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Review article

Major vascular traumas to the neck, upper limbs, and chest: Clinical presentation, diagnostic approach, and management strategies

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ABSTRACT

Major vascular traumas to the neck, upper limbs, and chest may arise from penetrating and/or blunt mechanisms, resulting in a range of clinical scenarios. Lesions to the carotid arteries may also lead to neurologic complications, such as stroke. The increasing use of invasive arterial access for diagnostic and/or interventional purposes has increased the rate of iatrogenic injuries, which usually occur in older and hospitalized patients. Bleeding control and restoration of perfusion represent the two main goals of treatment for vascular traumatic lesions. Open surgery still represents the gold standard for most lesions, although endovascular approaches have increasingly emerged as feasible and effective options, particularly for management of subclavian and aortic injuries. In addition to advanced imaging (including ultrasound, contrast-enhanced cross-sectional imaging, and arteriography) and life support measures, multidisciplinary care is required, particularly in the setting of concomitant injuries to the bones, soft tissues, or other vital organs. Modern vascular surgeons should be familiar with the whole armamentarium of open and endovascular techniques needed to manage major vascular traumas safely and promptly.

1. Introduction

Accidental trauma represents a frequent occurrence, constituting a potential cause of major disability and death [1]. Major polytraumas can be complicated by a concomitant vascular lesion in up to 4% of cases [1]; when the lesions caused by a blunt trauma and/or a penetrating trauma concern a major vessel, they may be responsible for the death of the patient during the prehospitalization phase in 75% of cases [2]. Vascular trauma remains a complex and difficult-to-treat entity, representing a formidable challenge for surgeons and patients alike. Along with increasing vascular access in hospital and community settings, there has been an increase in iatrogenic vascular injuries [3]. The anatomic sites most often involved are the lower limbs (45%), followed by the upper limbs (33%), neck and chest (12%), and abdomen and pelvis (10%) [1].

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Improvements in diagnostic skills, resuscitative approaches, and reconstructive techniques have contributed to progress in the management of these lesions [4,5]. Furthermore, the incorporation of endovascular techniques in trauma management represents a substantial advancement in the treatment algorithm, as they can serve to temporize or even definitively treat an injury [6]. In this narrative review, we provide a comprehensive overview of the etiology, clinical presentation, diagnosis, management (open and endovascular), and prognosis of major vascular traumas in the neck and thoracic outlet, upper extremity, and thoracic aorta.

2. Etiology and pathophysiology

Trauma currently represents the third leading cause of mortality in the United States, especially in people younger than 45 years; vascular injuries can encompass up to 3% of all civilian traumas and continue to be associated with high morbidity and mortality [7]. Vascular trauma is classified into different types on the basis of the mechanism of damage to the vessel, which includes penetrating or blunt injury [8]. The result of blunt or penetrating traumatic injury can include vasospasm, contusion, intimal flaps, intimal disruption or hematoma, external compression, laceration, transection, and focal wall defects with pseudoaneurysm or hemorrhage [9].

Penetrating trauma usually results in laceration or transection of the vessel without contusion [10]. In cases of complete transection, the artery may often retract and spasm with subsequent thrombosis. Conversely, when the blood vessel undergoes an incomplete transection, it may be more prone to massive bleeding. The extent of a projectile injury depends on several physical characteristics, including its velocity, mass, material, and angle of impact [11]. Blunt traumas can also differ in extent of damage to the vascular wall, from small intimal flaps to severe transmural damage with thrombosis or extravasation [12]. As a result of the high velocities that are usually involved in the situations that lead to major vascular trauma, severe injuries to soft tissues and/or bones are often concomitantly present. They lead to additional layers of technical complexity and can further worsen the functional prognosis of limbs, especially in cases of severe contamination and/or when coverage of a vascular reconstruction may be impacted by the presence of significant damage to the surrounding structures [13].

Vascular traumas that occur in civilian environments and on the battlefield are also fundamentally different. Blunt trauma is the leading cause of injury in civilians (especially from road traffic accidents and motor vehicle collisions), and military trauma is more likely to be caused by blast or gunshot [14,15]. However, the landscape of civilian vascular injuries has also been changing owing to a rise in urban violence leading to more penetrating vascular traumas [16–18]. Iatrogenic arterial injury is another pattern of vascular trauma, defined as any arterial injury sustained during an invasive diagnostic or therapeutic maneuver, and may comprise a large portion of civilian injuries, especially in older and hospitalized patients [19–21].

3. Clinical presentation and diagnosis

3.1. *Symptoms and signs*

Hemorrhage and ischemia are extremes on the clinical spectrum of major vascular trauma. In general, visual inspection may be sufficient to diagnose such vascular injuries, along with a high level of clinical suspicion based on the pattern of trauma. Nevertheless, diagnosing a vascular injury can be challenging, especially when overt external bleeding cannot be detected. Physical examination is needed to ascertain whether there is a vascular injury, assess its extent and severity, and then determine whether further imaging or immediate intervention are warranted. The signs and symptoms of vascular injury in the limbs have been described traditionally as “hard” or “soft” [4]. Hard signs include overt arterial bleeding, expanding hematoma, bruit or thrill, loss of pulse, and signs of ischemia. The classic 6 “Ps” of acute limb ischemia (ie, paresthesia, pulselessness, paralysis, pain, pallor, and poikilothermia), which can be used to diagnose damage to arteries in lower limbs, are clinically relevant for the upper limbs as well. Hard signs mandate expedited invasive treatment and soft signs usually require additional imaging for confirmation [22].

3.2. *Diagnostic tests and imaging*

The ankle-brachial index may also be useful in identifying limb ischemia. A normal ankle-brachial index ($>$ 0.90) has high sensitivity to exclude vascular injury in lower limbs [23]. If the ankle-brachial index is $<$ 0.90, further investigation is usually deemed necessary [24].

Duplex ultrasound is a noninvasive imaging modality to evaluate vasculature. It is cost-effective and widely available [25]; however, limitations of duplex ultrasound are operator-dependency and accessibility of some anatomic regions [25,26]. Duplex ultrasound has a diagnostic accuracy as high as 98% in the setting of vascular trauma in the extremities [27].

Computed tomography angiography (CTA) or magnetic resonance angiography can identify the location of injury, contrast agent extravasation, and thrombosis, while also providing useful information for surgical decision making and preoperative planning (especially when consideration is given to an endovascular intervention). CTA is usually the preferred diagnostic modality in the trauma setting, owing to its many advantages, including broad availability, quick acquisition times, and wide multiplanar reconstructions. Although the traditional dictum would be that CTA requires sufficient patient stability to allow for transport and time to complete the study, modern scanners are increasingly located in close proximity or directly adjacent to the trauma resuscitation area, and image acquisition is nearly instantaneous, thereby enabling CTA imaging in critical patients as well. The potential benefits of performing CT in unstable patients include differentiating patients who require operative intervention versus an interventional radiology procedure, and identifying patients who do not need an invasive procedure and can be spared an unnecessary major operation. Another critical decision is whether to perform a whole-body CTA scan or selective scanning based on the suspected site of injury. Ultimately, the appropriateness of CTA and its practical implementation, especially in unstable patients and/or those with unclear presentation, remains dependent on several factors that require an individualized approach based on local institutional protocols.

Angiography is still considered the gold standard for diagnosing vascular injury, especially in the extremities. However, it is an invasive examination that requires specialized equipment and skills [28]. Therefore, its role in the modern era is limited to intraoperative confirmation after open surgical repair or as an integral part of the procedure when an endovascular or hybrid approach is chosen.

4. Treatment and prognosis

Immediate bleeding control and rapid restoration of blood flow are the primary goals when managing any major vascular injury. Delay in diagnosis and treatment can be fatal to the patient or compromise limb salvage. There are many invasive treatment methods for vascular injuries, ranging from open surgery to endovascular techniques or any combination thereof (ie, hybrid repair). The mainstay of any operative repair is hemorrhage control and/or revascularization [8]. Different approaches and technical options can be used, depending on the location of the trauma: neck and thoracic outlet, upper extremity, and blunt thoracic aortic injury (BTAI).

4.1. *Neck and thoracic outlet*

Vascular trauma in the neck and thoracic outlet area may present with different patterns from hemorrhagic shock to subtle imaging findings that can develop into delayed hemispheric stroke. Carotid artery injury may result in contralateral extremity deficits, aphasia, or Horner's syndrome. Vertebral artery (VA) injuries seldom present with neurologic symptoms, which are related mainly to the posterior cerebral circulation (eg, ataxia, dizziness, or visual field deficits). Other symptoms, such as headache or periorbital pain, may also indicate trauma to the cervical vessels [29]. In cases of blunt cerebrovascular injuries, obvious neurologic signs may be absent at time of arrival and then progress to delayed deficit within the following hours or days [30]. Penetrating subclavian artery injuries can have high lethality rates, owing to severe noncompressible torso hemorrhage [31,32]. Furthermore, they are often associated with brachial plexus damage, which can cause additional significant morbidity [33,34].

Although some minor vascular injuries do not always mandate repair and can be followed with serial examination [34,35], major vascular defects invariably require prompt management, especially when they present severe local, systemic neurologic findings. In patients presenting with penetrating carotid injuries and overt neurologic symptoms or signs, it has been reported that repair will result in lower rates of stroke or death compared with vessel ligation [36]. Nonoperative management of neurologically intact patients who have sustained penetrating carotid injuries, especially if minimal, with observation and anticoagulation, has been advocated as an acceptable approach [37,38] (Fig. 1A, 1B). A recent meta-analysis of antiplatelet therapy versus anticoagulation therapy for carotid dissection did not find any significant differences in stroke rates or bleeding complications when comparing the two regimens [39]. Current recommendations state that antithrombotic therapy is recommended for patients with grade I to IV blunt cerebrovascular injuries

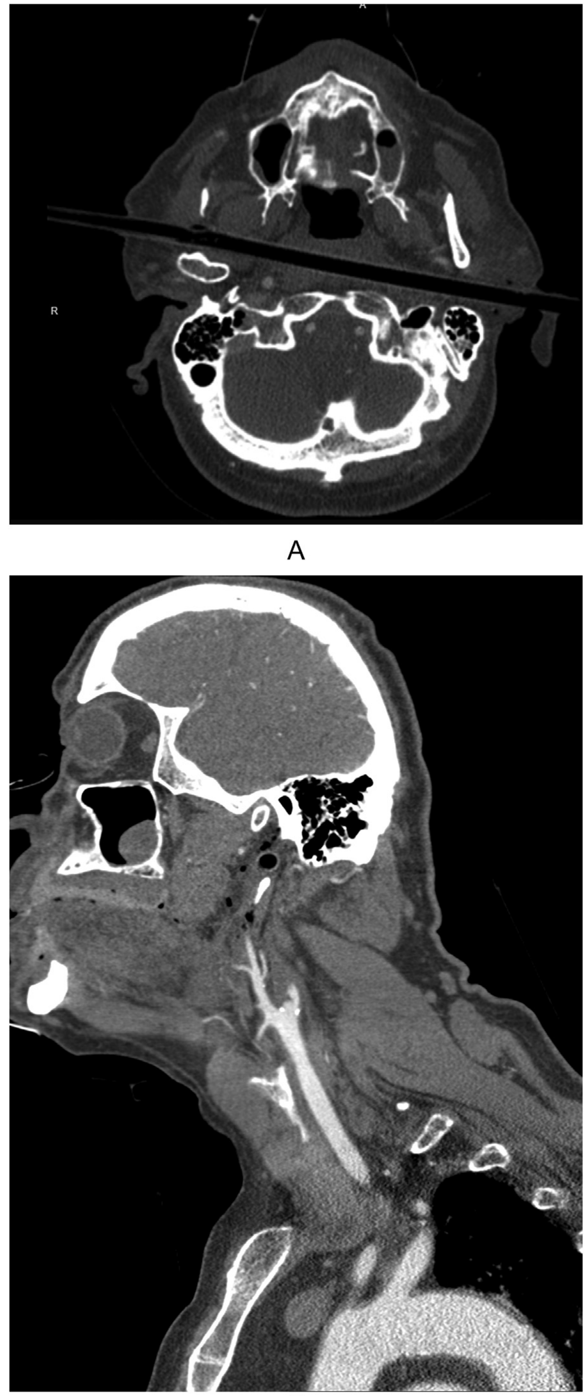

Fig. 1 – Axial computed tomography angiography (CTA) slice showing penetrating through-and-through injury in zone II of the neck. (B) Sagittal CTA slice showing complete thrombosis of the left internal carotid artery.

and grade V injuries should undergo surgical repair, if feasible [40,41].

Three zones of the neck have been classically described, according to bony landmarks [42,43]. The traumas that are more easily accessible are those in zone 2; those that are located in zone 1 generally require a median sternotomy and those in zone 3 are preferably dealt with using endovascular techniques, owing to the challenging surgical exposure. Intraluminal temporary vascular shunts can be placed to allow for temporary antegrade flow and delay the time to definitive repair where other concomitant injuries require more immediate attention. The modality of definitive repair is dictated by the location, type, and extent of injury. Lesions of the external carotid artery can usually be managed by means of ligation or with embolization. Conversely, lesions of the common carotid artery or internal carotid artery will most often require reconstruction. Primary repair or patch angioplasty is possible if the injury is anatomically simple, but more complex reconstructions (including end to end anastomosis and interposition graft or bypass graft) are required when the defect is more extensive. Use of the greater saphenous vein is generally recommended, especially if aerodigestive tract injuries are also present; however, if overt or suspected contamination is not associated, prosthetic grafts may be contemplated, especially for larger vessels. If a stent-graft is used in this setting, the main concern is the unavailability of cerebral protection systems (as used during carotid artery stenting). On rare occasions, ligation may be necessary, although this maneuver has a high risk of stroke [44,45]. The VA is classically divided into four anatomic segments and terminates at the level of the foramen magnum, where it joins with the contralateral vessel to form the basilar artery. Management of VA injuries depends on which anatomic segment is injured, the neurologic status of the patient, and the condition of the contralateral posterior circulation. Given the paucity of high-quality data on the subject, treatment of VA injuries is usually inferred from what has been recommended for the carotid territory. For most penetrating or blunt injuries, regardless of the above-mentioned considerations, ligation or nonoperative management are the most appropriate courses of action. Antithrombotic therapy, with either antiplatelet or anticoagulant drugs, can all be appropriate choices based on underlying extent of defect and status of collateral flow.

Penetrating traumas to the subclavian artery (SCA) (Fig. 2A and 2B) are frequently associated with hemodynamic instability, and temporizing measures (such as resuscitative thoracotomy or balloon tamponade) may be required. Median sternotomy or a supraclavicular incision may be the needed surgical approach depending on the site of vessel injury, with access to the proximal left SCA invariably requiring an intrathoracic approach. For simpler defects, primary repair may be feasible, although in most cases an interposition graft will be required; in these circumstances, prosthetic grafts are usually the first-line conduits, and the greater saphenous vein is usually employed when there is gross contamination (owing to poorer size match with the SCA). When more extensive repair is required and/or the patient is too unstable, ligation can be performed with delayed reconstruction. Endovascular repair of proximal SCA injuries has been performed with increasing frequency over the last years with excellent technical success [46,47]. It can be used as definitive treatment or as a bridge to destination therapy (Fig. 3). The procedures can be performed in conjunction via antegrade/femoral access by means of an ipsilateral retrograde/brachial approach, sometimes after establishment of a through-and-through guide-wire platform. Choosing the most appropriate type of stent (self-expanding *v* balloon-expandable) needs to take into consideration several factors, including the diameter of the SCA, zone of injury and its joint-related mobility, and need for precise positioning. A covered stent rather than a bare-metal stent is usually the preferred option and the only one that can be applied in case of active hemorrhage. If coverage of the ipsilateral VA is necessary, patency of the contralateral vessel should be documented; a VA transposition may be performed at a later stage, if required [48]. Endovascular management of SCA injuries is highly attractive due to its lower invasiveness, but long-term durability remains to be seen [49].

4.2. *Upper extremity*

Severe vascular injury to the upper extremity may result from a wide range of civilian and combat casualties; amputation and mortality associated with upper extremity vascular trauma are rare but not-negligible events [50,51]. Orthopedic and soft-tissue injuries can be present concomitantly with upper extremity vascular injuries; long-bone fractures usually should be brought to length first with temporary fixation. Indeed, when vascular and orthopedic injuries occur together, in most cases wound concerns require external fixation of the fracture with permanent internal fixation kept as an option if needed once other aspects of injury are optimized. Temporary intraluminal shunts can be considered as a temporizing measure before placement of external orthopedic fixation devices when perfusion to the limb is severely compromised [52]. This strategy or sequence allows for expedited perfusion to the extremity, a more thoughtful fixation and an easier platform for definitive arterial and/or venous reconstruction. Debridement of all devitalized tissues should always be pursued and, in extreme situations, primary amputation may be required [53]. At the end of the vascular reconstruction, orthopedic surgeons should be actively engaged in any repositioning of the limb to avoid excessive traction on the anastomoses. Immediate decision making for the best operative treatment in case of severe injury to the upper extremity may represent a challenging endeavor. Scoring systems have been developed to assist in decision making, such as the Mangled Extremity Severity Score, Mangled Extremity Syndrome Index, Predictive Salvage Index, and Limb Salvage Index [24,54]. Only the Mangled Extremity Syndrome Index has been proposed to evaluate mangled upper extremities, but the Mangled Extremity Severity Score has also been applied retrospectively in this setting [54,55].

Treatment of arterial lesions may be differentiated on the basis of anatomic location, extent of damage, and clinical status. Isolated injuries to the axillary artery do not often cause hemodynamic instability. Because of the rich collateral network of the upper limb, development of critical ischemia of the upper extremity is often precluded [56]. Primary end to end repair can be performed, but more extensive injuries usually mandate interposition or bypass grafting. Use of an autologous vein is a suitable option, especially if gross contam-

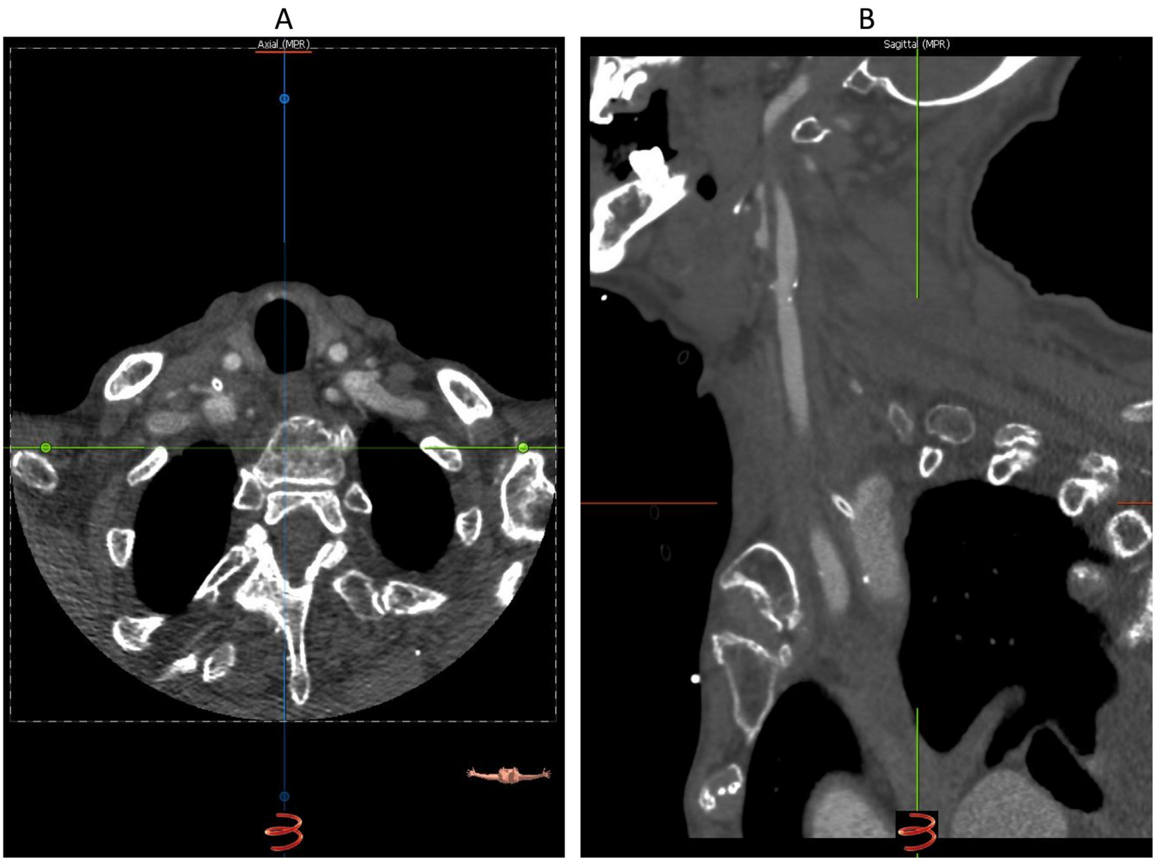

Fig. 2 – Computed tomography angiography of the neck in axial window (A) and in sagittal slice (B) with evidence of right subclavian artery central line, resulting in iatrogenic injury.

Fig. 3 – Intraoperative completion angiography through retrograde, ipsilateral brachial access demonstrates successful endovascular exclusion of the iatrogenic right subclavian injury with a covered stent graft (asterisk: proximal edge; arrow: distal edge). The nondominant vertebral artery was covered without neurologic consequence.

ination is present, and the brachial/basilic veins may be favored, as they can be accessed within the already prepared surgical field; alternatively, the greater saphenous vein may be harvested for reconstruction. Prosthetic grafts can be used if significant contamination is not encountered, and they come with some advantages, including prompt availability and uniform sizes. An endovascular approach can sometimes be implemented, although the axillary artery is highly mobile and this may predispose to increased rates of stent-related complications during follow-up [47,57].

In patients with brachial artery injury, the severity of ensuing ischemia will depend largely on whether the location of trauma was proximal or distal to the takeoff of the deep brachial artery. Some associated findings, such as a supracondylar fracture or elbow dislocation, increase the likelihood of a brachial artery injury [58]. In case of active bleeding, proximal control can be achieved by means of direct manual compression of the brachial artery against the humerus, but tourniquets can also be used. The type of repair will be selected according to the degree of anatomic derangement and may range from end to end anastomosis to bypass grafting. Endovascular interventions for brachial artery injury have also been reported, although the long-term results of this approach are unknown [59].

More distal lesions in the upper extremity that are limited to the radial/ulnar artery will typically result in less severe clinical scenarios. Typically, bleeding from the forearm can be effectively controlled with direct manual pressure. The management of arterial injury in the forearm is determined on the basis of the quality of Doppler signals at the wrist and hand. Indeed, if a robust triphasic arterial signal is detected in the palmar arch while the injured vessel is being held occluded, ligation of the artery can be performed reasonably. Conversely, if the hand presents with severe ischemia, then at least one of the two forearm arteries should be reconstructed. Primary repair with end to end anastomosis is feasible for simpler lesions, but in case of significant damage, an interposition vein graft is typically required [60].

Negative pressure wound therapy can be beneficial when primary skin closure is not feasible. Vascular repairs should always be covered with viable soft tissues to prevent contact with the vacuum dressing sponge and possible damage to the anastomosis [61,62]. Although less commonly observed in the upper extremity, compartment syndrome can still occur and may warrant fasciotomy, which should be carried out in a thoughtful fashion to release all of the compartments of the arm and/or hand. Finally, if severe peripheral neurologic damage is present, neurosurgical consultation may be required to allow for nerve repair.

4.3. BTAI

BTAI represents one of the most devastating scenarios of vascular trauma and is a significant cause of mortality in polytraumatized patients. Imaging-based classification schemes have been reported, with the aim of helping physicians tailor decision making on the basis of the individual patient's anatomy. Minimal aortic injury, defined as a small intimal flap with no periaortic hematoma, occurs in approximately 10% of BTAI cases [63]. More commonly, BTAI is classified according to the system proposed by Azizzadeh et al [64] from grade I to grade IV, where grade I injuries correspond to minimal aortic injury. It has also been suggested that small false aneurysms have similarly low risks of rupture [65]. Expedited treatment of grade IV injuries is usually recommended, and delayed treatment of grade III and stable grade II lesions is generally advocated. The management of grade I injuries or minimal aortic injury is still debated, as the long-term natural history of these injuries is unknown and they should be closely observed when a decision is made for nonoperative management.

The management of BTAIs (Fig. 4A) has witnessed a paradigm shift over the last decades that has led to a significant decrease in early mortality and morbidity [66]. Most BTAIs result from motor vehicle collisions, fall from height, and auto versus pedestrian accidents [67]. The overall incidence of BTAI may be higher than the actual number of injuries that occur, as many patients with this type of injury may not, in fact, reach a health care facility alive [67].

The most common location of BTAI is the inner aspect of the distal aortic arch, immediately beyond the origin of the left SCA, at the level of the aortic isthmus or immediately nearby [67]. Use of CTA scan (with electrocardiography gating if readily available) as the primary imaging modality for BTAI is currently endorsed when a high level of clinical suspicion is present [68–70]. Indeed, CTA might not only achieve excellent diagnostic accuracy rates, but also allow for precise anatomic measurements that are mandatory before endovascular repair. Transesophageal echocardiography is another diagnostic modality in the evaluation of suspected BTAI [71,72], but it has failed to gain traction due to concerns surrounding its reliability and availability [73].

The risk of free rupture is highest in the first few hours after the injury, and strict blood pressure control is mandatory to lower this risk [74]. Systolic blood pressure should be maintained within 90 to 110 mm Hg, although in patients with concomitant brain or spine injury, slightly higher levels may be acceptable in order to lower the danger of further neurologic damage [75,76]. The optimal time from injury to repair is still debated and should be individualized on the basis of several confounders, such as the characteristics of the lesion and its clinical presentations, but also the conditions of the patient and considering the potential presence of other associated major injuries that may pose more immediate threats to life.

Open surgical repair has for many decades been the gold standard treatment for BTAI [77]. The clamp-and-sew technique was initially performed without distal aortic perfusion, but often resulted in postoperative paraplegia, especially with cross-clamp times longer than 30 minutes. More recently, the adoption of roller or centrifugal pumps to provide distal aortic perfusion has been introduced to lower the risk of spinal cord injury [78,79]. The most common configuration is the partial left heart bypass, with the inflow cannula placed within the left atrium and the outflow cannula is placed in the femoral artery or descending thoracic aorta distally to the clamp. Interposition graft reconstruction is usually required and intercostal arteries in proximity of the aortic lesion are preferentially not ligated or oversewn but incorporated into the repair.

Thoracic endovascular aortic repair for BTAI has become, over time, the first-line option for most patients with BTAI, mainly owing to its reduced invasiveness and better immediate outcomes (Fig. 4B, 4C), as reported in several systematic reviews and meta-analyses [80,81]. In fact, clinical practice guidelines from the Society for Vascular Surgery currently endorse thoracic endovascular aortic repair over open repair for patients with grade 2 to 4 BTAIs, and medical management is only suggested for grade 1 injuries [82].

Proper sizing of the aortic endograft is the cornerstone and usually the oversizing will be in the range of 10% to 20%; poor oversizing may result in endoleaks and excessive oversizing may cause infolding of the device [83]. Due to the often compromised hemodynamic status of the patient, achieving optimal sizing can sometimes be challenging; the use of intravascular ultrasound may aid in this scenario to achieve better delineation of the aortic size. The anatomy of the aorta, especially the angulation of the aortic arch, can result in poor stent-graft apposition, especially in the inner curvature [84].

When required to avoid risk of a Type 1a endoleak, coverage of the left SCA ostium should be performed in the emergency setting to obtain a safe proximal landing zone. Although most patients will not have severe symptoms after left sinoatrial sacrifice, some may develop ischemic symptoms and require staged revascularization with a carotid–subclavian bypass or transposition [85,86]. Concomitant left sinoatrial revascularization at the time of index thoracic endovascular aortic repair may also be warranted under select circumstances (such as ipsilateral dominant VA, functioning ipsilateral hemodialy-

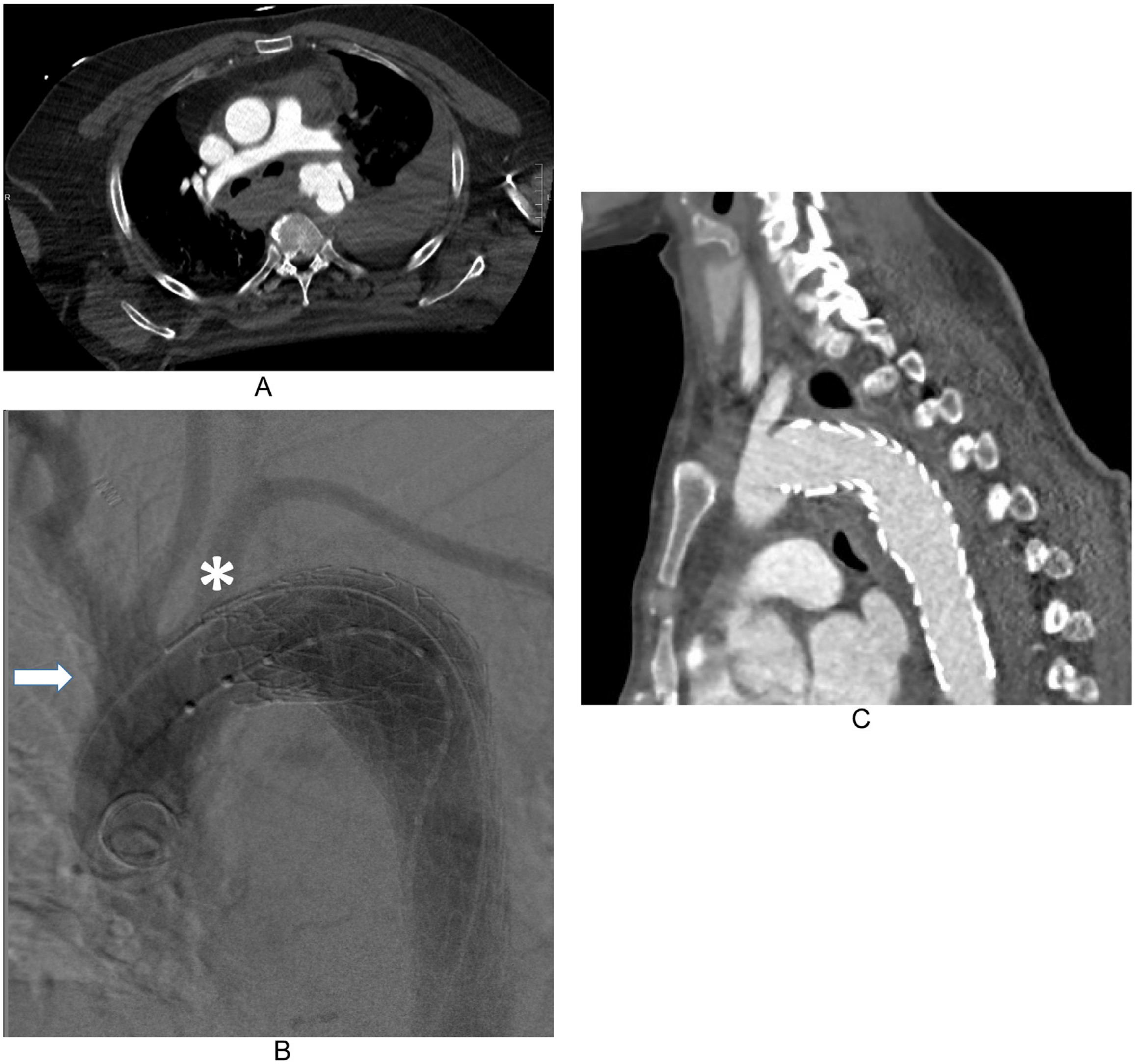

Fig. 4 – (A) Computed tomography angiography (CTA) chest with grade 3/4 blunt thoracic aortic injury (BTAI) with left hemothorax after high-speed mechanism. (B) Completion aortography with zone 3 thoracic endovascular aortic repair without evidence of endoleak. (C) Postoperative CTA chest at 6 months without evidence of endoleak and continued exclusion of BTAI.

sis access, or patent coronary grafts from the ipsilateral mammary artery), and can be achieved surgically or with adjunctive endovascular techniques, such as chimney grafts or in situ fenestration [87–90]. Future advances with the use of off-the-shelf branched grafts may obviate the need for these maneuvers, but further evidence is needed [91,92].

5. Conclusions

Major vascular traumas to the neck, upper limbs, and chest may arise from penetrating and/or blunt mechanisms and may range in severity from minor clinical scenarios to life-threatening and/or limb-threatening hemorrhagic or ischemic conditions. Immediate bleeding control and prompt restoration of perfusion represent the two main goals of care for vascular traumatic lesions. Open surgery still represents the gold standard for most lesions, although endovascular approaches have increasingly emerged as feasible and effective options, particularly for management of subclavian and aortic injuries. Modern vascular surgeons should be familiar with the whole armamentarium of open and endovascular techniques needed to manage major vascular trauma safely and promptly.

Declaration of Competing Interest

None of the Authors have competing conflicts of interest to disclose that may be pertinent to this work.

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