclavius tendon and costoclavicular ligament and dimensions of the costoclavicular space. In most patients with vTOS, the subclavian vein is situated closely adjacent to the costoclavicular ligament, and the subclavius tendon compresses the top of the vein within a narrowed costoclavicular space. With the vein in this compressed position, repetitive arm movements can easily traumatize the vein and produce fibrosis, stenosis, and eventually thrombosis. Therefore vTOS is a condition characterized by primary thrombosis of the axillosubclavian vein secondary to compressive symptoms from thoracic outlet pathology and should be differentiated from secondary thrombosis. Secondary thrombosis

of the vein may ensue following injury or iatrogenic causes, including central line or pacemaker lead placement.

Pathology

Many patients with vTOS have coexisting anatomic abnormalities. Some of the recognized anatomic anomalies include abnormalities of the scalenus minimus, pectoralis minor, subclavius, and anterior scalene muscles; ligamentous abnormalities of the costocoracoid ligament and bony abnormalities of the clavicles and ribs.^{31–37} In addition, as many as 43% of the patients treated for vTOS have been found to have evidence of occult first rib fractures.³⁸ A significant proportion also have osteophytic degeneration and costochondral calcification. The subclavian vein develops intimal injury and subsequent luminal narrowing. If thrombosis occurs, this event occludes the vein and precipitates acute symptoms of upper extremity deep venous thrombosis. Also characteristic of this condition is the formation of extensive venous collaterals when the occlusion is chronic.

Pathophysiology

Repeated compression injury of the subclavian vein is the inciting event leading to vTOS. As the vein traverses the thoracic outlet, the subclavian vein is in an anatomically tight space bounded by the subclavius muscle and costoclavicular ligament medially, the anterior scalene muscle laterally, the clavicle superiorly, and the first rib inferiorly (see Figs. 123.1 and 123.2).³⁰ Significant forces result from compression of the clavicle and first rib in a fulcrum-like effect during certain motions and maneuvers, particularly in young athletic males participating in activities that require repetitive overhead movement of the upper extremities. Cumulative trauma to the subclavian vein causes scarring, inflammation and eventual thrombosis.³⁹ If left untreated, venous hypertension ensues and prompts the subsequent development of venous collaterals. The symptoms of swelling and pain resulting from venous hypertension then subside once collaterals mature. Symptoms improve as a result of collateral formation and eventual recanalization of the vein in some patients, even in those untreated. However, thrombus may propagate into the venous collaterals and acute thrombosis of these vessels may occur, resulting in another relatively acute episode of arm swelling and pain characteristic of the presentation of Paget–Schroetter syndrome or vTOS.⁴⁰

Clinical Findings

Consistent with the pathophysiologic mechanism leading to this condition, vTOS is most common in young athletic individuals who perform frequent repetitive overhead movement in the upper extremities, such as pitchers, weightlifters, and mechanics.³⁰ Historical series have suggested a male preponderance but the largest case series to date actually demonstrated an equal gender ratio.⁴¹ Patients with vTOS are typically asymptomatic until the thrombotic event that results in pain, swelling, prominent superficial veins and cyanosis with a markedly

blue appearance in the acute thrombotic episode. This acute episode is frequently preceded by intense physical exertion, exercise, or labor, and the arm may become severely swollen and edematous, enlarging up to double its normal size in a distribution from the shoulder extending distally to the hand.⁴² Important elements in the history would be to rule out any secondary causes of upper extremity deep vein thrombosis such as upper extremity central venous catheters, pacemakers, or symptoms suggestive of malignancy (see Ch. 150, Acute Upper Extremity and Catheter-Related Venous Thrombosis).

A minority of patients develop pulmonary embolism and this complication occurs in 12% or fewer of patients with axilosubclavian venous thrombosis.^{31,43–47} The surprisingly lower rate of venous thromboembolism in these patients is explained by the small clot burden present in vTOS, as well as the anatomic subclavian vein narrowing resulting from vTOS, which sequesters thrombus and prevents embolization.

Physical Examination

In a large case series of vTOS, 93% of patients presented with arm swelling, 77% presented with bluish cyanosis, 66% had worsening of aching pain with exercise and 8% had minimal findings or symptoms.⁴¹ In addition to pronounced swelling and edema of the involved arm, dilated subcutaneous veins may be present over the upper arm, neck, and chest, and herald chronic venous obstruction. On occasion a tender palpable cord can be appreciated on physical exam in the axilla.³⁰

Diagnostic Evaluation

While the physical exam alone may be sufficient to reliably diagnose vTOS with a high degree of certainty in many cases, confirmatory testing is indicated. Duplex ultrasound is the imaging study of choice for the initial diagnosis of vTOS, as it is highly sensitive (78% to 100%) and specific (82% to 100%) for the diagnosis of venous thrombosis (Fig. 123.5).^{48–54} Duplex evaluation of vTOS should encompass the entire length of the vein to avoid missing the presence of a subtle or short-segment thrombus and to evaluate the extent of vessel involved. In vTOS, duplex ultrasound typically demonstrates near-complete or complete occlusion of the subclavian vein with loss of flow. It is important to conduct the venous duplex in a variety of provocative maneuvers with the arm in abduction with flow assessed through the axilosubclavian vein with color Doppler in these various positions. In the absence of axilosubclavian vein thrombosis, these maneuvers help establish the diagnosis of McCleery syndrome, which is characterized by intermittent compression of the subclavian vein resulting in upper extremity swelling without venous thrombosis.⁵⁵ This condition is diagnosed when significantly elevated velocities or flow occlusion are demonstrated at the thoracic outlet with these provocative maneuvers.

Venography is rarely necessary as an initial diagnostic maneuver, as ultrasound is both highly sensitive and specific for the diagnosis of subclavian venous thrombosis. In the rare instance that a negative duplex ultrasound result is obtained

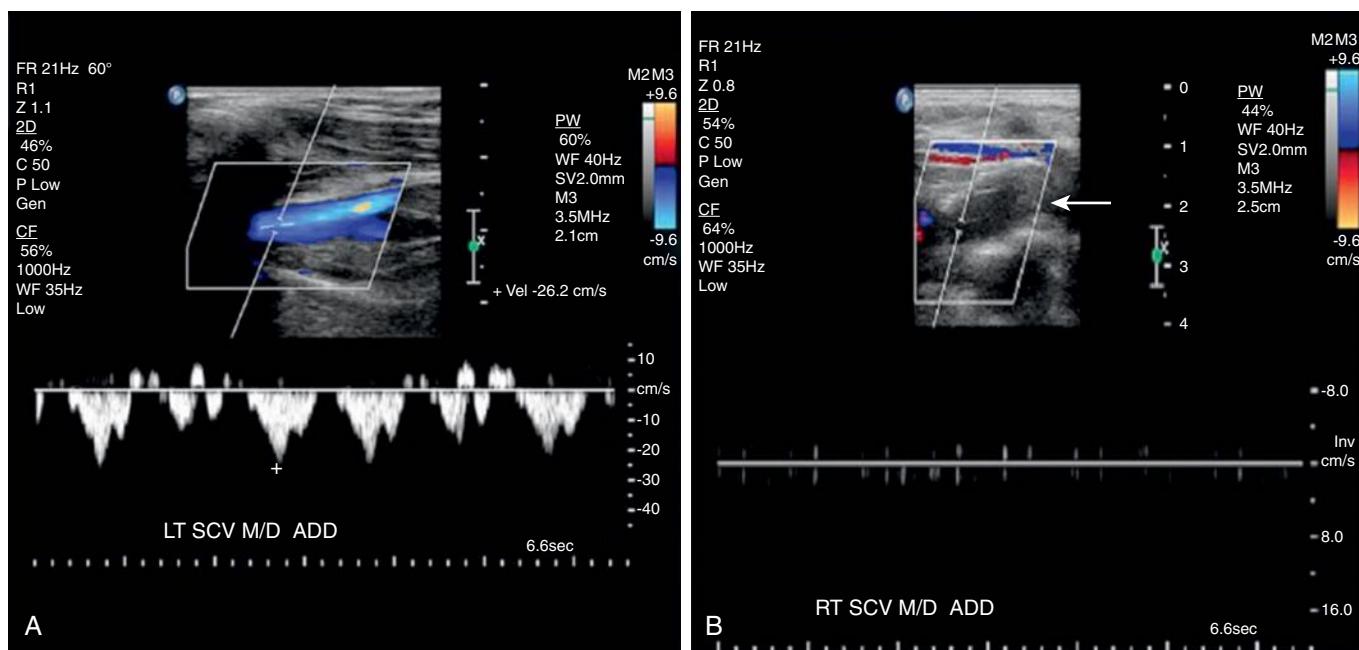


Figure 123.5 Duplex Ultrasound Images of the Axillosubclavian Vein. (A) Demonstrates a normal axillosubclavian vein. (B) Demonstrates a thrombosed axillosubclavian vein, as demonstrated by lack of both color flow and venous waveform, with the presence of an acute thrombus (see arrow).



Figure 123.6 Subclavian venogram in a patient with venous thoracic outlet syndrome demonstrating subclavian vein narrowing due to compression (arrow) as the vein traverses the costoclavicular space.

and the clinical suspicion remains high for venous thrombosis, contrast venography may play a helpful role (Figs. 123.6 and 123.7).³⁰ Contrast venography may also be utilized in the process of performing an initial endovascular intervention – most commonly thrombolysis.³⁰ Other imaging modalities described for venous imaging, including magnetic resonance venography (MRV) and computed tomographic

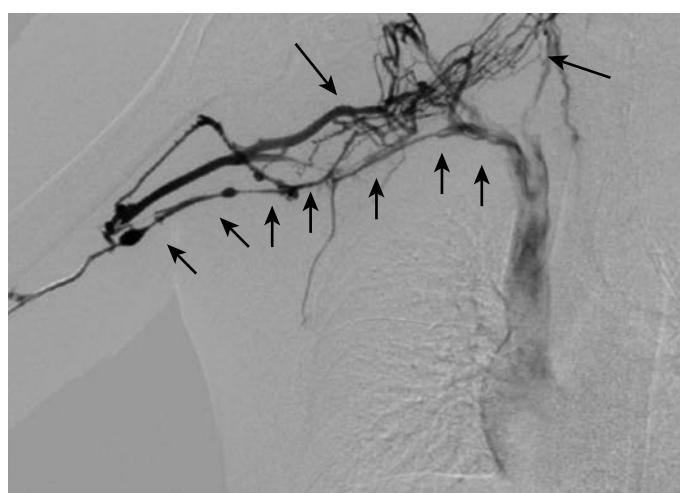


Figure 123.7 A contrast venogram demonstrating near-complete occlusion of the subclavian vein due to thrombus, prior to intervention, in a patient with venous thoracic outlet syndrome (TOS). Large black arrows indicate collateral venous drainage around thrombus. Small black arrows indicate the native axillary and subclavian vein.

venography (CTV), do not offer any advantages over venous duplex ultrasound, have equivalent sensitivity and specificity, are costly and time-consuming and should generally be avoided in the diagnostic evaluation for vTOS.⁵⁶ In addition, thrombophilia may play a role in the pathogenesis of vTOS. Some series have documented that a significant proportion of patients presenting with vTOS have a contributory thrombophilia in the pathogenesis of their condition.⁵⁷ As such, when a family history or personal history of prior venous thrombosis is present, patients should also be evaluated for the presence of thrombophilia.

ARTERIAL THORACIC OUTLET SYNDROME

The least common form of TOS, aTOS, accounts for 1% of cases,¹⁷ but represents the most firm indication for operative intervention, as this condition confers the potential for embolic phenomena and ischemic complications.⁵⁸ The syndrome is characterized by a predictable course of events resulting from arterial compression, poststenotic dilation resulting in aneurysmal degeneration and finally secondary embolism.

Pathogenesis

Arterial TOS is usually associated with a congenital or posttraumatic abnormality in the thoracic outlet. The inciting abnormality is usually a cervical or anomalous first rib, clavicular fracture, or rarely, an anomalous insertion of the anterior scalene muscle. Symptoms and signs are the result of arterial emboli arising from subclavian artery aneurysms or stenosis that resulted from the aberrant anatomy. In a compilation of case series representing 122 reported patients with aTOS, cervical ribs were present in 60%, anomalous first ribs in 18%, fibrocartilaginous bands in 15%, clavicular fracture in 6% and an enlarged C7 transverse process in 1%.⁵⁹ The ensuing arterial compression results in subclavian artery stenosis accompanied by poststenotic dilation that causes the appearance of an aneurysm. Thrombus forms within the dilated portion of the artery just distal to the stenosis as mural thrombus does in an aneurysm. The disease process is usually asymptomatic until emboli are dislodged.

The pathophysiology is based on the effects of arterial compression by an anomalous first rib, cervical rib, or anterior scalene muscle. Subclavian artery stenosis produces fluid hemodynamics that result in poststenotic dilatation or aneurysm formation, mural thrombus, and distal embolization. The most common presentation is microembolization to the hand causing ischemic symptoms.

History

Patients with arterial TOS are usually asymptomatic until arterial emboli occur. Symptoms include digital ischemia, claudication, pallor, coldness and paresthesia and pain in the hand. Symptoms seldom occur in the shoulder or neck. Patients may complain of exertional pain, easy fatigability, or a “dead arm” sensation.⁵⁸ It is important to document if other systemic constitutional symptoms such as fever or malaise are present, which could suggest the possibility of vasculitis, particularly in younger patients (see Ch. 138, Vasculitis and Other Arteriopathies). A history of an anomalous first rib or a cervical rib in any prior evaluation should also heighten the suspicion for arterial TOS.

Physical Examination

Evaluation for aTOS should focus on the presence of a subclavian aneurysm and on any signs of distal embolic phenomena. The supraclavicular fossa should be palpated for the presence of a cervical rib and for pulsatile mass.

Auscultation should be performed to assess for the presence of a bruit. Additional abduction maneuvers may be employed to elicit a bruit or a pulsatile mass if there is not an obvious finding on exam in the seated position with arms relaxed. In addition, brachial blood pressure measurements should be recorded bilaterally.⁵⁸ Additional provocative maneuvers may be employed in the evaluation for aTOS. Obliteration of the radial pulse with the Adson test, costoclavicular maneuver and hyperabduction maneuver may be observed in patients with aTOS. However, these tests are nonspecific, and many normal individuals have a positive result. The examiner should also pay particular attention to the fingers and hands, which should be inspected for skin changes consistent with thromboembolic or ischemic sequelae, including pallor, cyanosis, delayed capillary refill, mottling, discoloration, petechiae, and gangrene.

Diagnostic Evaluation

Duplex ultrasound should be performed in all patients presenting for evaluation of aTOS, with attention directed to the subclavian and axillary arteries and the presence of aneurysm, thrombus, turbulence and elevated velocities consistent with luminal narrowing (Fig. 123.8). Duplex should be performed with the patient upright and provocative maneuvers can be employed. In addition, chest radiography should be obtained on all patients presenting for evaluation of aTOS in order to identify the presence of bony abnormalities such as cervical ribs.

Spiral CT angiography plays a significant role in the diagnostic evaluation of patients with aTOS (Figs. 123.9 and 123.10). Additional diagnostic information can be obtained when the CT is performed with the arms at the sides and in a hyperabducted and externally rotated position in an effort to reproduce the arterial compression.^{60,61} The advantage of CT in the evaluation of this condition is the ability of this modality to identify the relationship between the vasculature and the bony structures of the thoracic outlet.⁵⁸ CT is superior to conventional angiography for diagnostic purposes, as conventional contrast angiography has a high (32%) false-negative rate when performed in the supine position.⁶² Angiography can also play a role in the management of aTOS, and is mainly indicated when intervention such as thrombolysis is performed or when planning for surgical revascularization.¹⁷

COEXISTING THORACIC OUTLET SYNDROMES

Some patients being evaluated for TOS present with coexisting thoracic outlet syndromes as a result of the compression of multiple neurovascular structures traversing the thoracic outlet. For this reason, the workup of TOS should be broadly directed toward evaluating for the presence of neurologic, venous, and arterial TOS during the initial physical and diagnostic evaluation. It is our practice to obtain vascular duplex ultrasound on patients presenting with signs and symptoms



Figure 123.8 Various Duplex Ultrasound Findings in Arterial TOS. (A) Post-stenotic dilation (arrow) in the subclavian artery as well as complete occlusion with arm abduction. (B) Left subclavian artery aneurysm in another patient. (C) Post-stenotic dilation in the subclavian artery with intimal plaque/thrombus (arrow).

of nTOS.⁶³ In our series from The Johns Hopkins Hospital, 5% of 423 patients presenting with nTOS were found to have coexisting aTOS.⁶⁴

Challenges in Diagnosis

Several modalities of imaging and testing have been described for the evaluation of a patient suspected to have TOS. Occasionally, an anomalous first rib or cervical rib is overlooked during the workup. It is therefore important to obtain chest



Figure 123.9 Three-dimensional reconstructed computed tomography angiogram of patient presenting with arterial thoracic outlet syndrome and post-stenotic dilation of the subclavian artery.



Figure 123.10 Three-dimensional reconstructed computed tomography angiogram of patient presenting with arterial thoracic outlet syndrome, post-stenotic dilation of the subclavian artery, and left arm ischemia resulting from thromboembolism to axillary artery (arrow), with resulting intraluminal filling defect and distal outflow thrombosis.

and/or neck radiographs to detect cervical and anomalous first ribs. Other tests that frequently accompany patients suspected to have TOS are noninvasive vascular lab studies such as photoplethysmography and duplex ultrasonography. It has been demonstrated that ultrasonography in combination with provocative maneuvers improves the specificity for diagnosis of TOS over either test alone.⁶⁵ Therefore patients with vTOS or aTOS should undergo duplex ultrasonography in conjunction

with provocative maneuvers to evaluate for compression of the subclavian vessels in vTOS or aTOS. Patients being evaluated for nTOS have been shown to demonstrate vascular compression on duplex ultrasound in up to 50% of cases.⁶³ When this is demonstrated, the suspicion for nTOS being the primary cause of their symptoms should be heightened, and standard management for nTOS should ensue.

One might suspect that compression of the nervous structures in the thoracic outlet would lead to abnormalities in neurophysiologic tests such as EMG studies and nerve conduction studies (NCS). However, the results of EMG and NCS studies are often negative or inconclusive. While these results may seem superfluous in the diagnosis for nTOS, they are nevertheless still useful in excluding other nerve entrapment syndromes that can mimic nTOS.

Emerging Diagnostic Studies

Two additional studies have demonstrated promise in the diagnosis of nTOS: measuring the responses of the medial antebrachial cutaneous (MAC) nerve, and magnetic resonance (MR) neurography. The MAC nerve is the lowest branch of the inferior trunk of the brachial plexus and appears to be more sensitive to compression compared with other branches of the plexus. Abnormal measurements of MAC amplitude were recorded in patients with clinical signs of nTOS and normal electromyography/nerve conduction velocity studies.⁶⁶ In all patients, the amplitude of the symptomatic arm was lower than that of the asymptomatic arm. Another study of the MAC test was performed between 2004 and 2006 in 41 patients operated on for clinical signs of nTOS.⁶⁷ Although Seror's study measured only amplitude,⁶⁶ the later study found that latency was a little more helpful than amplitude. In applying these criteria, it is important that each electrodiagnostic laboratory establish its own diagnostic criteria in healthy volunteers, because precise technique and equipment may vary.^{66,67}

There has been improvement in MR technology such that new 3T MRI scanners can perform MR neurography by processing high resolution 2D STIR (Short Tau Inversion Recovery) and isotropic three-dimensional (3D) T2 SPACE (Sampling Perfection With Application Optimized Contrasts Using Varying Flip Angle Evolutions, Siemens, Germany) imaging sequences. These processes result in imaging quality that can delineate subtle signal alterations, size changes, and mechanical course deviations of the brachial plexus within the thoracic outlet.⁶⁸

As both these techniques gain further widespread usage and acceptance, they may offer further diagnostic options that could prove to be better objective tests compared with what is currently available to support the diagnosis of nTOS. Nevertheless, more studies are needed for confirmation before accepting their validity.^{66–68}

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Thoracic Outlet Syndrome: Neurogenic

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Based on a previous edition chapter by Robert W. Thompson

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The management of neurogenic thoracic outlet syndrome (nTOS) requires a comprehensive, multidisciplinary approach, including a prominent role for surgical treatment in well-selected patients.^{1–3} Establishing the diagnosis can be challenging, and disappointing results of treatment have led some authorities to question the need for surgical

management of nTOS, and even to challenge whether the condition actually exists (see Ch. 123: Thoracic Outlet Syndrome: Pathophysiology and Diagnostic Evaluation).^{4–6} The purpose of this chapter is to review current understanding of the diagnosis, optimal management, and surgical techniques for nTOS.

ANATOMY

As shown in [Figure 124.1](#), the anatomy of the thoracic outlet is composed of several bony and soft tissue structures, as well as nerves and blood vessels which traverse the space.

Nerves in the Thoracic Outlet

The scalene triangle is traversed by the *brachial plexus*, organized into three trunks: the *upper trunk* (formed by the fused C5 and C6 nerve roots), the *middle trunk* (composed of the

C7 nerve root), and the *lower trunk* (formed by fusion of the C8 and T1 nerve roots). The phrenic nerve, the long thoracic nerve, and the cervical sympathetic chain also pass through the thoracic outlet. The *phrenic nerve* passes lateral to medial descending anteriorly along the anterior scalene muscle, and then behind the subclavian vein into the mediastinum to innervate the diaphragm. The *long thoracic nerve* passes through the middle scalene muscle, where its three components typically fuse into a single nerve, before descending to supply the serratus anterior muscle. The *cervicodorsal sympathetic chain* lies along the posterior inner aspect of the ribs.

Musculofascial Variations

The conventional description of scalene triangle anatomy occurs in no more than one-third of individuals, with several common variations in soft tissue structure.^{7,8} The most frequent muscular variation is the *scalene minimus muscle*, which originates within the plane of the middle scalene muscle, passes between various brachial plexus nerve roots and inserts upon the first rib with the anterior scalene muscle. Fascial bands across or between individual nerve roots can exist, attaching to either the first rib or extrapleural fascia. During TOS operations, a dense fascial band crossing over the T1 nerve root origin is commonly encountered. Several other muscular and fascial variations have been described and classified ([Table 124.1](#)).^{9,10}

Bony Anomalies

Cervical ribs occur in approximately 0.45%–1.5% of the population and up to 5% of TOS patients. They arise in the plane of the middle scalene muscle and typically attach to the mid-lateral first rib as an immobile bony fusion or as a fully developed joint ([Fig. 124.2A](#)).¹¹ *Incomplete cervical ribs* arise as bony or cartilaginous extensions from the C7 cervical vertebrae without joining the first rib, and in some cases are attached to the first rib only by a band of cartilage or tendinous tissue ([Fig. 124.2B](#)). *Rudimentary (hypoplastic) first ribs* are infrequently recognized, and tend to lie higher in the neck than normal and often insert into the second rib rather than the sternum. *Previous trauma* may also result in first rib abnormalities, such as fractures with formation of thickened callous at the site of bony healing ([Fig. 124.2C](#)).

Histopathology

Microscopic studies of scalene muscles from nTOS patients have consistently revealed two major abnormalities: (1) type I muscle fiber predominance and (2) endomesial fibrosis ([Fig. 124.3](#)).^{12,13} Although the anterior scalene muscle normally has an equal distribution of type I (“slow-twitch”) and type II (“fast-twitch”) muscle fibers, type I fibers compose up to 78% of scalene muscle fibers in nTOS patients with associated atrophy and pleomorphism of type II fibers. Additionally, markedly thickened connective tissue matrix surrounds individual muscle fibers, and in some cases there are mitochondrial

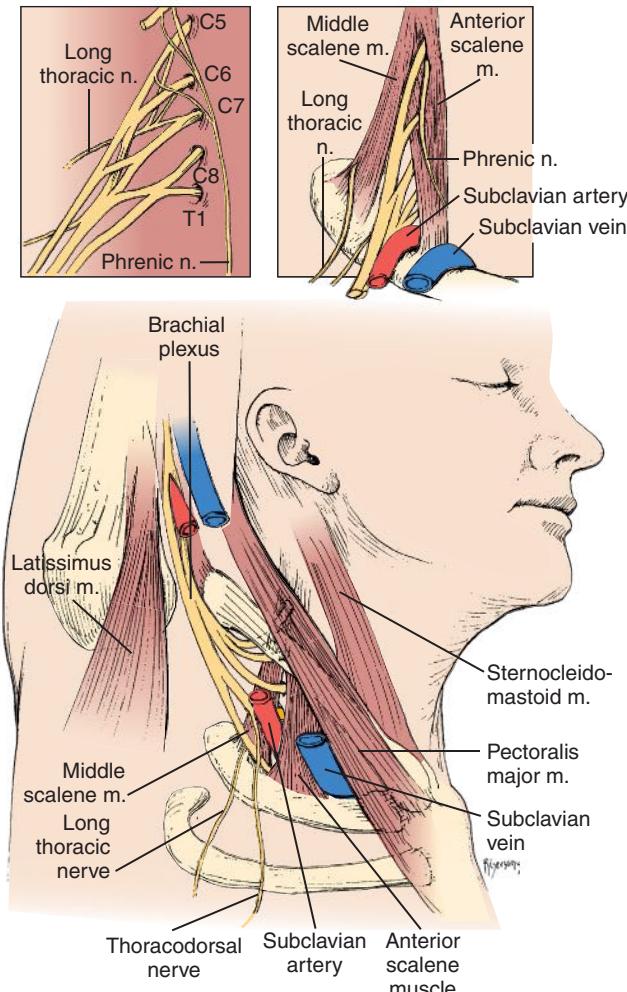


Figure 124.1 Anatomy of the Thoracic Outlet. The surgical anatomy of the thoracic outlet is centered upon spinal nerve roots C5 through T1, which interdigitate to form the brachial plexus as they cross under the clavicle and over the first rib. The long thoracic and phrenic nerves also arise within the thoracic outlet region. The brachial plexus nerve roots pass through the scalene triangle, bordered by the anterior and middle scalene muscles on each side and the first rib at the base. The subclavian artery also courses through the scalene triangle in direct relation to the brachial plexus nerve roots. The subclavian vein crosses over the first rib immediately in front of the anterior scalene muscle, before joining with the internal jugular vein to form the innominate vein. Symptoms of neurogenic thoracic outlet syndrome are often exacerbated by arm elevation, where greater strain is placed on the neurovascular structures passing through the scalene triangle. (Modified from Thompson RW, Petrinec D. Surgical treatment of thoracic outlet compression syndromes. I. Diagnostic considerations and transaxillary first rib resection. *Ann Vasc Surg*. 1997;11:315–323.⁶⁸)

TABLE 124.1 Classification of Congenital Bands and Ligaments within the Scalene Triangle

Type 1:	Extending from anterior tip of an incomplete cervical rib to the middle of the first thoracic rib; inserts just posterior to the scalene tubercle on the upper rib surface.
Type 2:	Arises from an elongated C7 transverse process in the absence of a cervical rib and attaches to the first rib just behind the scalene tubercle; associated with extension of the transverse process of C7 beyond the transverse process of T1 on AP spine radiographs.
Type 3:	Both originates and inserts on the first rib; starts posteriorly near the neck of the rib and inserts anteriorly just behind the scalene tubercle.
Type 4:	Originates from a transverse process along with the middle scalene muscle and runs on the anterior edge of the middle scalene muscle to insert on the first rib; the lower nerve roots of the brachial plexus lie against this band.
Type 5:	The scalene minimus muscle, arising with the lower fibers of the anterior scalene muscle, runs parallel to this muscle but passes deep to the muscle to cross behind the subclavian artery and in front of or between the nerve roots, and inserts on the first rib; any fibers passing anterior to or between the plexus but posterior to the artery.
Type 6:	Scalene minimus muscle inserting onto Sibson fascia over the cupula of the pleura instead of onto the first rib; labeled separately to distinguish its point of insertion.
Type 7:	Fibrous cord running on the anterior surface of the anterior scalene muscle down to the first rib, attaching to the costochondral junction or sternum; lies immediately behind the subclavian vein where it may be a cause of partial venous obstruction.
Type 8:	Arises from the middle scalene muscle and runs under the subclavian artery and vein to attach to the costochondral junction.
Type 9:	Web of muscle and fascia filling the inside posterior curve of the first rib, compressing the origin of the T1 nerve root.

Modified from Roos DB. Congenital anomalies associated with thoracic outlet syndrome. *Am J Surg.* 1976;132:771–778.

abnormalities resembling those seen in muscular dystrophy. These histopathologic changes are thought to occur in response to long-standing muscle injury, sustained muscle spasm, and abnormal tissue remodeling, and are therefore consistent with the frequent history of neck trauma in nTOS patients.

Etiology

Predisposing Anatomic Factors

Neurogenic TOS is caused by a combination of predisposing anatomical factors and previous neck trauma. Even with normal anatomy, neurovascular structures traversing the thoracic outlet are at risk for compression with regular daily activity. Activities involving sustained or repeated arm elevation or vigorous neck turning may place tension on the scalene muscles, potentiating positional compression of underlying nerve roots. Further anatomic risk factors include congenital structural variants, such as scalene muscle variations, abnormal tendinous bands, or cervical rib anomalies. However, many people without neurogenic symptoms harbor such variations; these variations lower the threshold for, rather than cause, symptom development following injury.

Neck Trauma and Repetitive Strain Injury

Most nTOS patients describe some form of previous head, neck, or upper extremity trauma, followed by a variable interval of days to weeks before symptom onset.¹ A varying temporal relationship between scalene injury and sustained brachial plexus compression and irritation may obscure recollection of the inciting injury. Persistent upper extremity use in aggravating activities may worsen symptoms and lead to progressive disability, and medical attention is not usually sought until symptoms are advanced. In many cases, injury results from repetitive strain on the scalene muscles from activities such

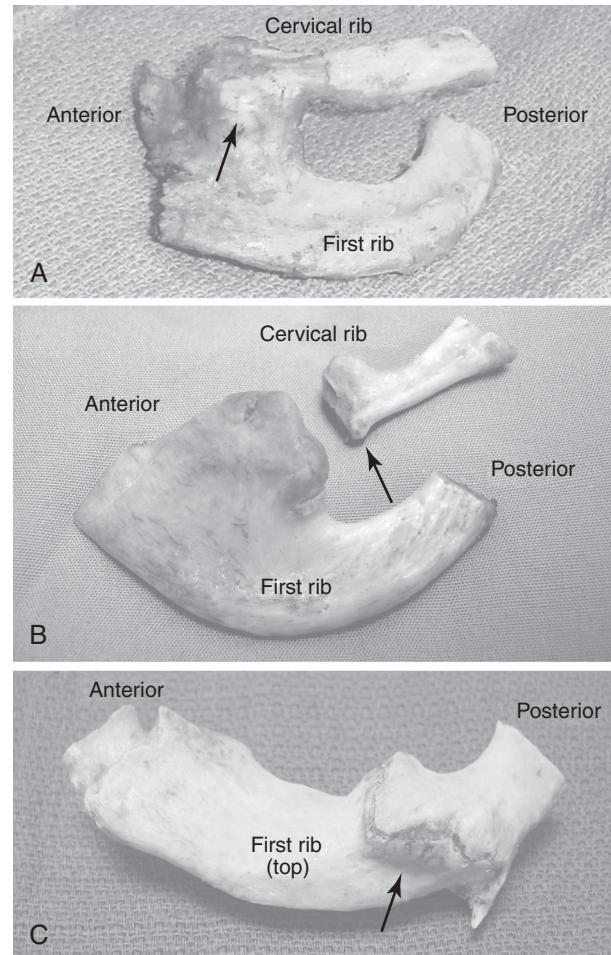


Figure 124.2 First Rib Anomalies. Operating room photographs depicting bony abnormalities associated with neurogenic thoracic outlet syndrome. (A) Resected specimen of cervical rib and attached first rib, exhibiting a completely formed joint (arrow). (B) Resected specimen of cervical rib and accompanying first rib, with attachment through a fibrous connection and a large exostosis on the first rib (arrow). (C) Resected specimen of a first rib that contained thickened callous associated with a healed fracture site from previous trauma (arrow).

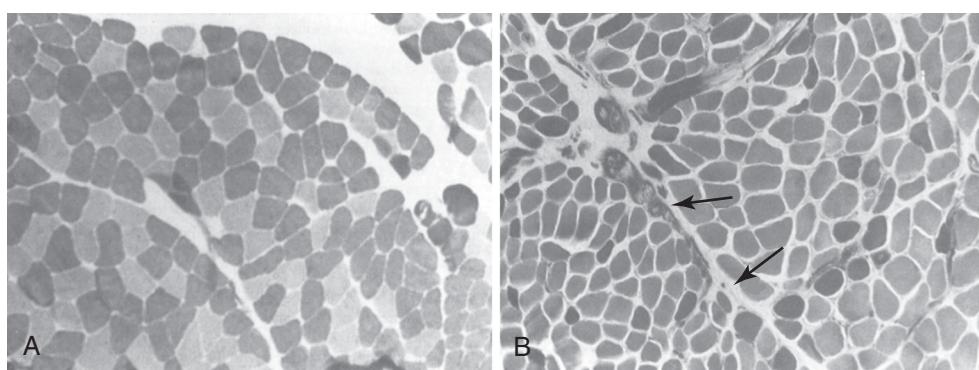


Figure 124.3 Scalene Muscle Histology in Neurogenic Thoracic Outlet Syndrome (nTOS). Muscle histopathology showing changes consistently observed in nTOS. Sections of the anterior scalene muscle were stained with myosin ATPase (pH 9.4) to visualize fiber types, with type I fibers staining lightly and type II fibers staining dark (original magnification $\times 100$). Normal muscle has an equal distribution of type I and type II fibers (A). The muscle from a patient with TOS (B) exhibits predominance of type I fibers, atrophy of type II fibers, and a significant increase in the connective tissue matrix between fibers (arrows). (Modified from Sanders RJ. *Thoracic Outlet Syndrome: A Common Sequelae of Neck Injuries*. Philadelphia: J.B. Lippincott; 1991.)

as prolonged computer keyboard use, rather than any single event. Age-related changes in posture (e.g., shoulder slumping and stooping of the neck) may also be significant factors leading to development of extrinsic neural compression.

CLINICAL FINDINGS

Demographics

Neurogenic TOS most frequently occurs between 20 and 40 years of age, and approximately 70% of patients are women. Individuals engaged in a variety of occupational or recreational activities involving heavy lifting or repeated use of the arm(s) in elevated positions may develop nTOS. Patients may also develop nTOS with no apparent anatomical variations or history of trauma. There are no medical conditions or known inherited patterns predisposing to nTOS.

Symptoms

The diagnosis of nTOS rests largely upon clinical pattern-recognition, with diagnostic suspicion raised by a stereotypical history and symptoms. The provisional diagnosis of nTOS is supplemented by physical examination and may be supported by a limited number of diagnostic studies. In most cases such studies are of value primarily in the exclusion of other (more common) conditions within the differential diagnosis. No single diagnostic test has a sufficiently high degree of specificity to completely prove or exclude the diagnosis of nTOS.^{1,14}

Pain and Paresthesia

Primary nTOS symptoms include pain, dysesthesias, numbness, and weakness. These symptoms usually occur throughout the affected hand or arm without localization to a specific peripheral nerve distribution, and often involve different areas of the entire upper extremity. Extension of symptoms to the shoulder, neck, and upper back is common, and in many patients such symptoms may be perceived as the most functionally

disabling. Although symptoms are often limited to one upper extremity, bilateral symptoms are seen; in such cases the dominant extremity is often more symptomatic at first, with the opposite extremity becoming involved over time, perhaps due to compensatory overuse. The aforementioned characteristics allow distinction of nTOS from nerve compression disorders affecting the ulnar nerve at the elbow (cubital compression syndrome), median nerve at the wrist (carpal tunnel syndrome), or other related conditions. Almost all nTOS patients describe reproducible symptom exacerbation by activities requiring elevation and/or sustained use of the arms or hands. Supine positioning and raising arms overhead may elicit symptoms, resulting in pain and difficulty sleeping at night.

Headache

Headaches are common in nTOS, most likely due to referred occipital pain from secondary spasm within the trapezius and paraspinous muscles.¹⁵ Although nTOS and migraine headaches often occur together, there is currently no evidence for a specific link between these conditions.

Weakness and Muscle Atrophy

Prolonged severe extrinsic peripheral nerve compression can result in muscle weakness and atrophy, but such findings are rare in nTOS patients, probably due to the intermittent nature of nerve compression. Most commonly, hand or arm pain with affected extremity use may be perceived as weakness, causing avoidance of using the arm or exacerbating positions. This distinction should be clarified to help identify alternative etiologies for these symptoms.

Disability

Positional complaints related to nTOS are usually mild, due to transient positional or activity-related brachial plexus irritation. Progressive injury risk is low in these situations, and no specific intervention is warranted. There remains a smaller subset of patients with clinically significant nTOS, however, who exhibit progressively disabling symptoms that effectively

prevent them from working or carrying out simple daily activities. These patients often describe a long history of consultations with different physicians and partial or ineffective treatments. It is particularly helpful to obtain a detailed description from the patient of activities that exacerbate symptoms, as well as required workplace activities. This assessment is important to document if restrictions from work are necessary, and for guiding decisions about the role of surgical treatment.

Vascular Symptoms and Complex Regional Pain Syndrome

Vascular symptoms, particularly hand discoloration or coldness, should be queried. Ischemia is very unusual in nTOS patients, whereas symptoms of vasomotor disturbance are seen in longstanding or severe nTOS. NTOS symptoms may progress to resemble those of complex regional pain syndrome type I (CRPS-I), with persistent vasospasm, disuse edema, and extreme hypersensitivity leading to avoidance and withdrawal from even light touch of the affected extremity. The CRPS-I diagnosis can be supported by vascular laboratory studies revealing abnormal vasoconstrictive responses (cold-pressor tests) or imaging studies of hand microcirculation, but mostly the diagnosis is made clinically and by response to sympathetic blockade. Identifying this condition in nTOS patients may lead to earlier recommendation for operative treatment and consideration of concomitant cervical sympathectomy.

When history suggests arterial insufficiency or thromboembolism, vascular laboratory studies and contrast-enhanced arteriographic imaging are necessary to exclude the presence of subclavian artery aneurysm or occlusive disease. Conversely, a history of arm swelling, cyanotic discoloration, and distended subcutaneous collaterals may indicate venous TOS due to obstruction of the subclavian vein, which requires contrast venography for full evaluation (see Ch. 126, Thoracic Outlet Syndrome: Venous).

Physical Examination

Physical examination should assess the degree of neurogenic disability and identify exacerbating factors. Upper extremity range of motion and lateral motion of the neck are assessed under both passive and active conditions. Pain and tenderness over the shoulder joint may suggest rotator cuff pathology, and tenderness over the trapezius muscle hints towards fibromyalgia. A thorough peripheral nerve examination is performed to exclude ulnar nerve entrapment or carpal tunnel syndrome, two conditions that may mimic nTOS. The base of the neck is examined to identify the extent of any local muscle spasm over the scalene triangle itself, as well as over the trapezius, pectoralis, and parascapular muscles, and to localize specific “trigger points” where palpation recreates upper extremity pain and paresthesia. Localization of such trigger points over the scalene triangle or subcoracoid space strongly reinforces the diagnosis of nTOS.

The most useful component of physical examination is the 3-minute elevated arm stress test (EAST), in which the patient elevates the arms in a “surrender” position and repetitively

opens and closes the fists. Most patients with nTOS report rapid onset of their typical upper extremity symptoms, often being unable to complete the exercise beyond 30 to 60 seconds. When there is no difficulty performing the 3-minute EAST, the diagnosis of nTOS is suspect, and alternative explanations for symptoms should be pursued.

In some patients, neurovascular compression by the pectoralis minor muscle tendon contributes substantially to nTOS. Localized tenderness and reproduction of upper extremity neurologic symptoms upon palpation over the pectoralis minor muscle can identify this etiology, for which pectoralis minor tenotomy may be an effective primary or adjunctive treatment.

Vascular Examination

The Adson maneuver can identify positional compression of the subclavian artery by detecting dampening of the radial pulse when the patient inspires deeply and turns the neck away from the affected extremity with or without elevation of the arm. Although this maneuver does not specifically reveal nerve root compression, positive findings may be associated with nTOS. However, a positive Adson sign is also quite common in the asymptomatic general population.

Patients presenting with symptoms of nTOS may on occasion have vascular findings related to either arterial or venous TOS (see Ch. 125, Thoracic Outlet Syndrome: Arterial and Ch. 126, Thoracic Outlet Syndrome: Venous).

Diagnostic Tests

Radiography

Plain radiographs of the neck are helpful in determining if an osseous cervical rib or abnormally wide transverse processes of the cervical vertebrae is present.

Cross-Sectional Imaging

The results of computed tomography (CT), magnetic resonance imaging (MRI), and other cross-sectional imaging are usually negative in nTOS because the anatomical factors causing compression are usually beyond the resolution of these studies. Even when abnormality exists in the scalene triangle on imaging, it is usually impossible to prove functional significance with respect to upper extremity complaints. Imaging studies are nonetheless valuable to exclude other conditions that could be responsible for upper extremity symptoms, such as degenerative cervical disc or spine disease, shoulder joint pathology, or various forms of intracranial pathology.

Advances in MRI and data processing have led to higher resolution scans with three-dimensional reconstruction, and enabled detection of localized abnormalities in nerve function (MR “neurography”).^{9,10,16,17} As this technique becomes utilized more frequently in patients with and without nTOS, it may provide a useful diagnostic tool to supplement clinical evaluation.

Neurophysiologic Testing

Electromyography (EMG) and nerve conduction studies (NCS) are often utilized in the evaluation of patients suspected of

TABLE 124.2 Differential Diagnosis of Neurogenic Thoracic Outlet Syndrome

Condition	Differentiating Features
Carpal tunnel syndrome	Hand pain and paresthesia in median nerve distribution; positive findings on nerve conduction studies.
Ulnar nerve compression	Hand pain and paresthesia in ulnar nerve distribution; positive findings on nerve conduction studies.
Rotator cuff tendinitis	Localized pain and tenderness over biceps tendon and shoulder pain on abduction; positive findings on MRI; relief from NSAIDs, local steroid injections or arthroscopic surgery.
Cervical spine strain/sprain	Posttraumatic neck pain and stiffness localized posteriorly along cervical spine; paraspinal tenderness; relief with conservative measures over weeks to months.
Fibromyositis	Posttraumatic inflammation of trapezius and parascapular muscles; tenderness, spasm and palpable nodules over affected muscles; may coexist with TOS and persist after surgery.
Cervical disc disease	Neck pain and stiffness, arm weakness, and paresthesia involving thumb and index finger (C5–6 disc); symptom improvement with arm elevation; positive findings on CT or MRI.
Cervical arthritis	Neck pain and stiffness; arm or hand paresthesia infrequent; degenerative rather than posttraumatic; positive findings on spine radiographs.
Brachial plexus injury	Caused by direct injury or stretch; arm pain and weakness, hand paresthesias; symptoms constant not intermittent or positional; positive findings on neurophysiologic studies.

CT, computed tomography; MRI, magnetic resonance imaging.

having nTOS, particularly when symptoms are suggestive of a specific radiculopathy, a peripheral nerve syndrome, or a general myopathy. Positive results of neurophysiologic testing are therefore useful in identifying specific alternative conditions to be evaluated. Results of conventional EMG/NCS studies are usually negative in nTOS, because nerve root compression occurs in an extremely proximal location, and is intermittent without permanent changes in motor nerve function.¹⁸ Positive EMG/NCS findings in patients with nTOS are a poor prognostic finding in the absence of an alternate explanation, indicating an advanced stage of neural damage unlikely to resolve despite adequate decompression. Recent evidence suggests that electrophysiologic testing of sensory nerve abnormalities may be more useful in the diagnosis of nTOS than conventional EMG/NCS.¹⁹

Scalene Muscle Blocks

Anterior scalene muscle injection with local anesthetic can be used as an adjunct to the clinical diagnosis of nTOS, particularly in predicting potential response to surgical decompression.^{20–22} Successful scalene muscle block is indicated by relief of symptoms in the hand or arm, along with reduced local tenderness over the anterior scalene muscle. Scalene muscle block with locally injected botulinum toxin is another method of treatment for nTOS, albeit with several limitations.²³ Side effects of botulinum toxin may occur early (e.g., dysphagia), the duration of beneficial effects is often limited from 2 to 3 months, and repeated treatment effects are diminished by the systemic immune response to the injected protein.

Making the Diagnosis

The differential diagnosis may include a number of conditions (Table 124.2), some of which can be distinguished by specific findings or diagnostic tests. The surgeon recognizing nTOS should not be dissuaded by the impression that these problems are frequently associated with psychiatric overtones, dependency on pain medications, and ongoing litigation. Careful

evaluation using clinical diagnostic criteria can usually detect patients with strong clinical evidence of nTOS, as well as identify those most likely to respond to treatment (Table 124.3; see Chapter Algorithm).²⁴

CONSERVATIVE MANAGEMENT

Physical Therapy

Physical therapy is the initial treatment for almost all nTOS patients.²⁵ It is important the patient is referred to an experienced therapist with expertise and interest in TOS, since its management is different from other disorders affecting the neck, shoulder, and upper extremity.²⁶ Many physical therapists are not experienced with nTOS, and incorrect therapeutic approaches can result in worsening of symptoms and premature failure of conservative management.²⁷

The physical therapist outlines a specific initial treatment plan for a 4- to 8-week period, to be followed by reassessment of progress. Initial assessment includes evaluation of posture, alignment, and movement patterns of the patient, specifically focusing on areas such as the slope of the shoulder girdle, angle of the clavicle, position of the scapula on the thorax, position of the humerus in the glenoid, posturing of the head and neck, and alignment of the cervical and upper thoracic spine. The therapist also examines dynamic patterns, such as scapular mechanics and timing during upper extremity movements, and any changes in muscle length, strength, and/or recruitment that may put stress on the brachial plexus (Fig. 124.4).

The therapist's role is to educate the patient on specific faults that may contribute to their condition, instruct them in an exercise program, and possibly implement use of external devices, such as bracing or taping, to take stress off of anatomical compression sites.²⁸ Principal areas addressed include the scalene triangle, the costoclavicular space, and the area between the pectoralis minor and the coracoid process. In addition, scapular mechanics may be poor in patients with nTOS, leading to

TABLE 124.3 Clinical Diagnostic Criteria for Neurogenic Thoracic Outlet Syndrome

Upper extremity symptoms which extend beyond the distribution of a single cervical nerve root or peripheral nerve, have been present for at least 12 weeks, have not been satisfactorily explained by another condition, AND meet at least 1 criterion in at least 4 of the following 5 categories:

Principal Symptoms

- 1A: Pain in the neck, upper back, shoulder, arm and/or hand
1B: Numbness, paresthesias, and/or weakness in the arm, hand, or digits

Symptom Characteristics

- 2A: Pain/paresthesias/weakness exacerbated by elevated arm positions
2B: Pain/paresthesias/weakness exacerbated by prolonged or repetitive arm/hand use, including prolonged work on a keyboard or other repetitive strain tasks
2C: Pain/paresthesias radiate down the arm from the supraclavicular or infraclavicular spaces

Clinical History

- 3A: Symptoms began after occupational, recreational, or accidental injury of the head, neck, or upper extremity, including repetitive upper extremity strain or overuse
3B: Previous ipsilateral clavicle or first rib fracture, or known cervical rib
3C: Previous cervical spine or ipsilateral peripheral nerve surgery without sustained improvement in symptoms
3D: Previous conservative or surgical treatment for ipsilateral TOS

Physical Examination

- 4A: Local tenderness on palpation over the scalene triangle and/or subcoracoid space
4B: Arm/hand/digit paresthesias on palpation over the scalene triangle and/or subcoracoid space
4C: Objectively weak handgrip, intrinsic muscles, or digit 5, or thenar/hypothenar atrophy

Provocative Maneuvers

- 5A: Positive ULTT
5B: Positive 3-minute EAST

Exclusion of other conditions typically includes nonspecific or negative findings on physical examination (Spurling test, axial compression test, Tinel sign over the carpal tunnel or cubital tunnel, and Phalen test), imaging studies (MRI of cervical spine and shoulder), and conventional electrophysiologic tests (upper extremity electromyography and nerve conduction studies).

EAST, elevated arm stress test; TOS, thoracic outlet syndrome; ULTT, upper limb tension test.

Modified from consensus diagnostic criteria developed by the Consortium for Research and Education on Thoracic Outlet Syndrome (CORE-TOS).

additional stresses with overhead motion.²⁹ The initial goals of physical therapy are to maintain and improve range of motion in the neck and affected upper extremity, using a combination of passive and assisted exercises.^{30–32} In particular, exercises designed to relax and stretch the scalene muscle are used, combined with hydrotherapy, massage, and other techniques. Nonsteroidal anti-inflammatory agents, muscle relaxants, and nonnarcotic pain medications, may serve as adjuncts as needed. Once initial improvement has been achieved, subsequent efforts are focused on strengthening muscles of posture and increasing activity level.

Results

Most patients with mild symptoms, or who started therapy early after symptom onset, will exhibit significant improvement. Therapy is then continued aiming to avoid the need for surgery. Though such an outcome is obtained in only 20%–30% of patients referred for nTOS management, the proportion of patients responding to conservative treatment is much higher in the general (non-referral) population.³³ If progress with initial conservative management is unsatisfactory, the basis for the diagnosis of nTOS is reviewed, and further testing carried out. When the physician is confident of the nTOS diagnosis, the level of

symptoms is disabling, and the patient has not responded sufficiently to conservative management, surgical treatment is considered.³⁴

SURGICAL TREATMENT**Historical Background**

The first operations for thoracic outlet compression were focused on treatment of subclavian artery aneurysms in patients with cervical ribs, as described by Coote in 1861.³⁵ By the turn of the century, “cervical rib syndrome” was widely recognized, and in 1927 Adson and Coffey described use of anterior scalenectomy for this condition, including symptomatic patients without a cervical rib anomaly.³⁶ The term “thoracic outlet syndrome” was introduced by Peet in 1956,³⁷ and in the 1960s several new operative approaches were described, including posterior thoracotomy (Clagett) and transaxillary first rib resection (Roos).^{38,39} Although transaxillary first rib resection became popularized during the 1970s, disenchantment arose when results were found to be no better than scalenectomy, and a national survey indicated a significant incidence of associated permanent nerve injuries.^{22,40} It was also noticed that symptomatic recurrences following

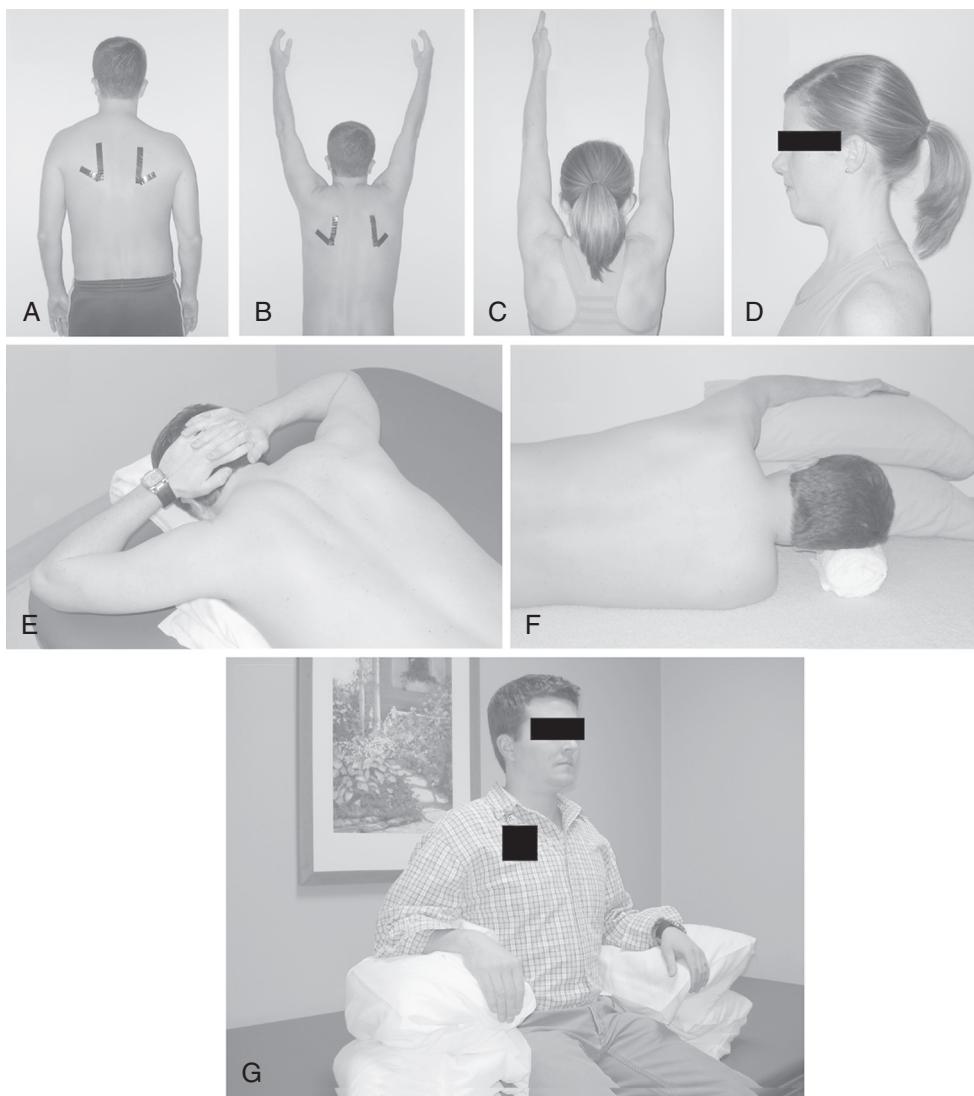


Figure 124.4 Physical Therapy for Neuromuscular Thoracic Outlet Syndrome. (A) An example of postural assessment including scapular depression with an increased slope of the right shoulder girdle. (B) Implementing an exercise to improve a scapular depression fault. (C) Upper trapezius muscle recruitment in standing while facing a wall. (D) Addressing cervical spine alignment. (E) Strengthening the middle trapezius musculature. (F) Exercises addressing overhead mechanics are initiated in a gravity-lessened position. (G) Sitting with arms supported helps to take weight off the shoulder girdle.

transaxillary first rib resection often involved reattachment of the unresected scalene muscles to remaining first rib ends or adjacent tissues, leading to diminished enthusiasm for first rib resection and reemphasis on complete scalene resection.⁴¹ Combined use of supraclavicular and transaxillary approaches was reported in 1984 by Qvarfordt et al.,⁴² followed by further description of the supraclavicular approach by Sanders and Raymer and by Reilly and Stoney.^{43,44} The supraclavicular approach has become the most commonly used approach.

Transaxillary Approach

Advantages of *transaxillary first rib resection* include a relatively limited operative field, a cosmetically placed skin incision, and sufficient exposure to reliably accomplish anterolateral first rib resection. At least partial anterior scalene muscle resection is feasible, as is identification and removal of most anomalous ligaments and fibrous bands that may be associated with TOS. Disadvantages of the transaxillary approach include incomplete exposure of scalene triangle structures, inability to achieve complete anterior and middle scalenectomy or brachial plexus neurolysis, and necessity for first rib resection in all cases. Vascular

reconstruction is also limited if needed, and in such cases patient repositioning and an additional incision is required.

Under general anesthesia, the patient is positioned supine with the table back raised about 30 degrees. A shoulder roll is used to elevate the affected side. The arm is prepped circumferentially and wrapped in stockinette, with the sterile field including the neck, upper chest, and posterior shoulder to the scapula. The arm is held and positioned by an assistant (Fig. 124.5) or retractor.

A transverse skin incision is made at the lower border of the axillary hairline, extending from the anterior border of the latissimus dorsi to the lateral edge of the pectoralis major (see Fig. 124.5). The long thoracic, thoracodorsal, and second intercostobrachial nerves are identified near the chest wall to avoid direct injury. Excessive elevation of the arm (unique to transaxillary exposure) is a potential mechanism of injury to the second intercostobrachial cutaneous nerve, resulting in postoperative pain and numbness along the medial aspect of the upper arm. The first rib is typically palpable at the upper reaches of the areolar tissue plane along the chest wall. Using a Deaver retractor to gently lift the subcutaneous tissues and axillary contents away from the chest wall, the first rib is more clearly exposed in the upper

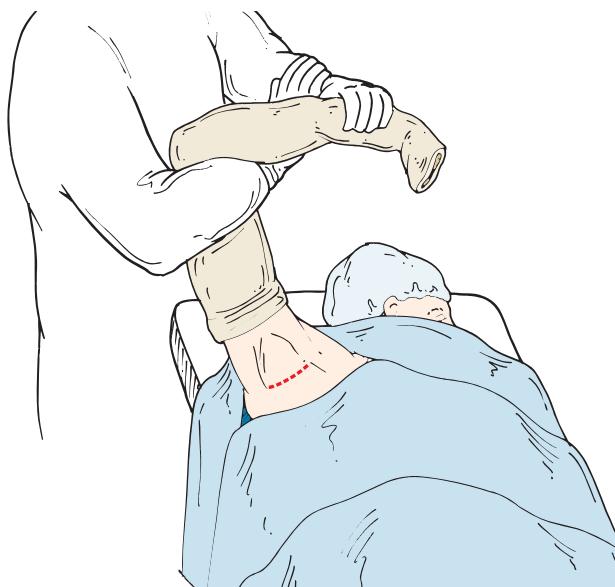


Figure 124.5 Positioning for Transaxillary First Rib Resection. With the arm carefully elevated by a reliable assistant, the initial skin incision is made at the lower edge of the axillary hair line. (Modified from Thompson RW, Petrinec D. Surgical treatment of thoracic outlet compression syndromes. I. Diagnostic considerations and transaxillary first rib resection. *Ann Vasc Surg*. 1997;11:315–323.⁶⁸)

aspect of the wound. Carefully lifting the arm facilitates this exposure, both at this stage and the remainder of the procedure, and the operating surgeon should use a fiberoptic headlight to properly illuminate the operative field.

Exposure obtained during the transaxillary approach is generally limited to the operating surgeon. To prevent serious injury, excessive traction must be avoided to the neurovascular structures visible above the first rib, including brachial plexus nerve roots and the long thoracic nerve, which exits the plane between the middle and posterior scalene muscles before coursing over the first rib to the serratus anterior muscle. Periodic inspection of retractors and relief for the assistants is recommended, using a staged operative approach as described by Machleder.⁴⁵

Once the first rib is sufficiently exposed, the subclavian vein and subclavian artery are identified, along with the intervening anterior scalene muscle (Fig. 124.6A). These structures are carefully dissected and the anterior scalene tendon encircled with a right-angle clamp just above its insertion onto the first rib's scalene tubercle. The anterior scalene muscle is exposed over several centimeters superior to the first rib, and while taking care to avoid the phrenic nerve, the muscle is divided using scissors at the highest level feasible. Resection of a portion of the scalene muscle, rather than simply dividing it, is important for prevention of recurrent TOS.

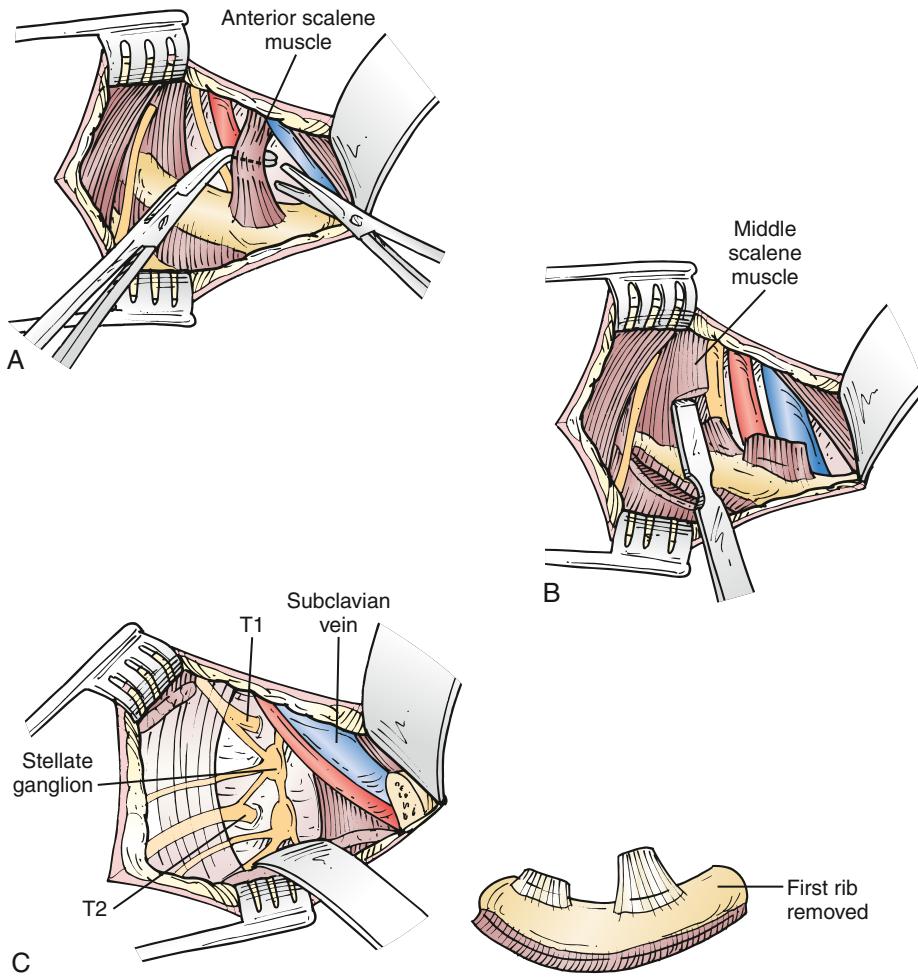


Figure 124.6 Transaxillary First Rib Resection. (A) Transaxillary division of the anterior scalene muscle. The tendinous insertion of the anterior scalene muscle onto the first rib is elevated with a right-angle clamp and divided with scissors. (B) Detachment of the middle scalene muscle. After the intercostal attachments to the first rib are divided, a periosteal elevator is used to detach the middle and posterior scalene muscles. Injury to the proximal portion of the long thoracic nerve is prevented by staying directly on the rib. (C) Removal of the first rib. The anterior and posterior aspects of the first rib are divided, with the operative specimen including the resected portion of the anterior scalene muscle and the site of attachment of the middle scalene muscle. (Modified from Thompson RW, Petrinec D. Surgical treatment of thoracic outlet compression syndromes. I. Diagnostic considerations and transaxillary first rib resection. *Ann Vasc Surg*. 1997;11:315–323.⁶⁸)

The soft tissues attaching to the inferior and medial borders of the first rib are progressively divided with scissors, beginning with the attachments medial to the subclavian vein (the subclavius muscle tendon and the costosternal and costoclavicular ligaments). A periosteal elevator is used along the inferior border of the rib, extending underneath the rib from the vantage point of the exposure used. The intercostal muscle is fully divided, and the parietal pleura is pushed away from the deep aspect of the rib by blunt dissection. The middle scalene muscle is detached from the superior surface of the rib, posterior to the brachial plexus nerve roots (Fig. 124.6B). Although the proximal aspect of the long thoracic nerve is not directly visualized during this maneuver, injury to this nerve must be prevented by keeping the periosteal elevator directly upon the rib during scalene muscle detachment, avoiding any deviation laterally. The long thoracic nerve is thereby gently pushed away from the rib indirectly as the middle scalene muscle is detached, effectively protecting it despite the lack of direct visualization. Once the posterior surface of the first rib is exposed and the T1 nerve root is in full view to protect it from injury, a bone-cutting instrument is carefully applied across the neck of the rib. The lateral portion of the divided rib is pulled downward, and its anterior aspect is cut in a similar fashion, just medial to the subclavian vein at the costochondral junction. The first rib is then fully detached and removed from the operative field (Fig. 124.6C). A bone rongeur is used to trim the remaining ends of the bone to a smooth surface well beyond the neurovascular structures. With an additional amount of extrapleural dissection, the same exposure can be used to perform adjunctive cervical sympathectomy for patients with nTOS complicated by CRPS-I.

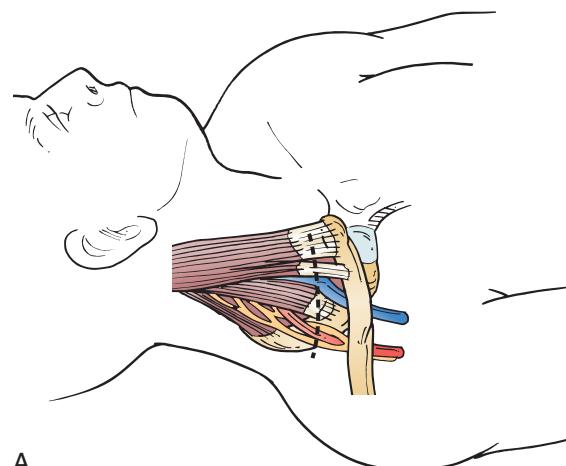
Any additional soft tissue bands found to be crossing the brachial plexus nerve roots are sought and carefully divided, particularly those that may insert upon Sibson's fascia, the thickened aspect of the apical pleural surface. After hemostasis is achieved, the wound is irrigated and the lung is inflated to detect any breaks in the pleural lining. If small air bubbles are observed during positive-pressure ventilation or if the irrigation fluid appears to be lost into the pleural space, a small chest tube may be placed through a separate wound. The incisional wound is closed in two layers after placing a small closed suction drain in the operative field.

Supraclavicular Approach

The *supraclavicular approach* carries advantages of wider exposure of all relevant anatomical structures, allowing complete resection of the anterior and middle scalene muscles, and brachial plexus neurolysis with direct visualization of all five nerve roots. This approach also allows resection of cervical ribs, anomalous first ribs, or the normal first rib. Additionally, all vascular reconstructions can be accomplished, though removal of the anteromedial first rib and distal vessel control may require a second infracervical incision (which can be done without patient repositioning). Accordingly, many prefer this approach for nTOS, with some adopting a highly selective algorithm reserving first rib resection solely for patients with vascular complications.⁴⁶

Under general anesthesia, the patient is positioned supine with the head of bed elevated 30 degrees. The hips and knees

are flexed and the neck extended and turned contralaterally. The neck, upper chest, and upper extremity are prepped into the field with the arm wrapped in a stockinette, then held comfortably across the abdomen. This allows for arm movement through an extended range of motion during the operation, when it may be necessary to assess residual neurovascular compression following scalenectomy. A transverse skin incision is made two fingerbreadths above the clavicle, beginning at the lateral border of the sternocleidomastoid muscle (Fig. 124.7A). This incision is carried through the platysma muscle layer to expose



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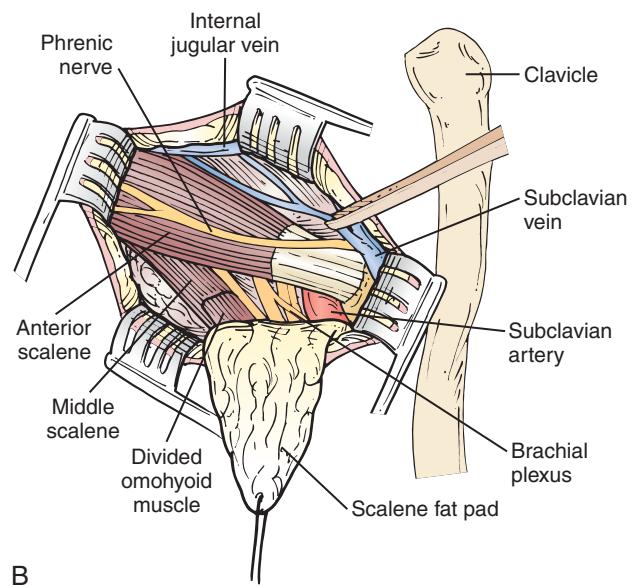


Figure 124.7 Positioning for Supraclavicular Thoracic Outlet Decompression. (A) A transverse skin incision is made two fingerbreadths above the clavicle to obtain full exposure of the structures associated with the scalene triangle. (B) The scalene fat pad is mobilized laterally to expose the underlying anterior scalene muscle, with identification and protection of the phrenic nerve. The omohyoid muscle is divided. The subclavian artery and the upper roots of the brachial plexus are identified behind the lateral edge of the anterior scalene muscle. (Modified from Thompson RW. Treatment of thoracic outlet syndromes and cervical sympathectomy. In: Lumley JSP, Hoballah JJ, eds. *Springer Surgery Atlas Series: Vascular Surgery*. London: Springer-Verlag; 2009:103–118.⁴⁶)

the scalene fat pad, which is mobilized beginning at the lateral border of the internal jugular vein. Entering this tissue plane, the fat pad is progressively dissected off the anterior surface of the anterior scalene muscle and reflected laterally (Fig. 124.7B). The phrenic nerve is identified within the investing fascia of the muscle, coursing lateral to medial. Lateral retraction of the scalene fat pad permits exposure of the underlying brachial plexus nerve roots. The anterior scalene muscle is dissected, avoiding excessive traction on the phrenic nerve (Fig. 124.8A). After circumferential mobilization of the anterior scalene muscle to its attachment to the first rib, a finger is passed behind the muscle and the muscle tendon is sharply divided at its insertion with curved scissors (Fig. 124.8B). There may be additional muscle

or tendon requiring division more posteriorly, including direct attachments to thickened pleural lining behind the rib itself.

The anterior scalene muscle is lifted superiorly to detach it from the pleural apex, subclavian artery, and brachial plexus nerve roots (Fig. 124.8C). This dissection can be carried out superiorly to the level of the scalene muscle origin on the transverse process of the sixth cervical vertebrae. Great care must be taken to avoid irretrievable neural injury while muscle fibers interdigitating with the proximal roots of the upper brachial plexus are removed. The entire anterior scalene is then removed and sent to the neuromuscular pathology laboratory.

Following anterior scalenectomy and removal of any scalene minimus fibers, each of the brachial plexus nerve roots

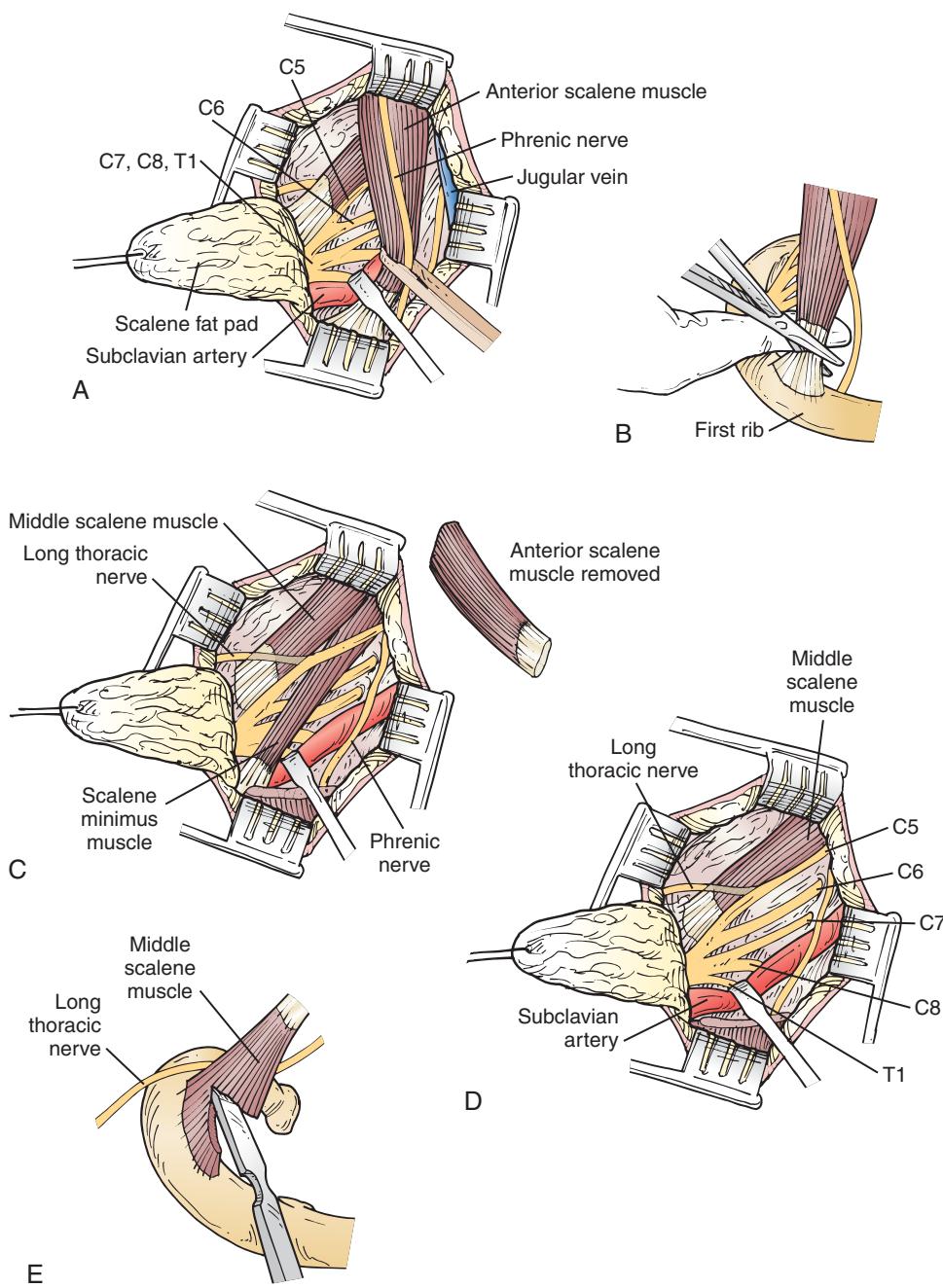


Figure 124.8 Supraclavicular Scalenectomy and Neurolysis. (A) The anterior scalene muscle is circumferentially mobilized from the underlying subclavian artery and roots of the brachial plexus. (B) The insertion of the anterior scalene muscle upon the first rib is sharply divided with scissors, with the surgeon's finger protecting the subclavian artery and the roots of the brachial plexus. (C) The anterior scalene muscle is reflected superiorly and dissected free of underlying structures to the level of its origin. Any muscle fibers passing between the upper nerve roots of the brachial plexus are also removed, including a scalene minimus muscle if present. (D) Complete dissection of the brachial plexus nerve roots from C5 to T1 is accomplished by resection of all perineural scar tissue. (E) The middle scalene muscle is detached from the first rib using a periosteal elevator, taking care to protect the long thoracic nerve. All muscle tissue lying anterior to the long thoracic nerve is resected. (Modified from Thompson RW. Treatment of thoracic outlet syndromes and cervical sympathectomy. In: Lumley JSP, Hoballah JJ, eds. *Springer Surgery Atlas Series: Vascular Surgery*. London: Springer-Verlag; 2009:103–118.⁶⁹)

is identified and meticulously dissected free of inflammatory scar tissue (Fig. 124.8D). Adequate neurolysis is essential for prevention of persistent nTOS symptoms, and should not be considered complete until each nerve root from C5 to T1 is completely dissected throughout its course in the operative field. Additionally, neuromonitoring can be a useful adjunct to demonstrate objective improvement after neurolysis.

Osseous cervical ribs or their soft tissue counterparts occur within the same plane as the middle scalene muscle. While the middle scalene muscle lies posterior to brachial plexus nerve roots, in some cases it may insert upon the first rib as far anteriorly as the scalene tubercle (where the anterior scalene muscle attaches). The middle scalene muscle's attachment to the first rib is divided using a periosteal elevator or curved Mayo scissors, extending to a point posterior to the brachial plexus nerve roots (Fig. 124.8E). If a cervical rib is present in the plane of the middle scalene muscle, it may also be detached from the first rib at this time. It is important to note the oblique course of the long thoracic nerve separating the middle and posterior scalene muscles, removing middle scalene muscle tissue anteriorly while leaving the nerve intact. The long thoracic nerve may exist as two or three branches at this level, rather than a single nerve.

Subsequently, an intraoperative decision is made regarding the potential role of the first rib in neurovascular compression. The surgeon's finger is placed alongside the brachial plexus nerve roots while the arm is elevated through a normal range of motion at the shoulder, allowing any residual compression to

be detected during arm elevation. In many patients, the first rib causes little residual compression following adequate scalenectomy, and does not necessarily require removal. Conversely, the first rib should be removed if any suspicion for contribution to residual neurovascular compression exists, and in all patients with arterial or venous TOS.

First rib resection is next performed (Fig. 124.9). Using a periosteal elevator, any remaining middle scalene muscle fibers are detached from their insertion on top of the posterior first rib. This dissection is always performed under direct vision, to protect the C8 and T1 nerve roots. Using a fingertip covered with gauze, the pleural membrane is bluntly dissected away from the inferior aspect of the first rib. Intercostal muscle attachments to the posterior and lateral aspects of the first rib are divided using a periosteal elevator, and any remaining attachments divided along the anterolateral aspect of the rib to the scalene tubercle. The brachial plexus nerve roots are displaced anteriorly to expose the posterior neck of the rib, which is divided with a rib cutter while protecting the nerve roots. A Kerrison bone rongeur is used to resect additional bone to ensure that rib's end will not impinge upon the lower nerve roots and to create a smooth surface on the posterior stump. The proximal rib is displaced inferiorly to open the anterior costoclavicular space, and divided immediately medial to the scalene tubercle with a bone cutter. The first rib is then extracted, and the remaining proximal stump smoothed with a rongeur.

Upon completion of the operation, the brachial plexus nerves may be wrapped with an absorbable film to act as a

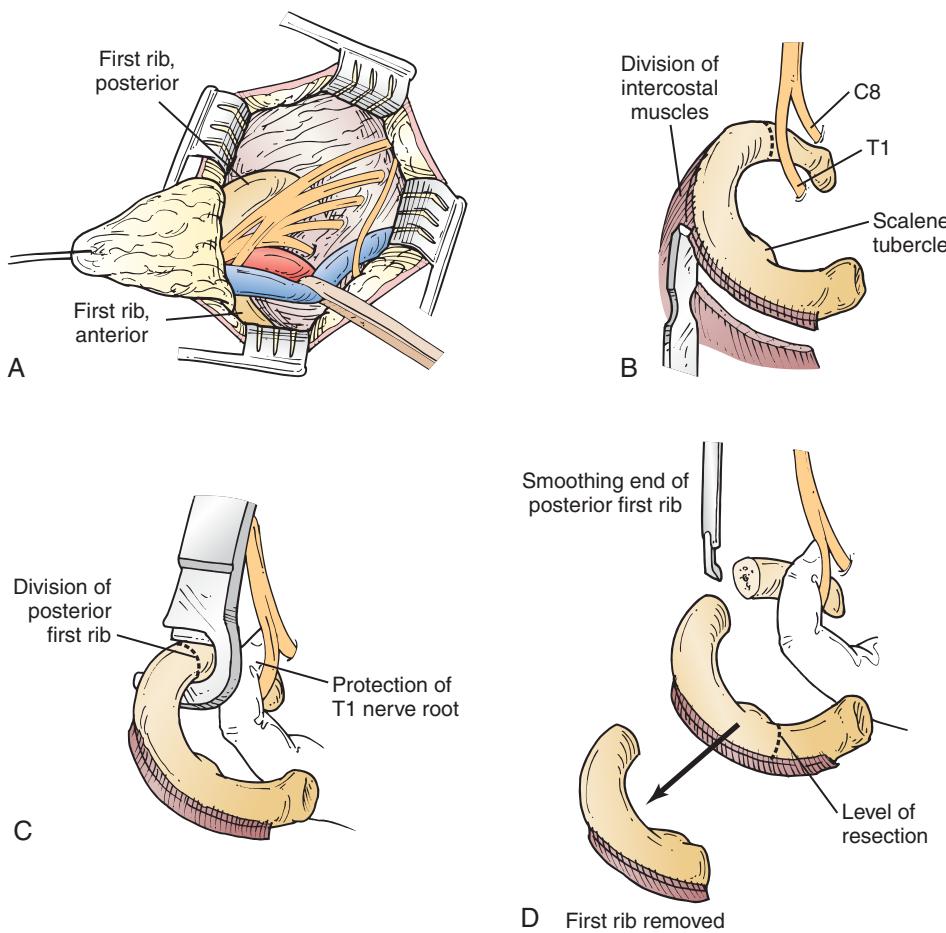


Figure 124.9 Supraclavicular First Rib Resection. (A) The first rib is shown in relation to the brachial plexus roots and the subclavian artery. (B) Intercostal attachments to the first rib are divided. (C) After division of the anterior first rib just proximal to the level of the scalene tubercle, the brachial plexus is reflected anteriorly to visualize the posterior neck of the rib. The T1 nerve root is displaced by a finger while the neck of the rib is divided. The anterior rib is cut and the specimen is removed from the field. (D) The remaining posterior edge of the rib is remodeled to a smooth surface using a Kerrison bone rongeur, ensuring that there is no residual impingement on the T1 nerve root. The anterior edge of the rib is similarly remodeled to a smooth surface (not shown). (Modified from Thompson RW. Treatment of thoracic outlet syndromes and cervical sympathectomy. In: Lumley JSP, Hoballah JJ, eds. *Springer Surgery Atlas Series: Vascular Surgery*. London: Springer-Verlag; 2009:103–118.⁶⁹)

temporary barrier deterrent to the formation of perineural adhesions. A closed-suction drain is placed into the supraclavicular field, and the scalene fat pad is reapproximated over the brachial plexus prior to wound closure.

Pectoralis Minor Tenotomy

When physical examination suggests brachial plexus nerve root irritation at the subpectoral space (“hyperabduction syndrome”),

pectoralis minor tenotomy may be added to either transaxillary or supraclavicular decompression. Isolated pectoralis minor tenotomy may also be performed when this site is the dominant location of nerve compression symptoms, or in patients who already underwent decompression by other approaches (persistent or recurrent nTOS). As illustrated in Figure 124.10, a short vertical incision is made in the lateral infraclavicular space adjacent to the deltopectoral groove. The lateral edge of the pectoralis major muscle is gently retracted medially, and the underlying

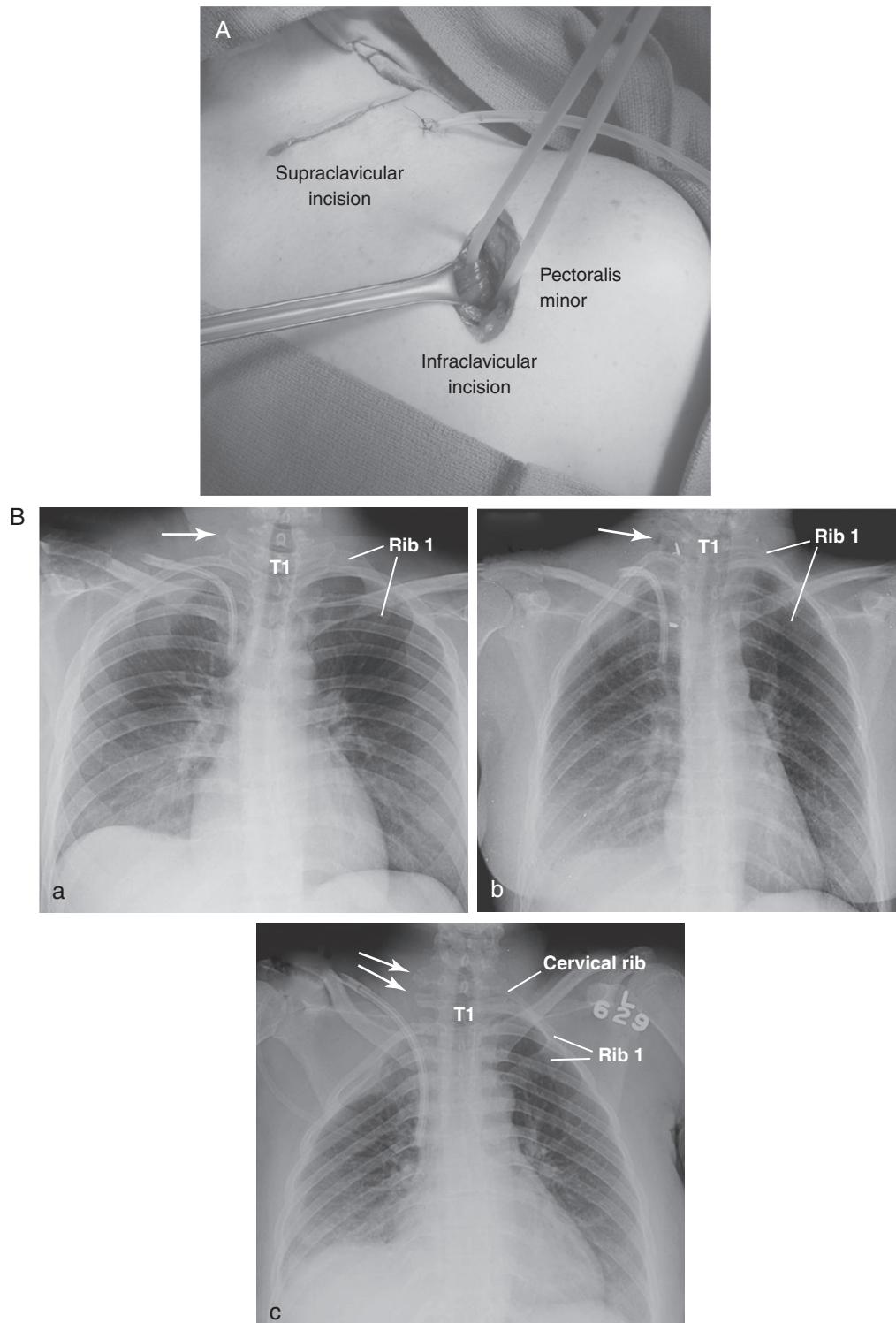


Figure 124.10 Pectoralis Minor Tenotomy and Postoperative Chest Radiographs. (A) Operative view of left lateral infraclavicular incision used to isolate the pectoralis minor muscle tendon, performed in conjunction with a supraclavicular thoracic outlet decompression procedure. (B) Postoperative chest radiographs. *a*, Chest radiograph after right supraclavicular decompression. The closed-suction drain is seen extending from the neck into the pleural apex, and the posterior end of the resected first rib is indicated (arrow). *b*, Chest radiograph after right supraclavicular decompression with an adjunctive cervical sympathectomy for reflex sympathetic dystrophy. The posterior end of the resected first rib is indicated (arrow), with the extent of sympathetic chain resection demonstrated by the position of radiodense clips at the first and fourth thoracic levels. *c*, Chest radiograph after right supraclavicular decompression with resection of the cervical and first ribs. The posterior ends of the resected cervical and first ribs are indicated (arrows).

pectoralis minor muscle encircled. The pectoralis minor tendon is then divided under direct vision, immediately inferior to its insertion on the coracoid process.

Postoperative Management

An upright chest X-ray is performed following all TOS decompressions, in part to detect residual pneumothorax or pleural fluid. Small air or fluid collections usually can be observed, although transthoracic aspiration may be required for large or expanding pneumothoraces. Postoperative pain regimens include a combination of narcotics, muscle relaxants, and nonsteroidal anti-inflammatory agents. The closed suction drain is removed 5–7 days postoperatively unless there is persistent lymphatic fluid, in which case the drain is removed in the outpatient setting once the leak has subsided.

There are no strict restrictions with respect to upper extremity use postoperatively, but patients are advised to avoid excessive reaching overhead or heavy lifting. Physical therapy is resumed as soon as feasible, usually upon hospital discharge or within 1 week postoperatively. The majority of patients resume fairly regular activity within several weeks, and in most cases can return to light-duty work by 4 to 6 weeks. Patients with longstanding nTOS can often display residual symptoms of dysesthesias, numbness, or other complaints even after thoracic outlet decompression. Yearly patient visits are used to assess long-term results.

SURGICAL COMPLICATIONS

Nerve Injuries

The most serious complications of TOS decompression are injuries to the brachial plexus nerve roots. Although infrequent, earlier rates of nerve injuries following transaxillary first rib resection contributed to diminished enthusiasm for this procedure in the 1980s.^{22,40} Although less likely to occur with the supraclavicular approach given improved exposure of the nerve roots, brachial plexus palsy can still occur secondary to retraction. In the absence of direct injury, however, these complications are temporary and usually resolve within weeks to months.

Temporary phrenic nerve dysfunction after supraclavicular thoracic outlet decompression occurs in ~10% of patients, most often associated with retraction during anterior scalenectomy, and results in temporary diaphragmatic paralysis. Although most patients are asymptomatic and only exhibit respiratory difficulty with extreme exertion, those with underlying lung disease may have more significant symptoms. While symptoms typically resolve within weeks, on occasion full recovery can take up to 10 months. In patients who require operation on the contralateral side, it is essential to ensure phrenic nerve paresis has completely resolved prior to the second operation, to avoid risking complete diaphragmatic paralysis and severe ventilatory incapacity. We therefore routinely perform fluoroscopic visualization of diaphragmatic function to ensure complete return of innervation before planning any contralateral operation.

Lymph Leakage

Minor lymphatic fluid collections are common within the first postoperative week. These may occur despite ligation of the thoracic duct on the left, usually due to lymph fluid leakage from small tributaries. In the majority of cases these lymph leaks will resolve spontaneously, usually within several weeks, and rarely require secondary interventions.

RESULTS OF SURGERY

Outcome Measures

Reported functional results vary considerably depending on severity or duration of symptoms preoperatively. Also complicating assessment of surgical results is the absence of well-established outcome measures or reporting standards for TOS decompression. Most authors divide results into categories: (1) excellent, with complete relief of symptoms; (2) good, with relief of major symptoms but some persistent symptoms; (3) fair, with partial relief but persistence of some major symptoms; and (4) poor, with no improvement. Many studies do not distinguish TOS categories (nTOS versus arterial or venous). Moreover, many reports have follow-up limited to only several months to a few years. Finally, most literature emanates from centers and surgeons well versed in thoracic outlet decompression, limiting generalizability to all vascular surgeons, many of whom seldom perform these procedures. A recent meta-analysis however demonstrated that surgical treatment of nTOS is beneficial in most patients and is relatively safe, with an improvement of 28.3 points on the Disabilities of the Arm, Shoulder and Hand (DASH) scoring system after operative treatment of nTOS.⁴⁷ The biggest challenge remains the diagnosis of nTOS, and underlines the importance of standardized diagnostic criteria prior to embarking on operative intervention.

Operative Results

Anterior Scaleneectomy

Anterior scaleneectomy was popularized by Adson as a means to avoid potential injury to the brachial plexus in patients with cervical ribs. In six reports published through 1989, encompassing 338 patients, there were good results in 26% to 89% (mean 56%), fair in 0% to 39% (mean 13%), and poor in 7% to 60% (mean 31%).^{48–61} At present, this operation is seldom performed in isolation for nTOS, in part because the long-term results do not appear as good as those achieved with approaches involving the resection of the first rib.

Transaxillary First Rib Resection

Since its introduction by Roos in 1966, transaxillary first rib resection has been one of the most frequently performed operations for nTOS. By 1989, more than 3000 such operations were reported in 21 publications. The largest of these series included 1315 patients, with a successful outcome in 92% and a failure rate of 8%.⁷⁷ As summarized in Table 124.4, the overall rate of good outcomes for transaxillary first rib resection has ranged from

TABLE 124.4

Collected Results for Transaxillary First Rib Resection

First Author	Year	# Operations	OUTCOMES REPORTED (%)		
			Good	Fair	Failed
Sanders et al. ⁷⁰	1968	69	90	0	10
Roeder et al. ⁷¹	1973	26	92	4	4
Hoofer and Burnett ⁷²	1973	135	100	0	0
Dale ⁷³	1975	49	94	0	6
Kremer and Ahlquist ⁷⁴	1975	48	86	0	14
McGough et al. ⁷⁵	1979	113	80	13	7
Youmans and Smiley ⁷⁶	1980	258	75	16	9
Roos ⁷⁷	1982	1315	92	0	8
Batt et al. ⁷⁸	1983	94	80	0	20
Sallstrom and Gjores ⁷⁹	1983	72	81	12	7
Heughan ⁸⁰	1984	44	75	0	25
Qvarfordt et al. ⁴²	1984	97	79	0	21
Narakas et al. ⁵⁴	1986	43	77	0	23
Tagaki et al. ⁵⁵	1987	48	79	0	21
Davies and Messerschmidt ⁸¹	1988	115	89	0	11
Selke and Kelly ⁸²	1988	460	79	14	7
Stanton et al. ⁸³	1988	87	85	4	11
Wood et al. ⁸⁴	1988	54	89	9	2
Cikrit et al. ⁶¹	1989	30	63	0	37
Lindgren et al. ⁸⁵	1989	175	59	0	41
Lepantalo et al. ⁸⁶	1989	112	52	25	23
Jamieson and Chinnick ⁸⁷	1996	380	53	25	22
Totals		3824	80%	6%	15%

Modified from Sanders RJ. *Thoracic Outlet Syndrome: A Common Sequelae of Neck Injuries*. Philadelphia: J. B. Lippincott Company; 1991.

52% to 100% (mean 80%), with fair outcomes in 0% to 25% (mean 6%) and failure of operation in 0% to 41% (mean 15%).

Supraclavicular First Rib Resection with Anterior and Middle Scalenectomy

Table 124.5 summarizes results of operation from seven different publications including a total of 1222 patients), the largest being the series reported by Hempel et al. (770 operations).³ Overall, the results for supraclavicular decompression were good in 59% to 91% (mean 77%), fair in 0% to 33% (mean 15%), and poor in 1% to 18% (mean 8%).

Comparison of Surgical Approaches

Sanders presented one of the most comprehensive analyses, in which the life-table method was used to compare

TABLE 124.5

Collected Results for Supraclavicular Scalenectomy/First Rib Resection

First Author	Year	# Operations	OUTCOMES REPORTED (%)		
			Good	Fair	Failed
Graham and Lincoln ⁸⁸	1973	78	91	5	4
Thompson and Hernandez ⁸⁹	1979	15	87	0	13
Thomas et al. ⁹⁰	1983	128	83	13	4
Reilly and Stoney ⁴⁴	1988	39	59	33	8
Loh et al. ⁶⁰	1989	22	68	23	9
Hempel et al. ³	1996	770	86	13	1
Axelrod et al. ⁶⁵	2001	170	65	17	18
Totals		1222	77%	15%	8%

Modified from Sanders RJ. *Thoracic Outlet Syndrome: A Common Sequelae of Neck Injuries*. Philadelphia: J. B. Lippincott Company; 1991.

outcomes for different nTOS operative procedures,^{1,22,62,63} including patients undergoing transaxillary first rib resection ($n = 112$), anterior and middle scalenectomy ($n = 286$), or supraclavicular scalenectomy with first rib resection ($n = 249$), finding no difference in initial success rate between the three procedures (91%, 93%, and 93%, respectively). As shown in Figure 124.11, percentages of patients with successful outcomes declined over time with all three procedures, without statistically significant difference between operations at 10–15 years.

Predicting the Outcomes of Surgery

Certain pre-existing clinical features appear to be associated with diminished operative success for nTOS, particularly work-related injury,^{24,64} longstanding symptoms,⁶⁴ major depression,^{24,65} chronic pain syndromes,^{24,66} diffuse upper extremity symptoms,²⁴ and lack of response to anterior scalene muscle blocks.²⁴ Anatomic anomalies also have prognostic implications. Sanders et al. reviewed long-term operative results in 54 nTOS patients with associated cervical ribs or anomalous first ribs, concluding that: (1) the presence of a cervical rib or anomalous first rib in nTOS patients does not improve surgical success rates compared to patients without rib abnormalities; (2) neck trauma is the most common cause for nTOS, even in those with abnormal ribs; (3) cervical and anomalous first ribs are predisposing factors rather than causes of nTOS; and (4) surgery in patients with cervical ribs should include both cervical rib and first rib resection.¹¹ Finally, outcomes appear to differ between adolescents and adults. Caputo et al. compared 154 adults and 35 adolescents at 3 and 6 months after supraclavicular nTOS decompression.⁶⁷ Although both groups saw improvement in functional outcome measures, more favorable functional outcomes occurred in adolescents as evidenced by significantly lower

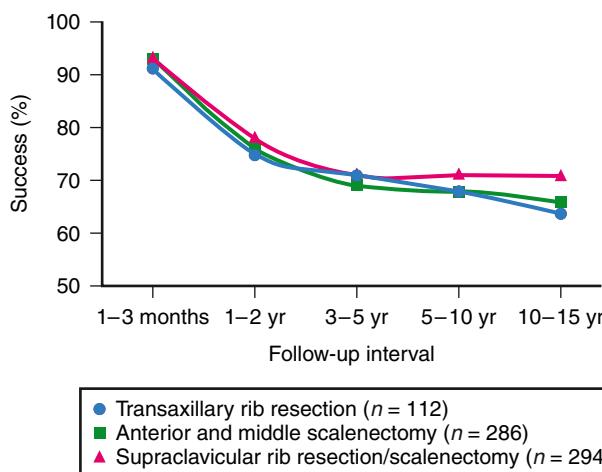


Figure 124.11 Long-Term Results of Three Operations for Neurogenic Thoracic Outlet Syndrome (nTOS). Outcome of 692 patients undergoing a primary operation for nTOS are shown in life-table format extending to follow-up intervals of 10 to 15 years. Data indicate results for patients having transaxillary first rib resection (circular symbols, $n = 112$), anterior and middle scalenectomy (square symbols, $n = 286$), or supraclavicular scalenectomy with first rib resection (triangular symbols, $n = 249$). There was no statistically significant difference between the three operations. (Modified from Sanders RJ. Thoracic Outlet Syndrome: A Common Sequelae of Neck Injuries. Philadelphia: J. B. Lippincott Company; 1991.)

mean nTOS Index (10.4 ± 3.1 vs. 39.3 ± 3.3) and less use of opiate medications (11.4% vs. 47.4%).

Ongoing Symptoms

Persistent neurogenic thoracic outlet syndrome

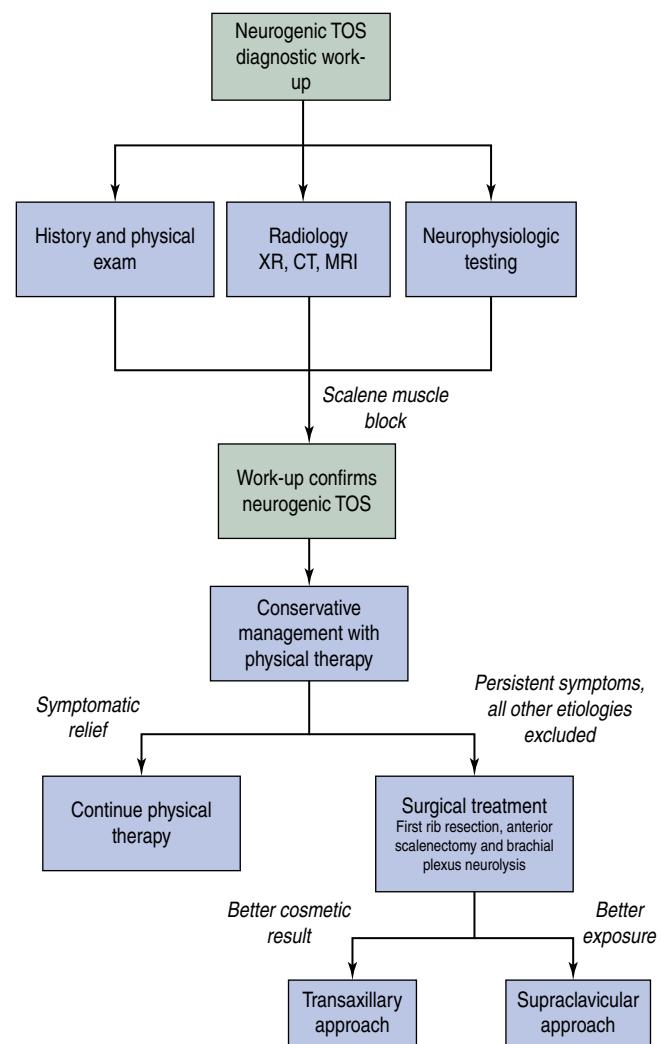
Persistent symptoms are those not relieved for any amount of time after the initial operation. In most cases, persistent symptoms are due to another condition. If symptoms cannot be attributed to another condition and resist conservative management for several months, the possibility of persistent nTOS is then considered. Persistent symptoms may occur after transaxillary first rib resection due to inadequate decompression of the upper nerve roots, since scalenectomy was not performed. In these cases, re-operative supraclavicular scalenectomy should be considered. Although it is unusual to observe persistent nTOS after supraclavicular scalenectomy, it is possible if the procedure did not include first rib resection. In such cases it may be reasonable to consider reoperation to remove the first rib, by either transaxillary or supraclavicular approach.

Recurrent neurogenic thoracic outlet syndrome

The majority of recurrences occur within the first 2 years of the primary operation. If reoperation is considered, the choice of procedure depends on the type of initial operation performed. If a transaxillary first rib resection was performed, reoperation should be through supraclavicular exposure to include scalenectomy, brachial plexus neurolysis, and resection of any remaining first rib. Experience with such operations shows that the anterior scalene muscle stump has often become attached to the extrapleural fascia or brachial plexus nerve roots; it is also common to find a segment of the posterior rib still

present, since this portion cannot be resected easily through the transaxillary approach. If the initial operation was a supraclavicular scalenectomy, a repeat operation should include first rib resection. Because the cause of recurrent nTOS following supraclavicular scalenectomy and first rib resection is usually the formation of perineural adhesions, reoperation through the supraclavicular route may still be of value since it permits complete brachial plexus neurolysis.

CHAPTER ALGORITHM



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Caputo FJ, Wittenberg AM, Vemuri C, et al. Supraclavicular decompression for neurogenic thoracic outlet syndrome in adolescent and adult populations. *J Vasc Surg.* 2013;57(1):149–157.

This report demonstrates excellent outcomes for both adults and adolescents undergoing supraclavicular decompression for nTOS, with analysis of various preoperative factors that may determine results.

Hempel GK, Shutze WP, Anderson JF, Bukhari HI. 770 consecutive supraclavicular first rib resections for thoracic outlet syndrome. *Ann Vasc Surg.* 1996;10(5):456–463.

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Thoracic Outlet Syndrome: Arterial

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Arterial complications from subclavian artery compression represent the least common type of thoracic outlet syndrome (TOS) in adults, but they also represent the strongest indication for operative intervention. Arterial manifestations usually follow a progressive course characterized by extrinsic compression, poststenotic dilatation, aneurysmal degeneration, thrombus formation, and secondary embolization. Because arterial TOS is typically associated with anomalous osseous structures, this form of TOS has a more easily definable clinical picture. In fact, arterial TOS was probably the first form to be described as early as 1831.¹ The first reported resection of a bone abnormality causing a subclavian aneurysm was by Coote in 1861.² Compression of the subclavian artery and brachial plexus was first termed Naffziger syndrome³ and evolved to the modern term *thoracic outlet syndrome* after a 1956 publication by Peet and coworkers.⁴

PATOPHYSIOLOGY

Arterial complications of TOS are associated with bone abnormalities in almost all cases. Cervical ribs that cause subclavian artery damage tend to extend beyond the transverse

process with partial or complete fusion to the first rib by a bony pseudarthrosis.⁵ This differs from the longer, thinner, and incomplete cervical ribs usually associated with neurogenic TOS. The cervical rib pushes the subclavian artery forward, angulating and compressing it between the first rib and the anterior scalene muscle. This compression causes injury to the inferior wall of the third segment of the subclavian artery, which may lead to localized intimal damage or poststenotic dilatation. Less common causes of arterial TOS include anomalous first ribs, fibrocartilaginous bands associated with the anterior scalene muscle, muscular hypertrophy in athletes, and hypertrophic callus from healed clavicle or first rib fractures.⁶⁻⁸ Poststenotic dilatation associated with chronic arterial compression may progress to aneurysmal change, whereas localized intimal damage may lead to embolization or thrombosis. The relative frequencies of anatomic abnormalities are shown in Table 125.1.

EPIDEMIOLOGY

The frequency of arterial TOS in the general population is undefined, but it represents a small subset of patients undergoing

TABLE 125.1 Relative Frequency of Anatomic Abnormalities Causing Arterial Thoracic Outlet Syndrome

Abnormality	Frequency (%) ^a
Cervical rib	64
Anomalous first rib	17
Fibrocartilaginous band	11
Clavicular fracture	7
Enlarged C7 transverse process	1

^aPercentages represent a compendium of 162 patients from six large series.^{6,7,13–16}

operative treatment for TOS. In the largest single-institution experience of 5102 patients treated for all varieties of TOS, Urschel and Kourlis⁹ performed primary neurovascular decompression on 294 (6%) for arterial TOS. Orlando et al.¹⁰ reported that 25 (4%) of 594 consecutive first rib resections were performed for arterial TOS. Similarly, Rinehardt et al.¹¹ reported that 44 (3%) of 1431 TOS cases from the NSQIP database were performed for arterial TOS. In contrast, arterial TOS is a relatively more common form in children and adolescents, accounting for 12% to 32% of cases.^{12,13}

Most patients presenting with symptoms of arterial TOS are young, active adults. The mean age in recent published series ranges from 32 to 45 years, with proportionately more women than men.^{7,10,11} No familial predisposition has been described. The condition appears to be related to bone abnormalities or trauma in nearly every circumstance.^{7,10,14–17} Orlando et al. reported arterial TOS is significantly more likely to be associated with a cervical rib than either venous TOS or neurogenic TOS: in their series, 60% of arterial TOS patients had a cervical rib versus 2.3% of venous TOS and 9.4% of neurogenic TOS.¹⁰ Vemuri et al. reported that only one (3%) of 40 patients with arterial TOS had no identifiable bony abnormality.⁷

CLINICAL PRESENTATION

Patients with arterial TOS have a characteristic history and physical examination, but diagnosis requires confirmation with objective testing.

Signs and Symptoms

The most common presentation is hand ischemia due to brachial artery embolus or distal microembolization. However, arterial TOS can be associated with less dramatic symptoms, and many cases go unrecognized because the condition tends to occur in young patients without atherosclerotic risk factors. Early in the disease process, patients may present with mild symptoms of exertional arm pain or unilateral Raynaud syndrome. Moderate to severe exertional pain may be associated with subclavian artery thrombosis. On occasion, a subclavian artery aneurysm may be discovered in an asymptomatic patient.⁷ Although rare, stroke from retrograde propagation of subclavian thrombus has been reported.^{7,18–20}

Clinical Assessment

Although acute hand ischemia with absent brachial and radial pulses is a common presentation, the clinical picture of arterial TOS may be more chronic and subtle. Clues to the diagnosis include the young age of the patient and the tendency for symptoms to be unilateral, which helps differentiate the condition from systemic pathologic states. The directed physical examination should consist of assessing upper extremity pulses, measuring bilateral arm blood pressures, and auscultating for bruits in the supraclavicular fossa. A bruit may be elicited on shoulder abduction or the overhead arm position if it is not present in the relaxed position. Specific findings on physical examination include a palpable cervical rib and a pulsatile supraclavicular mass. Evidence of microembolization to the hand, including digital ischemia and splinter hemorrhages, may also be present.

DIAGNOSTIC EVALUATION

Arterial TOS is a clinical diagnosis made by combining important elements from the history and physical examination. The following adjuncts may help support the diagnosis or suggest an alternative cause of the patient's symptoms.

Compression Maneuvers

Compression maneuvers such as the Adson test, costoclavicular maneuver (exaggerated military position), and hyperabduction maneuver (shoulder abduction beyond 90 degrees) have historically been used to aid in the diagnosis of TOS, but none is accurate. Ablation or reduction of the radial pulse with these maneuvers is considered a positive test result, but the incidence of false-positives in normal, healthy volunteers ranges from 9% to 57%.^{21–24} Another compression maneuver is the abduction–external rotation test, also referred to as the elevated arm stress test popularized by Roos and Owens.²⁵ Development of hand pain or paresthesias within 60 seconds is considered a positive test result. This test is used in the diagnosis of neurogenic TOS but is not helpful in arterial TOS (see Ch. 124, Thoracic Outlet Syndrome: Neurogenic).²⁶

Noninvasive Vascular Laboratory Studies

Duplex Ultrasonography

Duplex ultrasound examination of the subclavian and axillary arteries may demonstrate aneurysmal change, blunted waveforms, or elevated flow velocities correlating with a compressive stenosis (see Ch. 22, Vascular Laboratory: Arterial Duplex Scanning). The clavicle may interfere with complete ultrasound imaging of the subclavian artery, but significant ulcerations and intimal disruption may be visible. A subclavian artery flow velocity exceeding 240 cm/s may be considered evidence of a hemodynamically significant fixed stenosis.²⁷ In patients without a fixed stenosis, compression maneuvers during sonographic evaluation have been recommended, with decreased subclavian artery diameter or changes in peak systolic velocity thought to be diagnostic of arterial TOS. However, as with

the pulse-monitored compression maneuvers described before, there are a high number of false-positives in normal, healthy volunteers. Studies have shown that compression maneuvers are associated with complete occlusion or significant stenosis of the subclavian artery in approximately 20% of normal subjects.^{28,29} Therefore an abnormality detected on ultrasound during compression maneuvers should be used only to confirm a suspected diagnosis of arterial TOS.

Pulse Volume or Segmental Pressure Recording

Pulse volume or Doppler segmental pressure recordings taken at multiple levels in the upper extremities can help localize the level of arterial obstruction if embolization has occurred from arterial TOS (see Ch. 21, Vascular Laboratory: Arterial Physiologic Assessment). Diminished digital waveforms in the

affected extremity during compression maneuvers coupled with normal findings in the contralateral extremity suggest dynamic subclavian artery compression in the symptomatic patient (Fig. 125.1). Fixed waveform dampening is indicative of arterial insufficiency consistent with stenosis or distal embolism.

Radiologic Studies

Radiography

The American College of Radiology recommends chest radiography as the initial imaging modality in patients suspected of having TOS, given that it is easy to perform, noninvasive, and a low-cost test that can assess for several potential abnormalities.³⁰ Chest radiographs including cervical spine views will often demonstrate the offending bone abnormality. Cervical

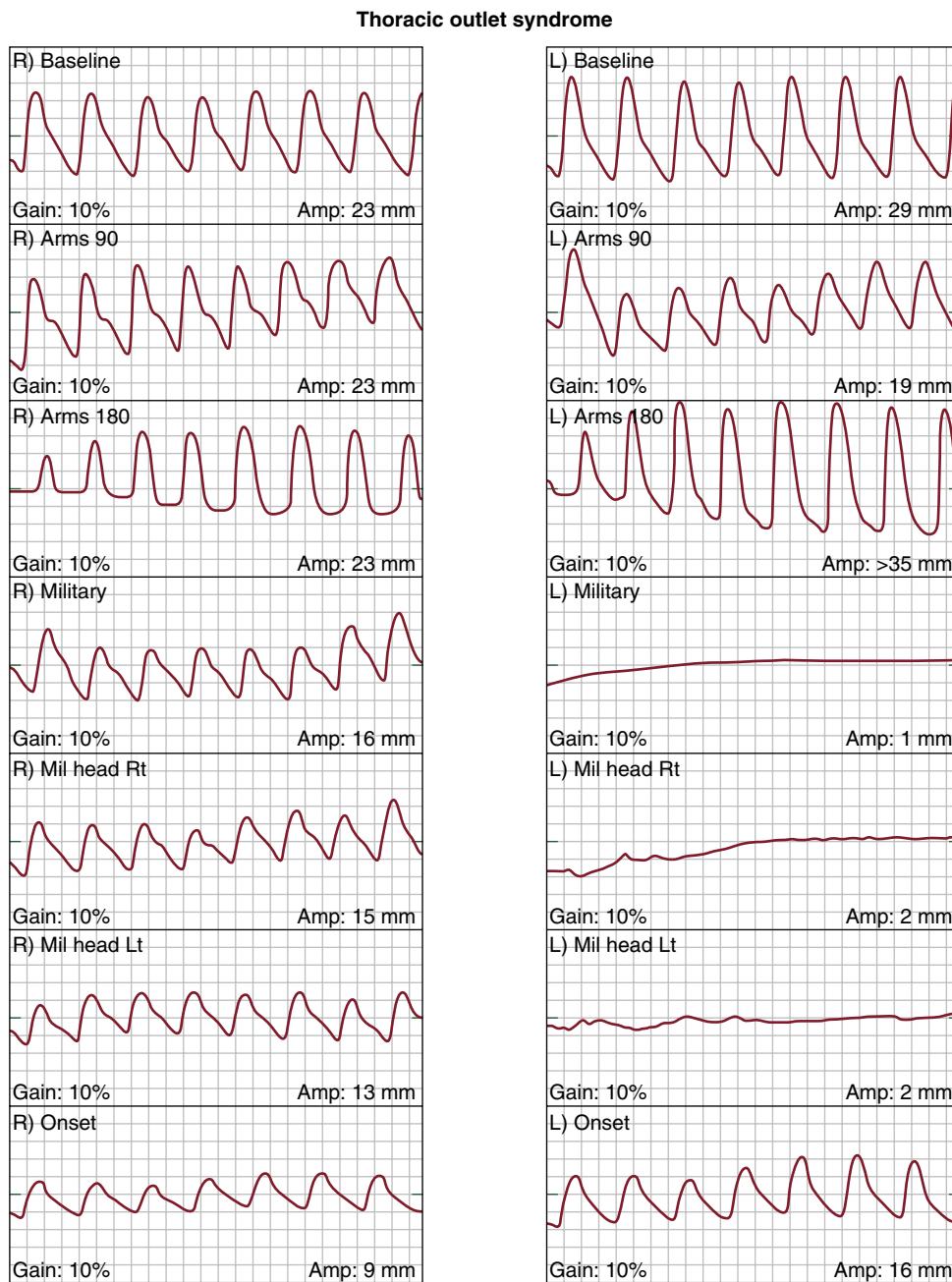


Figure 125.1 Digital photoplethysmography studies showing left upper extremity arterial waveform reduction with selected compression maneuvers.

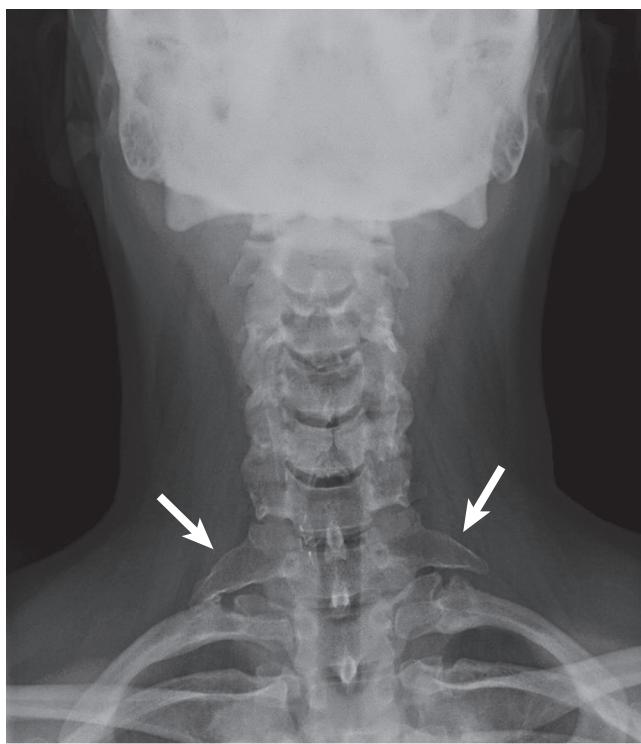


Figure 125.2 Chest radiograph demonstrating bilateral cervical ribs (arrows) in a patient with arterial thoracic outlet syndrome.

ribs, elongated transverse cervical processes, and large clavicle fracture calluses are easily seen (Fig. 125.2). Soft tissue abnormalities such as Pancoast tumors can also be detected, but anomalous first ribs and fibrocartilaginous bands are not likely to be detected on plain radiographs.

Computed Tomography

Computed tomographic angiography (CTA) with the intravenous administration of a contrast agent is a useful test to secure the diagnosis and to aid in surgical planning. CTA is typically performed in two views: one with the affected arm adducted, and the other with the arm abducted at 170 degrees or greater. In addition to identifying the exact point of compression, CTA may identify arterial disease that requires treatment such as subclavian artery aneurysm, arterial thrombosis, intimal irregularity, or fixed stenosis. With the ability to manipulate these images in three dimensions, there is usually no need for catheter-based arteriography (Fig. 125.3). In fact, CTA has replaced catheter-based angiography as the main radiographic test for diagnosis of arterial TOS at most centers. CTA can also be used to evaluate the distal arterial circulation, but catheter-based angiography may still be necessary to visualize the small arteries of the distal arm and hand. It should be re-emphasized that the diagnosis of arterial TOS is not made by identifying position-induced compression of the subclavian artery.³⁰ Because compression of the neurovascular structures in the thoracic outlet is common in normal, healthy subjects,³¹ dynamic compression maneuvers should be used only to confirm the diagnosis in patients with suspected arterial TOS.

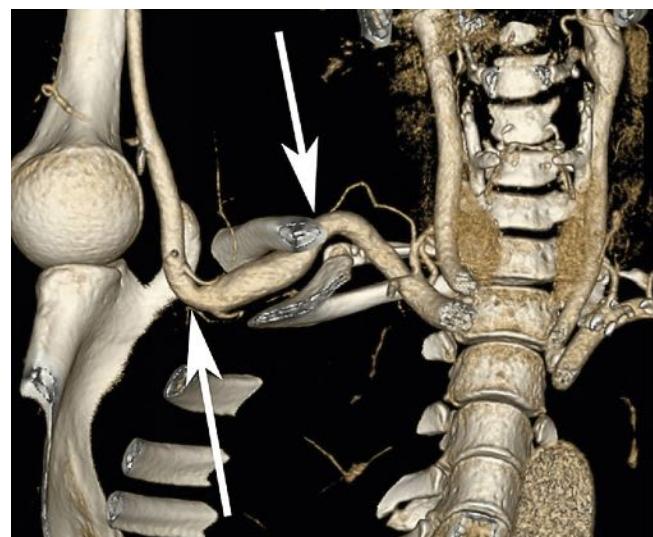


Figure 125.3 Three-dimensional reconstruction of a computed tomography angiogram showing compression of the right subclavian artery with poststenotic dilatation (arrows). (From White P, Fox CJ, Feuerstein IM. Cervical rib causing arterial thoracic outlet syndrome. *J Am Coll Surg*. 2009; 209:148–149.)

Magnetic Resonance Angiography

Magnetic resonance angiography (MRA) may be an acceptable substitute for CTA or catheter angiography and offers the advantage of avoiding ionizing radiation.³⁰ While MRA is considered the imaging modality of choice in some centers,³⁰ the sensitivity of MRA for diagnosis of arterial TOS appears to be low. Two reports of MRA in patients with arterial symptoms had 37% and 42% incidence of false-negative findings, respectively.^{32,33} Therefore a normal finding on MRA should not be used to rule out the diagnosis of a clinically suspected arterial TOS. To improve vascular imaging, a number of MRA sequencing options have been recommended.³⁴

Catheter-Based Angiography

Upper extremity arteriography was considered the “gold standard” for evaluation of arterial TOS and is still performed in the setting of endovascular treatment (Fig. 125.4). However, catheter angiography for evaluation of arterial TOS has been replaced by the less invasive CTA. Compared to CTA, arteriography is less reliable in demonstrating impinging structures and other anatomic abnormalities. Arteriography with magnified views remains the best method for demonstrating embolic occlusion of the small arteries of the hand and fingers (Fig. 125.5).

Laboratory Testing

There are no specific laboratory tests that are necessary to diagnose arterial TOS. However, specific laboratory assays are important to exclude systemic causes of upper extremity ischemia, such as vasculitis and connective tissue disorders (see Ch. 138, Vasculitis and Other Uncommon Arteriopathies and Ch. 141, Aneurysms Caused by Connective Tissue Abnormalities).



Figure 125.4 Left subclavian arteriogram demonstrating subclavian aneurysm with thrombus.

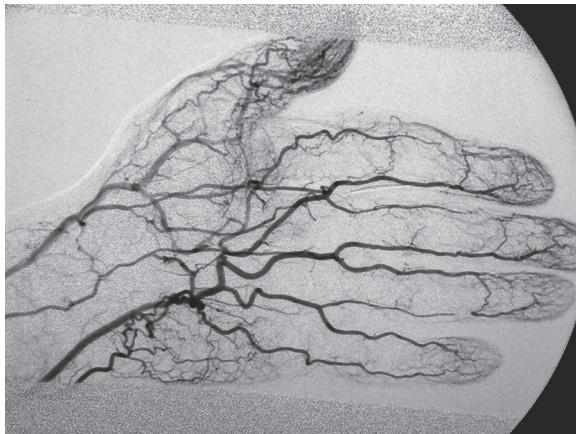


Figure 125.5 Hand arteriogram demonstrating distal embolization in the second, third, and fourth digits.

DIFFERENTIAL DIAGNOSIS

Although arterial TOS has a characteristic presentation, other causes of upper extremity ischemia may be suspected from the history and physical examination (Box 125.1). A history of cardiac disease, particularly mitral valve stenosis or atrial fibrillation, supports a cardioembolic etiology. A family history of venous thromboembolic disease suggests an underlying hypercoagulable state, and further tests to exclude paradoxical embolus may be warranted. Risk factors for atherosclerosis, particularly heavy tobacco use, raise the possibility of atherosclerotic occlusive disease as the underlying etiology. Associated symptoms of polymyalgia rheumatica suggest the possibility of vasculitis, whereas symptoms of arthritis, dermatitis, and esophageal dysmotility warrant evaluation for connective tissue disease. Other possible causes include dissection, radiation injury, and trauma, all of which can be suspected from the history and evaluated with imaging studies discussed above.

BOX 125.1

Differential Diagnosis of Arterial Thoracic Outlet Syndrome

- Cardiac embolus
- Aortic arch embolization
- Hypothenar hammer syndrome
- Acquired or congenital coagulopathies
- Vasculitis
- Takayasu arteritis
- Giant cell arteritis
- Radiation arteritis
- Connective tissue disorders
- Marfan syndrome
- Ehlers–Danlos type IV
- Pseudoxanthoma elasticum
- Arterial dissection
- Atherosclerotic upper extremity disease
- Thromboangiitis obliterans
- Traumatic
- Humeral head compression of axillary artery
- Circumflex humeral artery pseudoaneurysm (baseball pitchers)

Screening

There is no role for screening of asymptomatic patients to diagnose arterial TOS. As noted before, dynamic compression maneuvers are associated with a significant rate of false-positive results in asymptomatic patients; therefore, positive test results should be viewed with caution. On the other hand, it is reasonable to evaluate the contralateral side in a patient with symptomatic arterial TOS. The incidence of bilateral arterial TOS is not known. Among patients with TOS of all types, the prevalence of bilateral cervical ribs has been reported to be 42%.³⁵ Treatment may be indicated for evidence of arterial dilatation or severe intimal degeneration, even in asymptomatic individuals.

TREATMENT

See Chapter Algorithm for treatment outline.

Medical Treatment

Contrary to neurogenic TOS, there is no role for conservative treatment of symptomatic patients with arterial TOS. On the other hand, conservative treatment may be appropriate for some asymptomatic patients. Although the natural history is not well known, simple compression without evidence of arterial degeneration does not appear to convey a significant risk of complications in the asymptomatic patient. Therefore, watchful waiting with use of serial noninvasive tests, such as duplex ultrasonography, may be a reasonable approach. In addition, every attempt should be made to reduce compression forces in the thoracic outlet. This is especially true for high-performance athletes engaged in repetitive overhead arm motion, such as professional baseball pitchers and tennis players. Aggressive physical therapy and modification of arm motion have been recommended in these cases.³⁶

The natural history of arterial abnormalities in asymptomatic patients with arterial TOS is not completely understood.

However, some patients present with profound hand ischemia as the first manifestation of arterial TOS. Therefore, it seems reasonable to treat patients with subclavian artery compression and documented arterial disease, such as arterial dilatation or severe intimal disruption, before symptoms ensue, especially in young, active individuals. The role of anticoagulation in these circumstances is not known.

Surgical Treatment Principles

The three main components of treatment include relieving the arterial compression, removing the source of embolus, and restoring the distal circulation. At a minimum, relieving the arterial compression involves resection of cervical ribs and any other identified anomalies causing impingement in the thoracic outlet. As discussed below, most authors also recommend routine division of the anterior scalene muscle and resection of the first rib to avoid recurrence. Removal of the source of embolus involves resection of a subclavian aneurysm or repair of an arterial stenosis with intimal damage. The success of arterial reconstruction is usually related to the status of the arterial outflow in the limb. Restoration of the distal circulation may involve any combination of thrombolysis, thromboembolectomy, or bypass.

The decision to repair an artery after thoracic outlet decompression should be individualized. Resolution of poststenotic dilatation after decompression of the thoracic outlet has been described,^{6,37,38} but it is not certain that all lesions will heal spontaneously. Likewise, it is not known whether associated intimal damage will resolve after decompression. At some point, poststenotic dilatation progresses to an aneurysm. Symptomatic patients with subclavian artery aneurysms tend to have recurrent thromboembolic complications that may lead to digit or limb loss. Because of the numerous collaterals around the shoulder, the natural history of a subclavian artery thrombosis is uncertain. Most active patients with subclavian artery thrombosis will have significant arm fatigue with exercise, but arterial repair may be indicated in asymptomatic patients due to the reported risk of retrograde propagation with resultant stroke.^{18–20}

Treatment Selection

The appropriate treatment is dictated by the degree of arterial damage and the status of the distal circulation. Some definitions are important to consider here, as they differ from other

anatomic sites. Aneurysm of the subclavian artery associated with TOS is defined as an increase in diameter of more than two times the diameter of the adjacent artery.^{37,39} Poststenotic dilatation associated with TOS is then defined as an increase in diameter of less than twice that of the adjacent artery.

Scher Classification

The Scher classification system for arterial TOS provides a guide to appropriate treatment and is summarized in Table 125.2.³⁹ Stage I describes compression of the subclavian artery with minor poststenotic dilatation and no intimal disruption. Appropriate treatment consists of decompression of the thoracic outlet including cervical or first rib resection, division of the anterior scalene muscle, and resection of any anomalous fibrous bands. Regression of poststenotic dilatation after TOS decompression has been reported.^{6,37,39} Scher stage II includes subclavian arteries with intimal damage, aneurysmal change, and mural thrombus. Appropriate treatment includes decompression of the thoracic outlet and subclavian artery reconstruction. Scher stage III includes those patients presenting with distal embolization. Treatment should include a combination of thrombolysis or thromboembolectomy, thoracic outlet decompression, and vascular reconstruction.

Surgical Treatment

Surgical treatment is indicated for all symptomatic patients with ischemia and for asymptomatic patients with poststenotic dilatation, aneurysmal degeneration, or intimal damage. Asymptomatic individuals with compression of the subclavian artery at the thoracic outlet and no evidence of arterial changes do not require surgical intervention, but they should be monitored because their natural history is unknown. There are no specific contraindications to repair of arterial TOS; however, a few patients may be unfit for open surgery because of severe uncorrectable comorbidities.

Relevant Anatomy

The most common offending osseous abnormality in arterial TOS is a cervical rib, accounting for about three fifths of cases (see Table 125.1). Multiple other abnormalities may be encountered, including abnormal first ribs, fracture calluses, fibromuscular bands, and soft tissue defects.^{5–7} Figure 125.6 demonstrates several of these abnormalities.

TABLE 125.2 Scher Staging Classification of Arterial Thoracic Outlet Syndrome Complications

Stage	Arterial Complication	Treatment
Stage 0	Asymptomatic subclavian artery compression	No treatment indicated
Stage I	Stenosis of subclavian artery with minor poststenotic dilatation; no intimal disruption	Decompression of the thoracic outlet
Stage II	Subclavian artery aneurysm with intimal damage and mural thrombus	Decompression of the thoracic outlet Subclavian artery reconstruction
Stage III	Distal embolization from subclavian artery disease	Thrombolysis or thromboembolectomy Decompression of the thoracic outlet Vascular reconstruction

Modified from Matsumura JS, Rilling WS, Pearce WH, et al. Helical computed tomography of the normal thoracic outlet. *J Vasc Surg*. 1997; 26:776–783.

Operative Planning and Strategy

The first principle of treatment is decompression of the thoracic outlet. This may involve resection of a cervical rib, resection of fibrous bands, or anterior scalenectomy, but most experts agree that the first rib should usually be resected in addition to other associated disease.^{7,15,16,40} The first rib is a fixed structure that maintains tension in the thoracic outlet, and once it is released, the neurovascular bundle is allowed to relax and fall inferiorly. More importantly, it represents a common insertion for fibromuscular structures that cause vascular compression but are not recognized at the time of operation.

There are three main approaches to thoracic outlet decompression: transaxillary, supraclavicular, and infraclavicular. Each has some advantages. Proponents of the transaxillary approach describe a more complete visualization of the first rib for resection. However, this approach is generally not suitable for vascular reconstruction and is therefore more appropriate for patients without fixed arterial disease.⁴⁰ The supraclavicular approach facilitates removal of cervical ribs. This exposure allows identification of the cause of compression, visualization of brachial plexus trunks and scalene muscles, resection of the first rib, and subsequent vascular reconstruction. For this reason, we favor a supraclavicular exposure whenever an arterial reconstruction is necessary. Recent advances performed at some centers include video-assisted thoracoscopic surgery to improve visualization of the operative field during first rib resection⁴¹ and robot- or endoscopic-assisted transaxillary approaches.⁴² Because these approaches are not suitable for open vascular reconstruction, they are more appropriate to treat patients without fixed arterial disease and those with neurogenic TOS.⁴³

A large subclavian aneurysm or intimal damage that extends beneath the clavicle may require infraclavicular exposure in addition to the supraclavicular incision. This allows complete exposure of the subclavian and axillary arteries for vascular reconstruction. A single incision that affords both supraclavicular and infraclavicular exposure has been described.⁴⁴ Rarely, the subclavian artery has a focal abnormality that can be repaired with simple resection and primary anastomosis. More commonly, a conduit is required for replacement of the subclavian artery. Although some consider the greater saphenous vein to be the conduit of choice, reconstruction can be accomplished with femoral vein, cryopreserved femoral artery, or prosthetic grafts. Ringed polytetrafluoroethylene or femoral vein may offer some advantage in longer bypasses because these grafts resist kinking as they traverse under the clavicle. Although long-term advantages of one type of conduit over another have not been elucidated, the femoral vein conduit appears to offer excellent medium-term patency.⁴³

Description of Technique

Some key technical details merit emphasis.^{45,46} After the scalene fat pad is elevated, the phrenic nerve is mobilized off the surface of the anterior scalene before the muscle is divided (Fig. 125.7A). The subclavian artery is situated immediately behind the anterior scalene muscle. The middle scalene muscle is then divided off the first rib, with care taken to avoid the long thoracic nerve that is located on the posterior aspect of the middle scalene (see Fig. 125.7B). Intercostal muscles are freed from medial and lateral edges of the first rib with a periosteal elevator, and the first rib is divided just distal to the tubercle (see Fig. 125.7C).

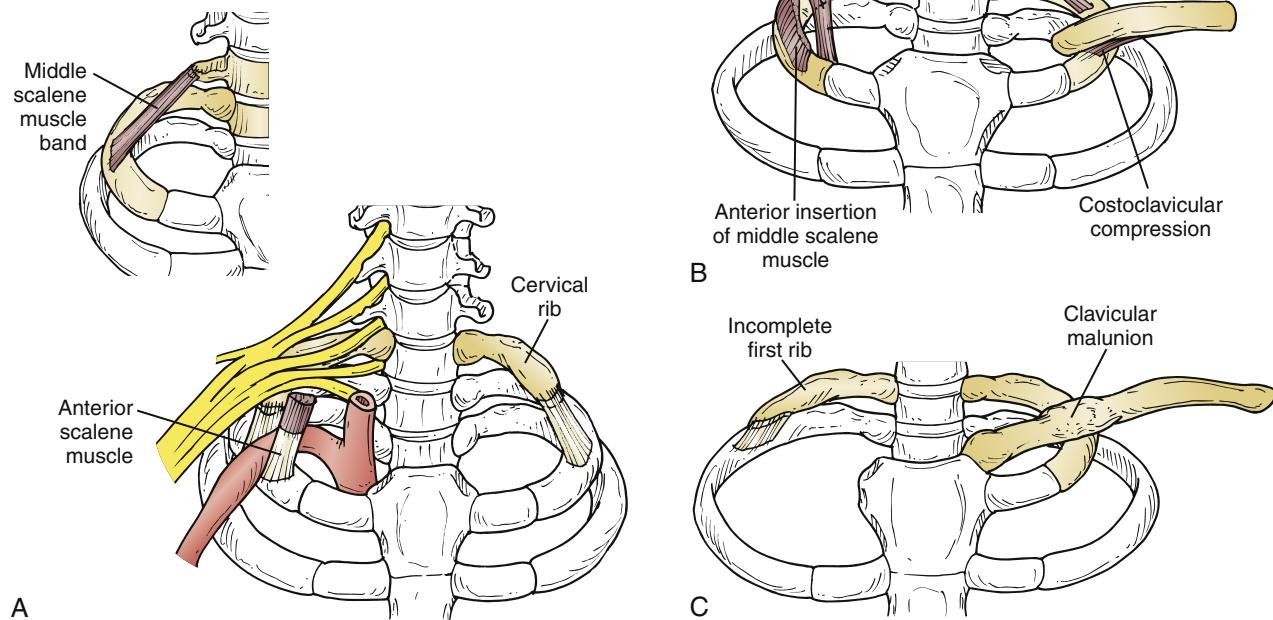


Figure 125.6 Pathologic Conditions Commonly Associated with Arterial Thoracic Outlet Syndrome. (A) Cervical ribs with associated fibrous bands and middle scalene muscle band. (B) Fascial bands and anomalous muscle insertions. (C) Incomplete first rib and clavicular fracture callus. (From Wind GG, Valentine RJ. *Anatomic Exposures in Vascular Surgery*. 3rd ed. Philadelphia: Lippincott Williams & Wilkins; 2013.)

The divided rib can then be used as a lever to assist with mobilization before it is divided anteriorly (see Fig. 125.7D).

Endovascular Options

Although open surgical reconstruction is the standard approach to arterial complications of TOS, there have been scattered reports of endovascular repair of associated fixed arterial disease combined with surgical decompression of the thoracic outlet.^{47–49} The importance of adjunctive decompression cannot be overemphasized because failure to decompress the thoracic outlet can lead to stent fracture or collapse, restenosis, and thrombosis.⁵⁰ However, limited published data suggest that long-term patency of endovascular repair is not favorable, even after decompression. In a series of seven TOS patients

undergoing stent graft repair of subclavian artery aneurysms, three required re-intervention for graft thrombosis or restenosis.⁴⁹ Fortunately, there were no cases of limb loss or decreased function. Although stent graft reconstruction of subclavian artery aneurysms associated with TOS has a high chance of immediate success, these data suggest that patients will require lifelong surveillance due to the risk of late complications.

Distal Revascularization

Patients with Scher stage III present with upper extremity ischemia due to distal embolization. Any degree of motor deficit or a significant sensory deficit should be considered an indication for immediate operation including embolectomy. Brachial artery embolectomy does not always require a separate distal

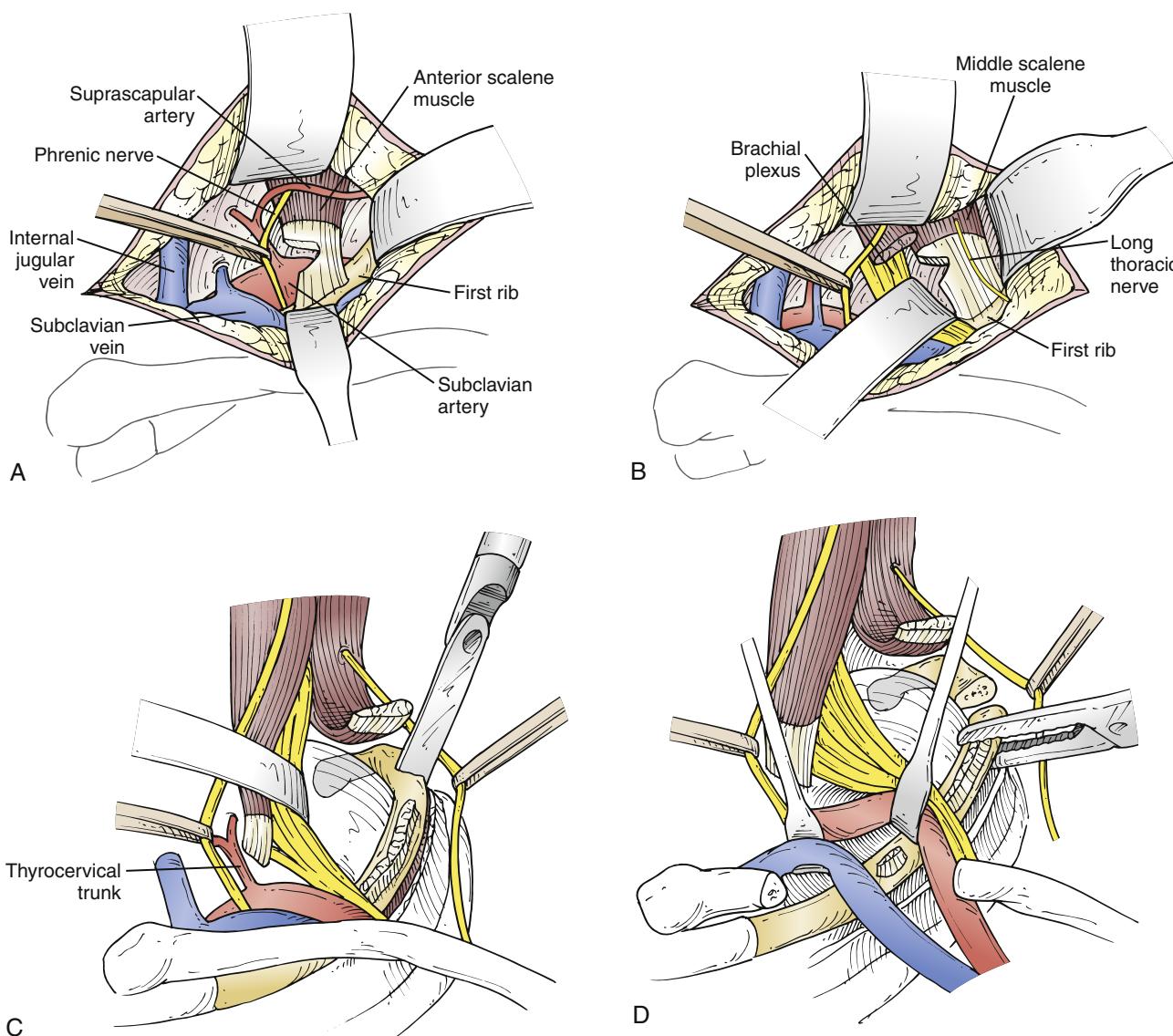


Figure 125.7 (A) Operative view of the supraclavicular approach to thoracic outlet decompression. After mobilization of the scalene fat pad, the phrenic nerve should be identified and carefully elevated before the anterior scalene muscle is divided. (B) The long thoracic nerve should be identified and protected during division of the middle scalene muscle. (C) Attachments are freed by an extraperiosteal approach to prevent recurrent symptoms from reossification of the periosteal bed. (D) Division of the first rib should be performed under direct vision to minimize the possibility of damage to the brachial plexus. After the first rib is divided just distal to the tubercle, the divided rib can be held as a lever to aid in clearing the overlying vessels. (From Wind GG, Valentine RJ. *Anatomic Exposures in Vascular Surgery*. 3rd ed. Philadelphia: Lippincott Williams & Wilkins; 2013.)

arm incision, as large emboli can be extracted through the subclavian artery in some cases. Although embolectomy is usually sufficient, distal bypasses are sometimes necessary in patients with chronic embolization. Patients who present with milder ischemia may be appropriate for thrombolysis before surgical repair.⁵¹ This may be particularly important in patients who have complete thrombosis of the forearm and hand vessels on arteriography.

Postoperative Management

In addition to supportive care, patients may benefit from physical therapy and range of motion exercises to shorten convalescence. Arterial repairs should be monitored with serial physical examinations and noninvasive studies such as duplex ultrasound. Examination intervals vary from institution to institution, but the Oregon group has recommended examinations at 3 months after open bypass procedures and every 6 months thereafter.¹⁷ The UCLA group recommends more frequent follow-up after endovascular repair.⁴⁰

Definition of Success and Determinants of Outcome

Successful outcome after treatment of arterial TOS is determined by relief of symptoms, avoidance of recurrence, patency of arterial bypasses, and limb salvage. Published series report complete relief of symptoms in more than 90% of patients.^{6,15,17} However, some patients may continue to have symptoms due to distal ischemic changes or late effects of concurrent neurogenic TOS.⁷ Bypass patency is reported in the range of 90% to 100%, depending on the status of the outflow vessels.^{6,7,15} Limb salvage should approach 100% in Scher stage I and stage II lesions; distal embolization may result in

finger amputation in patients with Scher stage III lesions, but arm amputation is distinctly uncommon.^{8,22,52}

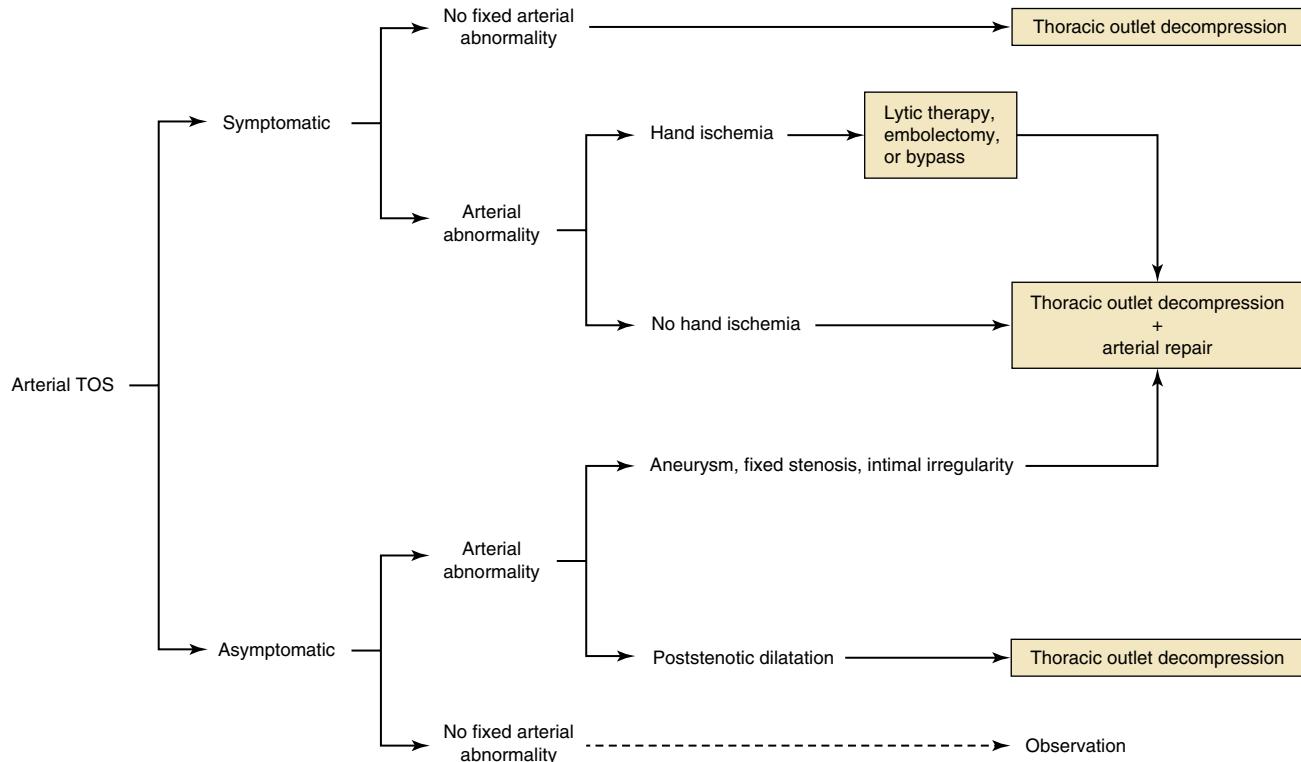
Results

Long-term results are related to the status of the distal vasculature. For Scher stage I lesions, decompression of the thoracic outlet alone is sufficient, with excellent results and the expectation that poststenotic dilatation will regress within a year.⁶ Limbs with compromised outflow secondary to distal embolization have a poorer prognosis. Vemuri et al.⁷ reported their series of 40 patients who underwent surgical treatment for arterial TOS. The early results included one unrelated death and one early readmission for pain control. After a mean of 4.5 ± 0.4 years, subclavian artery patency was 92%, and no patient had experienced further dilatation or embolism. Six patients (15%) manifested chronic symptoms due to distal ischemia or concomitant neurogenic TOS. Functional outcomes measured by the 11-item version of the Disability of the Arm Shoulder and Hand Outcome Measure demonstrated highly significant improvement overall. These results mirror those from earlier studies.^{6,15}

Complications

Operative mortality is negligible in these typically young patients. Morbidity is related to the closely related anatomic structures in the thoracic outlet and includes pneumothorax, hemothorax, chylous leak, brachial plexopathy, and vascular injury. Injury to the phrenic or long thoracic nerves is also possible. Rarely, injury of the cervical sympathetic chain may result in Horner syndrome. The overall morbidity rate in published series ranges from 7% to 40%,^{6,17,53} with pleural entry and transient brachial plexus injury being most frequent.

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Thoracic Outlet Syndrome: Venous

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INTRODUCTION

Venous thoracic outlet syndrome (vTOS) is thrombosis or severe stenosis of the subclavian–axillary vein secondary to chronic extrinsic mechanical compression. Most commonly, this stems from acquired anatomic changes in the thoracic outlet including anterior scalene or subclavius muscle hypertrophy or from previous bony trauma to the anterior chest. vTOS is the second most common form of thoracic outlet syndrome (TOS). Paget described the original disease process in 1875 as a syndrome of acute arm swelling and pain. He hypothesized the disease was due to vasospasm.¹ In 1884, von Schroetter described the symptoms of acute upper extremity pain and swelling as a result of subclavian and axillary vein thrombosis.² The eponym Paget–von Schroetter syndrome was first coined by Hughes in 1949 after a comprehensive review of the world's literature related to thrombosis of the subclavian and axillary veins.³ vTOS has also been described as *effort thrombosis*, which describes the association with young healthy individuals who engage in activities requiring repetitive arm and shoulder motion such as athletics or certain occupations.^{4–7}

Primary Subclavian–Axillary Vein Thrombosis

Upper extremity deep venous thrombosis (DVT) represents approximately 9% of reported episodes of DVT⁸ (see Ch. 150, Acute Upper Extremity and Catheter-Related Venous Thrombosis). Subclavian–axillary vein thrombosis in vTOS is a direct result of repetitive injury to the subclavian vein at the level of the costoclavicular space, the most anterior and medial aspect of the thoracic outlet (Fig. 126.1). The key anatomic structures resulting in compression of the subclavian vein are the first rib, the clavicle with its associated subclavius muscle and fibrous costocoracoid ligament, and the anterior scalene muscle/tubercle.^{3,6} A cycle of alternating post-traumatic inflammation and quiescence leads to perivenous fibrosis, endothelial injury, stasis of blood flow, and thrombosis.⁹

Although vTOS has been reported to occur in the absence of any identifiable anatomic abnormality,^{9,10} a diverse array of anomalies associated with the thoracic outlet has been reported at the time of surgery. These include abnormalities of the soft tissues including the anterior scalene muscle, the subclavius tendon, or the presence of scalenus minimus muscles. Other

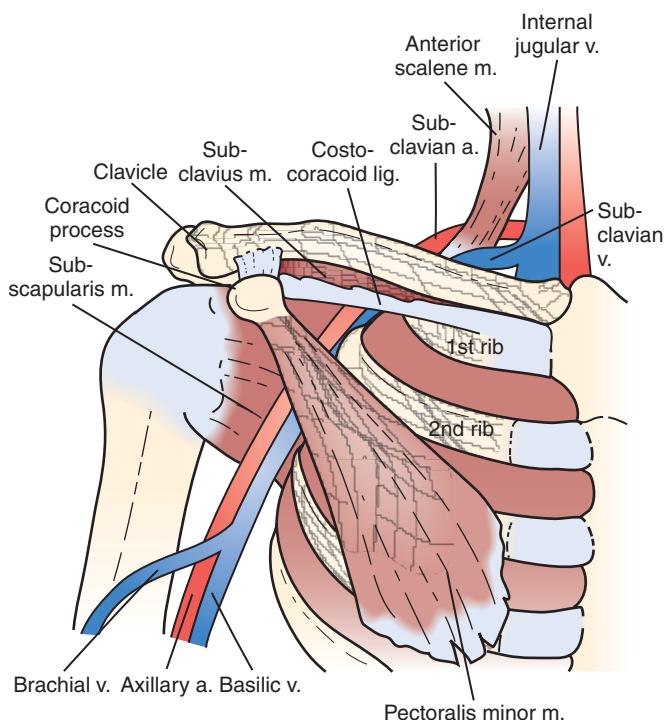


Figure 126.1 Anatomy of the Thoracic Outlet.

abnormalities include bony abnormalities of the clavicle and ribs as well as ligamentous abnormalities of the costocoracoid ligament.^{6,9–13} While commonly associated with other forms of TOS, the presence of cervical ribs can also be a cause of vTOS. In one of the largest retrospective series of TOS patients undergoing surgical intervention, Orlando et al. found that cervical ribs were associated with 68% of arterial TOS cases, 9.4% of neurogenic TOS cases, and only 2.3% of vTOS cases.¹⁴ Similarly, Weber and Criado found that cervical ribs were only associated with 2% of vTOS cases in their retrospective series.¹⁵ Post-traumatic changes following clavicular or first rib fractures are also commonly reported, with callus formation at the clavicle and pseudoarthrosis of the first rib being a potential source of thoracic outlet compression (Fig. 126.2).

Frequently, compression of the subclavian vein occurs at the costoclavicular space without the development of thrombosis. This point is underscored by venographic studies evaluating the contralateral subclavian vein in patients with confirmed subclavian–axillary vein thrombosis. Although narrowing of the contralateral vein with provocative measures is visualized in 56% to 80% of contralateral limbs, the incidence of bilateral thrombosis is markedly less, at 2% to 15%.^{5,16–18}

Because venous compression at the thoracic outlet can be caused by a multitude of primary factors, the Society for Vascular Surgery (SVS) has issued reporting guidelines to help facilitate data acquisition and analysis. In the case of venous compression, all venous compression in which the pathophysiological etiology involves the costoclavicular junction is classified as vTOS whereas those that occur at the pectoralis minor space are classified as VPMS (venous pectoralis minor syndrome). Patients in which the venous compression occurs at both spaces are classified as vTOS/vPMS.¹⁹



Figure 126.2 First Rib Specimen in Patient with Previous Fracture. Pseudoarthrosis (arrow) can be a source for venous compression and subsequent thrombosis.

McCLEERY SYNDROME

Described in 1951 by McCleery and colleagues, this syndrome represents intermittent obstruction of the subclavian vein without thrombosis.²⁰ The pathology results from compression of the vein between the subclavius tendon and the anterior scalene muscle that is worsened with arm abduction (Fig. 126.3). This syndrome manifests with blue discoloration of the arm, superficial venous distention, and swelling. Despite the lack of venous thrombosis, these patients are usually limited in the use of the affected extremity and should be treated with surgical decompression.²¹

SECONDARY SUBCLAVIAN–AXILLARY VEIN THROMBOSIS

Although vTOS typically refers to primary subclavian–axillary vein thrombosis, the differential diagnosis should include secondary upper extremity DVT. Issues associated with secondary upper extremity DVT include nephrotic syndrome, mediastinal tumors, malignancy, local surgery or trauma, hypercoagulable states, renal failure requiring dialysis, long-term use of peripherally inserted central catheters, and cardiac conditions requiring pacemaker placement. The two most common causes of mechanical secondary upper extremity DVT are the placement of central venous catheters and pacemaker wires.

Catheter-related venous thrombosis occurs in 5% or less of all inserted central venous catheters.^{4,22} Risk factors associated with a higher rate of catheter-related thrombosis in adult patients are catheter-related (malposition of the catheter, insertion of the catheter on the left, multiple catheter lumens),

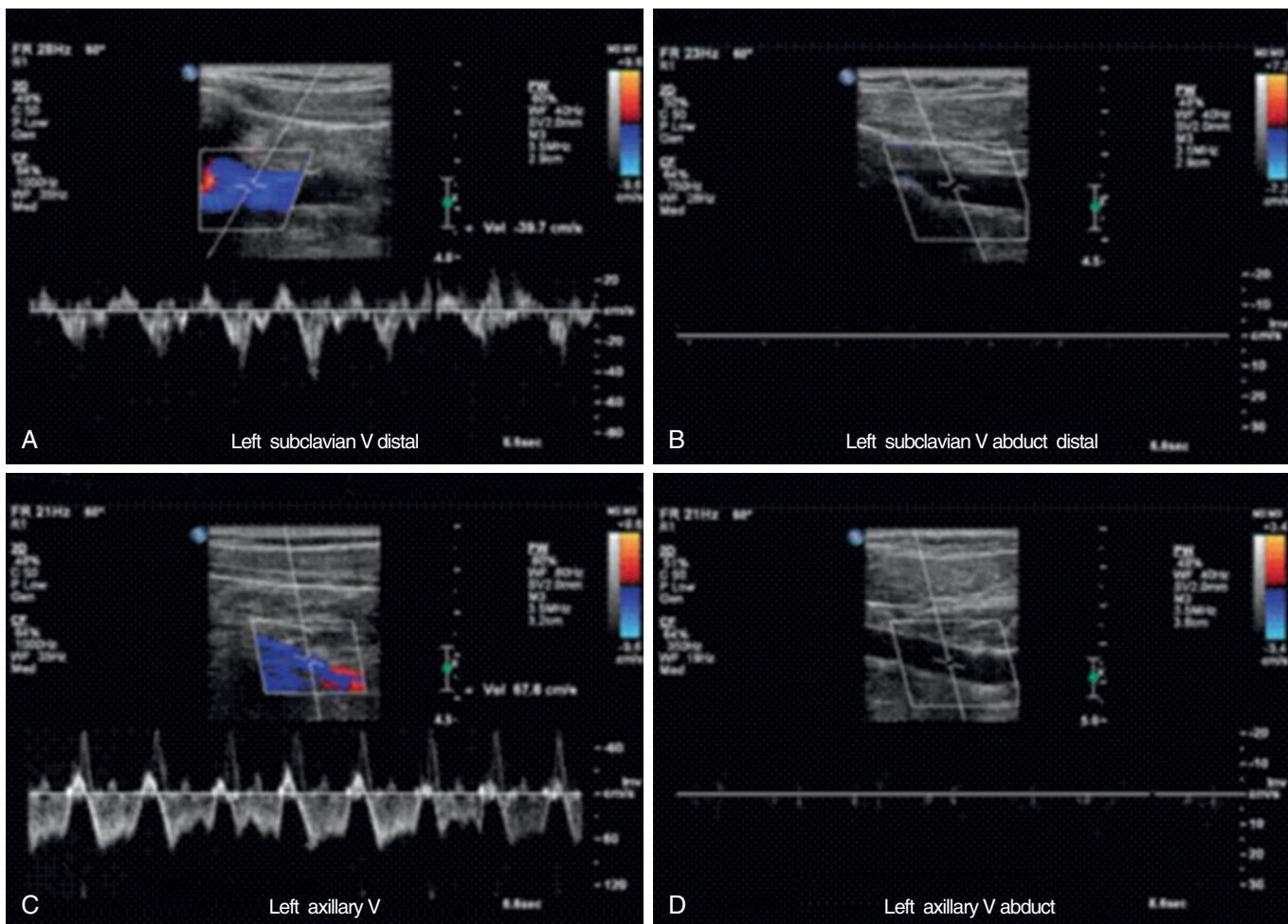


Figure 126.3 Venous Compression of the Left Subclavian and Axillary Vein. With the arm in the neutral position the subclavian (A) and axillary (C) veins demonstrate normal phasic flow. With elevation of the arm to 180 degrees, there is cessation of flow in the subclavian (B) and axillary (D) veins.

treatment-related (use of long-term antibiotics or total parenteral nutrition, bolus vs. dilute chemotherapy infusions), or patient-related (malignancy or hypercoagulable states).^{23–26} Patients with catheter-related venous thrombosis can be asymptomatic, but significant symptoms such as pulmonary embolism can occur in as high as 15% to 25% of patients.²⁷ It is important to remember that the rate of thrombosis is not necessarily due to the duration of catheter placement.²⁸

In addition to catheters, pacemaker wires are an increasing cause of secondary subclavian–axillary vein thrombosis. The number of leads, previous use of a temporary pacemaker, and left ventricular ejection fraction $\leq 40\%$ are predictive of venous stenosis.^{29,30} Infection of the pacemaker insertion site has also been shown to increase the risk of venous stenosis and occlusion.³¹ The use of anticoagulation is protective against the development of occlusion of the subclavian vein but has not been shown to prevent venous stenosis.³²

As in the case of primary upper extremity vTOS, the pathophysiology of secondary upper extremity subclavian–axillary thrombosis is vein wall damage. In some cases, catheter removal causes the fibrin sheath to break loose and subsequently embolize into the pulmonary circulation.³³

CLINICAL PRESENTATION

The mean age at diagnosis for vTOS is 32 years, with the majority of patients affected between the second and fourth decades of life.¹⁷ However, Orlando et al. have found that the mean age of patients being treated for vTOS may be trending to younger individuals.¹⁴ This may be attributable to more intensive athletic pursuits in younger individuals. Despite early reports showing a female predominance, more recent literature, including the largest series published to date (312 affected extremities), has reported an equal gender ratio.^{17,34,35} Individuals who perform strenuous or sustained upper extremity activities, whether athletic or occupational, are particularly prone to the development of subclavian–axillary vein thrombosis. The dominant arm is involved in the majority of cases.^{18,36} While not necessarily associated with primary hypercoagulable conditions, vTOS can be the initial presentation of venous thromboembolism in patients with underlying hypercoagulable conditions. In their retrospective review of 143 patients, Likes et al. found an underlying hypercoagulable condition in 25% of vTOS patients who underwent hypercoagulable testing.³⁶

Upper extremity edema is the hallmark finding associated with subclavian–axillary vein thrombosis. The edema is often, but not always, accompanied by pain and cyanosis of the affected extremity. The edema usually involves the shoulder, arm, and hand, and is characteristically non-pitting. Occasionally the associated discoloration of the extremity can be confused with cellulitis, delaying the diagnosis of vTOS. Dilated superficial veins over the shoulder, neck, and anterior chest wall can often be visualized as collateral veins try to accommodate the increased venous pressure (a pattern often referred to as *first rib bypass venous collaterals*).³⁷ A minority of patients may demonstrate symptoms resembling neurogenic TOS, such as numbness and tingling in the distribution of the inferior trunk of the brachial plexus. This association is likely due to the presence of muscular anomalies of the thoracic outlet anatomy and the performance of repetitive upper extremity arm activities.

Patients may report some degree of pain. The description can include aching, stabbing, or a feeling of tightness that worsens with exertion.⁶ Extended use of the arm leads to increased arterial blood flow, for which the limited collateral venous bed is unable to compensate. The subsequent venous hypertension worsens symptoms of venous stasis and arm congestion. Urschel and Razzuk reported that among 312 patients with extremities with vTOS in their 30-year experience, 93% complained of arm swelling, 77% demonstrated bluish discoloration, 66% had aching pain with exercise, and 8% were asymptomatic.¹⁷ Similarly, Van Rooden et al. reported that 52% of patients were symptomatic, 39% were completely disabled, and 9% were asymptomatic.³²

The two most potentially severe complications of subclavian–axillary vein thrombosis are pulmonary embolism and upper extremity phlegmasia cerulea dolens (venous gangrene). The reported incidence of a pulmonary embolism due to subclavian–axillary vein thrombosis is less than 10%.^{3,4,6,38,39} Compared with iliofemoral DVT, the small clot burden of upper extremity DVT may reduce the clinical impact of pulmonary embolism. Venous gangrene is exceedingly rare and has been limited to case reports in patients with malignant disease or an underlying hypercoagulable state.⁴⁰ No reports of venous gangrene occurring secondary to vTOS have been published.

DIAGNOSTIC EVALUATION

The diagnosis of vTOS is most often suspected after the performance of a thorough initial history and physical examination. Acute swelling, cyanosis, and pain in an isolated upper extremity of a young, active patient is the hallmark presentation. Typically, due to the acute nature of the presentation, the physical exam findings will consist of swelling from the shoulder to the hand that is often pronounced and can be up to twice the patient's normal arm diameter.⁴¹ These patients will typically have multiple collateral veins that can be visible on the chest. In older patients, other etiologies must also be considered including lymphedema and malignancy. In patients with clinical suspicion for vTOS, subsequent imaging is mandated to help confirm the diagnosis.

While historically relevant, the utilization of provocative maneuvers for the diagnosis of vTOS, are not as useful when compared to other forms of TOS. Adson's test (loss of radial pulse during hyperabduction maneuvers), traditionally described as a test to evaluate for thoracic outlet compression, is highly inaccurate in the diagnosis of vTOS as it can be positive in up to 40% of the normal population.⁴² Likewise, the elevated arm stress test (EAST), while very sensitive in neurogenic TOS, is not useful in the diagnosis of vTOS.⁴³

Duplex Ultrasound

In those patients who have physical exam findings consistent with vTOS, a more objective workup is necessary. Duplex ultrasonography is the most frequently used diagnostic modality for the evaluation of patients thought to have DVT of the upper limb (see Ch. 25, Vascular Laboratory: Venous Duplex Scanning). The study is noninvasive, does not require the use of a nephrotoxic contrast agent, and does not involve ionizing radiation. In addition, it can be performed at the bedside or in the emergency department. The use of diagnostic ultrasound in the upper extremity is different from that in the lower extremity. Overlying structures, such as the clavicle, make duplex interrogation of the vascular structures coursing through the thoracic outlet challenging. In the upper extremity, the compressibility of the targeted vein is not possible beneath the clavicle, nor is it possible to compress the brachiocephalic vein or superior vena cava. Therefore duplex examinations relying on B-mode ultrasound alone have historically demonstrated low sensitivity (54%) and high specificity (100%) for the detection of subclavian–axillary vein thrombosis.⁴⁴ The standard use of color-flow duplex imaging in conjunction with indirect criteria suggesting the presence of an occlusion (evaluation for phasicity of flow with respiration and augmentation with compressive maneuvers) have led to markedly increased sensitivity (81% to 100%) while maintaining high specificity (82% to 100%).^{45–47} However, with false-negative rates as high as 30%, a negative duplex examination should not exclude the diagnosis of vTOS in patients who have physical exam findings consistent with the disease.⁴¹ Findings that may suggest subclavian–axillary thrombosis include loss of flow in the subclavian vein, loss of phasicity in the axillary vein, or evidence of acute thrombus on B-mode imaging. Provocative positioning, such as external rotation and abduction of the upper extremity can allow for dynamic phlebography to help facilitate diagnosis. Likewise, the differentiation between McCleery syndrome and subclavian–axillary thrombosis can be achieved with dynamic imaging.^{43,48}

Magnetic Resonance and Computed Tomographic Venography

Magnetic resonance venography (MRV) and computed tomographic venography (CTV) are additional noninvasive imaging modalities that have been used with increasing frequency for the diagnosis of vTOS.^{12,49} The sensitivity and specificity of both modalities are comparable to those of

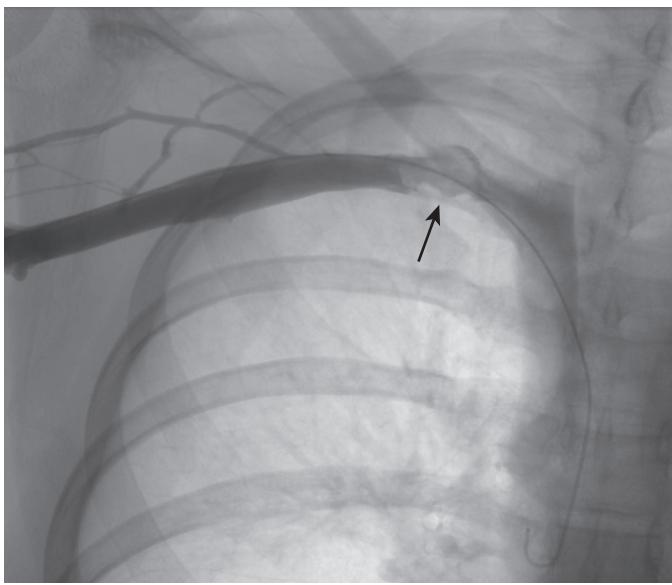


Figure 126.4 Venogram indicating an acute primary subclavian–axillary vein thrombosis (arrow).

duplex ultrasound.²⁷ CTV has the added advantage of being able to detect central vein thrombosis and the presence of pulmonary emboli, with appropriate arterial timed contrast. Similarly, CTV is very accurate in the detection of mechanical obstruction or occlusion of the subclavian vein at the thoracic outlet, the presence of collateral venous drainage, and the presence of chronic thrombus.⁴¹ However, MRV and CTV are rarely necessary for patients with suspected vTOS. The cost and time required for completion of the examination are substantial. MRI is routinely used in patients with neurogenic TOS, as dynamic MRI can identify the location and etiology of brachial plexus compression, as well as associated vascular compression.⁵⁰

Venography

Digital subtraction venography is considered the gold standard (Fig. 126.4) to diagnose vTOS. However, it is generally reserved for patients whose condition warrants an intervention. Venography is invasive and uses a nephrotoxic agent, in addition to requiring exposure of the patient to ionizing radiation. Up to 20% of patients do not qualify for venography because of a severe allergy to the contrast agent or the inability to cannulate the veins in the edematous extremity. The primary role of venography is in the patient whose duplex ultrasound findings are equivocal. In such patients, an additional objective study should be performed to confirm or to reject the diagnosis of upper extremity DVT.

When performed, venography should be done at rest and with positioning of the arm at 90 and 180 degrees (Fig. 126.5). These positional images are essential to confirm the presence of extrinsic compression of the subclavian vein at the level of the thoracic outlet. Evaluation of collateral circulation is another important function of venography. The extent of collateralization provides information about the hemodynamic significance

of the occlusion or stenosis and the chronicity of the occlusion. The chronicity of the occlusion, in turn, plays a key role in dictating management. Patients may be classified into one of three categories based on their history and venographic findings: (1) acute subclavian–axillary vein thrombosis, (2) chronic or recurrent subclavian–axillary vein thrombosis, or (3) high-grade symptomatic subclavian–axillary vein stenosis.

TREATMENT

Debate continues over the optimal treatment of vTOS. The disease has not been studied prospectively, and given the lack of consensus that experts in the field have over anticoagulation, thrombolysis, and surgical decompression, a prospective study is unlikely. Recently a collaborative national registry has been developed at the University of California, Davis. The registry has invited leaders in the field to add patients with both operative and nonoperative therapy to determine long-term outcomes for all patients with TOS. Likewise, the SVS has developed reporting standards for reporting on TOS in hopes of standardizing data reporting for future studies of outcomes in TOS patients.¹⁹

Anticoagulation Alone

Historically, treatment of acute primary subclavian–axillary vein thrombosis consisted of rest, elevation of the affected extremity, and variable duration of systemic anticoagulation. Retrospective reviews on this approach have demonstrated variable outcomes, but the initial report by Hughes on the conservative management of 320 patients with primary subclavian–axillary vein thrombosis found that 40% of patients had persistent symptoms or limited recovery.¹ More recent studies report the use of the objective Disability of the Arm, Shoulder, and Hand (DASH) questionnaire to assess quality of life after upper extremity venous thrombosis. In a retrospective review of patients treated with surgical decompression versus anticoagulation alone, patients that underwent surgical decompression had significantly improved quality of life and functionality DASH scores.⁵¹ Specific factors contribute to failure and should be considered when devising a patient-centered treatment plan. Young age, active lifestyle, and participation in sports at a competitive level are all associated with the long-term failure of anticoagulation.^{52–54}

The goals of treatment in secondary upper extremity DVT are to prevent pulmonary embolism and to achieve recanalization of the vein. Most patients with secondary upper limb DVT improve after removal of the venous catheter and institution of anticoagulation therapy. If a catheter causes extensive axillary vein thrombosis resulting in marked edema, thrombolytic therapy may be considered. If the catheter is nonfunctioning or no longer needed, it should be removed and the patient should be treated with 3 months of anticoagulation.^{55,56} Patients with a functional catheter needed for ongoing treatment should be systemically anticoagulated. Anticoagulation should continue for the entire time the catheter is left in place. Unless contraindicated, direct oral anticoagulant therapy (DOAC) is now the

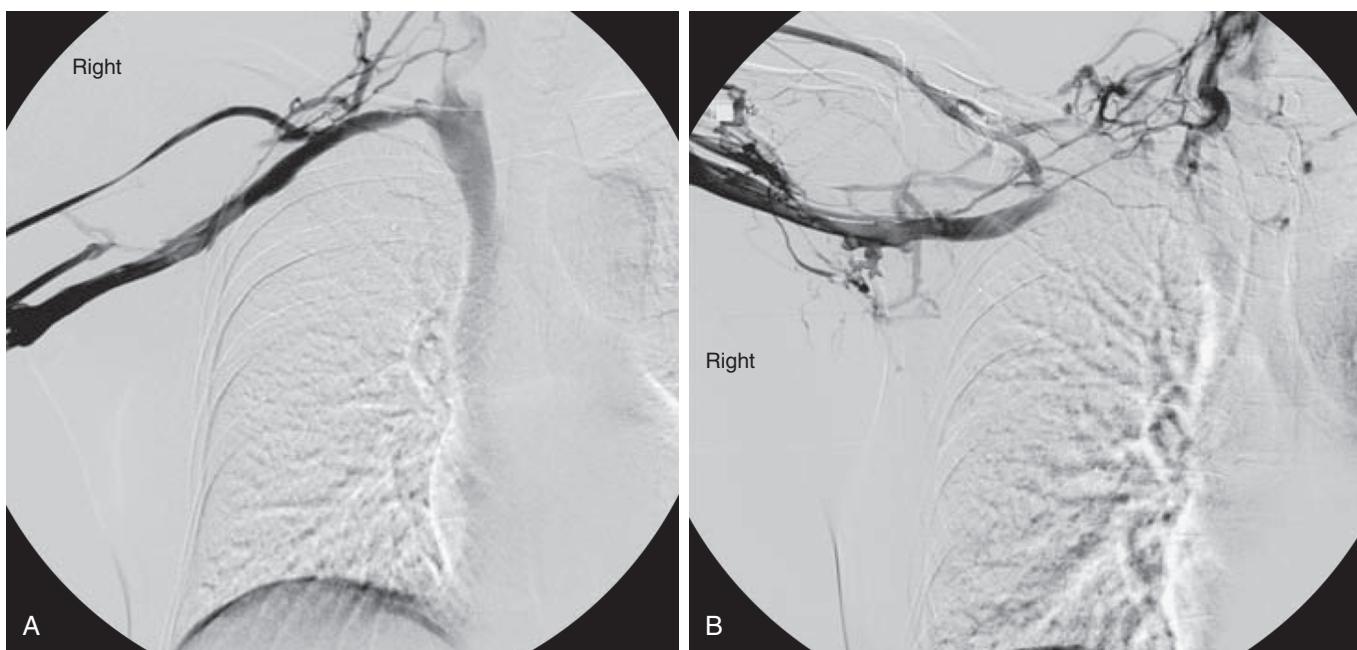


Figure 126.5 Venogram of the subclavian–axillary vein after successful thrombolysis with the extremity in full adduction (A) and in full abduction (B).

recommended anticoagulant (over vitamin K antagonists) in these patients in the absence of concurrent malignancy.⁵⁶

Patients with secondary upper limb DVT who may have contraindications to systemic anticoagulation, such as concurrent gastrointestinal bleeding, recent neurosurgery, or the presence of pulmonary embolism despite anticoagulation, may be candidates for SVC filter placement. SVC filters are not used widely, but in small limited studies, they are effective in preventing recurrent pulmonary embolism. The long-term patency rates of the small number of SVC filters that have been placed are reportedly high.⁵⁷ Nonetheless, concerns persist about the risk of SVC filter migration or thrombosis resulting in SVC syndrome. Because fatal pulmonary embolism from upper extremity DVT has been documented to be very rare and evidence of the safety of filters is limited, clinical judgment must be used in recommending their deployment.⁵⁸

Thrombolytic Therapy

Because of the significant recurrence of symptoms in patients who undergo anticoagulation alone, catheter-directed thrombolysis has emerged as an initial management strategy in the modern treatment paradigm of vTOS. The goal of catheter-directed therapy is to remove thrombus, restore the patency of the vein, and alleviate symptoms. Because subclavian–axillary thrombus is much more localized than lower extremity DVT, this approach usually lyses the subclavian–axillary vein thrombus quickly to restore luminal patency. In 1981, Zimmermann and associates documented, in a small case series, the successful use of systemic urokinase in 82% of patients with acute primary subclavian–axillary thrombosis.⁵⁹ Since this initial series, many authors have demonstrated high rates of success in re-establishing patency with catheter-directed thrombolysis

(Fig. 126.6). Lee and colleagues reported their experience treating 64 patients with primary subclavian–axillary thrombosis. As the first step in their treatment algorithm, 54 patients with symptom onset within 7 days underwent attempted catheter-directed thrombolysis; 100% experienced successful restoration of luminal patency.⁵³ When thrombolysis is initiated within 14 days of the onset of symptoms, the results are generally reported to be excellent with success rates nearing 84% in some studies.^{5,60} Treatment with thrombolysis in patients with more than 14 days of symptoms is possible, albeit with a decreased chance for successful re-establishment of luminal patency with only 50% recanalization reported in some studies.^{17,61,62}

While thrombolysis therapy has shown some success in recanalization in the acute setting, it is commonly accepted that the mainstay of therapy for vTOS involves decompression of the thoracic outlet. In those patients that do not undergo decompression after thrombolysis, re-thrombosis will occur in up to one-third of the patients within 30 days.^{63,64} Likewise, thrombolysis followed by angioplasty and stenting (without surgical decompression) has also been associated with significant re-thrombosis rates and stent fracturing.^{53,65,66}

In those patients that do undergo thrombolytic therapy before decompression, it is generally accepted that aggressive venoplasty and stenting are not recommended at that time. The technical aspects of thrombolysis performed before surgical decompression associated with poor long-term results include overly aggressive balloon venoplasty to achieve an optimal angiographic result and the use of venous stents.^{53,67}

Despite the excellent results with thrombolysis, whether or not preoperative thrombolysis affords any benefit to long-term venous patency is questionable. In a retrospective review of a decade treating 34 patients with vTOS, primary subclavian–axillary vein patency at 5 years was 84% in patients who

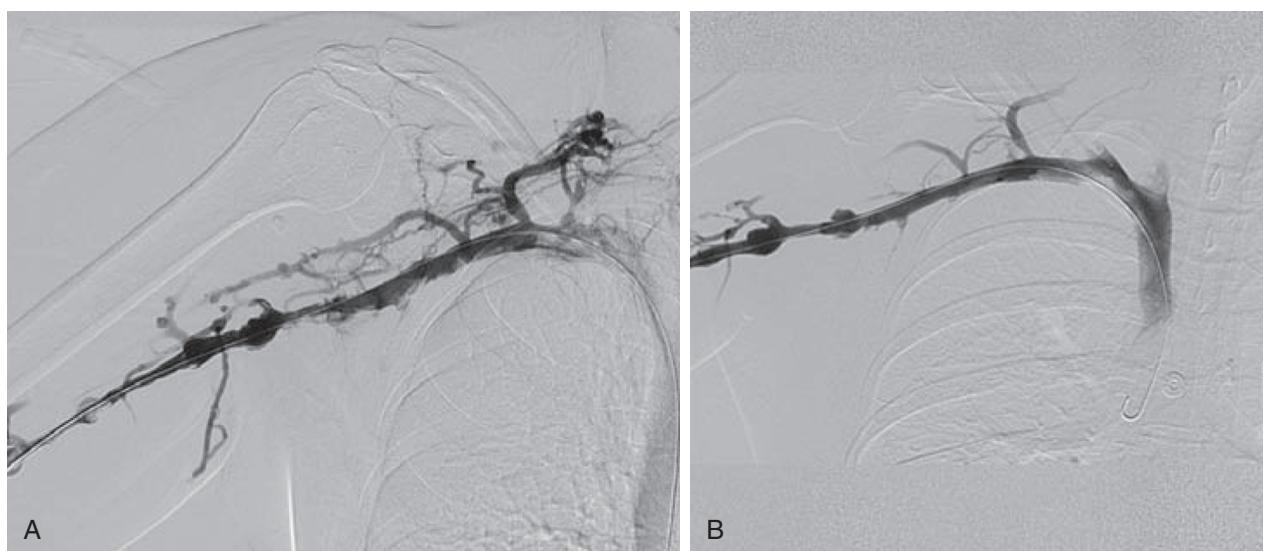


Figure 126.6 Venogram of the subclavian–axillary vein before (A) and after (B) thrombolysis.

underwent thrombolysis followed by surgical decompression and 83% in patients who underwent surgical decompression without thrombolysis.⁶⁰ A second study by Guzzo et al. retrospectively reviewed 110 patients with vTOS. At 1 year they also found the primary patency was identical in patients treated by thrombolysis followed by decompression and those treated with anticoagulation followed by surgical decompression (91% vs. 91%, $P = 0.99$).⁶⁷ Given the risks of bleeding, procedural expense, and use of limited resources, the cost-effectiveness of thrombolysis deserves future study. However, it has become our practice to no longer mandate thrombolysis before surgical decompression. Rather, our practice centers upon early initiation of systemic anticoagulation and subsequent decompression after the acute inflammatory changes have subsided.

Post-Thrombolysis Management

Patients with unsuccessful thrombolysis, defined as persistent total occlusion of the subclavian–axillary vein, should receive anticoagulation and measures aimed at control of local symptoms, such as rest, compression, and elevation. Unsuccessful thrombolysis of acute subclavian–axillary vein thrombosis is rare, and almost always seen in patients who have had repeated episodes of lysis with overly aggressive venoplasty or long-standing symptoms treated only with anticoagulation.

Whether or not these patients benefit from surgical decompression has only been reviewed in small series. In a group of 42 patients, Urschel and Razzuk reported a 57% rate of recanalization and resolution of symptoms with surgical decompression and extended length anticoagulation.¹⁷ In the second series of 16 patients with chronic venous occlusion due to vTOS reported by Chang et al., first rib resection followed by anticoagulation resulted in 88% recanalization at 6 months. The mean duration of anticoagulation in this study was 3 months.⁶⁸ Given the potential for recanalization, high volume centers do offer first rib resection to select patients with chronic occlusion.

Patients in whom thrombolysis was successful, defined as those with reestablishment of subclavian–axillary vein patency,

can be further classified based on completion positional venography, according to the absence or presence of demonstrable extrinsic compression at the thoracic outlet. Patients without extrinsic compression will not benefit from thoracic outlet decompression and should be treated with 3 to 6 months of systemic anticoagulation.⁵⁵

In patients found to have extrinsic compression, no effort should be made after successful thrombolysis to dilate a persistent subclavian vein stenosis. The resultant intimal injury of angioplasty without addressing the extrinsic compression results in inflammation and decreases the likelihood of re-establishing long-term patency of the vein.⁶⁹ Also, in no case should a patient that has not undergone surgical decompression have a stent placed in the subclavian vein. Multiple studies have documented the dismal results of subclavian vein stents.^{65,66,70} Immediate thoracic outlet decompression and subsequent subclavian–axillary vein venography/angioplasty should be performed early to decrease the risk of re-thrombosis.

Surgical Decompression of the Thoracic Outlet

The decision to perform surgical decompression should be considered in all patients with persistent stenosis or signs of extrinsic compression on positional venography after thrombolysis. These patients remain at significant risk of recurrent thrombosis with anticoagulation alone.⁶¹ When the underlying pathophysiologic process is not appropriately addressed, adjunctive therapies such as balloon angioplasty or stent placement may provide satisfactory immediate results but lack sufficient durability to be accepted as definitive therapy.^{53,62,65,66,70} Multiple reports have confirmed that the radial force associated with either a self-expanding or balloon-expandable stent is not adequate to compensate for the compressive force between the first rib and clavicle; stent deformation, fracture, and thrombosis in this setting are the norm rather than the exception (Fig. 126.7). Therefore, stents have no role in the treatment of vTOS before surgical decompression.

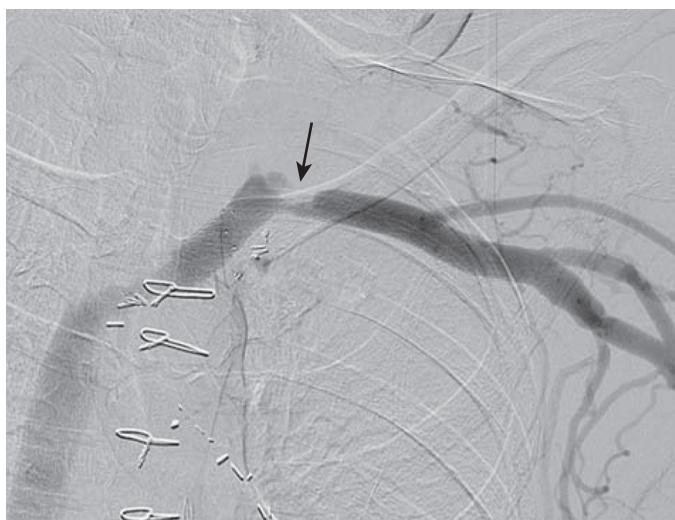


Figure 126.7 Deformed balloon-expandable stent (arrow) 6 weeks after treatment of primary subclavian–axillary thrombosis.

To alleviate extrinsic compression, first rib resection with external venolysis should be performed. Early studies advocated deferring surgical decompression for 1 to 3 months after thrombolysis to allow healing of the venous endothelium and resolution of the acute inflammatory process.^{71,72} However, early decompression, even during the same hospitalization as the thrombolysis, has been shown to significantly decrease the risk of re-occlusion that may occur between thrombolysis and deferred surgery.^{5,17,61,62,67,69,73,74} The shift to immediate surgery has virtually eliminated the vein re-thrombosis rate of 6% to 18% that had been reported to occur during the waiting period.^{5,72}

However, in our practice, we have moved away from thrombolysis as the first-line treatment for vTOS and have adopted an anticoagulation-first algorithm that is followed by decompression and subsequent venogram 2 weeks postoperatively.

SURGICAL APPROACH

The choice of surgical approach for vTOS has been the subject of extensive debate with some centers advocating para- or infraclavicular approaches and others preferring a transaxillary approach.

Paraclavicular Approach

The patient is placed on the operating room table in the semi-Fowler position. A small roll is placed transversely posteriorly just below the shoulders. The head is extended and rotated away from the operative site. The neck, chest, and affected extremity are prepared and draped steriley. The arm, forearm, and hand are wrapped in a stockinette. During the procedure the arm is maintained in the adducted position, the elbow is flexed at 90 degrees, and the arm is fixed so that there is no tension on the brachial plexus throughout the procedure.

A transverse incision is made one fingerbreadth above the clavicle beginning at the lateral border of the sternocleidomastoid muscle and extended just beyond the external jugular vein.

Extensive inferior and superior sub-platysmal flaps are created. Portions of the clavicular head of the sternocleidomastoid muscle can be divided to provide exposure. The scalene fat pad is then mobilized on a lateral pedicle. This mobilization is initiated by taking down the medial attachments of the fat pad at the level of the internal jugular vein. Usually, the tissue is tied with 3-0 silk suture to prevent postoperative lymph leakage. The dissection is carried down to the junction of the internal jugular and subclavian vein and extended laterally to the insertion of the external jugular vein into the subclavian vein. Finally, the fat pad is mobilized superiorly until one encounters the cutaneous nerves of the chest and shoulder region. A self-retaining retractor (Omnitrap, Minneapolis, MN) is put into position.

The medial and lateral borders of the anterior scalene muscle are mobilized, and the phrenic nerve is identified (Fig. 126.8A). The phrenic nerve is never directly grasped with an instrument. Rather, a generous length of fascia on either side of the nerve is incised and used to retract the phrenic nerve and expose the anterior surface of the anterior scalene muscle. Mobilization of the phrenic nerve is continued down to the thoracic inlet. The anterior scalene muscle is incised directly from its insertion on the tubercle of the first rib (Fig. 126.8B). It is then dissected posteriorly while hemostasis is maintained with bipolar cautery. Frequently, a portion of the anterior scalene or separate scalenus minimus will pass beneath the subclavian artery. The muscle is dissected proximally to the point of its attachments to the transverse processes of the cervical spine and then excised. The plane in the deep cervical fascia is developed laterally with a moistened sponge to expose the brachial plexus and the middle scalene muscle. After locating the long thoracic nerve, the middle scalene muscle is mobilized and then resected, with the long thoracic nerve used as the superior and lateral limits of this resection (Fig. 126.8C). The resection is carried down to the first rib. A periosteal elevator is used to dissect the attachments of the middle scalene muscle from the first rib. Often, some of the fibers of the middle scalene muscle extend to the second rib and are incised with Metzenbaum scissors. A plane is developed between the region of insertion of the anterior scalene and middle scalene muscles beneath the clavicle with a periosteal elevator. The intercostal fibers are incised similarly. The first rib is resected with a bone cutter or a Kerrison rongeur just distal to its articulation with the vertebra (Fig. 126.8D). Similarly, it is excised as medially as possible near its junction with the sternum. The subclavian vein is inspected and dissected circumferentially should any perivenous fibrosis be present.

It is critical that the first rib be resected at its junction with the sternum. To accomplish this, it is sometimes helpful to make a small counter incision just beneath the clavicle. The pectoralis major and minor fibers are separated and the rib identified. The remainder of the surface of the rib is then dissected with a periosteal elevator while taking care to note the location of the subclavian vein. This often requires resection of a portion of the subclavius muscle. After the rib is dissected thoroughly, it is resected up to the sternal junction (Fig. 126.8E). The scalene fat pad is reattached with interrupted 3-0 Vicryl suture. A Blake drain is placed routinely, and the platysma and skin are closed.

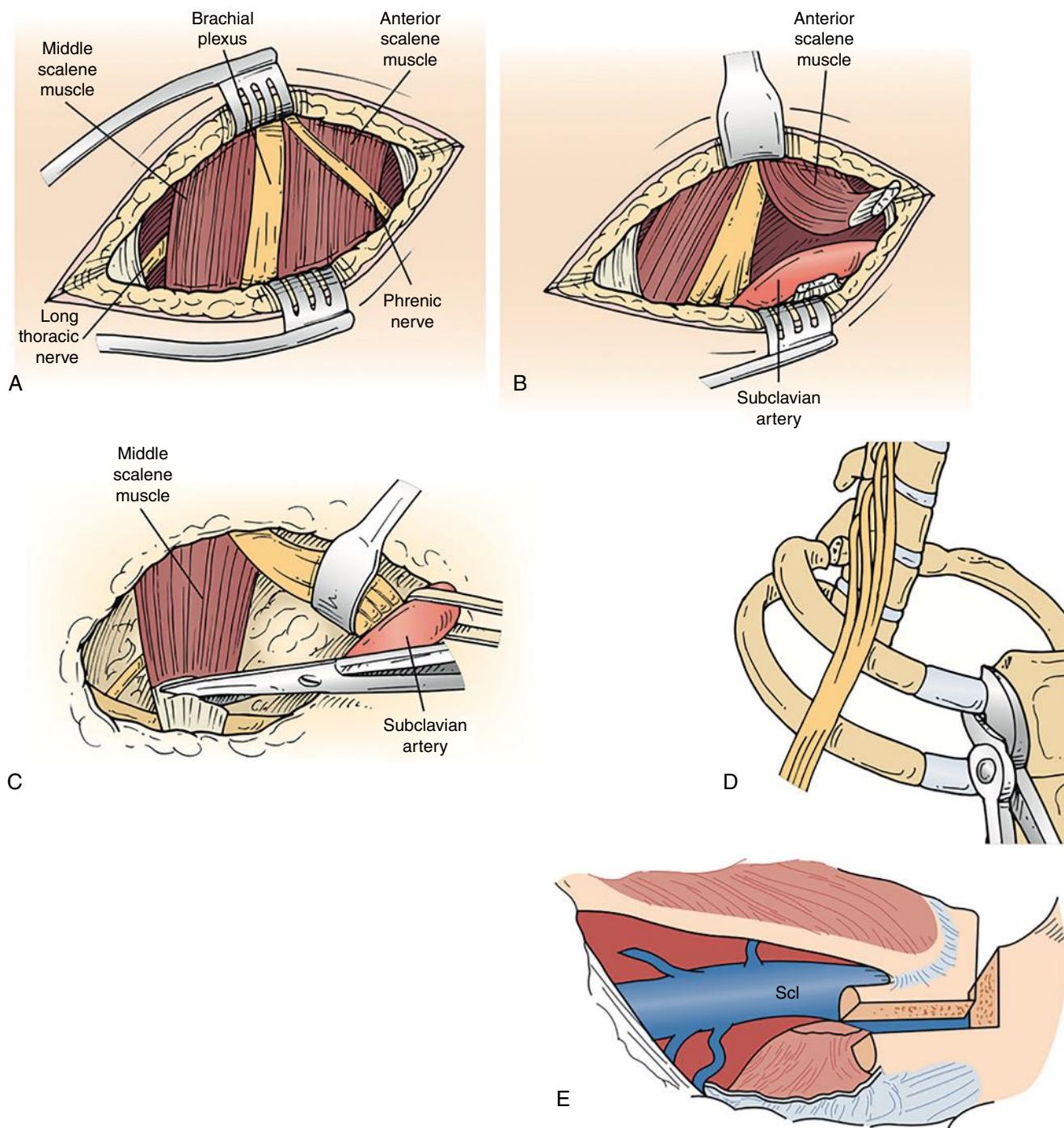


Figure 126.8 Paraclavicular Approach. (A) The brachial plexus is noted in its position between the anterior and middle scalene muscles. The phrenic nerve is seen coursing in a lateromedial direction across the anterior surface of the anterior scalene muscle. The supraclavicular nerves are being retracted. Also shown is the long thoracic nerve exiting the posterior border of the middle scalene muscle. (B) Division of the anterior scalene insertion from the first rib. The subclavian artery will be directly behind the anterior scalene muscle. (C) The middle scalene muscle is divided from the first rib. (D) The first rib is divided with a rib cutter. (E) In select cases, transmanubrial extension of the subclavicular incision to the center of the sternum and vertically up to the sternal notch exposes the entire subclavian (Scl) and innominate veins without any need to remove or to divide the clavicle. (A–D from Schneider DB, et al. Management of vascular thoracic outlet syndrome. *Chest Surg Clin North Am*, 1999;6:781–803. E from Molina JE, et al. Paget-Schroetter syndrome treated with thrombolytics and immediate surgery. *J Vasc Surg*. 2007;45:328–334.)

A lateral extension is added to the operating table, and the affected arm is abducted. The basilic vein is punctured and venography is performed in both the neutral and fully rotated

positions with the hand over the head. Complete thoracic outlet decompression will reveal no compression of the vein with the arm rotated above the patient's head. Should residual

stenosis be present, it can usually be dilated with balloon angioplasty. If this is not possible, the subclavian vein is opened, the residual chronic thrombus is removed, and a vein patch is placed. In our experience, more extensive replacement of the subclavian vein has not been necessary. Placement of stents after decompression should rarely be necessary.

Infraclavicular Approach

In Molina and colleagues' relatively large series of 114 patients who underwent treatment of venous TOS, all thoracic outlet decompressions were performed through an infraclavicular-only approach.⁷³

This approach is well described and involves partial resection of the anterior half of the first rib, removal of the subclavius tendon, and division of the anterior scalene tendon and part of the middle scalene muscle to the level of the subclavian artery. In this series, all patients underwent vein patch angioplasty of the subclavian vein with a segment of harvested great saphenous vein. Of note, in 12 patients found to have long stenoses (>2 cm), transmanubrial extension of the incision was performed. This consisted of extending the incision medially across the sternum to the midline and then angling 90 degrees up toward the sternal notch. These select patients were then managed with 6 weeks of postoperative arm immobilization. Angioplasty plus stent placement was used as an alternative strategy in seven patients with residual stenoses not amenable to local patch angioplasty. In this small group of patients, all stents were reported to remain patent on duplex follow-up (mean follow-up of 14 years). To date, this remains the largest published experience of central vein stenting after thoracic outlet decompression.

Transaxillary Approach

Several groups prefer and report excellent results with the use of a transaxillary surgical approach for first rib resection, scalenectomy, and venolysis (Fig. 126.9A).^{17,75–77} This has become the mainstay approach in our group. For a scholarly description of the technical steps required for successful transaxillary first rib resection, we recommend a review on this topic by Urschel and Razzuk.¹⁷ The key features include an incision below the axillary hairline between the pectoralis major and latissimus dorsi muscles. As the dissection is carried through the subcutaneous tissue cephalic to the first rib, attention is directed toward the preservation of the intercostal brachial cutaneous nerve (exits between the first and second ribs). The anterior scalene muscle is divided and resected up into the neck. The first rib is dissected subperiosteally and separated from the adherent parietal pleura. The anterior portion of the rib is dissected off the subclavian vein, the costoclavicular ligament is divided, and the rib is transected at the sternal border. The posterior rib is dissected off the subclavian artery and brachial plexus, the middle scalene muscle is divided, and the rib is transected at the level of the transverse process of the vertebra (Fig. 126.9B). Complete venolysis is then carried out before closure of the wound.

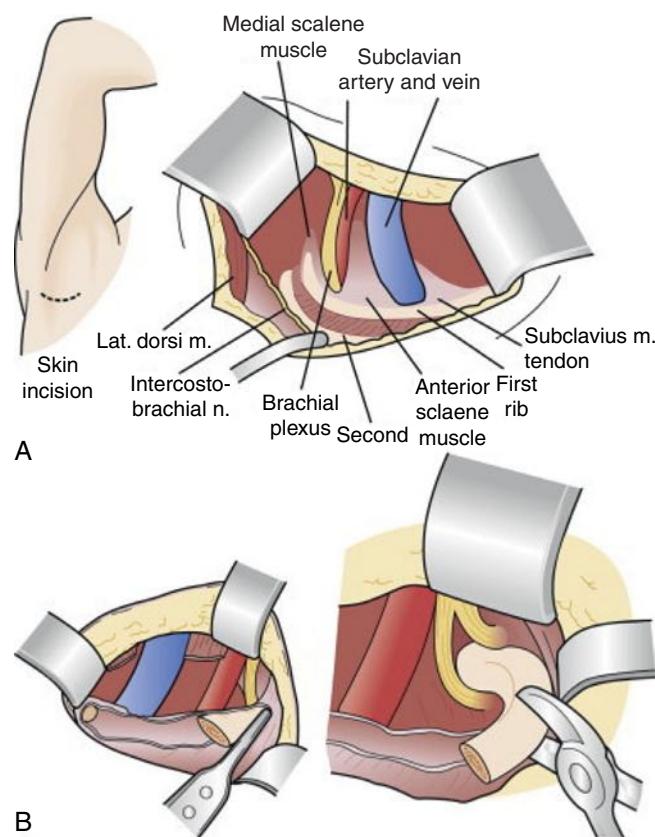


Figure 126.9 Transaxillary Approach. (A) View of the thoracic outlet from the transaxillary approach. (B) The posterior part of the rib is dissected subperiosteally to the transverse process, where it is divided with rib shears. The rib may be resected posteriorly with an Urschel-Leskell re-enforced rongeur. Care is taken to avoid injury to the C8 and T1 nerve roots as the middle scalene muscle is dissected from the rib. (A, from Machleder HI. Evaluation of a new treatment strategy for Paget-Schroetter syndrome: spontaneous thrombosis of the axillary-subclavian vein. J Vasc Surg. 1993;17:305–315. B, from Schneider DB, Azakie A, Messina LM, Stoney RJ. Management of vascular thoracic outlet syndrome. Chest Surg Clin North Am. 1999;6:781–803.)

Vein Treatment After First Rib Resection

The optimal management of the subclavian–axillary vein after surgical decompression of the thoracic outlet remains open for debate. The presence of residual subclavian–axillary vein stenosis, even after relief of the extrinsic compression, is not uncommon (Fig. 126.10). Recommended strategies to deal with these intrinsic lesions have spanned a diverse spectrum, ranging from completion venography and angioplasty with or without stenting to extensive venous reconstructions including thrombectomy, patching, or bypass. No direct comparisons between these strategies have been performed to date, but it is clear that extensive venous reconstructions are accompanied by a higher complication rate. This issue is underscored by the experience of Melby and colleagues, in which 44% of their 32 patients underwent direct subclavian–axillary vein reconstruction, and 100% experienced resolution of their symptoms (no patency data reported).⁶² However, 22% of their patients required secondary operations for complications. Furthermore, if closure of adjunctive radiocephalic fistulae is also included as a secondary procedure, the overall rate of secondary procedures

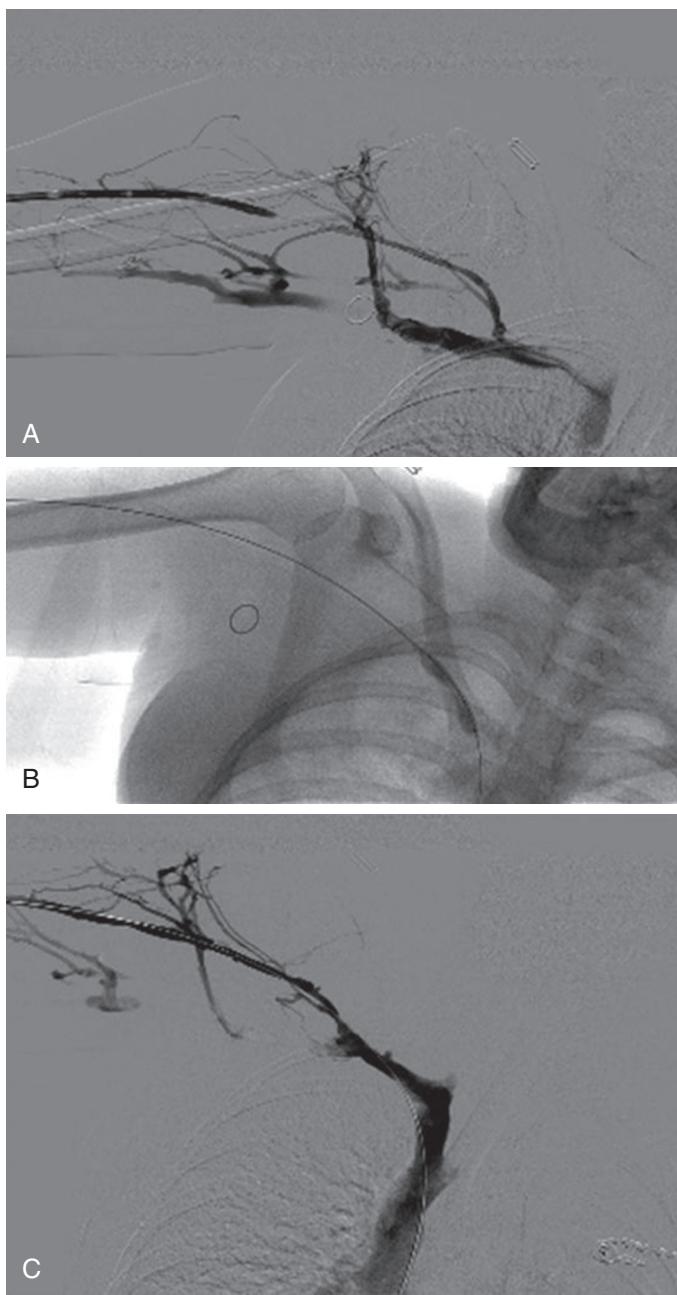


Figure 126.10 Venogram of the subclavian–axillary vein demonstrating (A) a fixed filling defect (B) treated by angioplasty after first rib resection and (C) demonstrating resolution.

increases to 53%. In this experience, no intraoperative venography was used to assess the status of the subclavian–axillary vein after decompression of the thoracic outlet. Consequentially, no attempts at intraoperative angioplasty of residual lesions were undertaken.

Most groups favor an endovascular approach after thoracic outlet decompression. Endovascular treatment can occur during the surgical rib resection case or within 2 weeks of the initial surgery. Advocates of the intraoperative strategy believe this approach can direct the surgeon to the most appropriate treatment of a residual stenosis before the patient leaves the operating room. In a study of the intraoperative strategy, 25 patients routinely underwent completion venography, with angioplasty

as necessary, at the time of thoracic outlet decompression. Their overall results demonstrated 100% technical success, 100% resolution of symptoms, and 1-year primary and secondary patency rates of 92% and 96%, respectively.⁶¹ Proponents of the delayed approach consider the possible complications with venoplasty and the need for immediate anticoagulation as risky. Routine postoperative venography within 2 weeks after thoracic outlet decompression was studied in 84 patients. Although the technical success of 100% was not achieved in this cohort, 1-year primary and secondary patency rates were 94% and 98%, respectively.⁶⁸ Until a prospective comparison of the two strategies is undertaken, at this time the best recommendation is to evaluate and address any residual venous stenosis with intravascular imaging after surgical decompression.

The role of intravascular ultrasound (IVUS) has more recently been debated as a better modality to evaluate residual stenosis on venography. In their retrospective review of 14 patients who underwent venography after first rib resection for vTOS, Kim et al. found that IVUS was more sensitive in the detection of a significant residual stenosis than venography. They suggested that IVUS be used during follow-up venography in patients after undergoing first rib resection.⁷⁸

Postoperative Care

Patients who undergo surgical decompression of the thoracic outlet for vTOS should start physical therapy after complete postoperative treatment of the subclavian–axillary vein. The physical therapy should be tailored for patients with TOS. This protocol should address soft tissue mobilization of the scar as well as restoration of movement of the entire shoulder girdle; improved function and flexibility to the upper cervical spine; activation and strengthening of the anterior, middle, and posterior scalene muscles (especially focused on maintaining posture throughout the day); stretching of the trapezius, the sternocleidomastoid, the levator scapular, and the pectoralis minor muscle; and finally graduated resistance shoulder elevation exercises. The minimum duration of physical therapy should be 6 weeks. It is important to have a strong working relationship with the physical therapist and understand that patients should not be “fast tracked” through physical therapy. Severely fibrotic scarring develops in the surgical field without adequate physical therapy. This results in the tethering of the brachial plexus and can result in neurologic symptoms. Patients should not be released from physical therapy early simply because they demonstrate the ability to have full range of motion. This cannot be overly stressed in young high-level athletes. In order for them to return to full function in their sport, a slow and consistent approach to recovery is essential.

Recurrence

Recurrent thrombosis after first rib resection is most likely due to residual anterior rib left in place at the initial operation or inadequate cutting of the subclavius tendon to free up the vein. When re-thrombosis is identified early, thrombolysis should be considered. The patient should be maintained on

TABLE 126.1

Reported Patency Results of Surgical Thoracic Outlet Decompression for Primary Subclavian–Axillary Thrombosis Published Since 2000

Author	No. of Patients	Technical Success (%)	Secondary Patency (%)	Follow-Up (Mean)
Urschel et al. ¹⁷	277	95	NR	NR
Schneider et al. ⁶¹	25	100	96 (1 year)	10 months
Lee et al. ⁵³	29	93	97 (4 years)	52 months
Doyle et al. ⁶⁰	34	100	92 (5 years)	33 months
Molina et al. ⁷³	97	100	100 (5 years)	62 months
Melby et al. ⁶²	32	100	NR	43 months
Bamford et al. ⁷⁹	35	91	91	44 months
de León et al. ⁸⁰	67	96	96 (1 year)	10 months
Guzzo et al. ⁶⁷	110	91	91 (1 year)	16 months
Hawkins et al. ⁸¹	30	100	100 (2 years)	24 months
Stone et al. ⁸²	36	100	94 (5 years)	65 months
Orlando et al. ¹⁴	225	100	97	NR

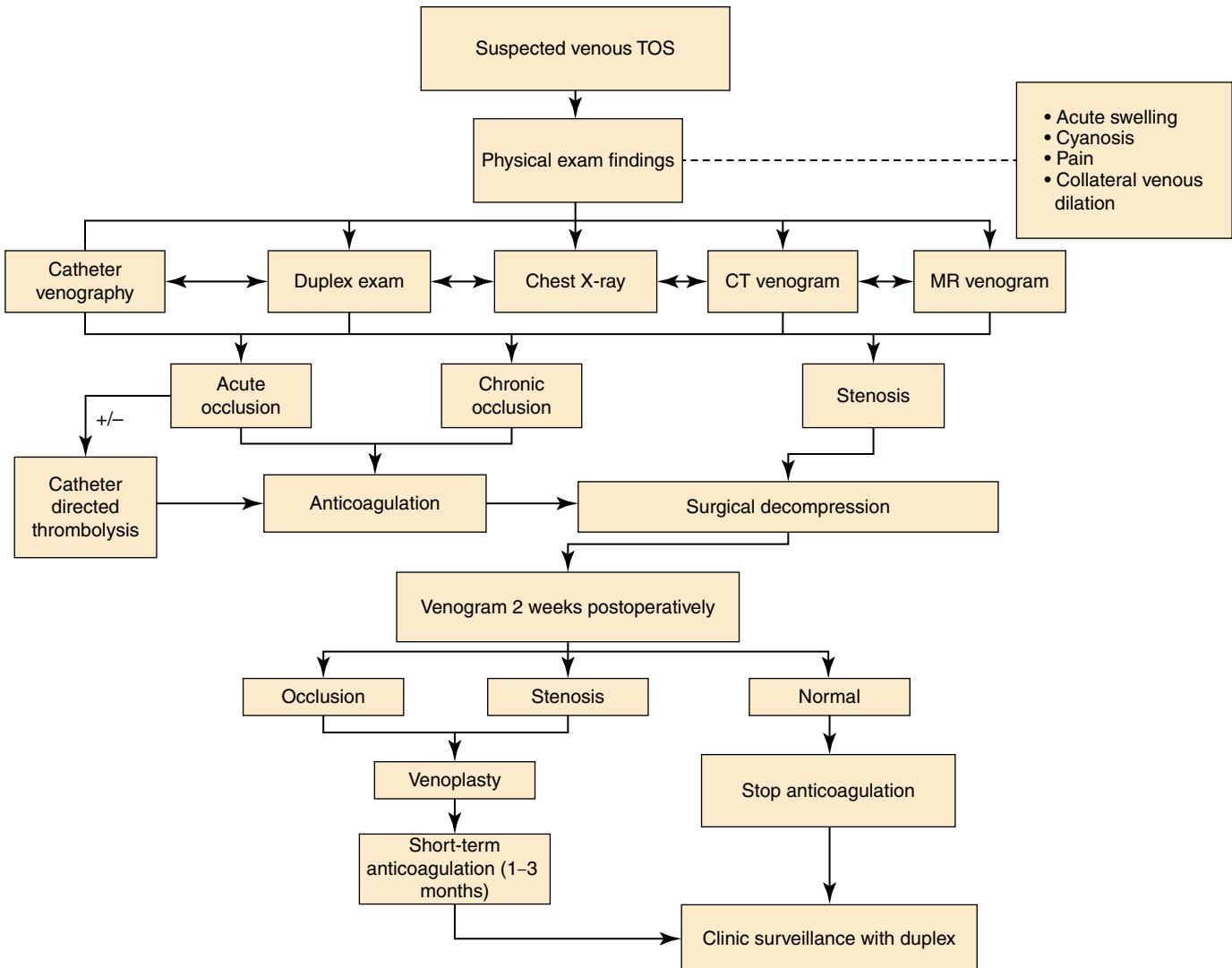
anticoagulation and undergo a workup to determine the cause. Plain radiographs can identify residual anterior rib that was left behind at the first operation. If the cause of recurrent thrombosis is scarring of the subclavian–axillary vein, an infraclavicular incision with repair of the vein can be considered. When thrombosis is thought to be due to inadequate first rib resection, either a supraclavicular or transaxillary approach may be used. Care must be taken when operating in a redo field, especially in the small space of the thoracic outlet. Injury to the vein, artery, or nerve can easily occur when the patient has large amounts of residual scar tissue.

Results

For the most part, reports on the treatment of vTOS are limited to case series, often with relatively small sample sizes.

Nonetheless, in aggregate, the overwhelming evidence suggests that in properly selected patients, restoration of subclavian–axillary vein patency and decompression of the thoracic outlet result in excellent and durable outcomes. Table 126.1 summarizes the results of multiple series that have been used, albeit with varying techniques, strategies to achieve the goal of vein patency and decompression of the thoracic outlet in patients with vTOS. It should be mentioned again that although subclavian vein occlusion after abduction can be documented in a high percentage of the contralateral limbs of these patients, the risk of thrombosis has proved to be low. For this reason, prophylactic procedures should not be considered for routine patients with vTOS. In specific cases of high functioning athletes, contralateral surgical decompression should be considered in order to maintain full function and performance.

CHAPTER ALGORITHM



SELECTED KEY REFERENCES

Molina JE, Hunter DW, Dietz CA. Paget-Schroetter syndrome treated with thrombolytics and immediate surgery. *J Vasc Surg.* 2007;45:328–334.

This study reports one of the largest series of patients to undergo treatment of venous thoracic outlet syndrome. The outcomes were excellent, and the discussion emphasizes many key issues that are central to the management of this challenging syndrome.

Orlando MS, Likes KC, Mirza S, et al. A decade of excellent outcomes after surgical intervention in 538 patients with thoracic outlet syndrome. *J Am Coll Surg.* 2015;220(5):934–939.

This study is one of the largest retrospective reviews of patients treated for TOS. This study outlines a standard protocol for vTOS patients undergoing surgical intervention for vTOS.

Sajid MS, Ahmed N, Desai M, Baker D, Hamilton G. Upper limb deep vein thrombosis: a literature review to streamline the protocol for management. *Acta Haematol.* 2007;118:10–18.

Comprehensive review of key studies describing the etiology, diagnosis, and management of upper limb venous thrombosis.

Schneider DB, Dimuzio PJ, Martin ND, et al. Combination treatment of venous thoracic outlet syndrome: open surgical decompression and intraoperative angioplasty. *J Vasc Surg.* 2004;40:599–603.

This study describes the first significant series of patients who underwent venothrombolysis, immediate surgical decompression of the thoracic outlet and intraoperative venography, and definitive treatment of residual stenosis. The outcomes indicate that it is unnecessary to delay surgical decompression in most patients, and the study emphasizes the importance of intraoperative venography to determine the optimal strategy for treating any residual stenosis.

Urschel HC Jr, Razzuk MA. Paget-Schroetter syndrome: what is the best management? *Ann Thorac Surg.* 2000;69:1663–1668; discussion 1668–1669.

This study provides a clear and detailed description of the transaxillary approach to thoracic outlet decompression.

A complete reference list can be found online at www.expertconsult.com.

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Renovascular Disease: Pathophysiology, Epidemiology, Clinical Presentation, and Medical Management

CULLEN K. McCARTHY and RANDOLPH L. GEARY

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INTRODUCTION

Renovascular disease (RVD) encompasses a range of disorders that affect renal artery structure and kidney blood flow. The primary importance of RVD relates to renal hypoperfusion causing hypertension (HTN) and loss of renal excretory function. Both in turn contribute to cardiovascular morbidity,

dialysis dependence, and death.^{1–5} The most common pathology and major focus of the present chapter is atherosclerotic renal artery stenosis (RAS), found in 7% of elderly individuals in the United States (Fig. 127.1).¹ Less common etiologies include renal artery fibromuscular dysplasia (FMD); dissection, aneurysms, and trauma; arteritis; and developmental abnormalities of the middle aorta and its branches.^{6–8}

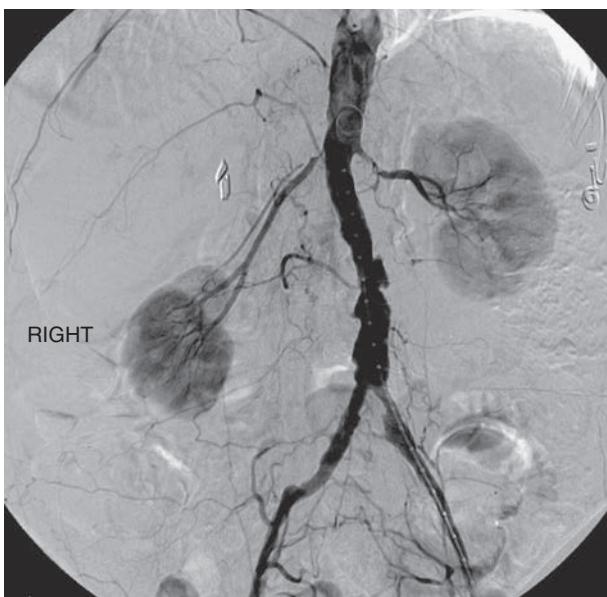


Figure 127.1 Digital subtraction angiogram illustrating bilateral atherosclerotic renal artery stenosis.



Figure 127.2 Operative specimen from transaortic sleeve endarterectomy illustrating ostial renal artery plaque extending perpendicular to a contiguous sleeve of calcified aortic plaque.

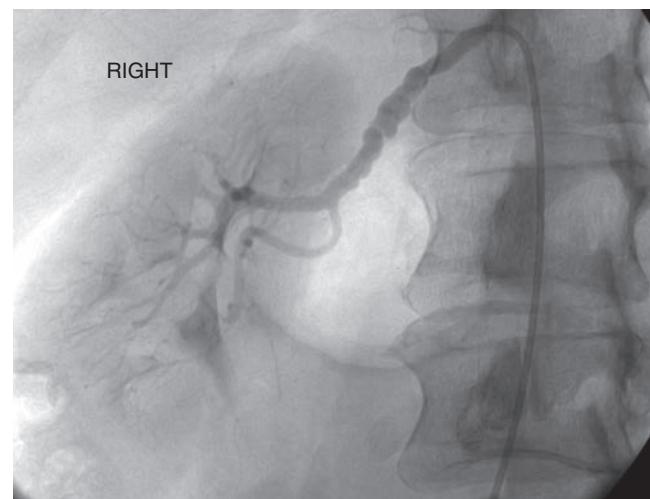


Figure 127.3 Angiogram demonstrating “string of beads” appearance in renal fibromuscular dysplasia.

PATHOGENESIS OF RENOVASCULAR DISEASE

Etiology of Renal Artery Lesions

Most patients with RVD have atherosclerotic lesions, including more than 90% of patients referred for renal artery stenting.^{9,10} In 840 patients undergoing open renal revascularization at our institution, 81% had atherosclerotic lesions, 14% FMD, and 1% dissection. The other 3% were children with hypoplastic renal arteries, mid-aortic syndrome, or dissection.

Atherosclerotic RVD is typically most severe at the renal artery ostia, but stenosis may occur at any level, including small intraparenchymal branches.^{11,12} Ostial lesions are typically contiguous with a sheet of aortic plaque perpendicular to the renal artery (Fig. 127.2). This sheet is often heavily calcified and resistant to simple balloon dilation and more effectively overcome with balloon-mounted stents.^{9,10}

FMD in contrast typically affects the main renal artery and its branches away from the ostia (see Ch. 143, Fibromuscular Disease).⁶ In adults, FMD often creates a series of web-like stenoses, alternating with segments of normal or dilated lumen caliber, giving rise to the classic “string of beads” morphology typical of the medial fibroplasia subtype (Fig. 127.3). Renal FMD in children is more often the intimal fibroplasia subtype and less likely to cause this stereotypical angiographic appearance.

Dissection of the renal arteries can be spontaneous or caused by blunt or penetrating trauma, endovascular manipulation (e.g., guide wires and catheters), severe HTN, or by renal artery wall pathology such as FMD. Renal dissection often originates from aortic dissection that can obstruct the ostia with flaps or extend out the renal artery and branches. Dissection can result in acute occlusion or thrombosis of the renal artery with infarction of the kidney. Dissections may

extend into the kidney parenchyma, limiting options for revascularization, and as they heal, dissections may create stenosis or aneurysmal degeneration (see Ch. 130, Renovascular Disease: Acute Occlusive and Ischemic Events). Less common renal artery pathologies include the various arteritides and congenital syndromes (see Ch. 132, Renovascular and Aortic Developmental Disorders and Ch. 138, Vasculitis and Other Uncommon Arteriopathies).

Pathophysiology of Renovascular Hypertension

Late in the 19th century, Tigerstedt and Bergman isolated a substance from rabbit kidneys they called “renin” that elevated the blood pressure (BP) of control animals after infusion.¹³ Reduced kidney blood flow would later be linked to elevated BP, and Goldblatt’s landmark experiments in the 1930s demonstrated that HTN from RAS could be reversed by correcting renal artery stenosis or by removing the ipsilateral kidney.¹⁴ This work laid the foundation for research that would define components of the renin–angiotensin–aldosterone system (RAAS) as biochemical mediators of BP regulation.

Hypertension in response to RVD results from a complex cascade of molecular and cellular events precipitated by hypoperfusion of one or both kidneys. A flow-limiting RAS creates a pressure drop sensed distal to the stenosis by the juxtaglomerular apparatus that prompts granular cell release of renin into the systemic circulation in an attempt to normalize the BP.¹⁵ Renin catalyzes cleavage of angiotensinogen to form the decapeptide angiotensin I, which is then cleaved primarily in the pulmonary circulation by angiotensin converting enzyme (ACE) to form the octapeptide angiotensin II (Ang II).¹⁶ Circulating Ang II is then the primary effector of renin-mediated increases in systemic BP, promoting peripheral vasoconstriction and blood volume expansion.^{16,17} Ang II acts on a variety of cell types through specific G protein-coupled receptors designated ATR1 and ATR2.¹⁸ ATR1 activates intracellular signaling pathways that promote vasoconstriction and mitogenic responses within the vessel wall and myocardium.^{17–20} Ang II also indirectly promotes vasoconstriction by upregulating expression of norepinephrine and endothelin-1.¹⁸ ATR1 activation also can also promote formation of reactive oxygen species that inactivate nitric oxide. Crosstalk between ATR1 and other receptors (e.g., growth factor-activated receptor tyrosine kinases) amplifies smooth muscle cell vasoconstrictor and proliferative signaling pathways^{18–20} (see Ch. 46, Systemic Complications: Renal).

Fluid retention also contributes to renovascular HTN. Ang II acts directly on renal tubules to promote sodium and water reabsorption²¹ but also stimulates adrenal release of aldosterone, a potent mediator of renal tubular sodium reabsorption.²² Adaptive responses can limit volume expansion in patients with unilateral RAS as the contralateral normal kidney mounts a compensatory natriuresis.^{14,23,24} Patients with bilateral RAS or RAS in a solitary kidney cannot compensate, resulting in so-called “Goldblatt volume-dependent” renovascular HTN, which can be severe.¹⁵ Ang II and its downstream product, Angiotensin III (Ang III) also contributes to HTN via acting on specific regions of the brain responsible for autonomic control of BP, water retention, blunting of the baroreceptor reflex, and by stimulating the release of ACTH and vasopressin from the pituitary to promote synthesis of cortisol by the adrenal glands and the thirst response, respectively.^{20,24–26}

More recent research has illustrated a far more complex RAAS with independently functioning tissue-specific RAAS, the most important of which is the renal RAAS. Overactivation of the intrarenal RAAS in the setting of hypertension or renal malperfusion can autoamplify Ang II production independent of the systemic RAAS. This provides a continuous source of the Ang II to potentiate vasoconstriction, attenuate natriuresis and maintain hypertension.²⁷ Additionally, intracellular renin has been described in the brain but it is unclear if this indicates local synthesis. The biochemical and functional complexity of the central RAS remains to be fully defined but likely contributes to BP regulation.^{26,28,29} Angiotensin-(1–6) (Ang 1–6), an alternative product of angiotensinogen processing, has been shown to counteract some of the deleterious effects of Ang II excess, attenuating hypertension, inflammation and fibrosis.³⁰

While renovascular HTN begins with activation of the RAAS, chronic structural changes sustain and amplify the problem.³¹ The structural changes in RVD are distinct from those observed in essential HTN, in which resistance vessels exhibit eutrophic remodeling, with little change in wall mass. However with RAS, chronic Ang II excess promotes cell proliferation, fibrosis, inflammation and oxidative stress within the vasculature, which subsequently contributes to hypertrophic remodeling of the wall of resistance vessels and myocardium.^{30,32} Wall thickening and stiffening amplifies mechanical leverage in wall constrictor function to promote cardiovascular embarrassment. Hypertrophic changes in wall structure persists after RAS is corrected, which may limit clinical improvement in BP.³¹ Hypertrophic remodeling in RVD may be reversed over time with inhibition of the RAAS (e.g., ACE inhibition) by blunting Ang II production and potentiating the formation of Ang 1–7.

Pathophysiology of Ischemic Nephropathy

Ischemic nephropathy refers to loss of renal excretory function attributed to RVD, but its molecular and cellular basis are incompletely understood.³³ The kidney lacks significant collateral arterial flow, so acute renal artery occlusion generally leads to infarction within minutes to hours. In contrast, the kidney can adapt to a broad range of systemic blood pressures, preserving parenchymal oxygenation and glomerular filtration. Chronic hypoperfusion, however, eventually impairs kidney function through a number of mechanisms, some of which are irreversible. Severe hypoperfusion drops glomerular filtration pressure and leads to ischemic damage.³³ Chronic excess Ang II and aldosterone promote expression of profibrotic cytokines and growth factors, including transforming growth factor-β, a master regulator of extracellular matrix production, and platelet-derived growth factor, a potent mitogen for smooth muscle cells, renal fibroblasts, and glomerular mesangial cells.^{31,33,34} Ang II also induces nuclear factor-κB, a potent master switch for proinflammatory pathways. Each of these contributes to glomerulosclerosis and tubulointerstitial injury.^{34–36} Atherosclerotic lesions themselves may contribute to loss of excretory function by chronically releasing microembolic debris.^{37–40} If perfusion is severely compromised, the renal parenchyma will become hypoxic, with resulting ischemic injury and inflammatory infiltration associated proinflammatory cytokine release, but the contribution of frank ischemic necrosis to renal parenchymal atrophy is less well-established.³³

Severe systemic HTN resulting from unilateral RAS may directly injure the opposite kidney. The damage to excretory function may be irreversible despite subsequent renal revascularization or medical control of HTN.

The etiology of chronic kidney disease is often complex and multifactorial, particularly in patients with established atherosclerosis where risk factors for medical renal disease include diabetes, hyperlipidemia, essential HTN, smoking, and others. Thus patients with atherosclerotic RAS typically have other risk factors that may contribute to renal insufficiency independent of reduced parenchymal perfusion; patients with intrinsic

parenchymal disease and those with advanced parenchymal atrophy from chronic ischemia benefit little from revascularization.

EPIDEMIOLOGY

While animal experiments and clinical experience have proven that reduced kidney blood flow can cause renin-mediated HTN, loss of excretory function, kidney atrophy or even infarction, many individuals found to have RAS on imaging will be entirely asymptomatic.^{3,5} These individuals have “anatomic” disease that is “functionally” silent, because their lesions are hemodynamically inconsequential, or intrinsic adaptive responses are robust enough to maintain BP and glomerular filtration, or the ipsilateral kidney may be so damaged that it is incapable of significant renin release.³

The clinical significance of a stenotic renal artery may be confounded by the high prevalence of essential HTN and intrinsic kidney disease among older individuals with atherosclerosis^{1,3} and increased circulating Ang II among patients with obesity and insulin resistance.^{41–43} Thus the prevalence of RVD defined by imaging alone may overestimate the prevalence of disease that will benefit from intervention. Provocative tests and chemical assays have been of limited value in helping prove a particular renal lesion is driving HTN or ischemic nephropathy. This creates an awkward dilemma: to prove a particular RAS will respond to reconstruction with improved BP and renal function, one often has to first perform the reconstruction.

Prevalence of Renovascular Disease

Historically, estimates of the prevalence and natural history of RAS in the general population was extrapolated from high risk cohorts (see below) (Table 127.1). To address this, Hansen and colleagues used renal duplex ultrasonography (RDU) to screen for RAS among healthy individuals aged 65 and older who were living independently in the community, without regard to BP or renal function (Cardiovascular Health Study- CHS).¹ Subjects were screened at enrollment and then prospectively monitored for incident disease over time. The prevalence of a hemodynamically significant RAS at baseline

was 7%, of which one in eight had bilateral disease, illustrating the significant number of relatively healthy older individuals in the United States with undiagnosed RAS.¹ Additionally, 50% of subjects without RAS had elevated BP versus 72% of those with RAS, and 28% of those with RAS were normotensive. Therefore, many individuals with RVD likely have essential HTN unrelated to their stenosis.^{1,3} The majority of subjects in both groups had normal renal function, but elevated creatinine was twice as likely in those with RAS (16% vs. 8%).³

The prevalence of RAS has also been estimated from autopsy series. Schwartz and White reported RAS in 6% of individuals <55 years of age and 40% of those >75, with bilateral lesions found in approximately half of these patients.¹¹ In another autopsy series, Holley reported 22% had significant RAS.¹² The prevalence of atherosclerotic RVD in autopsy series is clearly impacted by atherosclerosis being the leading cause of death in developed countries.

Angiographic series have screened for RVD in patients with coronary, carotid, and peripheral artery disease (PAD) and found rates of RAS ranging from 22% to 40% of patients (Table 127.1).^{44–52}

Given the impact of RAS on BP and renal function, its prevalence will be higher in cohorts prescreened for HTN or renal failure.⁵³ We used RDU to evaluate 629 adults with newly diagnosed HTN and found 25% had significant RAS. This doubled in patients over 60 years old with severe HTN. RAS has been reported in 9% to 41% of patients requiring dialysis, but prevalence varies significantly by age, gender, and ethnicity. It is highest in the elderly and surprisingly infrequent among African Americans with end-stage renal disease.^{54–58}

Natural History of Renal Artery Stenosis Anatomic Progression

Understanding the natural history of RAS is critical in order to properly balance risks and benefits of various treatment options. Older studies used serial arteriography to monitor severity of stenosis and reported progression in 11% to 35% of lesions managed medically.^{59–62} Arteries with severe baseline stenosis went on to occlude in 10% of individuals.^{59,61} Zierler

TABLE 127.1 Prevalence of Renal Artery Stenosis in High-Risk Populations

Series	Year	Number of Patients	Risk Factor	Patients with RAS (%)	Comments
Hansen et al. ⁷⁵	2002	834	Age >65 years	6.8	Elderly living independently
Jean et al. ⁴⁶	1994	196	CAD	22	Suspected CAD, undergoing angiography
Miralles et al. ⁴⁸	1998	168	Peripheral arterial disease	40	Aortoiliac occlusive disease
Appel et al. ⁵⁴	1995	45	Dialysis	22	New-onset dialysis
Davis et al. ⁵³	2009	434	Hypertension (adult)	32	—
Lawson et al. ¹⁴⁰	1977	74	Hypertension (children)	78	—
Wu et al. ⁴⁹	2007	163	Carotid stenosis	20	—

CAD, coronary artery disease; RAS, renal artery stenosis.

employed serial RDU to follow 80 patients with established renovascular HTN after classifying baseline stenosis for each artery as >60%, <60%, or normal.⁶³ After 3 years, 8% of normal arteries and 43% with <60% stenosis had progressed to a high-grade stenosis, and 7% with >60% stenosis at baseline went on to occlude. Factors associated with progression included age, systolic BP, smoking, female gender, and poorly controlled HTN.⁶³

Functional Progression

Chronic activation of the RAAS, severe HTN, and impaired renal excretory function each contribute to cardiovascular morbidity, dialysis, and death. This relationship provides the rationale for medical and/or surgical treatment of RAS. Loss of functioning nephrons is accompanied by a rise in serum creatinine and fall in eGFR, although an individual must lose more than half of functioning nephron mass before creatinine rises. Surrogates for loss of kidney function, such as kidney shrinkage, can be valuable in understanding the progressive impact of RVD. Kidney atrophy can be assessed with RDU and cross-sectional imaging measuring loss of kidney length, cortical thickness, or volume. Schreiber reported significant decline in renal function over time in patients with RAS, regardless of whether the degree of stenosis progressed.⁶⁰ Dean randomized 41 patients with RAS and severe HTN to medical management and found 46% had a significant rise in serum creatinine while 37% showed loss of kidney length on follow-up.⁵⁹ In a prospective study of 122 patients with renovascular HTN, Caps reported that 21% of kidneys ipsilateral to >60% RAS lost more than 1 cm in length at 2 years with an increase in creatinine, and that atrophy correlated with degree of stenosis and elevated systolic BP.⁶⁴ Others have also documented shrinking kidneys and loss of excretory function in patients with RAS, and progression to dialysis has been reported in 7% to 12% of patients managed medically within 3 to 4 years.^{65,66}

In contrast, none of the elderly subjects followed by Hansen et al. (described above) with >60% RAS at baseline progressed to complete occlusion at a mean follow-up of 8 years.^{1,67} However, nine kidneys with normal renal arteries at baseline went on to develop critical RAS, including one complete occlusion. In this relatively healthy cohort, enrolled independent of HTN or renal dysfunction, the rate of progression was only 4%, far below the previously mentioned series in patients preselected for severe concomitant HTN. Taken together, these studies demonstrate that progression of RAS is less likely in low-risk patients in whom lesions are found incidentally, but loss of renal mass and function are common in older patients with high-grade RAS and severe HTN.^{1,3}

Associated Morbidity

RAS has been associated with cardiovascular morbidity and mortality, and progression to dialysis. Risk of end-organ damage is much higher in patients with atherosclerotic RAS compared with patients with essential HTN, as measured by left ventricular hypertrophy, elevated serum creatinine, and proteinuria.⁶⁸ Mailloux projected that RVD accounts

for 10% to 18% of incident dialysis dependence among the elderly.⁵⁶ Others have associated RAS with cardiovascular events, including stroke and perioperative complications.^{53,68,69} Conlon showed that among 1235 patients with coronary artery disease (CAD) on angiography, the 4-year survival was significantly lower in those with concomitant RAS (67% vs. 88%). Increased mortality was attributed mostly to excess cardiovascular events.⁷⁰ Edwards reported that the incidence of new coronary events among 870 CHS study participants (see above) was twice as high in those with RAS after only 14 months' follow-up, and the association remained significant after controlling for HTN and preexisting cardiovascular disease.²

CLINICAL PRESENTATION

History and Physical Examination

Due to the high volume of cross-sectional imaging employed in contemporary medicine, a large number of patients are referred for RAS found incidentally. The most common indications for referral to our vascular laboratory for RDU screening are severe HTN (e.g., resistant to three or more medications); unexplained renal insufficiency in patients with risk factors for RVD; and regular surveillance of patients with known RVD or for patients with prior renal revascularization. All children with unexplained HTN should be screened for RVD, and practitioners should be reminded that blood pressure ranges that define HTN in children are far lower than in adults (e.g., a systolic BP of 110 mm Hg is 99th percentile for a 1-year-old child).^{71,72}

HTN associated with critical RAS is typically more severe and refractory to medical therapy than essential HTN.^{3,21} For example, in 500 patients with atherosclerotic RAS treated with open surgical renal revascularization at Wake Forest, the mean preoperative systolic and diastolic pressures were 200 mm Hg and 104 mm Hg, respectively, on an average of three antihypertensive medications (Table 127.2).^{73,74}

TABLE 127.2 Demographics of Patients Undergoing Open Renal Revascularization

Parameter	Value
Age	65 ± 9 years
Gender	49% male, 51% female
Systolic BP	200 ± 35 mm Hg
Diastolic BP	104 ± 21 mm Hg
Number of antihypertensive medications	2.6 ± 1.1
Creatinine concentration (mean)	2.6 mg/dL (230 µmol/L)
Comorbid extrarenal atherosclerosis	90%
Coexisting coronary artery disease	70%
Diabetes	16%

BP, blood pressure.

Advanced age, atherosclerosis risk factors, or a history of coronary, carotid, or peripheral arterial disease should raise suspicion of RAS in adults with severe HTN. Patients with RAS can have impaired renal function, but the etiology is often multifactorial. In our experience, ischemic nephropathy caused by RAS is nearly always associated with severe HTN.^{73–75} Renal insufficiency in patients with only mild or moderate HTN typically have medical renal disease unlikely to stabilize or improve with revascularization.⁷³ Patients who demonstrate acute renal insufficiency after starting an ACE inhibitor or angiotensin II receptor blockers (ARB) should be screened by RDU for bilateral RAS where both kidneys rely on efferent arteriolar tone mediated by Ang II to maintain glomerular filtration.^{76,77}

Individuals with unrecognized or poorly controlled renovascular HTN may present in “hypertensive crisis” with neurologic or cardiovascular embarrassment when HTN is severe (e.g., systolic BP >200 mm Hg).⁷⁸ Long-standing HTN leads to left ventricular hypertrophy and abnormal diastolic relaxation. A stiff ventricle then predisposes patients to “flash” pulmonary edema after relatively minor increases in volume status or further increases in BP. Severe HTN also drives fluid into the extravascular space, causing edema and inflammation of various tissues, including the brain. Neurologic manifestations may include headache, visual disturbance, mental status change, acute stroke, or intracranial hemorrhage. HTN can also damage the opposite kidney in patients with unilateral RAS, resulting in proteinuria and elevated serum creatinine that corrects as BP is normalized.^{33,78} It is important to allow a patient in this setting to recover before imaging with iodinated contrast.

On physical examination patients may manifest severe systolic and diastolic HTN, peripheral edema, abdominal bruits, and nonspecific stigmata of atherosclerotic heart and vascular disease. Diminished lower extremity pulses can be found in adults with associated atherosclerotic PAD, Takayasu arteritis, and aortic dissection, while in children decreased lower extremity pulses may indicate aortic coarctation or mid-aortic syndromes. Differential diagnostic considerations are provided in Table 127.3.

Laboratory Findings

Laboratory testing in individuals being evaluated for HTN may include urinalysis, blood chemistries, fasting blood glucose or hemoglobin A_{1c}, lipid panel, and 12-lead EKG. Although nonspecific, blood urea nitrogen and creatinine concentrations may be elevated in patients with RVD. An electrocardiogram may show a strain pattern and increased voltage consistent with left ventricular wall thickening. Echocardiography can confirm ventricular hypertrophy with impaired diastolic relaxation, and in the pediatric patient can also exclude aortic coarctation. Measuring systemic renin levels in patients with RVD is rarely useful unless combined with invasive selective renal vein renin sampling (see below). In patients with diabetes, urinary albumin excretion should be measured to assess the extent of intrinsic kidney damage.⁷⁹

Spontaneous hypokalemia (<3.5 mmol/L) or severe hypokalemia after initiating diuretics should raise suspicion for primary hyperaldosteronism (Conn syndrome), which can be

confirmed by measuring plasma aldosterone (Table 127.3).^{22,80} These patients also typically manifest a metabolic alkalosis and depressed or unmeasurable plasma renin activity. An incidental finding of adrenal adenoma on abdominal imaging in a patient with refractory HTN should prompt screening for hypersecretion of aldosterone and catecholamines. Patients with catechol-excreting adrenal tumors (pheochromocytoma) may have episodic HTN associated with headache, palpitations, sweating, panic attacks, and pallor. In these patients, paroxysms of HTN can be triggered by starting β-blockers or MAO inhibitors, or by micturition and other activities that increase intraabdominal pressure.^{80,81} Patients with MEN2, neurofibromatosis type-1, and von Hippel–Lindau are also at risk for pheochromocytomas. Diagnostic algorithms are influenced by local expertise, and our preferred screen is a 24-hour urine assay for fractionated metanephrenes and catecholamines. Fractionated plasma metanephrene assays are also commonly employed.

Diagnostic Imaging

Renal Duplex Ultrasonography

RDU is an excellent screening test for RAS (see Ch. 22, Vascular Laboratory: Arterial Duplex Scanning). When performed by an experienced technologist, a typical study is rapid, noninvasive, accurate, and reproducible. RDU avoids ionizing radiation and iodinated contrast material, does not require intravenous access, is safe in patients with medical implants, and is relatively inexpensive. Therefore, RDU has become the primary tool in most centers for screening and following patients with RAS.⁸² Limitations include that it is technically demanding relative to other studies performed in the average vascular laboratory and thus somewhat operator-dependent, and RDU is also of limited use in characterizing other manifestations of RVD (e.g., aneurysm, dissection, FMD, etc.). Patient factors that can interfere with renal artery insonation include obesity, bowel gas, and excessive resistance from advanced disease within the kidney parenchyma.

In our laboratory, after an overnight fast to reduce bowel gas, the exam begins with the patient supine. From the anterior approach, the perirenal aorta is examined for aneurysmal change, stenosis, or occlusion and a peak systolic velocity (PSV) is recorded. Each renal artery is then imaged and velocities and waveforms recorded from proximal, mid-, and distal segments. Velocity profiles are recorded within the kidney parenchyma at the superior, mid-, and inferior pole to calculate resistive index (RI) and acceleration times. The exam concludes with the measurement of pole-to-pole kidney lengths.

The accuracy of RDU in detecting significant RAS (e.g., >60% stenosis), validated against conventional arteriography, can exceed 90% in experienced hands.^{83–86} Criteria used to define a critical stenosis vary, but in our hands a PSV of >200 cm/s in the main renal artery when associated with post-stenotic turbulence has proven accurate in defining a >60% stenosis.^{83,86} Other centers rely on the ratio of renal artery to aortic PSV (RAR) to define a critical RAS (e.g., >3.5),⁸⁵ but in our hands the RAR has been unreliable.^{83,87} Others still have proposed different criteria for their laboratories, including slightly higher PSV cutoffs (e.g., 285 cm/s) and higher RAR (e.g., 3.7); AbuRahma

TABLE 127.3 Differential Diagnosis in Patients Evaluated for Renovascular Hypertension

Underlying condition	Signs/Symptoms	Diagnostic Tests
Cardiovascular		
Essential Hypertension	Strong family history	
Collagen Vascular Disease	Hx or symptoms of SLE, rheumatoid arthritis, sclerodactyly	Elevated ESR, abnormal complement levels, positive anti-DNA, anti-RNP, anti-Smith, positive rheumatoid factor
Aortic Coarctation	Childhood onset, BP differential between upper and lower extremities, absent femoral pulses	CTA, MRA, DSA
Renal		
Chronic Renal Failure	Pruritis, halitosis, edema, decreased urine output	Increased serum creatinine, chronic anemia, sclerotic or polycystic kidneys on RUS
Renal Parenchymal (e.g., glomerulonephritis, nephrotic syndrome, UTI, calculi)	History of renal disease, nocturia, dysuria, hesitancy, incomplete emptying, pyuria, flank pain	BUN, creatinine, urinalysis, urine culture, 24-hour urine for protein and creatinine clearance
Renal Artery Stenosis	Typically younger patients with difficult to control HTN, renal artery bruit possible	Renal duplex US, CTA, MRA, DSA
Endocrine		
Hypoaldosteronism	Muscle weakness, cramps or paresthesia	Hypokalemia, increased plasma aldosterone, low plasma renin, failure of aldosterone suppression with decreased salt
Hypothyroidism	Dry skin, cold intolerance, weight gain, sluggishness, goiter	Elevated TSH
Hyperthyroidism	Heat intolerance, weight loss, hyperphagia, palpitations, exophthalmos	Elevated free T ₃ and suppressed TSH
Hyperparathyroidism	Nephrolithiasis, renal colic, abdominal pain, vomiting, bone pain/fracture	Hypercalcemia with elevated PTH
Cushing Syndrome	Weight gain, moon facies, dorsocervical fat pad, abdominal striae, easy bruising	Abnormal dexamethasone suppression, 24-hour free urine cortisol
Pheochromocytoma	Paroxysmal HTN, flushing, headache, palpitations	Increased 24-hour urine VMA, metanephrines and/or catecholamines
Acromegaly	Hand/foot/jaw enlargement	Elevated IGF-1, serum growth hormone levels not suppressed by glucose load
Carcinoid	Flushing, diarrhea	24-hour urine 5-HIAA
Pharmacologic		
Drug-Induced	Signs of acute intoxication or withdrawal; history of treatment or ingestion of NSAIDs, OCPs, sympathicomimetics, herbal medications, licorice	Drug toxicology screen
Neurologic		
Sleep Apnea	Obesity, daytime somnolence, snoring or choking during sleep, morning headache	Polysomnography with nocturnal oxygen desaturation
Increased Intracranial Pressure	Headache, neurologic symptoms, papilledema	Increased CSF pressure
Volume Overload	Excess salt and water intake, CHF or renal failure, iatrogenic (large intravenous volumes)	Chest radiograph

Modified from Lawton, William J., Friedrich C. Luft, and Gerald F. DiBona. "Normal blood pressure control and the evaluation of hypertension." *Comprehensive Clinical Nephrology* (2010): 395-410; and Epocrates. *Essential Hypertension*. 2014. Available at: <https://online.epocrates.com/diseases/2635/Essential-hypertension/Differential-Diagnosis>

and colleagues have reported that a PSV of 285 cm/s or an RAR value of 3.7 or higher alone were better than any combination of PSV, EDV, or RAR in detecting stenoses >60%.⁸⁶

Hilar and parenchymal analyses have been proposed as less complicated approaches to identify an RAS. Blunted waveforms

with delayed systolic upstroke are indicative of proximal stenosis. Acceleration times estimate delay in systolic upstroke from onset of systole to its peak, with values exceeding 100 ms suggesting flow-limiting RAS.^{84,87-89} In our hands acceleration time provides a positive predictive value of 97%, but sensitivity is too

low to be used alone for screening.⁸⁷ The RI has been proposed to screen for RAS but is best suited to identify patients with intrinsic kidney disease. A normal value is <0.7. Values >0.8 may indicate a critical RAS but more often are nonspecific, frequently caused by intrinsic medical parenchymal kidney disease. Radermacher measured RI in 131 patients undergoing renal revascularization and found a value >0.8 predicted a poor BP response and likely progression of renal insufficiency after surgery, consistent with irreversible medical renal disease.⁸⁴ In contrast, 94% of patients with an RI <0.8 showed improved BP and freedom from dialysis after reconstruction. The role of the RI in managing RVD is controversial, although at our center we place little emphasis on RI in guiding treatment decisions.⁸⁸

Computed Tomographic Angiography

Advances in speed, resolution, and postprocessing have contributed to the widespread application of computed tomographic angiography (CTA) for vascular imaging (see Ch. 29, Computed Tomography). Modern multichannel scanners provide precise three-dimensional visualization of vascular abnormalities not possible with digital subtraction angiography (DSA) alone.^{90–93} CTA is noninvasive and widely available, and image acquisition and formatting are less technically demanding than for RDU or for contrast-enhanced magnetic resonance angiography (MRA) of the renal arteries. Disadvantages of CT include exposure to ionizing radiation and iodinated contrast. CTA delivers 87 to 260 times more radiation to the patient than a chest X-ray,⁹¹ and a typical renal CTA uses 120 to 140 mL of contrast, which may cause nephrotoxicity in some patients.^{92,93} Studies comparing CTA with DSA report a sensitivity, specificity, and accuracy approaching 100% for defining significant lesions of the main renal artery (Table 127.4). CTA also provides detailed information about surrounding tissues and organs, such as kidney length and parenchymal thickness and quality of the adjacent aorta and visceral arteries. The latter are helpful when planning surgery, identifying locations suitable for cross-clamping and inflow sources for bypass.

Magnetic Resonance Angiography

MRA has also proven useful for imaging RVD and has the advantages that it avoids ionizing radiation and iodinated contrast.^{93–96} MRA is preferred in children or young patients to avoid radiation. Limitations include long scan times subject to motion artifact and a lower spatial resolution than for CTA

or DSA. Patients can become claustrophobic in typical closed scanners and many have metal implants incompatible with the magnetic field.⁹⁵ Also, gadolinium contrast cannot be used in patients with significant renal impairment because of the risk for nephrogenic systemic fibrosis, a scleroderma-like syndrome most commonly affecting the extremities that may also involve the lung, diaphragm, esophagus, heart, and vasculature.^{97–99} The pathogenesis is ill-defined, but most patients have end-stage renal disease, and a dose-effect is likely.⁹⁹ The Food and Drug Administration has issued a black-box warning to avoid the administration of gadolinium to patients with eGFR less than 30 unless it is absolutely necessary. If exposure is unavoidable, patients should be dialyzed immediately afterward, but this may not provide complete protection. When comparing MRA with DSA, accuracy in defining a critical RAS is excellent but MRA can overestimate the degree of stenosis (Table 127.4) (see Ch. 30, Magnetic Resonance Imaging and Arteriography).

Digital Subtraction Angiography

DSA remains the gold standard for renal imaging, providing lumen morphology in high resolution and allowing for endovascular treatment. It can be done with minimal use of iodinated contrast, especially relative to CTA, and allows for utilization of carbon dioxide to further mitigate the risk of contrast nephropathy in patients with renal insufficiency.¹⁰⁰ DSA does not provide three-dimensional information on vessel wall structure or adjacent tissues and organs, as seen on axial imaging (Fig. 127.4), and image quality can be degraded by a number of patient factors, including obesity, bowel gas, heavy calcification, retained gastrointestinal contrast material, and movement (see Ch. 27, Arteriography). DSA is invasive, with risk of access site bleeding and other complications that are higher than generally appreciated (e.g., 13% in the roll-in phase of CORAL),¹⁰¹ and it exposes patients to nephrotoxic contrast and patients and operators to heavy doses of ionizing radiation. DSA is also labor-intensive, requiring a team of trained specialists, and is expensive.

Given these issues, and noninvasive alternatives outlined previously, DSA is generally reserved for patients undergoing planned renal artery reconstruction. In this group, it is important to define accessory renal arteries, branch vessel disease, blood supply to the contralateral kidney, and status of the adjacent aorta and visceral vessels as potential inflow sources. In patients with renal insufficiency it is important to provide

TABLE 127.4

Accuracy of Duplex Ultrasonography, Computed Tomographic Angiography, and Magnetic Resonance Angiography for the Evaluation of Renal Artery Stenosis

Series	Year	Modality	Number of Kidneys	Sensitivity (%)	Specificity (%)
Hansen et al. ⁸³	1990	Duplex	122	93	98
Hua et al. ⁸⁵	2000	Duplex	58	91	75
Fraioli et al. ⁹⁰	2006	CTA	50	100	98.6
Rountas et al. ⁹³	2007	Duplex, CTA, MRA, DSA	129	75 (duplex) 94 (CTA) 90 (MRA)	89.6 (duplex) 93 (CTA) 94.1 (MRA)

CTA, computed tomographic angiography; DSA, digital subtraction angiography; MRA, magnetic resonance angiography.

preprocedural hydration and strategies to limit volume of contrast, such as using carbon dioxide to reduce risk of contrast-induced nephropathy (Fig. 127.5).

Functional Studies

A pervasive problem in evaluating patients with RVD has been a lack of practical screening tests to identify patients who will respond to revascularization.¹⁰² Each imaging modality described previously can detect anatomic RAS, but none can link a particular lesion to HTN or impaired renal function that will correct after revascularization. To address this, a number of adjuncts to imaging have been developed, including direct pull-back pressure measurements to define gradients during DSA¹⁰¹ and loss of kidney length on RDU^{63,64} as a surrogate for ischemic nephropathy, indicating severe kidney hypoperfusion likely to progress without intervention. Split renal function



Figure 127.4 Comparison of digital subtraction angiography (left) and volume-rendered computed tomographic angiography (right) in a patient with bilateral proximal renal artery stenosis.

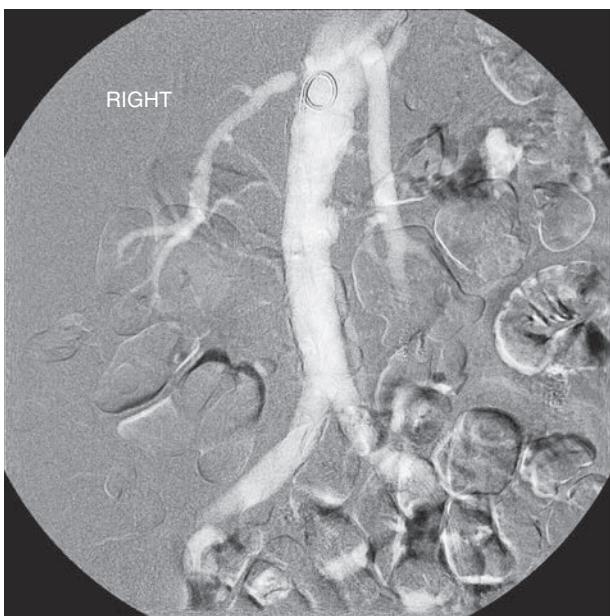


Figure 127.5 Strategies to limit exposure to nephrotoxic contrast material during renal angiography include the use of alternative contrast agents, such as carbon dioxide (shown) and gadolinium.

studies using radionuclide renography can screen for loss of excretory function ipsilateral to an RAS that can be compared with an opposite normal kidney in patients with unilateral disease. While each of these methods can help support or refute functional impact to a known RAS, none has proven reliable in identifying patients who respond to revascularization.¹⁰² New tools to define renal parenchymal ischemia are being tested but have yet to be validated for clinical decision making.¹⁰² Two older functional assays that have been studied extensively and remain in use in some centers today are captopril renography and selective renal vein sampling.

Radionuclide Renography

Split renal function can be measured by quantifying the uptake and excretion of radiolabeled molecules, such as technetium Tc-99m-labeled mercaptoacetyltriglycine.^{103–106} Abnormal uptake and excretion by a kidney downstream of an RAS suggests a causal relationship, but renography is often normal in patients with RAS. In patients with unilateral RAS and renal insufficiency, a defect on renography is as likely to be in the contralateral kidney.¹⁰⁶

ACE inhibitor renography, commonly called “captopril renography,” uses pharmacologic inhibition of Ang II or its ATR1 receptor to unmask intrinsic renal compensation to RAS, creating a pressure drop that impacts glomerular filtration (see the Pathophysiology section noted previously). With unilateral critical RAS, the affected kidney will show an acute decline in excretion of the radiolabel after inhibiting Ang II with an ACE inhibitor or ARB.^{103,104,106} The contralateral kidney may show enhanced excretory function after ACE inhibition, as efferent arteriolar dilatation leads to increased glomerular filtration in the setting of a normal perfusion pressure.¹⁰⁶

In patients with unilateral RAS, ACE inhibitor renography may distinguish between renovascular and essential HTN, and thus identify patients more likely to benefit from revascularization.¹⁰⁴ A normal study effectively excludes renovascular HTN. The assay is inaccurate in patients with severe azotemia or small, poorly functioning kidneys. In these settings, an abnormal baseline renogram is less likely to change significantly with ACE inhibition, causing false-negative or indeterminate results. However, Erbsloh-Moller studied 20 azotemic patients with serum creatinine levels greater than 1.8 mg/dL (159 µmol/L) and reported that sensitivity and specificity of a positive study exceeded 90% in predicting BP response to revascularization.¹⁰⁶

Renal Vein Renin Assays

Documenting excess renin production by the affected kidney should support a functional link between RAS and HTN. Selective renal vein renin assays can be used for this purpose, but their use is limited by the complexity and invasive nature of the procedure. Renin levels can be altered by a number of variables unrelated to RAS, so careful patient preparation and standardization of the procedure are essential.

We start patients on a low-sodium diet and attempt to stop all antihypertensive medications except diuretics and calcium channel blockers 5 days before the assay. Furosemide (40 mg, PO) is given the evening before the study. Patients are kept supine at strict bed rest 4 hours before and during the assay.

Separate catheters are placed percutaneously under fluoroscopy into the inferior vena cava and each renal vein. A reference systemic sample is drawn from the cava, followed by simultaneous aspiration of right and left renal vein catheters. Sampling is repeated two or three times at 5-minute intervals and then a final systemic caval sample collected.

A ratio of renal vein renin to systemic renin of 1.5 times or higher is typically considered positive, linking RAS to excess renin production.^{71,98} Lateralizing renins generally predict a BP benefit from open revascularization,^{71,98} but failure to lateralize has a low negative predictive value. The ratio for the opposite uninvolved kidney may be low because of compensatory suppression of renin release in response to HTN.¹⁰⁷

Renin assays are of little use in patients with bilateral RAS, those with solitary kidneys, or with RAS in accessory renal arteries. The value of renin ratios in predicting a positive response to revascularization in patients with ischemic nephropathy is also unclear. In these circumstances, decisions regarding intervention are left to clinical judgment factoring in degree of stenosis, severity of HTN, and trajectory of any decline in eGFR. Presently in our practice we obtain renin assays sparingly, but they can be useful when making decisions about open revascularization in patients with unilateral RAS.

TREATMENT OF RENOVASCULAR HYPERTENSION

A diagnosis of RAS is associated with a high risk of cardiovascular morbidity and mortality^{2,4}; significant risk of lesion progression and loss of kidney mass, particularly in cohorts with severe RAS and HTN (Table 127.5)^{63,64}; and risk of progression to dialysis and death.^{2,4,56} Despite these compelling statistics, the benefits of renal revascularization have been challenged by better medical treatments,⁸¹ an evolving experience with open renal revascularization,^{73,74,108} and by a growing body of Level I data contesting the value of renal stenting for many patients with atherosclerotic RAS.¹⁰⁰ As a result, most centers are now limiting revascularization to patients with severe manifestations of atherosclerotic RAS and those with nonatherosclerotic RVD.

Medical Management of Atherosclerotic Renovascular Disease

Mounting Level I data from randomized trials, including the CORAL trial, support a recommendation that most patients with atherosclerotic RAS should receive medical therapy without intervention.^{81,102,108–111} Risk factors for atherosclerosis and renal impairment should be aggressively controlled.^{81,101,110,111} Patients should be provided resources to help promote healthy lifestyles, including smoking cessation, regular exercise, and appropriate nutrition. Lipid levels should be monitored, and if high, lowered to accepted targets for secondary prevention in cardiovascular disease (e.g., LDL <100 mg/dL).¹¹¹ Patients should receive antiplatelet and statin therapy regardless of baseline lipid levels, unless there is a specific contraindication.¹¹¹ Statins may reduce progression of RAS¹¹² and inhibit restenosis after renal stenting,¹¹³ and they clearly protect from cardiovascular morbidity and mortality in patients with established atherosclerosis. The protocol for medical treatment in CORAL included statin therapy adjusted to achieve these targets, which along with aggressive protocol-driven BP treatment likely contributed to low rates of RVD progression, cardiovascular events, and death.¹⁰¹

As mentioned previously, renal dysfunction in RVD patients is often multifactorial, given the overlap in risk factors for medical renal disease and atherosclerosis. Renal function should be monitored regularly, and patients with abnormal eGFR should be evaluated for common causes of chronic kidney disease and treatment tailored to limit further injury, generally in concert with a nephrologist. Individuals with a BMI >25 should be encouraged to lose weight, and those with diabetes should carefully manage glucose. In centers experienced with RDU, patients with RAS and those with prior renal revascularization should be studied annually to assess patency and kidney length, particularly after stenting, given high rates of restenosis.^{10,101} RDU should also be considered to assess for progression in patients with sudden worsening of HTN or renal impairment. HTN should be treated aggressively, and BP goals for adults with RVD are the same as for essential HTN. Current consensus recommendations in the United States and Canada⁸¹ include a systolic BP of <140 mm Hg and diastolic BP <90 mm Hg. These targets drop to <130/80 for patients

TABLE 127.5 Natural History of Renal Artery Stenosis: Selected Series

Series	Year	Number of Patients	Imaging Modality	Anatomic Progression (%)	Occlusion (%)
Dean et al. ⁵⁹	1981	41	Angiography	17	12
Schreiber et al. ⁶⁰	1984	85	Angiography	44	11
Tollefson et al. ⁶¹	1991	48	Angiography	53	9
Zierler et al. ⁶³	1994	80	Duplex ultrasonography	8	3
Crowley et al. ⁶²	1998	1178	Angiography	11	0.3
Caps et al. ⁶⁴	1998	170	Duplex ultrasonography	31	3

Modified from Corriere MA, Edwards M, Hansen K. Abdominal aortic aneurysm and renal artery stenosis. *Vasc Dis Management*. 2008;5:16–21.

with concomitant diabetes or renal insufficiency.^{81,110} Hypertensive patients should avoid excessive salt intake, limit alcohol consumption, reduce stress, and get regular exercise.

Renovascular HTN typically requires multiple classes of antihypertensive medications to achieve BP goals, and a number of individuals will never reach consistent control without revascularization. There are no large randomized trials comparing efficacy of different combinations of antihypertensive medications in RAS, but given the central role of the RAAS, ACE inhibitors and ARBs should be among first-line choices.^{81,110} The safety of these agents in RVD has been demonstrated in a number of studies, including CORAL,¹⁰¹ but when initiating treatment in patients with bilateral RAS or solitary kidneys, the creatinine should be monitored for a sudden decline in eGFR. If this occurs, the offending medication should be promptly discontinued and renal function typically returns to baseline.^{76,77} Other first-line agents for treating renovascular HTN include thiazide diuretics, calcium channel blockers (dihydropyridines; e.g., amlodipine), and beta blockers.^{81,110} Diuretics are often helpful in RVD because of associated volume excess, particularly in patients with bilateral lesions, but patients should be monitored to avoid hypokalemia. Spironolactone should be used with caution with ACE inhibitors or in the setting of impaired renal function to avoid hyperkalemia. In patients intolerant or refractory to first-line agents, second-tier agents can be considered with caution (e.g., hydralazine, clonidine, etc.)^{81,110} (see Ch. 14, Hypertension).

Renal Revascularization

Historical Perspective

In 1938, Leadbetter reported that removing an ischemic ectopic kidney normalized BP in a child with severe HTN, which led to the popularization of nephrectomy for adults with uncontrolled HTN attributed to RVD.¹¹⁴ Unfortunately, the impact of nephrectomy on BP control and renal function proved difficult to predict.¹¹⁵ Successful renal artery reconstruction was first reported by Freeman in 1954, after normalization of BP following endarterectomy in a patient with previously uncontrolled HTN and bilateral ostial RAS.¹¹⁶ As experience with open renal artery reconstruction for HTN mounted, reports emerged that revascularization could also improve renal excretory function.^{117–122} Dean and others coined the term ischemic nephropathy, describing renal insufficiency resulting from RAS or occlusion, and provided provocative reports of patients removed from dialysis after revascularization.^{117–122} As open revascularization was refined, the use of nephrectomy was largely abandoned.

Open revascularization proved effective but inconsistent at improving HTN. Surgery carried significant risk in the elderly with advanced atherosclerosis and ischemic nephropathy, and not every patient benefitted. Less invasive approaches to the management of RVD were developed in parallel with the emergence of new classes of antihypertensive agents that greatly reduced the number of patients requiring revascularization for refractory HTN.^{123,124} Gruntzig et al. first described angioplasty to treat RAS in the 1970s¹²⁵ but subsequent clinical studies

demonstrated high rates of restenosis. Within a decade, however, renal restenosis rates were substantially reduced with the development of balloon-expandable stents leading to an explosion in endovascular interventions and precipitous drop in the numbers of patients undergoing open revascularization.^{10,126–129} Open renal artery reconstruction has become uncommon in contemporary vascular practice with few surgeries performed outside of centers with a particular interest in RVD.

Although renal stenting was initially employed enthusiastically,¹²⁸ results from large prospective randomized clinical trials comparing stenting to best medical management in atherosclerotic RAS (e.g., ASTRAL and CORAL), have shown no clear benefit from stenting.^{129–132} Although these trials have shortcomings – a number of patients not meeting the threshold for intervention at our center and others were included – their impact has been to (appropriately, in our opinion) limit stenting to select subsets of patients with atherosclerotic RVD.

Few studies have directly compared open renal revascularization with medical management, angioplasty, or stenting, and all were too small to provide meaningful guidance.^{133,134} Therefore, the application of open surgery in RVD is guided largely by single center cohort studies and expert opinion (discussed later).

Open Revascularization

No large prospective randomized trials have compared open renal artery reconstruction to medical management, angioplasty, or stenting.^{133–135} Fewer open surgical procedures are being performed for symptomatic RAS because of a better understanding of the natural history of RAS without intervention, the availability of less invasive alternatives, refinements in patient selection,^{74,75,102} and improved outcomes with medical management.^{131,132} Results from prospective series by our group and others have helped shift the focus of surgery in RVD away from BP control and toward preservation of excretory renal function.⁷⁵ We consider open repair in good-risk patients with bilateral RAS or branch vessel disease who have failed to respond to medical treatment and for children with developmental RVD. Open repair of atherosclerotic RAS is much more durable than stenting, with patency rates well over 90% on long-term follow-up, but carries a higher mortality^{74,75,136–141} reported as 10% among renal bypass patients ($N = 6608$) across a broad range of hospitals in the U.S. National Inpatient Sample from 2000 to 2004.¹³⁵ In a series of 500 patients undergoing open renal reconstruction for atherosclerotic RAS at Wake Forest, the 30-day mortality was 4.6% and was 7% in the subset with ischemic nephropathy,^{74,75} and we came to understand that survival correlated most strongly with postoperative renal function.^{74,75} If the decline in estimated glomerular filtration rate (eGFR) from RAS stabilized or improved after surgery, then patients demonstrated improved dialysis-free survival, independent of the impact on HTN.^{74,75}

In our experience 85% of patients with successful open repair of all hemodynamically significant renal lesions improve or are cured of HTN,^{74,75} which is much higher than for our results with stenting (see Ch. 128, Renovascular Disease: Open Surgical Treatment).^{138,139}

Endovascular Revascularization

Restenosis rates for renal artery stenting have declined over time, but in recent prospective trials were still >10%.^{129–131} BP responses vary in the literature. Multiple randomized trials comparing renal artery stenting to medical management for

atherosclerotic RAS and a meta-analysis summarizing these data,¹³² including the CORAL trial,¹³¹ have concluded that stenting provides no advantages over medical treatment alone (Fig. 127.6). However, it is worth pointing out that patient demographics in ASTRAL¹³⁰ and CORAL¹³¹ differ substantially from the average patient undergoing revascularization at our

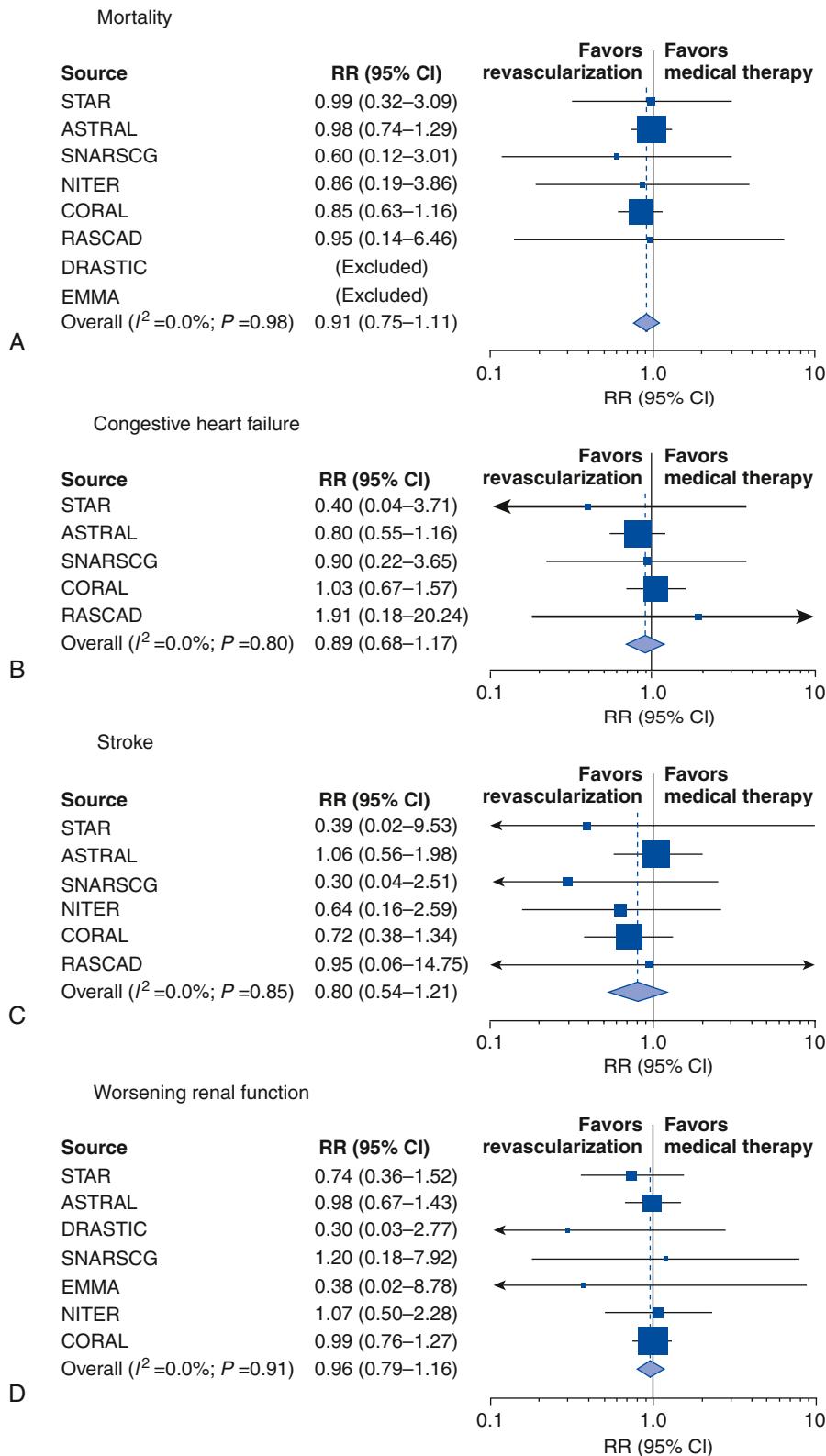


Figure 127.6 Histogram summarizing data from randomized trials of renal revascularization. (Adapted from Bavry AA, Kapadia SR, Bhatt DL, Kumbhani DJ. Renal artery revascularization: updated meta-analysis with the CORAL trial. *JAMA Intern Med.* 2014;174:1849–1851.)

center.^{74,75} For example, the baseline systolic BP in CORAL was only 150 mm Hg, and for ASTRAL mean BP was only 149/76 or 152/76 for the stent and control groups, respectively.^{130,131} The number of antihypertensive medications taken by patients to achieve these values averaged 2.1 and 2.8 in CORAL and ASTRAL, respectively. However, further analyses of the CORAL data looking specifically at subgroups with severe HTN, high grade stenosis, and CKD all failed to predict significant survival benefit or BP response from stenting.^{142,143} A low urine albumin to creatinine ratio showed early promise in predicting response, perhaps illustrating a better response with less parenchymal disease, but further large-scale evaluation of this metric is needed.^{142,143}

We therefore believe that most patients with RVD can be approached conservatively. Interventions should be reserved for those with severe disease that fails to respond to aggressive medical therapy, or patients with nonatherosclerotic RVD. When an intervention is deemed appropriate, the approach should be tailored to the patient's anatomy and clinical status with consideration to local expertise.

At Wake Forest we reserve renal artery stenting or open renal revascularization in atherosclerotic RAS for patients that have failed aggressive medical management with severe refractory HTN; those with a significant abrupt decline in eGFR without another explanation with concomitant severe HTN, particularly when RAS is bilateral; and those with hypertensive crises precipitating cardiopulmonary or neurologic embarrassment (e.g., flash pulmonary edema).^{81,102} Our threshold for recommending renal revascularization is much lower for children with severe RVD^{7,8,140} and for adults with FMD complicated by severe HTN.^{141,144}

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