Management of Vascular Injury: A Comprehensive Review of Current Concepts and Advances

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ABSTRACT

INTRODUCTION

Vascular injury is among the most time-critical emergencies in trauma surgery. Despite representing only 1 to 3% of civilian trauma admissions, it carries a disproportionate burden of mortality and permanent disability, with hemorrhage remaining the leading preventable cause of early trauma death.

This review critically evaluates current evidence for the diagnosis and management of vascular injuries across anatomical regions, appraises open and endovascular strategies, and identifies ongoing controversies and evidence gaps in contemporary practice.

MATERIAL AND METHODS

A narrative review of published literature was performed using MEDLINE, Embase, and the Cochrane Library. Priority was given to prospective studies, multicenter registries, systematic reviews, and current clinical practice guidelines published between 2000 and 2024. Landmark historical studies were included where they defined foundational practice.

RESULTS

Advances in damage-control resuscitation, CT angiography, endovascular technology, hybrid operating rooms, and resuscitative endovascular balloon occlusion of the aorta (REBOA) have substantially improved outcomes. However, evidence for several management decisions remains largely observational. Open repair retains primacy for most peripheral arterial injuries, while thoracic endovascular aortic repair (TEVAR) has supplanted open surgery for blunt thoracic aortic injury in hemodynamically stable patients. Critical appraisal reveals important controversies regarding REBOA deployment, optimal conduit selection, venous injury management, and the role of endovascular therapy in resource-limited settings.

CONCLUSION

Prompt recognition, multidisciplinary coordination, and individualized selection of open or endovascular repair remain the cornerstones of vascular trauma management. Future progress depends on high-quality prospective registries, standardized outcome reporting, and equitable access to endovascular technology.

KEYWORDS

Vascular njury, Trauma, Endovascular therapy, Damage-control surgery, REBOA

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INTRODUCTION

Vascular injury is an infrequent but potentially lethal consequence of trauma. Population-based data indicate it occurs in 1 to 3% of civilian trauma admissions, yet it accounts for a far greater share of preventable trauma deaths because uncontrolled hemorrhage kills rapidly.[1,2] Extremity injuries predominate, comprising 50 to 70% of all vascular trauma cases in most civilian series, whereas truncal and cervical injuries carry higher case fatality rates.[3]

The historical evolution of vascular trauma care is instructive. During the First and Second World Wars, arterial ligation was standard, and amputation rates exceeded 50% for major extremity arterial injuries. The Korean War saw a paradigm shift: arterial repair by Hughes and colleagues reduced the amputation rate to approximately 13%, demonstrating that restoration of flow rather than ligation was achievable in a combat setting.[4] The Vietnam conflict further refined temporary shunting and fasciotomy, and the ensuing decades brought prosthetic and autologous conduits, microsurgical anastomosis, and eventually endovascular options.[5]

The contemporary management landscape is shaped by three intersecting forces: the wider adoption of endovascular technology, the formalization of damage-control surgery and resuscitation principles, and the growth of multicenter trauma registries that have begun to generate comparative outcome data. However, many management decisions in vascular trauma are still guided by retrospective single-center series, expert consensus, or from elective vascular surgery, rather than by randomized controlled trials.[6,7]

This review aims to provide a critical, evidence-based appraisal of current practice in vascular trauma management. It covers epidemiology, pathophysiology, diagnostic evaluation, damage-control strategies, open and endovascular techniques, region-specific considerations, and emerging technologies. Where evidence is robust, recommendations are clearly stated; where it is limited or conflicting, controversies are explicitly identified.

EPIDEMIOLOGY AND MECHANISMS OF INJURY

The global burden of vascular trauma varies markedly by geography, conflict status, and socioeconomic context. In high-income civilian settings, penetrating mechanisms account for 30 to 70% of vascular injuries depending on the urban environment, while blunt trauma from road traffic collisions, falls, and industrial accidents predominates in many regions.[8] The American Association for the Surgery of Trauma Prospective Observational Vascular Injury Treatment (PROOVIT) registry, which enrolled over 1,000 patients across 14 US trauma centers, reported that the superficial femoral, popliteal, and brachial arteries were the most frequently injured vessels in civilian practice.[7]

Military vascular injuries differ substantially from their civilian counterparts. Data from Operations Iraqi Freedom and Enduring Freedom showed that blast and high-velocity gunshot wounds predominated, vascular injury rates among combat casualties were 12 to 15 times higher than historical conflicts, and associated soft tissue, bony, and nerve injuries were far more complex.[9] The Joint Theatre Trauma Registry documented that 70% of combat fatalities occurred before hospital arrival, with hemorrhage responsible for the majority of potentially preventable deaths, a finding that directly drove the development of tourniquet protocols and prehospital transfusion programmes.[10]

Iatrogenic vascular injuries deserve specific attention because their incidence is rising in parallel with the expansion of endovascular, cardiac, orthopedic, and laparoscopic procedures. The femoral artery at the common femoral access site is most frequently affected. A systematic review by Tsetis reported that access-site complications including pseudoaneurysm, arteriovenous fistula, thrombosis, and retroperitoneal hematoma occur in 0.5 to 9% of arterial catheterizations, with rates varying by sheath size, anticoagulation intensity, and operator experience.[11]

Outcomes in vascular trauma are sensitive to ischemia time. Muscle tolerates warm ischemia for approximately 4 to 6 hours before irreversible damage occurs, though nerves are injured sooner. Perkins et al. demonstrated in a systematic review of 2,395 patients that ischemia time exceeding 6 hours was independently associated with a significantly increased amputation rate (OR 3.1, 95% CI 1.9 to 5.1), underscoring the importance of rapid diagnosis and definitive revascularisation.[12]

CLASSIFICATION OF VASCULAR INJURIES

A standardized classification system is necessary for consistent communication, treatment planning, and inter-institutional outcome comparison. Vascular injuries are categorized by vessel type (arterial, venous, or combined), anatomical location, wounding mechanism, and pathological morphology. The pathological types encountered in clinical practice include intimal tear, intramural hematoma, arterial thrombosis, partial laceration, complete transection, segmental vessel loss, pseudoaneurysm, arteriovenous fistula, vessel spasm, and dissection. Each pattern has distinct hemodynamic consequences and implications for repair strategy.

The American Association for the Surgery of Trauma (AAST) Organ Injury Scale provides a standardized grading system for major vascular structures. Moore et al. originally described this scale to facilitate multicenter outcome comparisons, and subsequent revisions have extended grading to the thoracic aorta, abdominal aorta, inferior vena cava, and major named visceral vessels.[13] Blunt cerebrovascular injuries are graded using the Biffl scale, which stratifies carotid and vertebral artery injuries into five grades based on CT angiographic morphology and correlates grades with stroke risk and treatment response.[14]

A practical distinction of clinical importance is the differentiation between hard and soft signs of vascular injury. Hard signs include pulsatile or uncontrolled hemorrhage, rapidly expanding hematoma, absent distal pulses, palpable thrill, or audible bruit, and signs of acute limb ischemia (pallor, paresthesia, paralysis, pain, and pulselessness). Their presence mandates immediate operative intervention without further imaging in an unstable patient. Soft signs such as a history of arterial hemorrhage at the scene, a non-expanding hematoma, neurological deficit, and proximity of a wound to a major vessel warrant imaging evaluation, typically CT angiography.[2]

PATHOPHYSIOLOGY

The systemic consequences of vascular injury are driven by four interacting processes: hemorrhage and hemodynamic shock, tissue ischemia and reperfusion injury, coagulopathy, and the systemic inflammatory response. Their interaction creates self-reinforcing cycles that rapidly become lethal if not interrupted.

Severe hemorrhage triggers hemorrhagic shock, which exists along a continuum from compensated tachycardia to cardiovascular collapse. Cannon et al. described the lethal triad of hypothermia, acidosis, and coagulopathy as the central pathophysiological mechanism of death in major haemorrhage.[15] Hypothermia impairs platelet function and coagulation factor activity; acidosis compounds coagulopathy and myocardial depression; and trauma-induced coagulopathy, now recognized as an endogenous acute coagulopathy rather than simply a dilutional or consumptive process, further amplifies bleeding through hyperfibrinolysis and thrombin generation dysregulation.[16]

Tissue ischemia below the level of vascular injury causes progressive cellular dysfunction through depletion of ATP, intracellular calcium accumulation, and cell membrane failure. Skeletal muscle is relatively ischemia-tolerant for 4 to 6 hours of warm ischemia, but peripheral nerves sustain functional injury within 1 to 2 hours, which explains the clinical observation that sensorimotor deficits often persist despite successful revascularisation.[17] Reperfusion after prolonged ischemia paradoxically accelerates injury through generation of reactive oxygen species, neutrophil activation, and release of xanthine oxidase-derived free radicals. At the systemic level, reperfusion of a large ischemic muscle mass can cause acute kidney injury, acute respiratory distress syndrome, and multi-organ dysfunction, particularly when combined with pre-existing hemorrhagic shock.[18]

Compartment syndrome is a direct mechanical consequence of reperfusion oedema in a closed fascial space. Intra-compartmental pressures exceeding 30 mmHg, or within 30 mmHg of diastolic blood pressure, are generally accepted thresholds for fasciotomy, though clinical judgement is essential.[19]

INITIAL ASSESSMENT AND DAMAGE-CONTROL RESUSCITATION

Initial assessment follows the principles of Advanced Trauma Life Support (ATLS), prioritizing airway, breathing, and circulation. External hemorrhage is controlled with direct pressure, wound packing, and tourniquet application. The Committee on Tactical Combat Casualty Care demonstrated that early tourniquet use in the pre-hospital setting reduced hemorrhage-related deaths among combat casualties with extremity injuries, a finding subsequently incorporated into civilian prehospital protocols.[20]

Damage-control resuscitation (DCR) is now the standard of care for patients with major hemorrhage. Its principles, derived from data from the major trauma centers in the US and UK, include permissive hypotension targeting a systolic pressure of 80 to 90 mmHg in penetrating torso injury (avoiding aggressive fluid resuscitation that dilutes clotting factors and propagates coagulopathy), early balanced blood product administration in a 1:1:1 ratio of packed red blood cells, fresh frozen plasma, and platelets, and early administration of tranexamic acid.[21] The CRASH-2 trial, enrolling over 20,000 trauma patients across 40 countries, demonstrated that tranexamic acid administered within 3 hours of injury significantly reduced all-cause mortality and death due to bleeding, with the benefit greatest when given within 1 hour.[22] The PROPPR trial, a randomized controlled trial of 680 patients with major hemorrhage, confirmed that a 1:1:1 transfusion ratio compared with 1:1:2 reduced 24-hour mortality and improved hemostasis, providing level I evidence for balanced resuscitation.[23]

Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) has emerged as an adjunct for temporary hemorrhage control in patients with non-compressible torso hemorrhage not amenable to external compression. A catheter-mounted balloon is deployed in the aorta, most commonly Zone I (descending thoracic aorta) for abdominal or pelvic hemorrhage, or Zone III (infrarenal aorta) for pelvic hemorrhage. Morrison et al. reported in a systematic review of 130 patients that REBOA achieved hemorrhage control and increased proximal arterial pressure in the majority of cases.[24] However, the evidence base remains predominantly retrospective. The AAST AORTA (Aortic Occlusion for Resuscitation in Trauma and Acute Care Surgery) registry, the largest prospective comparative dataset, reported that REBOA was associated with lower in-hospital mortality compared with resuscitative thoracotomy

(30% vs 56%) in abdominal and pelvic injury, though patient selection differences limit causal inference.[25] Concerns persist regarding distal ischemia from prolonged balloon inflation, access-site complications, and the learning curve required for safe deployment. Ongoing randomized trials, including the UK REBOA Trial, are expected to provide higher-quality evidence.

CLINICAL DIAGNOSIS

Clinical assessment remains the cornerstone of vascular injury diagnosis. A focused history should establish the mechanism, time of injury, estimated blood loss, and pre-injury anticoagulant use. Physical examination assesses for hard and soft signs as outlined above.

The ankle-brachial index (ABI) is a simple, non-invasive bedside test. An ABI of 0.9 or greater reliably excludes significant arterial injury with a negative predictive value exceeding 99% in most series, and has become standard practice to triage patients with proximity injuries or soft signs toward or away from further vascular imaging.[26] An ABI below 0.9 mandates CT angiography or formal angiography.

Neurological assessment is essential because peripheral nerve injuries frequently accompany vascular trauma and have independent prognostic significance for functional recovery. The presence of foot drop after popliteal artery injury, for example, is a stronger predictor of long-term disability than the vascular outcome alone.

IMAGING MODALITIES

CT angiography (CTA) has become the diagnostic standard for hemodynamically stable patients with suspected vascular injury. Published sensitivity and specificity exceed 95% across multiple prospective studies.[27] Its principal advantages are speed, wide availability, multiplanar reconstruction capability, and simultaneous assessment of associated skeletal and visceral injuries. Modern 64-slice and dual-energy CT scanners have further improved spatial resolution and reduced acquisition time. CTA has largely supplanted formal diagnostic angiography for evaluation purposes, reserving the latter for simultaneous therapeutic intervention.

Duplex ultrasonography is valuable for evaluating peripheral arterial injuries, pseudoaneurysms, arteriovenous fistulae, and postoperative graft surveillance. Its limitations include operator dependency, reduced accuracy in obese patients or deep anatomical locations such as the subclavian and iliac vessels, and inability to adequately assess the thoracic aorta or intracranial vessels.

Digital subtraction angiography (DSA) remains the reference standard for detailed vascular imaging and affords simultaneous therapeutic intervention including embolization, balloon tamponade, and covered stent placement. In contemporary practice, DSA is most often employed when endovascular treatment is anticipated rather than purely for diagnosis.

Point-of-care ultrasound (POCUS) has an evolving role in the emergency assessment of vascular injury, particularly for detecting hemopericardium, hemoperitoneum, and pneumothorax during the primary survey. Focused cardiac ultrasound can rapidly identify tamponade in penetrating thoracic trauma. However, POCUS does not replace CTA for definitive vascular injury characterization.

OPEN SURGICAL MANAGEMENT

Open surgical repair remains the standard of care for most peripheral arterial injuries and for hemodynamically unstable patients with truncal vascular trauma. The fundamental operative principles are proximal and distal vascular control before entering the hematoma, systemic anticoagulation with heparin where hemorrhage risk permits, meticulous debridement of devitalized vessel wall, tension-free anastomosis or interposition, and confirmation of distal perfusion by completion angiography or intraoperative Doppler assessment.

Repair technique selection is guided by injury morphology and vessel caliber. Lateral arteriography is appropriate for small partial lacerations not exceeding 50% of the vessel circumference, beyond which patch repair or resection is preferred to avoid luminal stenosis. Primary end-to-end anastomosis is feasible only when vessel mobilization permits a completely tension-free repair, typically when segmental loss is less than 2 cm. Interposition using the reversed great saphenous vein graft is the conduit of choice for most peripheral arterial reconstructions: it is infection-resistant, size-matched to most extremity vessels, and durable.[28] A meta-analysis by Vertrees et al., examining outcomes in the PROOVIT registry, found that autologous vein grafts had significantly lower rates of graft failure and amputation compared with prosthetic conduits in contaminated or soft-tissue-deficient wounds.[29]

Prosthetic grafts (polytetrafluoroethylene or Dacron) are acceptable for large-caliber reconstructions such as the iliac or femoral vessels in clean, well-vascularized fields, and when autologous vein is unavailable due to injury or previous harvest. However, prosthetic graft infection in a contaminated traumatic wound carries a high rate of anastomotic disruption and limb loss, and their use in grossly contaminated fields should be avoided where possible.

Temporary intraluminal vascular shunting (TIVS) is a critical damage-control adjunct. A shunt (typically an Argyle, Javid, or improvised intravenous tubing) is placed across the injured vessel to restore distal perfusion while the patient undergoes resuscitation, fracture stabilization, or evacuation before definitive repair. Rasmussen et al. reported in a series from the Iraq conflict that TIVS maintained limb viability for a mean of 10.5 hours without systemic anticoagulation, with a limb salvage rate of 86%, demonstrating its value as a bridge to definitive repair under austere or damage-control conditions.[30]

Fasciotomy should be performed liberally and is mandatory in patients with prolonged ischemia (generally exceeding 4 to 6 hours), combined arterial and venous injury, crush mechanism, significant soft-tissue swelling, or any clinical evidence of compartment syndrome. A complete four-compartment lower-leg fasciotomy through two incisions is the standard technique; single-incision fibulectomy fasciotomy is an alternative but does not achieve equivalent decompression of all compartments.[19] Delayed fasciotomy carries substantially higher morbidity than prophylactic fasciotomy in high-risk situations.

ENDOVASCULAR MANAGEMENT

Endovascular techniques have expanded the therapeutic armamentarium for vascular trauma, particularly in anatomically challenging locations, hemodynamically stable patients, and elderly patients with significant comorbidity who carry high open operative risk. Available techniques include covered stent grafts, bare-metal stents, balloon tamponade, transcatheter embolization with coils or vascular plugs, thrombin injection for pseudoaneurysm, and catheter-directed thrombolysis.

The evidence base for endovascular vascular trauma management is dominated by retrospective series and registry data. Branco et al., in an analysis of 8,631 vascular injuries from the National Trauma Data Bank, reported that endovascular management increased from 4% to 18% of cases over a 10-year period, with shorter operative time and lower intraoperative blood loss compared with open repair.[31] However, endovascular repair was associated with higher rates of late reintervention, a finding replicated in other series and of particular relevance given that young trauma patients may live with their repairs for decades.

Specific indications where endovascular therapy has demonstrated clear advantage include blunt thoracic aortic injury (discussed below), subclavian and proximal axillary artery injuries where open exposure requires morbid thoracotomy or clavicular division, pelvic arterial hemorrhage, carotid and vertebral artery injuries in anatomically inaccessible zones, and traumatic pseudoaneurysms of visceral vessels amenable to embolization or stenting.[32]

Limitations of endovascular repair in the trauma context include the requirement for a hybrid or endovascular-capable operating suite, the need for adequate arterial access (compromised in shock or small-caliber vessels), the inability to address associated venous injury or soft-tissue contamination, and the need for long-term surveillance with CT angiography. In low- and middle-income settings, the technology, consumables, and specialist expertise required are frequently unavailable, and open surgery remains the only feasible option for the majority of patients.

HYBRID APPROACHES

Hybrid procedures combine open surgical exposure and endovascular intervention within a single operative episode, either sequentially or simultaneously. The hybrid operating room, equipped with fixed high-resolution fluoroscopy or a mobile C-arm, enables intraoperative angiography, balloon occlusion, and endovascular repair without patient transfer. This is particularly advantageous for injuries involving the subclavian-axillary junction, the thoracic outlet, the iliac bifurcation, and complex pelvic vascular injuries where proximal control by open surgery and distal or intraluminal repair by endovascular means are complementary.

Avaro et al. and subsequent series have demonstrated that hybrid strategies can reduce intraoperative hemorrhage, operative time, and need for extensive dissection compared with fully open approaches for selected injuries, while preserving the ability to address associated skeletal and soft-tissue injuries in the same anaesthetic.[33] Nevertheless, hybrid operating rooms represent a significant infrastructure investment and are not universally available even in high-income trauma centers.

REGION-SPECIFIC MANAGEMENT

Cervical Vascular Injuries

Cervical vascular injuries are classified into three anatomical zones. Zone I extends from the clavicles to the cricoid cartilage and encompasses the proximal common carotid and vertebral artery origins; Zone II spans the cricoid to the angle of the mandible; and Zone III extends from the mandibular angle to the skull base. This classification has direct operative implications: Zone II injuries are generally accessible to open surgical exploration, whereas Zone I and III injuries involve anatomically difficult access and are preferentially managed by endovascular means when feasible.

Carotid artery repair is preferred over ligation when the patient is neurologically intact or has a mild deficit, because ligation carries a stroke risk exceeding 30% in some series, while repair is associated with neurological improvement or stability in the majority of patients.[34] In neurologically devastated patients with a completed stroke on CT imaging, repair may worsen outcome by converting an ischemic infarct into a hemorrhagic one through reperfusion, and ligation or observation may be appropriate. Blunt carotid and vertebral artery injuries (BCVIs) are identified by CTA and graded by the Biffl scale; Grade I and II injuries are typically managed with antiplatelet therapy or anticoagulation, while Grade III and above (pseudoaneurysm or occlusion) may require endovascular stenting, particularly for vertebral injuries where surgical access is prohibitive.[14]

Thoracic Vascular Injuries
Blunt thoracic aortic injury (BTAI) is the most lethal form of blunt vascular trauma, with a prehospital mortality approaching 80%. Survivors who reach hospital typically have Grade III injuries (pseudoaneurysm contained by adventitia) at the aortic isthmus, the site of maximal shear stress during rapid deceleration. Thoracic endovascular aortic repair (TEVAR) has become the preferred treatment for hemodynamically stable patients with Grade III and IV BTAI. A landmark systematic review by Demetriades et al. comparing TEVAR and open repair in 7,768 patients found TEVAR was associated with significantly lower 30-day mortality (7.2% vs 19.2%), lower rates of spinal cord ischemia, and fewer respiratory and renal complications.[35] The Society for Vascular Surgery and the Eastern Association for the Surgery of Trauma both endorse TEVAR as first-line treatment for Grade III and IV BTAI in suitable anatomical candidates.[36]

Key controversies in BTAI management include the optimal timing of repair, the management of Grade I and II injuries (most authorities recommend non-operative management with anti-impulse therapy and repeat imaging), and the long-term durability of thoracic stent grafts implanted in young trauma patients who may require device surveillance for decades. Emergency open thoracotomy retains a role in hemodynamically unstable patients with aortic or great vessel injury refractory to resuscitation.

Abdominal Vascular Injuries
Abdominal vascular trauma is associated with the highest case fatality rates of any vascular region, driven by the high volume of blood loss before vascular control can be achieved. Injuries to the suprarenal aorta, suprahepatic inferior vena cava (IVC), and portal vein carry mortality rates exceeding 50 to 70% in most series.[37] The fundamental surgical principle is rapid proximal vascular control, achieved by aortic compression at the diaphragmatic hiatus or supra-celiac clamping before formal repair.

IVC injuries merit specific comment. While primary repair is preferred for lateral injuries, circumferential IVC injuries and those in hemodynamically unstable patients may require ligation. IVC ligation is compatible with survival but requires aggressive postoperative management of lower limb oedema and venous hypertension.[37] Selective angioembolization of isolated solid organ vascular injuries (renal, splenic, or hepatic arterial injuries) has become well-established in hemodynamically stable patients at high-volume trauma centers, with success rates of 85 to 95% for grade III to IV splenic injuries reported in prospective studies.[38]

Extremity Vascular Injuries
Extremity vascular injuries account for the majority of civilian vascular trauma and, when promptly treated, carry the best outcomes. Restoration of arterial perfusion is the primary goal, and the reversed great saphenous vein graft is the conduit of choice for most peripheral arterial reconstructions.[28] The popliteal artery warrants special attention: injuries at this level carry the highest amputation risk of any peripheral vessel, ranging from 15 to 20% even in experienced hands, primarily because of associated injury to the popliteal vein, tibial nerve, and posterior knee capsule, combined with limited collateral circulation around the knee.[39] Combined arterial and venous injury at this level is associated with a significantly higher amputation rate than isolated arterial injury, and venous repair or shunting is recommended when feasible in stable patients.

Orthopedic-vascular co-injuries (fracture with adjacent arterial injury) present a sequencing dilemma: skeletal stabilization before vascular repair risks prolonging ischemia, while vascular repair before orthopedic fixation risks graft disruption during fracture reduction. Temporary vascular shunting elegantly resolves this dilemma by restoring flow while permitting fracture stabilization before definitive arterial repair.[30]

Pelvic Vascular Injuries
Pelvic fracture-associated hemorrhage is a major cause of preventable trauma death. The hemorrhage may originate from fractured cancellous bone surfaces, disrupted pelvic venous plexus, or arterial injury, most commonly the superior gluteal, internal pudendal, or lateral sacral arteries. Contemporary management integrates pelvic ring stabilization (external fixation or pelvic binder), preperitoneal pelvic packing (PPP), and angiographic embolization. A comparative study by Burlew et al. demonstrated that PPP, when added to angioembolization, reduced transfusion requirements and mortality compared with embolization alone in the most severely injured patients, though the two modalities are complementary rather than competing.[40] REBOA Zone III deployment may provide temporary aortic inflow control as a bridge to definitive hemostasis in exsanguinating pelvic haemorrhage.[24]

Venous Injuries
Major venous injuries are underappreciated contributors to traumatic hemorrhage and long-term morbidity. Repair of major named veins is preferred over ligation where patient stability permits, because ligation of the femoral, popliteal, or iliac vein is associated with significantly higher rates of limb oedema and post-thrombotic syndrome.[41] Small lateral

venous lacerations are repaired primarily; larger defects may require patch venoplasty or interposition grafting. Ligation is reserved for hemodynamically unstable patients, when repair would require prohibitive operative time, or for tibial and peroneal veins where ligation is generally well-tolerated.

IVC injuries remain among the most lethal in vascular trauma, with reported mortality ranging from 40 to 60%.[37] Retro hepatic IVC injuries are particularly challenging; aortocaval shunting, hepatic vascular isolation, and staged packing strategies have all been described, but no single approach has demonstrated clear superiority, and outcomes are primarily determined by the volume of hemorrhage at presentation.

SPECIAL POPULATIONS

Pediatric Vascular Trauma

Pediatric vascular injuries present distinctive challenges. Vessel diameter is smaller, vasospasm is more pronounced than in adults (potentially masking injury on initial examination), and the use of appropriately sized endovascular devices is limited. Whitehouse et al. reviewed 1,319 pediatric vascular injuries from the Kids Inpatient Database and reported an overall amputation rate of 4.8%, with penetrating mechanism, lower extremity involvement, and delayed presentation as independent predictors of amputation.[42] Autologous vein grafts are strongly preferred in children because they have the potential for somatic growth, avoiding the anastomotic stenosis that occurs when a fixed-diameter prosthetic graft is placed in a growing child. Long-term surveillance is mandatory given this growth-related risk.

Geriatric Vascular Trauma

Elderly patients with vascular injury carry higher operative risk attributable to atherosclerosis, vascular calcification, frailty, reduced physiological reserve, and the high prevalence of anticoagulant and antiplatelet therapy. The latter significantly increases hemorrhagic complications and requires rapid reversal strategies (prothrombin complex concentrates, idarucizumab for dabigatran, andexanet alfa for factor Xa inhibitors) as part of resuscitation.[43] Endovascular approaches may reduce the physiological stress of open surgery in selected patients, but the generalized atherosclerosis that characterizes this population can complicate access, device sizing, and deployment.

IATROGENIC VASCULAR INJURY

Iatrogenic vascular injuries are an increasingly prevalent category, with the femoral artery at the common femoral access site most frequently affected. Access-site complication rates following arterial catheterization range from 0.5 to 9% depending on sheath size, anticoagulation, and operator experience.[11] Ultrasound-guided puncture reduces access-site complications compared with anatomical landmark technique and is now the recommended approach in published guidelines.[44]

Femoral pseudoaneurysm is the most common access-site complication and is managed initially by ultrasound-guided thrombin injection, which achieves primary closure in 85 to 95% of cases.[11] Failed thrombin injection, large pseudoaneurysms (greater than 3 cm), rapidly expanding hematomas, skin ischemia, or distal embolization are indications for open or endovascular repair. Retroperitoneal hematoma from high arterial puncture or guidewire perforation may be catastrophic and should be suspected in any patient with unexplained hemodynamic deterioration after arterial catheterization.

Surgical procedural injuries involve a wide range of vessels depending on the procedure type. Renal and hepatic artery injuries are recognized complications of laparoscopic nephrectomy and hepatectomy respectively; iliac vessel injury is a recognized complication of lumbar disc surgery and colorectal resection. Management follows the same principles as traumatic vascular injury, with prompt recognition being the critical determinant of outcome.

COMPLICATIONS

Early complications include:

- Recurrent hemorrhage from technical failure or coagulopathy
- Acute graft or repair thrombosis
- Distal embolization
- Compartment syndrome
- Acute limb ischemia
- Wound infection and dehiscence
- Acute kidney injury from ischemia or contrast nephropathy
- Multi-organ dysfunction syndrome

Late complications include:

- Pseudoaneurysm at the anastomosis or repair site
- Arteriovenous fistula formation
- Anastomotic or conduit stenosis requiring reintervention
- Graft infection, particularly with prosthetic material
- Chronic venous insufficiency and post-thrombotic syndrome
- Limb length discrepancy and growth disturbance in children
- Chronic pain and neuropathy
- Amputation

The distinction between early and late graft failure is clinically important. Early graft thrombosis (within 30 days) typically reflects technical problems at the anastomosis or inadequate outflow, whereas late failure is more commonly attributed to neointimal hyperplasia or progressive atherosclerotic disease in the runoff vessels. Regular duplex ultrasound surveillance at 1, 3, 6, and 12 months, and annually thereafter, enables detection of graft stenosis before occlusion occurs.

POSTOPERATIVE CARE AND SURVEILLANCE

Postoperative management requires multidisciplinary input from vascular surgery, critical care, hematology, physiotherapy, and where relevant, orthopedic surgery. Hemodynamic monitoring, optimization of tissue perfusion, correction of coagulopathy, pain control, and careful fluid balance are fundamental. Regular neurovascular assessment of the repaired extremity is essential in the immediate postoperative period.

Antiplatelet or anticoagulant therapy following vascular repair is individualized according to the type of repair, conduit used, and hemorrhagic risk. Prosthetic grafts in the infra inguinal position generally warrant antiplatelet therapy; venous grafts in well-vascularized beds with good runoff may not require anticoagulation in the absence of other indications. Simultaneous venous injury managed by ligation represents an indication for postoperative thromboprophylaxis, but its timing must be balanced against bleeding risk from the vascular repair and associated injuries.

Nutritional support and early rehabilitation are integral to functional recovery. Prolonged immobility following vascular trauma contributes to venous thromboembolism, pressure injury, respiratory complications, and delayed wound healing. Psychological support should be offered to patients sustaining limb-threatening or amputating injuries, given the high prevalence of post-traumatic stress disorder and depression in this population.

RECENT ADVANCES

Several technological and system-level advances have meaningfully altered vascular trauma outcomes over the past decade, though their evidence base varies considerably in quality.

TEVAR for blunt thoracic aortic injury represents the most robustly evidence-supported advance in the field, with multiple systematic reviews and national registry data consistently demonstrating mortality benefit over open repair.[35] The rapid diffusion of TEVAR across trauma centers has been one of the most significant practice changes of the past two decades.

Hybrid operating rooms integrate surgical and endovascular capability in a single space and have facilitated complex combined procedures for injuries that previously required staged operations or patient transfer. However, evidence that hybrid rooms improve clinical outcomes compared with sequential open then endovascular approaches in a standard operating theatre is limited to registry series, and their high capital cost must be weighed against benefit in resource allocation decisions.

Artificial intelligence and machine learning applications in vascular trauma are at an early stage. Computer-aided detection algorithms for CTA interpretation have demonstrated comparable sensitivity to experienced radiologists for aortic injury detection in preliminary studies, and machine learning models trained on registry data have shown promising discrimination for predicting amputation risk and mortality.[45] However, prospective validation in diverse populations is lacking, and none has yet demonstrated improved patient outcomes compared with standard care in a controlled study.

Resuscitative endovascular balloon occlusion of the aorta, discussed above, represents a genuine advance in pre-operative hemorrhage control, but its definitive role, optimal patient selection, safe inflation duration, and impact on mortality relative to resuscitative thoracotomy remain to be established by ongoing prospective trials.

Tissue-engineered vascular grafts, incorporating biodegradable scaffolds seeded with autologous cells, have demonstrated patency and remodeling in animal models and in small human series for elective vascular reconstruction. Their application in acute trauma settings, where operating time is limited and scaffold preparation requires days to weeks, remains a future rather than a contemporary clinical tool.

FUTURE PERSPECTIVES

The most important unmet need in vascular trauma research is the generation of high-quality prospective comparative data. The PROOVIT registry represents a significant step forward, but registry data cannot substitute for randomized trials in answering specific questions about treatment choice. Key unanswered questions include the role of REBOA versus resuscitative thoracotomy in pre-hospital cardiac arrest, the optimal timing of TEVAR for blunt thoracic aortic injury, the management of Grade I and II blunt cerebrovascular injuries, and the long-term outcomes of endovascular repair in young trauma patients.

Precision medicine approaches, incorporating biomarkers of coagulopathy, inflammation, and ischemia, may eventually enable individualized resuscitation and repair strategies. Thromboelastographic and rotational thermoelectrometry are already in clinical use at major trauma centers to guide targeted resuscitation and are associated with reduced transfusion volumes in some series, though mortality benefit remains inconsistently demonstrated.[46]

Simulation-based training for both open and endovascular vascular trauma techniques is increasingly recognized as an important component of surgical education, given the low volume and unpredictable timing of vascular trauma cases that limits trainee operative exposure. High-fidelity hybrid simulation models and cadaveric workshops have demonstrated improved operator performance on technical metrics, though translation to patient outcomes requires further study.

Global equity in vascular trauma care deserves explicit attention. The burden of vascular trauma falls disproportionately on low- and middle-income countries, where limited access to CT angiography, endovascular equipment, blood products, and vascular surgical expertise means that outcomes lag far behind those reported from high-income trauma centers. Telemedicine, task-sharing models, and international collaboration are potential mechanisms to narrow this gap, but require deliberate investment and policy commitment.

CONCLUSION

Vascular injury remains a time-critical surgical emergency demanding rapid diagnosis, coordinated multidisciplinary response, and individualized treatment. Open repair remains the standard of care for most peripheral arterial injuries and for hemodynamically unstable patients, while TEVAR has clearly supplanted open surgery for blunt thoracic aortic injury in stable patients. Endovascular and hybrid approaches offer genuine advantages in selected injuries, particularly in anatomically challenging locations, but their evidence base remains predominantly observational and late reintervention rates require long-term surveillance. Damage-control resuscitation with balanced blood products, early tranexamic acid, and judicious use of REBOA has improved outcomes for patients with major hemorrhage, though optimal REBOA patient selection and deployment protocols continue to be refined.

Critical gaps persist in the evidence base, particularly regarding definitive comparative data for several endovascular versus open decisions and for the management of blunt cerebrovascular injuries. Addressing these gaps requires investment in multicenter prospective registries with standardized outcome reporting, international research collaboration, and in selected questions, randomized controlled trials. Simultaneously, equitable access to basic vascular trauma care for patients in resource-limited settings must remain a global health priority alongside technological innovation in high-income settings.

CONFLICT OF INTEREST

None

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