Chapter 19
Endovascular Therapy in Trauma

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Abbreviations

BAAI	Blunt Abdominal Aortic Injury
BTAI	Blunt Thoracic Aortic Injury
CT	Computerized Tomography
cTAG	Conformable Thoracic Aortic Graft
EVAR	Endovascular Aneurysm Repair
FACS	Fellow of the American College of Surgeons
FDA	Food and Drug Administration
IVC	Inferior Vena Cava
IVUS	Intravascular Ultrasonography
MD	Medical Doctor
REBOA	Resuscitative Endovascular Balloon Occlusion of the Aorta
SVS	Society for Vascular Surgery
TEVAR	Thoracic Endovascular Aneurysm Repair
V1, V2, V3, V4	First Through Fourth Segments of the Vertebral Artery

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Introduction

The last 25 years have seen a transformation in vascular surgery practice as the specialty has incorporated endovascular and interventional techniques. The treatment of vascular trauma has undergone an identical and parallel change; multiple National Trauma Data Bank analyses have consistently demonstrated an increasing shift in operative treatment of vascular trauma from open surgery to a treatment scheme that relies heavily on endovascular therapies [1–5]. At least some of these studies have also shown a concomitant decrease in the morbidity and mortality associated with these injuries [4, 6]. Although a direct causative relationship between endovascular intervention and improved survival is unlikely, a related improvement in the speed of hemorrhage control may be involved.

As endovascular surgery has increased in prevalence, so, too, has the construction and use of hybrid operating rooms with full angiographic capabilities. These rooms allow the simultaneous performance of open surgery and endovascular intervention [7]. This has eliminated transit delay between the angiography suite and the operating room. Additionally, the trauma surgeon no longer has to choose initial angiography or laparotomy for the unstable, multiply injured patient. Finally, the presence of hybrid rooms has allowed the development of novel techniques combining both endovascular and open methodologies.

A full explication of endovascular trauma techniques is outside the scope of this chapter. It is our hope that a description of the conceptual basis underlying endovascular intervention and a review of specific methods and contexts will enable the trauma surgeon to recognize the possibility of an endovascular solution to their patient's injuries.

Endovascular Principles

All endovascular trauma surgery is divisible into four parts: intra-arterial catheterization and injection, balloon occlusion, embolization, and stent emplacement.

Catheterization and Intra-arterial Injection

Catheter angiography is the intraluminal instillation of radiopaque dye under fluoroscopic visualization, whether by direct radiography or subtraction angiography, using a catheter that may be advanced far from the point of vascular access. Injection may be from any vessel into which the catheter has been positioned, whether the aorta or a subsegmental pulmonary artery. It is a dynamic study that can reveal flow, occlusion, or extravasation.

As multidetector CT angiography has increased tremendously in both sensitivity and specificity over the last decade, the advantage of catheter-based angiography in detecting injury is no longer overwhelming. Rather, it is the dynamic depiction of flow combined with the ability to select vessels that makes angiography valuable in selected patients. This becomes particularly important in well-collateralized beds such as the pelvis, where even injury laterality can be obscure.

An additional advantage of angiography is the ability to identify the site of vascular injury or obtain vascular control before and after other, nonvascular intervention. Identification of arterial continuity before and after reduction and fixation, for example, allows orthopedic and trauma teams to work in coordination. Angiography also facilitates open exploration and repair of vascular injury, particularly in the extremities.

In addition to contrast, intra-arterial injection of agents such as nitroglycerin may be useful in distinguishing true vascular injury from the severe vasospasm that is frequent in extremity trauma in the younger population [8].

Balloon Occlusion

Endovascular access allows obstruction of blood flow from within the lumen but has some advantages over traditional extrinsic clamping.

Balloon occlusion has been employed for vascular control before the advent of endovascular surgery. In the past, this was usually achieved using balloon catheters inserted through the injury itself and advanced blindly. Through image-guided balloon occlusion with access distant to the injury, the surgeon is able to treat a broader range of vascular injury without extensive proximal exposure. This, in turn, allows open repair of axillosubclavian, common carotid, and common femoral injury without the need to enter the thorax or pelvis for proximal control. The use of aortic balloon occlusion is discussed later in this chapter.

A critical point when performing balloon occlusion is the sizing of the occlusion balloon to the inflow vessel. The principles of angioplasty do not apply – applying significant radial force can prove catastrophic. Insufflation to the point of control and no further is the guiding principle.

Embolization

If balloon occlusion is endovascular clamping, embolization is endovascular vessel ligation. Embolization involves the selective delivery of permanent or semipermanent occlusive material through catheter or sheath. Four methods of embolization are widely available: large-diameter devices, coils, hemostatic slurry, and liquid/particulate agents. The injury and anatomy determines the optimal modality.

Pseudoaneurysm sacs from arterial injury may be embolized, but care must be taken to avoid migration of coils from the sac into the adjacent flow stream. A “coil-and-cage” strategy may be employed in which an uncovered stent is deployed across the injury and coils are delivered through its cells. Slurry and liquid-phase agents are generally inappropriate.

End-vessel bleeding is often amenable to treatment with embolization; this is most often seen in pelvic injury. The ability to select and embolize as distally as possible while arresting bleeding reduces the chances of ischemia and minimizes the likelihood that collateral flow will cause bleeding to recur. Occasionally, vessel transection is best treated with embolization, for instance, distal cervical vertebral artery transaction [9].

In solid organ injury, selective distal embolization can preserve organ viability while controlling bleeding [10]. Splenic injury warrants special mention. Blunt splenic injury often involves diffuse bleeding. Selective embolization is not possible in such a wide area and, even if performed, would result in significant splenic infarction. Traditional nonoperative management has a substantial risk of failure and even recurrent bleeding. Proximal occlusion of the splenic artery, however, increases the rate of successful nonoperative management and allows resolution of hemorrhage with preserved splenic function. This is likely due to the preservation of perfusion from collateral supply and the decrease in perfusion pressure [11].

Stenting

The proliferation of elective stenting in the coronary and peripheral vasculature in the last 25 years has provided the endovascular surgeon with myriad options for treatment. In the context of trauma, only two categories need to be remembered: uncovered and covered stents, with the latter including stent grafts.

Uncovered stents are used in trauma when durable radial force is desired without the need for control of extravasation. This is a rare occurrence, usually with "cage and coil" embolization or when intimal flaps require aggressive reapposition to the arterial wall.

Covered stents, including both peripheral and aortic devices, are used frequently in trauma. They involve a metal framework with a fabric or polymer sheath. The covered stent is used to exclude extraluminal flow. This includes both pseudoaneurysm and free extravasation but also includes branch vessels of the target artery. Use of covered stents, whether in the superficial femoral artery or the aorta, must include awareness of potential branch occlusion.

In addition to branch occlusion, covered stents must be correctly sized. Undersized stents are prone to migration, and oversized stents may collapse, thrombose or, if balloon-expandable, exacerbate injury.

Exhaustive study of medium-term and long-term patency of stents, both covered and uncovered, has been made, but only in the elective context and in patients with chronic occlusive or aneurysmal disease who suffer from the expected comorbidities. Long-term performance in patients composing the trauma demographic is essentially unknown aside from case series, but in-stent stenosis, distal embolization, and stent occlusion must always be a consideration after implantation.

Practical Endovascular Trauma Surgery

Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA)

Emergent thoracotomy was described as early as the 1870s, with resuscitative thoracotomy advocated in the 1960s [12–14]. Clamping the descending thoracic aorta drastically reduces hemorrhage pressure distal to the clamp allowing exposure and treatment of the patient in extremis. Endovascular occlusion of the descending thoracic aorta with a Foley catheter was first described in the Korean conflict [15].

As endovascular aneurysm repair increased and “modelling” balloons designed for aortic diameters became commercially available, interest in endovascular balloon occlusion for resuscitation returned. REBOA appears to have equivalent efficacy to emergency thoracotomy but offers several advantages [16, 17]. Transfemoral arterial access is rapid and requires only standard trauma bay equipment. Placement of the balloon itself can be done at the bedside using estimated distances for positioning. Confirmation can be done with plain portable radiography [18].

Unlike open thoracotomy, REBOA allows positioning of the occlusive balloon in either the thoracic or the infrarenal aorta. In the case of distal injury, this allows simultaneous temporizing hemorrhage control while maintaining renal and mesenteric perfusion [19]. This flexibility has allowed REBOA to be used in a variety of non-trauma patients, including elective hepatobiliary, orthopedic, and oncologic pelvic surgery as well as ruptured aortic aneurysm and postpartum hemorrhage (Fig. 19.1) [20–26].

Further endovascular intervention for hemorrhage is possible while the REBOA is present. The periodic and partial deflation of the balloon to identify, localize, and treat vascular injury while maintaining hemodynamic stability is a subtle art, as is maneuvering wires, catheters, and sheaths around the REBOA catheter [27].

Cerebrovascular Injury

Intracranial

Though the methods of intracranial endovascular trauma surgery are not dissimilar from those described here, neurosurgical practices are outside the scope of this review. The changing practices in this area are of significant interest, however, as the advances in military medical treatment of traumatic brain injury, both blunt and penetrating, increasingly involve endovascular surgery [28].

Cervical Carotid Artery

The potential for endovascular treatment of cervical carotid injury varies by both mechanism of injury and zone of the neck.

Antiplatelet or anticoagulant therapy is sufficient for the majority of blunt cerebrovascular injury [29]. In selected dissections with significant luminal encroachment or with pseudoaneurysm, intervention may be considered. Case series of covered stent placement demonstrate that this is a possible modality, but compliance with postoperative anticoagulation or antiplatelet agents is critical [30–32]. Coil embolization of the pseudoaneurysm sac carries the risk of catastrophic distal

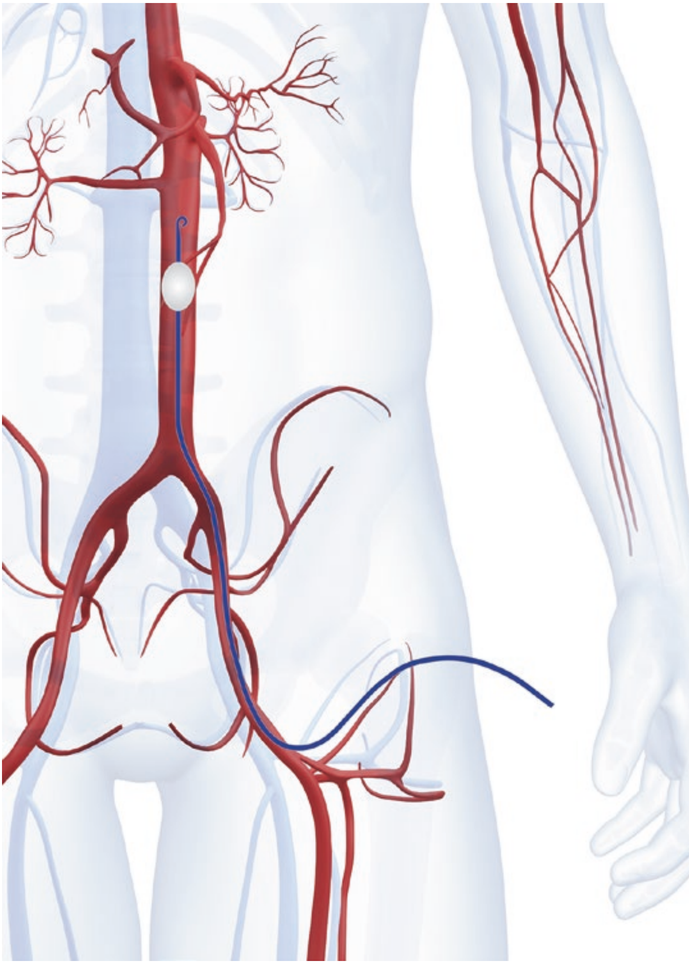

Figure 19.1 Diagram illustrating position of deployed and inflated REBOA catheter. Initial efforts utilized guidewire placement, but proprietary, dedicated devices are now designed for wireless advancement. As shown, the REBOA balloon is positioned in Zone III. This would be ideal placement for control of pelvic hemorrhage. (Courtesy of Prytime Medical Devices, Inc., Boerne, TX, USA)

migration of the embolization medium. Intraprocedural balloon exclusion or a “coil-and-cage” strategy can be used to address this risk [33, 34].

In penetrating carotid trauma, endovascular instrumentation is of greatest benefit in Zones I and III. Penetrating injuries to Zone II are best addressed through open surgery.

Open repair of Zone I injury may benefit from preoperative aortography or selective angiography to determine the location of disease or intraoperative balloon occlusion if patient anatomy otherwise requires intrathoracic proximal control. Stent graft repair of a common carotid injury has been reported [35].

Penetrating Zone III injuries have been treated by both stenting and, in the case of complete transection, coil embolization. The difficult exposure of the carotid artery at the skull base makes successful endovascular treatment of injuries at this level appealing.

Vertebral Artery

Blunt vertebral artery injuries are rarely candidates for surgical treatment. A small proportion of these injuries are immediately catastrophic, and these are usually associated with severe basilar skull or high cervical spine fracture [36–38]. The overwhelming majority are adequately treated with medical management. Coil embolization is used for selective high-grade injuries.

Penetrating vertebral artery injuries are more common. The V2 and V3 segments are enclosed by the vertebrae, and open exposure is arduous, but endovascular repair is also challenging. Tortuosity and small vessel diameter are prohibitive of stent grafting the vertebral arteries, and the vessels’ mobility and tendency to retract after transection make successful bridging unlikely. Significant hemorrhage is thus best treated with coil embolization of the area of extravasation distally and the stump lumen proximally. Injuries in the V1 and V4 segments are hostile to endovascular intervention.

Upper Extremity

Subclavian and Axillary Arteries

Injury to the intrathoracic and proximal extrathoracic portions of the subclavian and axillary arteries carries substantial mortality. In their seminal review of penetrating trauma to these vessels, Demetriades and colleagues demonstrated a mortality of over 34% [39].

The anatomy of these vessels presents several challenges. The retroclavicular location of the proximal artery makes temporizing direct pressure difficult, necessitating practices such as extraluminal Foley balloon compression through the wound tract [40]. Exposure of the subclavian and axillary arteries is challenging in the elective, controlled environment. In the context of trauma, the need for proximal control can require progressive extension of exposure to median sternotomy or trapdoor or even clamshell thoracotomy [41]. Open exposure also carries a significant risk of iatrogenic injury to the densely packed adjacent arterial, venous, and neural structures.

Endovascular surgery offers the potential for definitive endoluminal repair of both penetrating and blunt injuries of the subclavian and axillary arteries without the need for open exposure. In a retrospective, propensity-matched, 10-year experience, Branco and colleagues showed that endovascular treatment of axillosubclavian injury was associated with a nearly fivefold lower mortality over open repair with a tendency toward less complications postoperatively [42]. Smaller case reports have found shorter operative times and lower transfusion requirements as well [43–45].

Definitive endovascular repair of axillosubclavian injury can consist of stent grafting of an injured artery or coil embolization of avulsed branches (Fig. 19.2a, b). The vessel's large diameter and tendency to maintain patency distal to injury facilitates wire crossing and stent graft shunting of the transected artery, allowing open repair after resuscitation and resolution of other injuries [46]. Definitive repair of the proximal subclavian artery is anatomically limited by the ves-

FIGURE 19.2 (**a**, **b**) Definitive endovascular repair of penetrating injury to the right subclavian artery. (**a**) Massive extravasation is evident. Brachial access has been obtained and a Gore Viabahn stent graft advanced but not deployed across the injury. (**b**) After deployment, extravasation is not seen. Note the preservation of the vertebral artery and occlusion of the internal thoracic artery and thyrocervical trunk

sel's flexion point and by the vertebral artery. Occlusion of other small branches presents less of a dilemma because of copious collateral flow. Even if open repair is necessary, a hybrid approach involving angiography and balloon occlusion for antegrade control may be advantageous [47–49]. Access may be obtained from femoral or brachial points. Radial access is not advised because of the larger sheath sizes required for covered stent placement.

Brachial Artery and Beyond

The presence of ischemia or compressive hematoma combined with the speed and ease of exposure usually makes open treatment of vascular injury distal to the shoulder preferable. Asymptomatic dissection of the brachial artery may be appropriately treated with low-pressure balloon inflation to reappose the intimal flap to the arterial wall [50]. Balloon tamponade may be used to treat small perforations in the forearm vasculature, and selective embolization is useful in small branches such as the common interosseous artery and its branches [51].

Aorta

Descending Thoracic Aorta

The endovascular treatment of blunt injury to the descending thoracic aorta (BTAI) has progressed rapidly in the last decade. A review of the National Trauma Data Bank by Grigorian and colleagues confirms that endovascular repair was performed for 25.7% of all BTAI in 2015, compared with 12.1% in 2007; over that same period, open repair of BTAI decreased from 7.4% to 1.9%. Endovascular repair was associated with decreased mortality, renal injury, and length of stay compared to open aortic repair [52]. The Society for Vascular Surgery (SVS) guidelines recommend that endovascular repair be performed preferentially over open repair or nonoperative management.

Treatment of BTAI is generally protocolized and is contingent upon grade. The SVS classification system works from the lumen outward: Grade I, intimal tear; Grade II, intramural hematoma or extensive intimal flap; Grade III, pseudoaneurysm; and Grade IV, free intrathoracic rupture. The guidelines derived from this system mandate observation and repeat CTA of Grade I injury and immediate repair of Grades II–IV [53]. Starnes and colleagues have proposed a simpler, modified version involving minimal (intimal injury), moderate (anything distorting the normal aortic contour), and severe (extravasation) classes and recommends observation, semi-elective repair, and emergent repair, respectively [54]. DuBose and associates performed a multi-institutional analysis demonstrating no advantage to endovascular repair in patients with Grade I–II injury over observation [55].

Patients who are managed nonoperatively should be treated, if possible, with β-blockade and an antiplatelet agent.

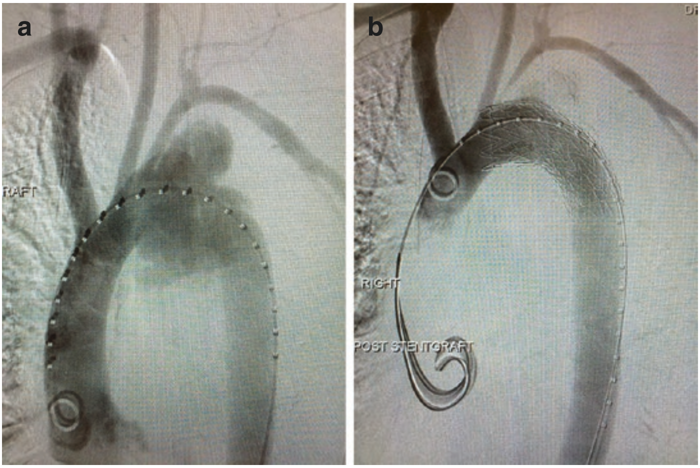

FIGURE 19.3 (**a**, **b**) Endovascular repair of Grade IV blunt thoracic aortic injury. (**a**) Diagnostic aortography showing classic injury at the location of the ligamentum arteriosum. Advancement of the marking pigtail catheter and a left anterior oblique projection allows maximal visualization of the arch. (**b**) After deployment, exclusion of the injury is obvious. A double-curved Lunderquist wire has been advanced until it rests against the cusps of the aortic valve, as seen by the organized motion artefact. The orifice of the left subclavian artery has been covered, but preserved flow via collaterals is seen. The origin of the left common carotid artery is encroached upon by uncovered wireforms, and flow is not impeded

Repeat imaging with CT angiography is generally performed within 7 days. Progression should prompt endovascular repair (Fig. 19.3a, b).

Preparation for endovascular repair should entail careful review of CT angiography, preferably with workstation reconstructions. Careful measurement of required coverage length, as well as proximal and distal landing zones, must be performed. In the emergent setting, the left subclavian artery origin may be covered with impunity. The left common carotid artery, however, cannot be encroached upon, and so, taking proximal sealing zone into account, aortic injury less than 15 mm from the left common carotid artery is generally not reparable through endovascular surgery. CTA measurement of aortic diameter in the hyperdynamic, hypovolemic patient is exceedingly unreliable. Wallace and associates have demonstrated significant variation in aortic diameters on admission CT angiography and intraoperative, pre-TEVAR intravascular ultrasound. IVUS is strongly recommended for confirmation of proximal and distal diameter measurement prior to deployment of endograft [56].

There are currently four thoracic endografts approved by the FDA for repair of aneurysmal disease. Only the Medtronic Valiant and the Gore cTAG have been approved by the FDA for treatment of BTAI, but off-label use of the Bolton and Cook devices is common [57]. Thoracic endografts with branches to preserve flow through the great vessels will likely become available in the near future, and their suitability in trauma will become apparent with time (Fig. 19.4a, b) [58].

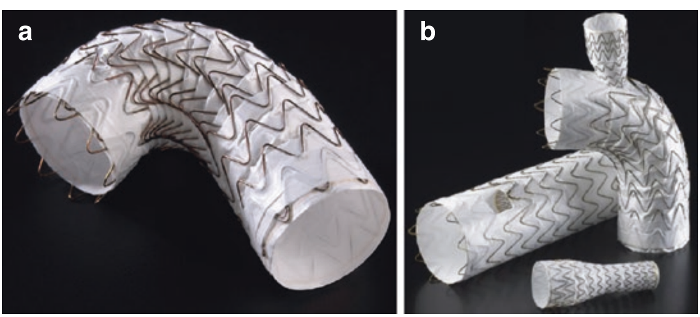

Figure 19.4 (**a**, **b**) Thoracic endografts. (**a**) Gore Conformable TAG® (cTAG) endoprosthesis. This and the Medtronic Valiant have FDA approval for treatment of BTAI, and the size ranges are accordingly consistent with aortic sizes of young patients. Note the proximal extent of the wireforms compared with the extent of the fabric. (**b**) The Gore TAG® thoracic branch endoprosthesis is an investigational device that theoretically allows continued perfusion of the left subclavian artery and therefore more proximal aortic coverage. It is investigational and not approved for use. (Both: Courtesy of W.L. Gore and Associates, Inc., Neward, DE, USA)

In experienced hands, percutaneous access for both TEVAR and EVAR can be performed rapidly. In the hypotensive patient with non-palpable pulses, however, direct femoral exploration and arterial cutdown may be faster.

Complications of endograft repair include poor apposition of the proximal stent graft to the aortic arch because of poor conformation, undersizing, and infolding. Consequences may be minimal or catastrophic. Thorough planning and familiarity with device deployment is essential.

Long-term results of endovascular treatment of BTAI are unknown. Normal growth of the thoracic aorta has been observed in young patients in the years after endograft placement, but this growth appears to be attenuated in the grafted segment [56].

Abdominal Aorta

Abdominal aortic injury is rarely compatible with definitive endovascular intervention both because of presentation and because of anatomy. Penetrating injury to the aorta by definition removes the ability of the retroperitoneum to tamponade bleeding, usually resulting in hemodynamic instability and immediate laparotomy. Blunt abdominal aortic injury (BAAI) is exceedingly rare. Retrospective studies report an annual incidence of 0.02% to 0.1% of all trauma admissions [59, 60]. Even among autopsy series, BAAI was found in only 0.2% of blunt trauma mortalities.

BAAI may be graded in the same way as BTAI, ranging in severity from intimal flap to intramural hematoma, pseudoaneurysm, and free rupture. Intimal injury, however, carries greater risk in the abdominal aorta than in the thoracic. Evolution to overt dissection carries significant potential for occlusion of critical mesenteric and renal branches. Circumferential dissection, seen most often with flexion, extension, or distraction spinal injury, usually presents as acute aortic occlusion, a condition with extraordinarily high mortality. Early endovascular intervention for circumferential intimal injury has been described with successful preservation of aortic patency [61]. As with penetrating injuries, free rupture is almost always treated with immediate laparotomy.

BAAI is classified by anatomic location into three zones. Zone I extends from the diaphragm to the superior mesenteric artery and Zone II from there to the renal arteries. The infrarenal aorta is Zone III. When considering endovascular repair, the location of the injury relative to branches of the aorta is the primary consideration. A 20-year retrospective review by Deree and associates found that more than 55% of all abdominal aortic injury fell into Zones I or II [62].

Acute occlusion of the superior mesenteric artery or celiac artery will result in fatal visceral ischemia. A critically stenosed orifice in a patient with chronic mesenteric occlusion, however, can often be sacrificed without consequence. Acute occlusion of the renal arteries will result in acute and permanent renal failure, but in the face of lethal exsanguination, this may be preferable. Coverage of one renal artery by aortic endograft does not necessarily result in clinically significant renal insufficiency.

Elective repair of paravisceral aneurysmal disease currently requires fenestrated endografts created for individual patients. Standardized fenestrated and branched grafts may become available in the next several years, and these devices may allow endovascular repair of the aorta in Zone I and Zone II.

Most injuries to the abdominal aorta may be treated with tube stent grafts, but Zone III injuries, if sufficiently close to the aortic bifurcation, will require either a bifurcated endograft or an aorto-uni-iliac endograft with femorofemoral bypass.

Abdominal aortic injury, both penetrating and blunt, with hemodynamic instability classically requires laparotomy for hemorrhage control with no opportunity for endovascular repair. The increasing prevalence of REBOA may allow a more frequent definitive endovascular repair of abdominal aortic injuries.

Lower Extremity

Pelvis

The utility of endovascular intervention in the treatment of blunt pelvic trauma has been very well established. The combination of orthopedic fixation and angiography with embolization has been in widespread use since the 1970s [63–67].

Historically, interventional radiologists have performed angioembolization. The distinction between the operating room and radiology suite has resulted in a temporal and spatial separation between pelvic fixation and angiography, both of which contribute to hemorrhage control [68]. This results not only in a delay in addressing pelvic bleeding but results in an unstable patient being outside of a resuscitative setting.

A drive to combine fixation and embolization has led to development of both temporary pelvic fixation systems and preperitoneal packing, both of which are designed to compensate for a delay that may not be necessary.

Similar to the upper extremity, penetrating injury to the iliac arterial system carries significant morbidity and mortality. The 30-day mortality of iliac vascular trauma ranges from approximately 25% to 40% depending upon accompanying injuries [69].

The use of endovascular strategies to treat penetrating iliac arterial injuries is particularly appealing given the frequency of accompanying bowel spillage and infectious risk of open prosthetic repair as well as the progressive difficulty presented by internal iliac arterial exposure.

Stent grafting of the common or external iliac arteries is made easier by the widespread availability of iliac arterial stents in a wide range of sizes.

The prolific collateralization across the pelvis as well as from the external iliac and common femoral arteries makes internal iliac artery embolization for penetrating trauma a definitive hemorrhage control procedure worth consideration. The associated risks include colon, buttock, and spinal cord ischemia but decrease as embolization is performed more proximally [70]. Immediate or delayed crossover revascularization may preserve perfusion to the leg or to the internal iliac system enabling permanent occlusion of the common or external iliac arteries.

Infrainguinal

The ubiquity of peripheral arterial disease has resulted in a larger armamentarium and volume of experience with endovascular surgery in the lower extremity compared to the upper. The greater challenge of vascular exposure in the leg compared to the arm makes endoluminal intervention more appealing, but caution must be exercised.

The utility of contralateral retrograde access and placement of a working sheath cannot be overstated whether open or endovascular repair is performed. Angiographic localization of injury, intra-arterial instillation of vasodilators, and balloon control of proximal inflow are all enabled by sheath placement.

The treatment of common femoral arterial disease should be performed using an open technique but may be performed with proximal endoluminal balloon occlusion. This will allow repair of the entire vessel without entering the pelvis. Endovascular repair is not advised. The epigastric and circumflex branches of the common femoral artery are easily exposed and ligated. The vessel lies at a flexion point, and stents therein may kink, fracture, or thrombose. If a stent graft acutely occludes the profunda femoris, catastrophic thigh necrosis will result.

The most frequent etiology of profunda femoral injury is orthopedic and iatrogenic. Penetrating traumatic injury, however, is not unknown [71–76]. The root and proximal profunda are readily uncovered and repaired, but the distal branches are not easily exposed and extremely friable. They are easily embolized, however, and occlusion of any given branch is unlikely to have adverse effect [77]. In a patient with peripheral arterial disease, the profunda may provide the entire lower extremity arterial supply, and its branches must be embolized with care. Repair of the midportion of the profunda with a stent graft has been reported [78].

The superficial femoral and popliteal arteries, whether injured through blunt or penetrating means, provide attractive targets for endovascular repair, but several factors must be taken into consideration before pursuing aggressive treatment.

The only information provided by angiography is endoluminal profile. The extent and degree of traction, thermal, blast, or crush damage is impossible to determine. If angiography demonstrates vessel occlusion, this may reflect thrombosis of a dissection, transection, or even extrinsic compression. Pharmacomechanical thrombectomy, angioplasty, or primary stent grafting is not advisable in any of these cases. The popliteal artery is also subject to flexion stress, and even elective stenting in this vessel is undertaken knowing the increased risk of kink, fracture, or occlusion [79, 80].

Endovascular repair of the femoropopliteal segment should only be considered if preoperative CT angiography confirms that the vessel has not been completely transected and if luminal patency is confirmed on initial angiography. Suction catheter thrombectomy has been performed in this setting, but the danger of worsening an injury or causing distal embolization is enormous [81]. Definitive placement of a stent, particularly a stent-graft, should be performed only if the patient is appropriate for postoperative anticoagulant or antiplatelet therapy.

Tibial endovascular intervention is not often performed for trauma due to the relative rarity of treatable injury. Tibial artery injury rarely results in life-threatening hemorrhage rather than contained pseudoaneurysm, but loss of patency correlates with the need for amputation [82]. While there are no stents approved for use below the knee in the United States, use of covered, drug-eluting, and bare metal coronary stents for injury has been described in several case reports and series [83–86]. The well-established poor patency of tibial stents placed for occlusive disease probably does not represent their performance in younger, healthy arteries. Coil embolization of traumatic tibial pseudoaneurysm is well described [87–90].

Endovascular Therapy of Venous Trauma

Although the above discussion relates to arterial injury, endovascular treatment of venous injury is widely performed, if less frequently [91–98]. When formulating an endovenous trauma surgical plan, several critical differences from arterial therapy should be noted.

The variability in vessel size in the venous circulation is tremendous. Moreover, venous capacitance means that in the setting of trauma, the size of a vessel on venography is representative of neither the usual nor the maximal sizes of the target. For example, radiography studies have shown an average normal IVC diameter of around 20 mm. Similar studies on patients in hypovolemic shock demonstrated an average diameter of less than 7 mm [99, 100].

Flow in the venous system is directed centrally rather than peripherally. Inadvertent migration of arterial coils may result in ischemia requiring snare retrieval; migrated venous stents may result in foreign bodies in the heart or pulmonary circulation with immediate and detrimental physiologic effect [101–104].

The endovascular exclusion of arterial trauma with stent grafting is significantly aided by intraluminal pressure. Venous stents are not "pinned" to the vessel wall in the same way and rely much more upon the radial force of the stent to prevent "floating" of the conduit. This makes proper sizing all the more important.

Conclusion

The last 30 years have seen a revolution in not only the scope and techniques of vascular surgery. The principles of the field remain inviolate, but their application from within and without the vessel lumen has changed the conceptual understanding of vascular surgery. Endovascular techniques afford rapid diagnostic and therapeutic maneuvers that supplement open surgery and enlarge the potential for treatment of all vascular conditions. Vascular trauma is no exception. For the trauma surgeon, a familiarity with the technical principles of endovascular surgery and with their application in various anatomical and injury contexts will enable assessment of the injured patient and consideration of open, endovascular, or hybrid treatment. As hybrid operating rooms become more widespread, endovascular and open procedures performed simultaneously will enable the patient to receive coordinated care without delays. Basic vascular surgical principles have not changed since Hallowell's brachial artery repair in 1759; endovascular trauma surgery simply allows their application more quickly and efficiently.

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