## Title
Torso vascular trauma



**Journal**
Seminars in Pediatric Surgery, 30(6)

**ISSN**
1055-8586

**Authors**
Evans, Lauren L
Aarabi, Shahram
Durand, Rachelle
et al.

**Publication Date**
2021-12-01

**DOI**
10.1016/j.sempedsurg.2021.151126

Seminars in Pediatric Surgery 30 (2021) 151126

Contents lists available at ScienceDirect

Seminars in Pediatric Surgery

journal homepage: www.elsevier.com/locate/sempedsurg

# Torso vascular trauma

Lauren L. Evans[a], Shahram Aarabi[b], Rachelle Durand[c], Jeffrey S Upperman[d], Aaron R Jensen[a,*]

[a] Division of Pediatric Surgery, UCSF Benioff Children's Hospitals, Department of Surgery, University of California San Francisco, San Francisco, CA 94611, USA
[b] UCSF-East Bay Surgery Program, Department of Surgery, University of California San Francisco, San Francisco, CA 94611, USA
[c] UCSF Benioff Children's Hospitals, and Department of Radiology and Biomedical Imaging, University of California San Francisco, San Francisco, CA 94611, USA
[d] Department of Pediatric Surgery, Vanderbilt University Medical Center, Nashville, TN 37232, USA

ARTICLE INFO

*Keywords:*
Child
Pediatrics
Vascular surgical procedures
Vascular system injuries
Arteries
Endovascular procedures
Balloon occlusion
Wounds and injuries
Wounds, Penetrating
Wounds, Nonpenetrating
Abdominal injuries
Thoracic injuries

ABSTRACT

Vascular injury within the chest or abdomen represents a unique challenge to the pediatric general surgeon, as these life- or limb-threatening injuries are rare and may require emergent treatment. Vascular injury may present as life-threatening hemorrhage, or with critical ischemia from intimal injury, dissection, or thrombosis. Maintaining the skillset and requisite knowledge to address these injuries is of utmost importance for pediatric surgeons that care for injured children, particularly for surgeons practicing in freestanding children's hospitals that frequently do not have adult vascular surgery coverage. The purpose of this review is to provide an overview of torso vascular trauma, with a specific emphasis in rapid recognition of torso vascular injury as well as both open and endovascular management options. Specific injuries addressed include blunt and penetrating mediastinal vascular injury, subclavian injury, abdominal aortic and visceral segment injury, inferior vena cava injury, and pelvic vascular injury. Operative exposure, vascular repair techniques, and damage control options including preperitoneal packing for pelvic hemorrhage are discussed. The role and limitations of endovascular treatment of each of these injuries is discussed, including endovascular stent graft placement, angioembolization for pelvic hemorrhage, and resuscitative endovascular balloon occlusion of the aorta (REBOA) in children.



## Introduction

Vascular injury within the chest or abdomen represents a unique challenge to the pediatric general surgeon. Major torso vascular injury is exceedingly rare in children, with major vascular injury found in less than 1% of trauma registry patients.[1] Despite being rare, major vascular injuries are life-threatening, often require emergent intervention, and are associated with a 10–20% rate of mortality.[1–3] Vascular injuries to the torso are associated with mortality in over 40% of cases, particularly if patients present in extremis.[4,5] Maintaining the skillset and requisite knowledge to address these injuries is of utmost importance for pediatric surgeons that care for injured children, particularly for surgeons practicing in freestanding children's hospitals that frequently do not have adult vascular surgery coverage.[6] The purpose of this review is to provide an overview of torso vascular trauma, with a specific emphasis in rapid recognition of torso vascular injury as well as both open and endovascular management options. Endovascular techniques have been primarily developed to treat major vascular injury to the chest or abdomen in adult patients, as these injuries are more commonly – although still quite rare – found in adults. These endovascular techniques may be suitable for use in adolescent patients that approach adult sizes in centers that have endovascular expertise and resources,[7] but may be limited for use in younger patients due to size limitations of devices and access vessels and are currently only employed in 3% of pediatric vascular trauma cases nationally.[8] This review will provide a high-level overview of applicable endovascular techniques and open operative exposure, as well as point out useful references and training

*Abbreviations:* ATLS, advanced trauma life support; TBI, traumatic brain injury; FAST, focused abdominal ultrasound for trauma; CT, computed tomography; TEVAR, thoracic endovascular aortic repair; SMA, superior mesenteric artery; IVC, inferior vena cava; SMV, superior mesenteric vein; VTE, venous thromboembolic disease; REBOA, resuscitative endovascular balloon occlusion of the aorta; BEST, basic endovascular skills for trauma; EDT, emergency department thoracotomy; ASSET, advanced surgical skills for exposure in trauma.

* Corresponding author.
*E-mail addresses:* lauren.evans@cshs.org (L.L. Evans), shahram.aarabi@ucsf.edu (S. Aarabi), rachelle.durand@ucsf.edu (R. Durand), jeffrey.upperman@vumc.org (J.S. Upperman), Aaron.Jensen@UCSF.edu (A.R. Jensen).

https://doi.org/10.1016/j.sempedsurg.2021.151126
1055-8586/

resources to facilitate maintenance of a working knowledge of managing these injuries in children.

## Injury epidemiology, risk factors, and initial trauma bay assessment

The most critical aspect for managing a major torso vascular injury is rapid recognition of the injury to be addressed, which requires a keen awareness of associations with mechanistic and anatomic risk factors and a high index of suspicion in the trauma bay. While major vascular injury may commonly present with unmitigated hemorrhage and hypotension, some injuries – particularly blunt injury – may present with signs of vascular occlusion and ischemia from dissection or thrombosis. Many pediatric surgeons may never see one of these injuries, as even the busiest trauma centers publish rates of one to four cases of pediatric torso vascular injury per year.[2,3,5,9] While major vascular injury most commonly results from a penetrating mechanism (57–68% of cases overall), blunt trauma does contribute to a significant number of torso vascular injuries.[1,2,5] Blunt torso vascular injures are generally associated with rapid deceleration injury sustained in a high-mechanism motor vehicle collision or fall, or with crush injury leading to a rapid change in intra-thoracic or intra-abdominal pressure.[10,11] Blunt arterial injury can present with dissection or luminal thrombosis, rather than free hemorrhage. Blunt free aortic rupture is generally associated with immediate death at the scene of injury and these patients generally do not undergo evaluation at trauma centers.[12] Blunt venous injuries often occur in combination with arterial injury in the context of multisystem trauma, and are associated with fatality in 68% of cases.[13] Children that survive to trauma center evaluation are more likely to have contained rupture rather than unmitigated hemorrhage from major branches of the aorta or vena cava.

Initial resuscitation should follow Advanced Trauma Life Support (ATLS) protocols to maintain perfusion. Permissive hypotension has been demonstrated to be beneficial in adult patients with penetrating torso injuries and massive hemorrhage, but the benefits of this strategy have not been studied in children.[14,15] As most children with blunt torso vascular injury have multisystem trauma and associated traumatic brain injury (TBI) ,[16–18] we do not recommend employing permissive hypotension in this population. The strongest predictors of early mortality in children are penetrating mechanism, hypotension, and need for thoracotomy, highlighting the need for early and timely intervention.[19] Early recognition of massive hemorrhage with associated hemorrhagic shock can be facilitated with standardized criteria (e.g. tachycardia, hypotension, penetrating mechanism, positive Focused Assessment with Sonography for Trauma (FAST), and acidosis) that can trigger activation of a pediatric massive transfusion protocol.[20]

As with other types of injuries, torso vascular injury is more common in specific sub-populations and has a variable mechanistic injury profile associated with age. Overall, motor vehicle collision and firearm injuries are the leading causes of torso vascular injury and mortality from torso vascular injury. While the incidence of major vascular injury secondary to motor vehicle collision has decreased over the past decade – likely related to improvements in child passenger safety devices and practices, major torso vascular injury and mortality from firearm injury has not decreased.[8] Penetrating major torso vascular injury is more commonly due to assault in the infant (child physical abuse) and adolescent populations, while accidental penetrating injury is more common from ages one to ten years.[1] This highlights the importance of child abuse and violence intervention programs. Aortic injuries have a bimodal distribution, being more common in children under one year of age (again, likely to abuse) and in adolescence, while all other torso vascular injuries have a gradual increase in incidence with increasing age.[1]

Diagnostic workup during the resuscitative phase for an unstable patient may be limited to a chest radiograph and a FAST exam – prompting urgent chest tube placement, thoracotomy, or laparotomy. In pediatric patients, initial chest tube output of 20–30% of total blood volume (15–20cc/kg) or subsequent output in excess of 2–3cc/kg/h should prompt urgent thoracotomy for hemorrhage control.[21] Computed tomography (CT) scan can provide useful preoperative information for patients that have responded to initial resuscitation – particularly for patients with contained blunt vascular injuries – but the surgeon must be prepared to proceed with emergent surgical exploration and hemorrhage control with limited preoperative information in unstable patients. The presence of a widened mediastinum in a child with significant deceleration injury or crush injury should prompt a contrast-enhanced chest CT to assess for contained blunt aortic injury. In the absence of an abnormal mediastinum, chest CT is not indicated – even for high-risk associated injuries used to mandate chest CT in adults such as first rib fracture, scapula fracture, and sternal fracture – as a normal mediastinum on a supine AP chest radiograph that is unobstructed by artifact or overlying objects is sufficient for essentially ruling out mediastinal vascular injury.[22–24] Determining a ‘normal’ mediastinum in young children can be challenging due to the overlying thymic silhouette, and an ‘abnormal’ mediastinum without associated high-energy deceleration or crush mechanism does not necessarily mandate chest CT and relies on provider judgement.

In stable patients, specific skeletal injuries and exam findings should prompt vascular imaging to rule out occult vascular injury. Asymmetric brachial pulses with penetrating injury, major deceleration, or crush injury – particularly in the presence of a fracture to the medial 1/3 of the clavicle, or an apical pleural cap on chest radiograph should prompt CT angiogram of the chest to assess for subclavian injury. As administration of venous contrast can create significant artifact on the ipsilateral side of the contrast injection, contrast should be administered either through the contralateral extremity or through a femoral catheter to optimize visualization of vascular structures on the concerning side. Diminished or asymmetric femoral pulses with penetrating injury, an abdominal seatbelt sign, or pelvic fracture should warrant special attention to vascular detail upon reviewing abdominal CT images.

## Penetrating mediastinal vascular injury

Penetrating injury to mediastinal vessels is highly likely to lead to prehospital mortality unless the injury occurs in close proximity to the receiving center and transport time is short.[25] While a discussion of penetrating cardiac, tracheal, or esophageal injuries is outside the scope of this paper, it goes without saying that the surgeon needs to be prepared to deal with these associated injuries. Children that do survive transport to a trauma center are generally highly unstable and are taken to the operating room for exploration with minimal preoperative imaging. Mediastinal vascular structures are best accessed through median sternotomy and pericardiotomy, although in many cases anterolateral thoracotomy may have already been performed and can be either extended across midline to a clamshell thoracotomy and/or extended up as a median sternotomy. We will discuss specific approaches to superior mediastinal vasculature, pulmonary hilar injuries, and descending thoracic injuries separately. The specific approach to subclavian injury will be discussed in the next section.

The left brachiocephalic vein traverses the superior mediastinum and is the first structure that will be encountered. The brachiocephalic vein can usually be retracted with a vessel loop, but ligation is generally well-tolerated and can be performed with little consequence if needed to facilitate rapid exposure of underlying arterial structures.[26] Non-circumferential venous injuries can be primarily repaired, but the post-operative thrombosis rate is high and anticoagulation should be considered if that is undertaken. While ligation of the proximal subclavian or brachiocephalic vein is tolerated, ipsilateral upper extremity edema should be expected and managed with arm elevation and compression sleeves. While endovascular venous interventions are rarely required in the acute setting, treatment of an occluded central vein (i.e., subclavian or brachiocephalic) in the setting of chronic arm swelling has good outcomes with endovenous recanalization with angioplasty and stenting.

Most penetrating mediastinal arterial injuries that survive transport to our trauma center can be primarily repaired and seldom require cardiopulmonary bypass. Penetrating injury to the aortic arch is controlled with side-biting clamps and is primarily repaired after debridement. Injury to the proximal innominate artery requires proximal control at the aortic takeoff. A vascular shunt is generally not required for these injuries due to excellent collateral flow to the arm and brain. Short-segment injuries can generally be primarily repaired, but longer segment injuries may require an interposition graft. Back-bleeding prior to final closure of the anastomosis is essential to avoid cerebral air embolism. Therapeutic anticoagulation with systemic intravenous heparin can be challenging during repair given other injuries but should be used if at all possible. If not, then copious irrigation of the inflow and outflow vessels with heparinized saline is recommended. Extension of the sternotomy incision up the right neck along the sternocleidomastoid can be used if exposure of the remainder of the common carotid artery is required. Similarly, extension of the sternotomy into a supraclavicular incision through the deltopectoral groove can facilitate exposure of the rest of the subclavian artery (discussed below). Needless to say, this area is rife with surgical pitfalls (i.e., brachial plexus, thoracic duct, major veins). Unless contra-indicated by associated TBI or nonoperatively managed solid organ injury, we generally recommend anti-coagulation after primary repair followed by transition to anti-platelet agents, although this is controversial, and the optimal duration is unknown.

We are highly collaborative with our congenital heart surgery colleagues for blunt injuries given their experience with mediastinal vascular reconstruction. Blunt injury to either the innominate artery or to the takeoff of the left common carotid generally leads to a dissection flap that can cause thrombosis or cerebrovascular embolism. An exclusion-bypass technique is utilized to replace the injured segment of innominate or left common carotid artery with synthetic graft. Distal control of the carotid beyond the extent of the dissection and injury is essential to prevent intraoperative embolism. Once proximal and distal control are obtained, an aortotomy is created off the ascending aorta using a side-biting clamp, and a synthetic interposition graft is sewn on proximally (**Fig. 1**). At this point, the injured innominate is opened to assess extent of injury and the interposition graft is trimmed to length and the distal anastomosis completed. The native innominate takeoff is then debrided and closed primarily. Endovascular approaches in this area can be challenging depending on the proximity of the injury to the innominate artery bifurcation into the right common carotid and subclavian arteries. A covered stent graft can be effective in excluding the innominate injury if at least 1 cm of healthy innominate artery is present distal to the injury, providing an adequate seal for stent positioning without branch exclusion. However, an injury close to the bifurcation of the innominate artery is not be well managed using endovascular techniques and open repair is recommended in order to preserve right common carotid artery and vertebral artery integrity and prevent devastating stroke.

Pulmonary hilar injuries result in catastrophic hemorrhage. Rapid takedown of the inferior pulmonary ligament and control of the entire hilum can temporize blood loss and allow for resuscitation, but the anesthesia team must be aware of the effects on the right heart as the acute increase in pulmonary vascular resistance from hilar occlusion is generally not well tolerated in children. Volume and inotropic support for the right heart is universally needed. Pneumonectomy is an option for proximal injuries, but primary vascular repair (often with the assistance of the congenital heart / cardiac transplant surgeons) or resection limited to a single lobe or bi-lobectomy is preferred to improve long-term outcomes. Stapled pulmonary tractotomy may facilitate the rapid exposure and identification of more peripheral vascular injuries in this area.[27]

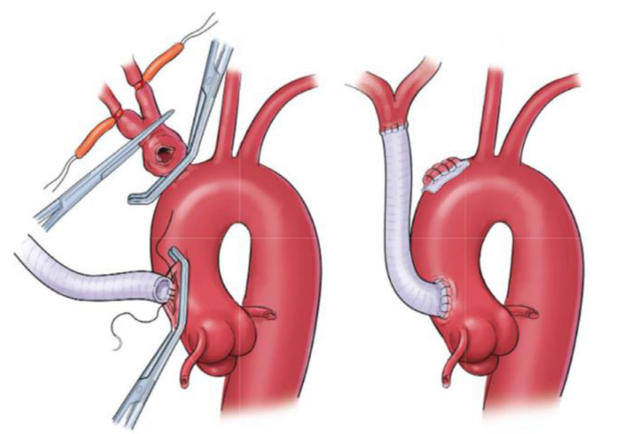

**Fig. 1.** Operative technique of exclusion and bypass grafting for repair of blunt injury to the proximal innominate artery. *Used with permission, from Feliciano DV. Cardiac, Great Vessel, and Pulmonary Injuries, in Rich's Vascular Trauma, TE Rasmussen and NRM Tai, eds. Elsevier 2016. Copyright 1981 Baylor College of Medicine.*

Survival to the ED with penetrating injury to the descending thoracic aorta is generally only observed with small injuries from knife wounds. These injuries can be through-and-through, which can be challenging to repair as mobilization of the aorta circumferentially is limited by posterior branches to the spine that should not be ligated over significant lengths of the aorta due to the risk of paraplegia. Injures to the front wall of the aorta can generally be repaired with vascular control obtained with a side-biting vascular clamp. Through-and-through injuries, however, may require opening the anterior wall of the aorta and fixing the posterior wall from the inside of the lumen. If this approach is utilized, the surgeon should expect substantial back bleeding from intercostal and spinal branches from the aorta that cannot be controlled effectively. Use of cell-saver and rapid repair of the back wall injury are key. Some have advocated the use of a shunt or partial bypass with retrograde perfusion through a femoral cannula, though this technique is more often applied to blunt aortic injury that is associated with more extensive repair and/or tube-graft replacement at this level.[28] If endovascular capabilities are readily available, stent grafts in the descending thoracic aorta have excellent outcomes. However, unlike patients with blunt aortic injuries, penetrating aortic injuries typically require immediate intervention, which should not be delayed to mobilize endovascular teams if not readily available. Additionally, current thoracic stent graft size availability limits their use in smaller aortic diameters. The smallest commercially-available aortic stent graft is currently 21 mm, and oversizing the graft more than 10% of the aortic diameter is not recommended – limiting stent graft placement to patients with a resuscitated aortic diameter of 18–19 mm. Population-based nomograms have been generated for children, with 18-year-old children having a median aortic size of 18–19 mm at the aortic isthmus. Younger 'adult-sized' children may be candidates for endovascular repair, depending on

**Table 1**
Harborview classification of blunt aortic injury.

| Injury Classification | Imaging Findings | Recommended Treatment |
|---|---|---|
| Minimal | • No External Contour Anomaly<br>• Intimal Tear or Intraluminal Thrombus < 10 mm | • No Intervention Needed<br>• Optional Follow-up Imaging |
| Moderate | • Contained External Contour Anomaly<br>• Intimal Tear or Intraluminal Thrombus > 10 mm | • Semi-Elective Repair<br>• Stabilization of Concomitant Injuries<br>• Impulse Control |
| Severe | • Active Extravasation<br>• Left Subclavian Artery Hematoma > 15 mm | • Immediate Repair<br>• Blunt Aortic Injury Takes First Priority Over Associated Injuries |

*Adapted from Heneghan RE,* et al. *J Vasc Surg 2016.*

aortic size measured on CT. Smaller aortas have alternatively been treated with off-label use of non-aortic stent grafts with unknown long-term results.

## Blunt thoracic aortic injury

Blunt injury to the thoracic aorta is well-characterized in adult patients, but rare in children – particularly young children.[17,18] Blunt injury generally occurs just distal to the subclavian takeoff at the site of the ligamentum arteriosum where the descending aorta is naturally tethered. As previously mentioned, free rupture of the aorta is universally fatal at the scene of injury, while patients surviving to the hospital generally have a contained rupture. Screening chest radiograph generally demonstrates widened mediastinum and confirmatory diagnosis is obtained with CT angiogram (preferably through a right upper extremity intravenous cannula or a central venous catheter to minimize contrast artifact) (**Fig. 2a–c**). Adult grading systems may be useful to determine the approach and speed with which the injury needs to be addressed. We prefer the Harborview criteria (**Table 1**) for its simplicity, although the SVS, Vancouver, and other systems are also used.[29] For minimal aortic injuries, no aortic-related treatment or follow up is required. For moderate aortic injuries, the focus is on the other injuries the patient has – generally these patients have high ISS scores and TBI is common – and the aortic injury can be fixed within the first several days or up to one week after presentation. In this case, impulse control (we prefer esmolol, starting dose 100mcg/kg/min with rapid up-titration usually needed) is only used if it does not compromise other injured organ systems (e.g., TBI). Pediatric blood pressure targets for blunt aortic injury have not been studied, but most children with these injuries are adolescents and adult blood pressure targets (systolic blood pressure < 100 and HR < 100) can be utilized in this age group.[30] For severe aortic injuries, immediate repair is required, and the aortic injury takes precedence over other injuries. In these cases, impulse control, right radial arterial line, central venous catheter, and rapid transport to the OR are paramount.

Historically, open repair of blunt aortic injury was routinely utilized – either with the “clamp and sew fast” technique or with partial bypass with retrograde perfusion via a femoral cannula. Although historical data for open repair of adult blunt aortic injury demonstrated 10–20% rates of paraplegia, modern series in adults show low paraplegia rates in both open and endovascular approaches.[31,32] The rate of paraplegia in children is similarly low, with modern data showing no cases of reported paraplegia after open or endovascular repair of blunt aortic injury.[33] In our center, we collaborate with the congenital cardiac surgery team for these cases due to their expertise in aortic surgery in young children derived from experience with aortic coarctation repair. Children undergoing open repair of thoracic aortic injury ($n = 35$) in this modern series have an 8% mortality rate, and significant morbidity at discharge with a 5.7% cerebrovascular accident rate and 48% of patients being discharged to acute care or long-term care facilities after a median 21-day hospital stay.[33]

In adult patients, thoracic endovascular aortic repair (TEVAR) has widely replaced the open technique for this injury (**Fig. 3a,b**).[31] Most blunt aortic injuries occur in adolescent patients, and this approach is feasible in many cases, with the youngest reported case in a seven-year-old child.[18,33,34] As noted above, TEVAR is limited in adolescents by graft size. FDA approved devices for blunt aortic injury have a minimum aortic size of 21 mm and, unlike in the treatment of aneurysms, graft oversizing is discouraged in the setting of blunt aortic injury. Poorly sized grafts can have devastating consequences: rupture or migration for undersized grafts and dissection or graft collapse for oversized grafts. In the absence of an appropriately sized graft, off-label use of other stents and stent-grafts has been described, but the long-term outcomes of these are unknown. Equally challenging in an adolescent may be the minimum access vessel size for introducing the device sheath; common femoral or external iliac arteries smaller than 7 mm cannot be accessed by currently available grafts. In all cases, detailed review of the patient’s CTA (pre-operatively) and intravascular ultrasound (intra-operatively, if available) are required along with previous familiarity of the specific device being used in order to ensure good results. Long-term outcomes after TEVAR in growing adolescents are unknown, and data suggesting ‘pseudocoartcation’[34] at the site of the stent graft as the child grows is equivocal. The common proximity of the thoracic aortic injury often requires occlusion of the left subclavian takeoff to provide an adequate length of landing zone for the covered stent-graft. While still somewhat controversial, intentional occlusion of the left subclavian takeoff is well-tolerated in the majority of cases, and most agree that selective subclavian revascularization via carotid-subclavian transposition for symptoms after TEVAR is preferred to routine prophylactic revascularization.[35]

## Subclavian injury

Injury to the subclavian vessels represents a unique challenge to the pediatric surgeon, as vascular exposure of these vessels is not routinely performed in any other aspect of pediatric general surgical practice. Penetrating injury may present with hemodynamic instability due to hemorrhage from the tract or into the ipsilateral hemithorax. Hemorrhage control with external compression is not attainable due to the overlying bony clavicle. Temporizing hemorrhage control with a foley catheter inserted through the tract into the chest with upward pressure on the back of the clavicle with the balloon up has been described and may be effective (**Fig. 4**).[36] Similarly, we have used manual pressure of the vessel against the clavicle by an eager surgical assistant while the rest of the team performs the exposure. If endovascular capabilities are readily and rapidly available, this is an ideal location for endovascular balloon occlusion and then subsequent either open or endovascular repair. Anterolateral thoracotomy or clamshell thoracotomy do not provide adequate exposure for these injuries. Similarly, in our experience, a high anterior thoracotomy as has been often described does not provide adequate exposure of all parts of the subclavian artery. Our preferred approach is a sternotomy with supraclavic-

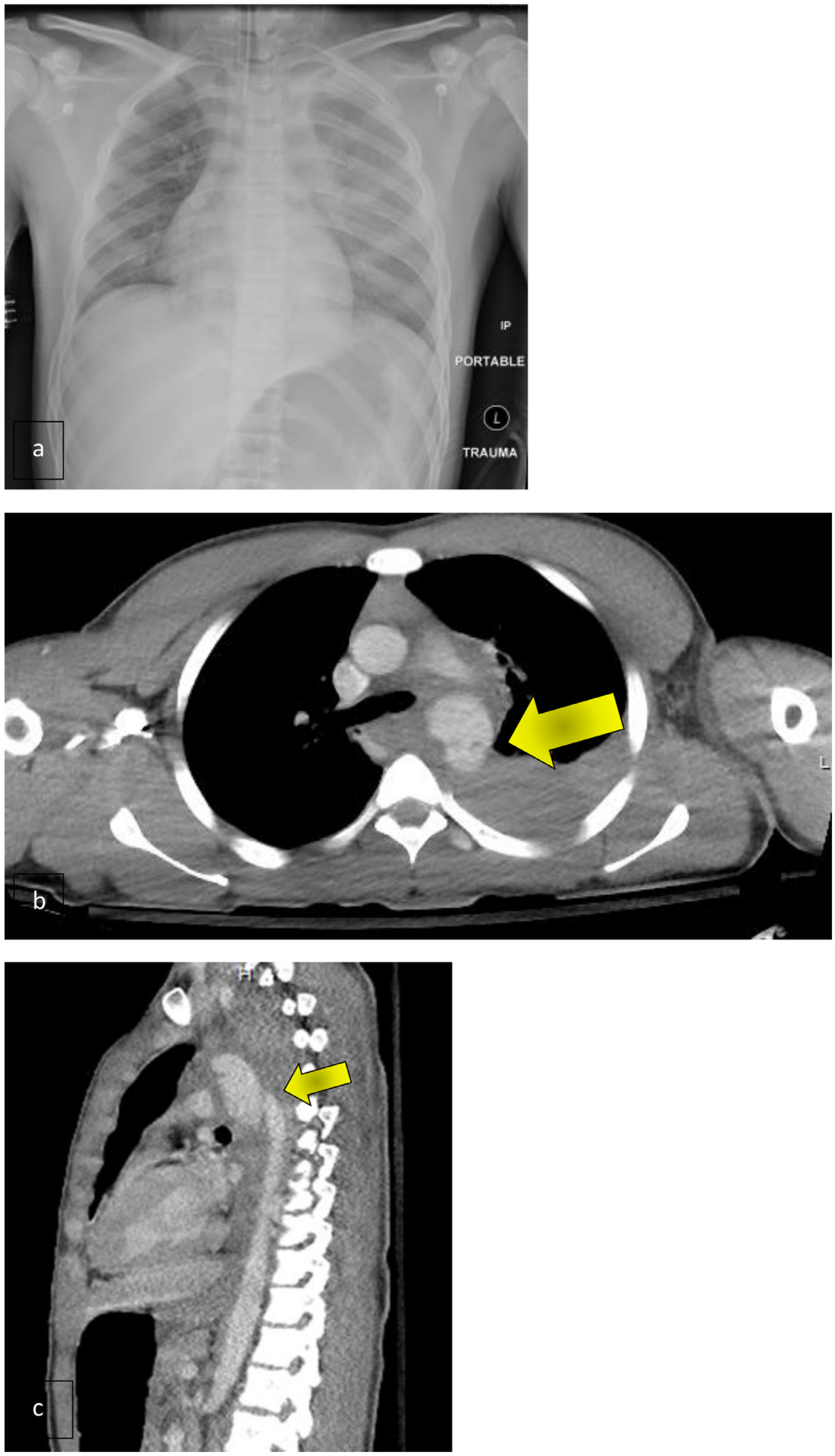


**Fig. 2.** Images from a 14-year-old child involved in a head-on motor vehicle collision demonstrate (a) widened mediastinum and pleural effusion on initial AP chest radiograph, and severe blunt aortic injury in (b) axial and (c) sagittal section on contrast-enhanced chest CT.

ular extension for proximal/mid subclavian artery injuries and a supraclavicular incision extended into the deltopectoral and bicipital grooves for distal subclavian or axillary artery injuries **(Fig. 5)**.[37] These provide wide exposure and reliable proximal control which are ideal for trauma. Although the so-called trap-door thoracotomy provides excellent exposure and may be used in cases where one has already committed to an anterior thoracotomy, it is quite morbid and should be avoided if possible. Control of the entire subclavian artery requires attention to the recurrent laryngeal nerve (proximal), division of the anterior scalene and preservation of the phrenic nerve and thoracic duct (middle), and careful attention to the brachial plexus (distal).

Blunt injury to the subclavian artery may occur from high-mechanism blunt trauma with deceleration injury, or as a proximity injury from a nearby passing missile. These injures may present with a contained hematoma or with intimal disruption with a dissection flap or thrombosis. For the patient with a contained hematoma and to prevent free rupture, we prefer endovascular balloon control followed by stenting if available. These endovascular techniques can be performed in collaboration with

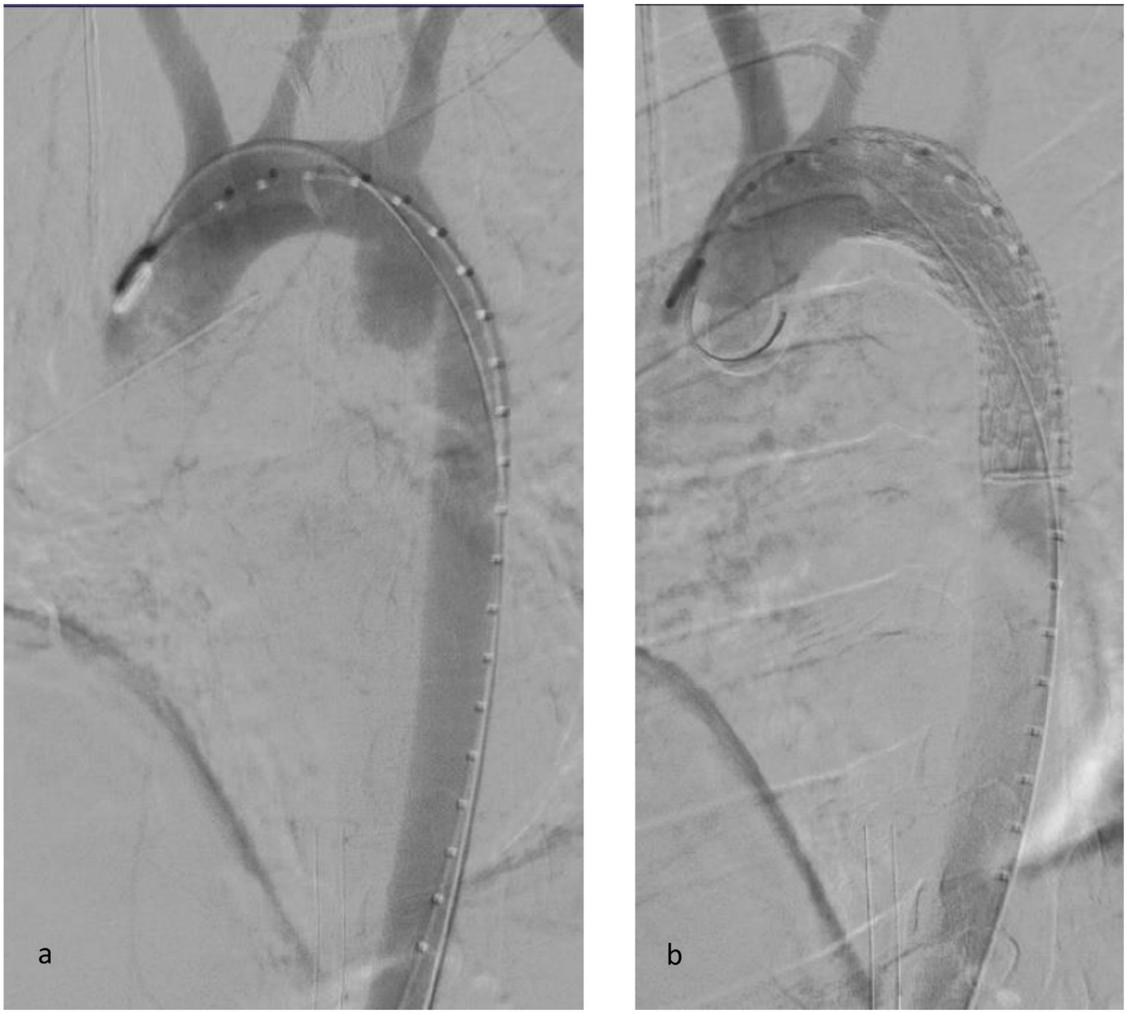


**Fig. 3.** Aortogram demonstrates (a) blunt aortic injury at the typical location distal to the left subclavian takeoff, which is (b) excluded by endovascular placement of a covered stent graft. Due to proximity of the injury, the left subclavian takeoff must be covered by the stent graft to adequately exclude the injury.

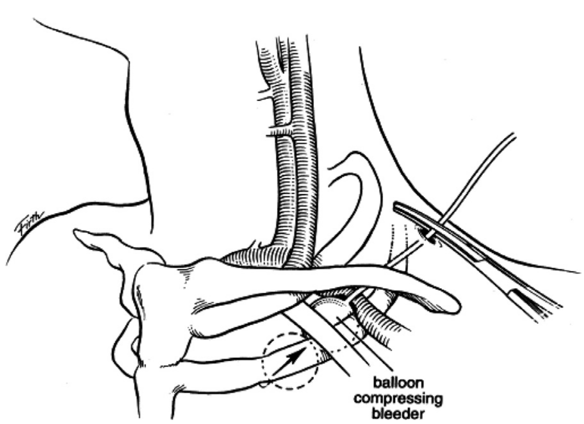


**Fig. 4.** Illustration of the use of a foley catheter to attempt hemorrhage control from penetrating subclavian injury. The catheter is advanced through the missile tract, the balloon inflated in the pleural space, and traction pulled up on the catheter to compress the injury against the posterior aspect of the clavicle. *Used with permission, from Demetriades D, Chahwan S, Gomez H,* et al. *Penetrating Injuries to the Subclavian and Axillary Vessels. J Am Coll Surg. 1999;188(3):290–295.*

interventional pediatric cardiology, interventional radiology, or adult vascular surgery. Stent graft occlusion is particularly common in this location[38] given that the stent graft is subject to extrinsic compression where it passes under the clavicle and through the thoracic outlet. Interestingly, most cases remain asymptomatic and do not develop arm ischemia even despite stent graft occlusion. For indications of vessel thrombosis, these injuries only need to be addressed urgently (typically with open revascularization) in the rare cases that they have stroke or arm ischemia symptoms at initial presentation. Otherwise, they can be observed and have attempted endovascular balloon angioplasty or repaired electively if they develop symptoms of chronic arm ischemia (i.e., claudication) using open techniques.

## Abdominal vascular injury

Unlike adults, abdominal vascular injuries in pediatric trauma most frequently occur after blunt injury from mechanisms involving a high velocity energy transfer such as in motor vehicle collisions and pedestrian injuries.[3,16,39] While the surgeon may occasionally have the benefit of a preoperative CT scan with detail of vascular anatomy, most children with abdominal vascular injury are too unstable to obtain a CT and will be taken for empiric exploration. A substantial amount of hemoperitoneum should be expected and systematic packing to allow identification of the source of hemorrhage should be employed. Proximal control of the aorta can be obtained rapidly at the level of the diaphragm by opening the pars flaccida of the hepatogastric ligament and applying compression to the spine at the level of the crura. Opening the crura posterior to the gastroesophageal junction is more time

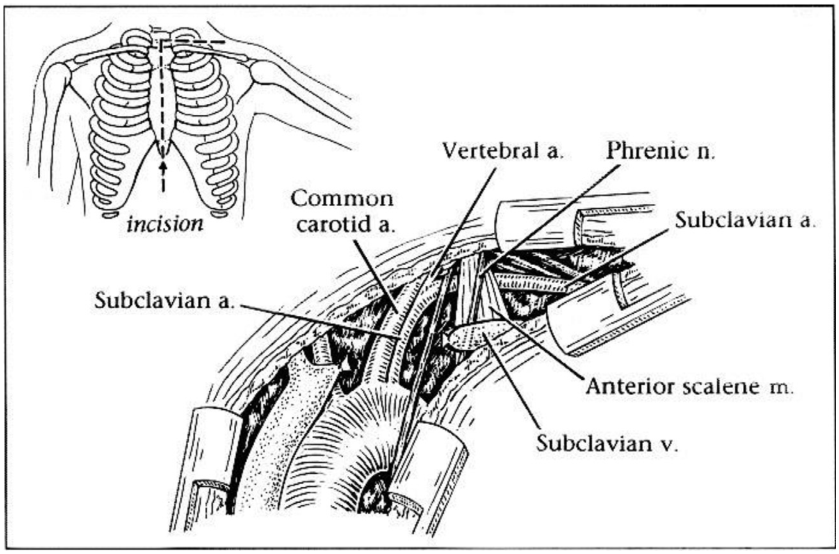


**Fig. 5.** Exposure of subclavian vascular injury is best achieved by median sternotomy to achieve proximal control with clavicular incision (including transection and removal of the proximal clavicle) extending out to the deltopectoral groove. Division of the anterior scalene may be necessary, and injury to the adjacent phrenic nerve, recurrent laryngeal nerve, thoracic duct, and brachial plexus must be avoided. *Used with permission, from Hajarizadeh H, Rohrer MJ, Cutler BS. Surgical exposure of the left subclavian artery by median sternotomy and left supraclavicular extension. J Trauma. 1996 Jul;41(1):136–9.*

consuming but will allow encirclement of the aorta with a Rommel tourniquet or application of an aortic clamp to free up the surgeon's hands. Supra-celiac control of the aorta should be limited in duration due to postoperative complications of visceral ischemia with reperfusion injury, multisystem organ failure, and late mortality.[40] Data from endovascular supraceliac occlusion has reported occlusion times to be safe if confined to under 20 min,[41] although longer occlusion of 30–60 min has been tolerated.[42] Changes in the fibrinolytic cascade have been demonstrated after just 30 min of crossclamp time in animal studies.[43]

*Mesenteric vascular injuries*

Exposure of the supra-celiac aorta and the origins of the visceral segments is best obtained via a left medial visceral rotation, bringing the descending colon, spleen, and tail of the pancreas medially. The left kidney may or may not need to be medialized, depending on the injury being addressed. Injury to the celiac origin and its proximal branches is rare. The left gastric, splenic, or common hepatic proximal to the gastroduodenal artery can all be ligated rather than repaired as long as the superior mesenteric artery (SMA) remains patent to provide collateral supply.[39] Injuries to the proximal SMA cannot be simply ligated. Simple injuries can be primarily repaired with fine prolene, but transection or near-transection requires an interposition graft. A temporary vascular shunt can be inserted for damage control and to allow time to harvest saphenous vein for the interposition graft. Our preference is the commercially available argyle shunt kit (contains four shunts – sizes 8–14 french, Cardinal Health, Dublin, OH) that we keep on the shelf in the operating room, or an argyle straight chest tube will suffice for larger vessels. Injuries to the distal SMA can be ligated with a plan for second-look laparotomy and resection of segments that develop ischemia. Injuries to the inferior mesenteric artery can be ligated with minimal consequence.

*Inferior vena cava injuries*

Inferior vena cava (IVC) injuries occur more commonly from a penetrating mechanism and have a high associated mortality.[13,44] Blunt injury contained to the retroperitoneum without other injuries necessitating laparotomy should generally be nonoperatively managed as the low-pressure flow may tamponade.[45,46] For patients with retroperitoneal cava injury that require laparotomy for associated injuries, we prefer to manage the cava injury with packing and temporary abdominal closure and rely on tamponade in most cases. Judicious fluid resuscitation avoiding fluid overload and increased central venous pressures may increase the probability of successful nonoperative management. Penetrating injuries or blunt injuries with free hemorrhage into the peritoneum and hemodynamic instability require operative control. Exposure is best attained via a right-sided medial visceral rotation bringing the ascending colon medial with a broad kocherization of the duodenum and head of the pancreas. Inflow and outflow control of the IVC can be obtained with manual compression or sponge sticks either above or below the renal veins. Back-bleeding from lumbar veins should be expected despite inflow and outflow control. As most of these patients are in extremis, we recommend simple repair for small injuries and ligation without reconstruction for larger injuries, regardless of location of the injury on the IVC. For more stable patients, reconstruction can be attempted via patch or (more likely) Dacron interposition graft, particularly for injuries above the renal veins. For repairs, we recommend using a large needle, as blood may well up quickly from back-bleeding and a small needle can be challenging to locate. Similar to aortic through-and-through injuries, backwall injuries to the IVC are best repaired transluminally, as exposure of the posterior wall can be challenging due to tethering by lumbar vessels that limit mobility and can bleed significantly if avulsed. A series of Allis clamps along the line of injury can be used to approximate the vein wall to facilitate repair. Patients generally tolerate ligation of the IVC below the renal veins in the short term surprisingly well; in our experience they do not progress to lower extremity compartment syndrome or require fasciotomies. To minimize post-operative and chronic lower extremity edema, the lower extremities should remain elevated and compression dressings with wraps should be applied.[39] Survivors may experience chronic venous insufficiency of the lower extremities, but otherwise long-term sequelae are rare.[47] Regardless of type of repair, a course of 3 to 6 months of therapeutic post-operative anticoagulation is required to prevent thromboembolic complications.

Injuries to the retrohepatic IVC represent a major challenge and are associated with a high rate of mortality.[39] The patient's best chance at survival is if the bleeding can be controlled with peri-hepatic packing and allowed to tamponade. We intentionally do NOT mobilize the liver as to not release the retroperitoneal containment of the hematoma. For bleeding that does not stop with packing, complete mobilization of the liver to expose the retro-hepatic cava and taking down the diaphragm to expose the supra-hepatic segment may be necessary to repair the injury. Inflow control needs to be obtained inferiorly above the level of the renal veins and at the porta hepatis with a Pringle maneuver. Control of the supra-hepatic cava is challenging due to the short length of this vessel. Sternotomy with pericardiotomy and control of the IVC within the pericardium offers a clean approach to suprahepatic cava control. These maneuvers, in theory, provide vascular isolation, but take a considerable amount of time and clamping the IVC at the level of the diaphragm in a hypovolemic patient risks immediate cardiovascular collapse. For this reason, we emphasize attempts at control with packing to allow for resuscitation and re-exploration with the assistance of a multidisciplinary team. We have found that this multidisciplinary approach with pediatric surgery, transplant surgery, and cardiac surgery is beneficial. In centers with endovascular expertise, fenestrated stent grafts that do not occlude hepatic venous drainage have been used to address retrohepatic IVC injuries.[48]

*Portal and mesenteric venous injuries*

Portal venous injures are exceedingly rare and are associated with a high rate of mortality.[16] If the hepatic artery is patent, the portal vein can be ligated if tissue loss precludes primary repair. However, ligation is poorly tolerated and associated with poor outcomes and high mortality.[39] Exposure is improved with takedown of the hepatic flexure and a wide kocherization of the duodenum and pancreatic head. If ligation is necessary, the surgeon should anticipate high postoperative fluid resuscitation requirements and massive bowel wall edema. Temporary abdominal closure (leaving the fascia and skin open with a negative pressure wound dressing over a fenestrated bowel bag covering the abdominal wall defect) with intra-abdominal pressure monitoring and planned second-look laparotomy is mandatory.[39,49] Injuries to the proximal superior mesenteric vein (SMV) are challenging due to the anatomic location behind the pancreas, anatomic distortion from the retroperitoneal hematoma, and back-bleeding from splenic venous return. The pancreas may need to be divided to control injuries to the most proximal aspect of the SMV. Injuries without tissue loss should be repaired primarily, but the approach to long-segment repairs is controversial. Repair with a saphenous vein interposition graft is possible but takes time and leads to ongoing blood loss in an unstable patient. Outcomes analysis suggests that patients that undergo SMV ligation have similar mortality to those that undergo repair.[50] Venous shunting as a temporizing measure with a large shunt (we would use a trimmed piece of a large chest tube) has been described and could help in select cases so that reconstruction could be performed after the patient is stabilized.

## Iliac injuries

Injuries to the iliac vessels commonly involve concomitant injury to both the artery and the vein.[51] Penetrating injury with an expanding pelvic hematoma should be explored unless endovascular expertise is immediately available to embolize internal iliac branches. Exposure is obtained with medial rotation of the descending and sigmoid colon, with care to identify the ureter as it crosses the iliac blood vessels at the pelvic brim. Inflow control can be obtained initially at the level of the distal aorta just above the bifurcation and obtained more distally once the source of bleeding is identified. Care must be taken encircling the iliac arteries as the accompanying veins are immediately posterior and easy to injure – if they are not injured already. Back-bleeding from cross-pelvis flow through the internal iliac system can be brisk, so external iliac repairs require inflow control of the common iliac as well as the ipsilateral internal iliac artery. Focal injuries to the common or external iliac arteries can be primarily repaired, but long-segment injuries will require interposition graft or patch angioplasty and are often in a contaminated field from bowel injury, so prosthetic is a poor option. We favor shunting these injuries and returning for reconstruction after resuscitation and contamination have been addressed. Reconstruction is challenging in this area because of contamination and concomitant venous injury. We prefer saphenous vein to reconstruct the external iliac artery and rifampin-soaked Dacron or cryograft for common iliac artery injuries as the saphenous vein generally has poor size match in this location. In heavily contaminated fields, an extra-anatomic bypass (fem-fem bypass) is preferred. Internal iliac injuries are challenging to access, and proximal ligation will not control deep pelvic back-bleeding and occludes the access conduit for angioembolization. An intraoperative multidisciplinary discussion with the endovascular team should occur to determine the best course of action, which is generally endovascular control with coil embolization.

Iliac venous injuries are often found in conjunction with arterial injuries and are associated with a high likelihood of mortality.[52] Primary repair can be attempted for focal injuries but has a high rate of thrombosis. Ligation is often tolerated and preferred for anything but the most accessible venous injuries, as ligation has similar rates of venous thromboembolism (VTE), lower extremity fasciotomy, and amputation to those found after repair of venous injuries. Exposure of the iliac veins is a challenge – especially on the right side – due to the overlying arteries. Ligation of the internal iliac artery can facilitate wider mobilization of the common and external iliac artery. In addition, depending on the location of the venous injury, division of the overlying common or external iliac artery can be (temporarily) performed to expose and ligate the injured vein. The divided common or external iliac artery can then be reconstructed at the same time in a stable patient or shunted and reconstructed later in an unstable patient.

## Pelvic fracture with arterial hemorrhage

Approximately 12% of pediatric pelvic fractures are associated with vascular injury, 5% of which are associated with arterial contrast extravasation on CT.[53] These fractures of the immature pelvis, however, are very rarely associated with life threatening arterial hemorrhage.[54] The boney pelvis becomes less cartilaginous around puberty and adolescents over 13 years of age are prone to unstable pelvic fractures consistent with adult injury patterns that are associated higher risk of bleeding.[55] The source of bleeding associated with a pelvic fracture may be arterial branches, the presacral venous plexus, or from bony fracture sites.[56] Specific fracture patterns are associated with risk for specific vascular injuries. Adult-pattern anterior-posterior compression injuries, including open book fractures, have the highest risk of arterial hemorrhage from branches of the internal iliac vessels in close proximity to the anterior sacroiliac joint.[54,57] If pelvic bleeding is suspected during the initial evaluation and resuscitation of a patient with an anterior-posterior pelvic compression fracture, a pelvic binder or sheet should be applied early to decrease the volume of the of the pelvis and tamponade venous and fracture site bleeding.[57] In hemodynamically stable patients, ongoing pelvic hemorrhage can be identified with contrast-enhanced CT with excellent accuracy.[57]

A standardized multi-disciplinary management algorithm designed to facilitate synergistic application of multi-modal interventions is essential to successful management of unstable pelvic frac-

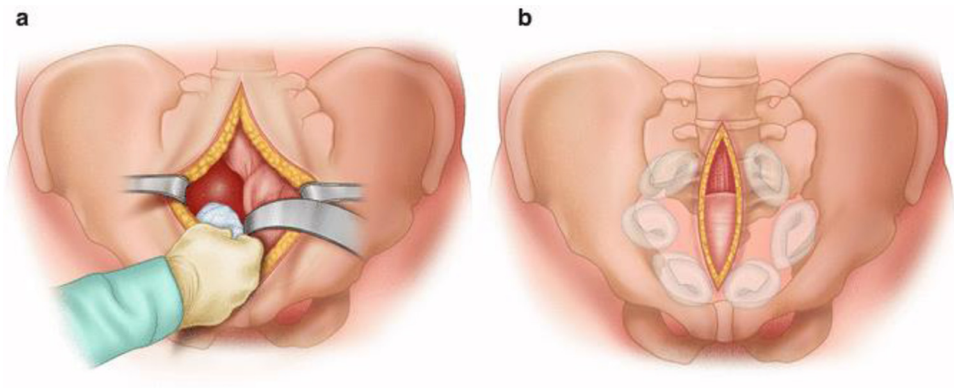


**Fig. 6.** (a) A low midline incision is used to open the abdominal wall fascia and dissect in a pre-peritoneal plane away from the pubic symphysis and pelvic brim on the left and the right, while avoiding entering into the presacral space, and (b) sequential placement of three laparotomy pads on each side of the pelvis to achieve tamponade permission, from Hak D.J., Mauffrey C. (2016) Management of Pelvic Ring Injuries. In: Pape HC., Sanders R., Borrelli, Jr. J. (eds) The Poly-Traumatized Patient with Fractures. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-47212-5_10.

tures associated with hemorrhage. Management algorithms must be based on institution-specific capabilities, resource availability and staff expertise. Persistent hemodynamic instability despite mechanical stabilization of the pelvis can be managed with preperitoneal packing or angioembolization depending on timing and resource availability.[54,57] Angioembolization for control of arterial bleeding in a hemodynamically unstable patient with pelvic fractures is outlined in the Eastern Association for the Surgery of Trauma management guidelines.[58] However, the most common source of hemorrhage in pelvic fracture is venous and will tamponade. For patients with ongoing venous bleeding despite transfusion, arterial embolization may be helpful in addressing venous bleeding by decreasing inflow. Pre-peritoneal packing is an alternative that achieves direct hemostasis for control of venous bleeding and can help temporize arterial bleeding.[57]

*Preperitoneal packing*

Preperitoneal packing can be performed quickly (20 min) and controls venous bleeding which most commonly originates from the presacral venous plexus.[56] While there are numerous indications, preperitoneal packing is particularly useful for patients in extremis despite stabilization and aggressive resuscitation with need for immediate intervention to temporize hemorrhage before angiographic resources are available. At institutions who do not offer angiography, it can be life saving for patients who are otherwise too unstable to transport.[59] Additionally, preperitoneal packing is indicated for patients with indications for emergent laparotomy and need simultaneous control of pelvic hemorrhage.

In the operating room, the patient should be placed in the supine position. The pelvis must be mechanically stabilized, or further manipulation of the pelvis can worsen hemorrhage. A low midline incision is made from the umbilicus to the pubic symphysis. The peritoneum is bluntly dissected away from the pubic symphysis and pelvic ring, leaving the peritoneum on the sacrum intact. Laparotomy pads are then placed sequentially in the space between the peritoneum and pelvic ring, below the pelvic brim, beginning posteriorly below the sacroiliac joint (Fig. 6**a,b**). The laparotomy pads are intended to tamponade branches of the iliac vessels and the venous plexus located just lateral to the sacrum. Generally, three laparotomy pads are placed on each side of the pelvis, however, open fractures may require more pads as the volume of the pelvis is increased. If a laparotomy is preformed simultaneously, the incisions are the same, but the peritoneum must be left intact distally to ensure pelvic tamponade is preserved.[59] The abdominal wall fascia is closed to facilitate tamponade, and the patient is re-explored at 24–48 h to remove the laparotomy pads. New packs should be placed if persistent bleeding is noted.[55] Local wound infection is the most common complication and is more common in patients with an open pelvic fracture. Risk of wound infection increases significantly in patients who require repacking at the time of initial takeback.[56,59]

*Internal iliac artery ligation*

Internal iliac artery ligation is rarely (if ever) needed in children, but can be used as an immediately available operative damage control technique to temporize pelvic exsanguination that persists despite preperitoneal packing until angioembolization can be performed.[60] Arterial control with vessel loops and Rummel tourniquets allows temporary control, but still permits subsequent access to the pelvic vasculature by the interventional radiology or endovascular team for more selective embolization. Bilateral internal iliac control may be needed due to cross-pelvis back-bleeding, and the long-term impact of permanent occlusion of bilateral internal iliacs and associated pelvic ischemia in a developing child is not known. Indications include persistent hemodynamic instability despite preperitoneal packing preventing safe transport to angiography, patients in extremis who will not survive to reach angiography, patients rapidly deteriorating in the setting of multiple sources of significant hemorrhage with need for rapid control of pelvic sources of hemorrhage, and in environments without access to angiography and alternative interventions.

*Angioembolization*

Pelvic angioembolization has been shown to be both safe and beneficial in pediatric trauma patients,[61,62] with 87% of children undergoing only a single embolization for effective control of hemorrhage.[63] Embolization has been used in approximately 20% of anterior-posterior compression fractures, vertical sheer injuries, and complex pelvic fractures.[57] Patient selection for pelvic angioembolization should be based on clinical evaluation and physiologic signs of ongoing hemorrhage, and should not be performed solely on the basis of the presence of contrast extravasation on CT in a stable patient.[64,65] The EAST guideline for adult pelvic trauma recommends angiography and possible embolization for patients with contrast extravasation on CT angiogram,[58] but some patients with active extravasation on CT can be safely and definitively managed without pelvic angioembolization.[61,65,66] Pelvic angioembolization in hemodynamically stable pediatric trauma patients has been associated with an increased risk of hospital mortality.[65] The most significant barrier to utilization of angioembolization remains the time required to mobilize necessary resources and staff, particularly for patients in extremis. In addition to preperitoneal packing, resuscitative endovascular balloon occlusion of the aorta (REBOA) can be placed as an additional temporizing measure until angioembolization is available for control of exsanguinating lower extremity hemorrhage.[39]

## Resuscitative endovascular balloon occlusion of the aorta (REBOA)

REBOA has emerged as a viable minimally invasive alternative to resuscitative thoracotomy for control of noncompressible torso hemorrhage in the adult trauma population and is utilized at over 100 level 1 adult trauma centers nationwide.[67,68] REBOA is currently indicated for control of abdominopelvic hemorrhage after blunt or penetrating trauma and is positioned in one of three locations, or zones, based on the source of bleeding (**Fig. 7**).[69] Zone I is the distal thoracic aorta and allows for supradiaphragmatic control of hemorrhage. Zone II is located between the celiac trunk and renal arteries but is rarely utilized as placement must be highly accurate. Zone III is between the renal arteries and iliac bifurcation and is indicated for bleeding from the pelvis and lower extremities.[70] REBOA is typically employed in the emergency department or operating room and access is obtained via direct cutdown, ultrasound visualization, or direct percutaneous cannulation of the common femoral artery.[41] Occlusion time is zone dependent and should be minimized to limit sequela of distal ischemia-reperfusion injury. Most studies have reported occlusion times around 20 min[41] though longer occlusion times can be tolerated (Zone 1: 30–60 min, Zone III: 60–90 min).[42] If persistent hemorrhage from the pelvis is identified after hemostasis is achieved proximally, the balloon can be repositioned from Zone I to Zone III with intra-operative fluoroscopy to facilitate preperitoneal packing and subsequent angioembolization.[68] Complications related to groin access are likely related to inadvertent cannulation of the superficial femoral artery and occur in 4–5% of patients including thromboembolic events to the lower extremity, thrombosis with limb ischemia and pseudoaneurysm.[41,71]

The use of endovascular aortic occlusion in a pediatric patient was first described in 2010 for control of a ruptured aortoesophageal fistula.[72] However, the small caliber of the femoral artery and variable size of the aorta remain barriers to adoption of REBOA in pediatric trauma patients. The REBOA-ER™ (Prytime Medical Inc., Boerne, TX) requires arterial cannulation with a 7Fr delivery system with a 3 mm outer layer. The caliber of the common femoral artery in younger patients may be too small to accommodate a 7Fr sheath, prohibiting arterial access. The pediatric aortic diameter is also smaller and varies with the child's size. However, new devices with a lower 4Fr profile (Control of Bleeding, Resuscitation, Arterial Occlusion System (COBRA-OS), Frontline Medical Technologies, Inc., London, Ontario, CA) are emerging, which may increase the adoption of REBOA in pediatric trauma patients. A recent study reported initial success estimating pediatric aortic and vascular dimensions for REBOA using the Breslow method, but further investigation is needed.[73] The common femoral artery reaches adult size during adolescence[74] and successful application of REBOA in adolescents with favorable outcomes has been reported in 2 small studies.[68,75] However, the corresponding age or weight that can safely accommodate the 7Fr catheter – as well as age-specific aortic caliper to accommodate the large adult-sized balloon, which may cause rupture or dissection – has not been investigated. Endovascular control of the aorta may be achieved in younger children by using a smaller sheath and other compliant balloons, aside from commercially available REBOA kits, under fluoroscopy and in collaboration with pediatric interventional radiology or pediatric interventional cardiology.

Concerns for over-use of REBOA due to its ease of placement have been raised in the adult population. A recent study of the American College of Surgeons Trauma Quality Improvement Program registry demonstrated that adults that received REBOA had higher mortality and complications of renal failure and lower extremity amputation (presumed from ischemia) when compared to propensity-matched controls.[76] Further study to define zone-specific indications for blunt vs penetrating trauma, improve patient selection and delineate intervention timing are needed – not only in children, but also for REBOA use in adults. Accurate and expeditious cannulation of the common femoral artery determines success of REBOA placement. Standardized provider training improves insertion skills using percutaneous and ultra-sound guided approaches for faster arterial access.[41] The Basic Endovascular Skills for Trauma (BEST) workshop and course are offered through the American College of Surgeons as an introduction to and in-depth training for REBOA.

## Emergency department thoracotomy in children

Emergency department thoracotomy (EDT) can be performed in the emergency department for patients arriving in extremis. Though potentially life-saving, the literature suggests EDT in children is over-performed by pediatric and adult trauma surgeons and has dismal associated prognosis unless applied for those patients who present with a penetrating mechanism and a witnessed loss of signs of life.[77,78] Pediatric patients without signs of life on arrival to the emergency department, regardless of mechanism, have a 100% mortality.[79,80] Mortality after EDT with witnessed loss of signs of life for blunt trauma, in particular, nears 100%.[78,79] In the last 40 years, only 2 patients have been reported to survive after EDT for blunt trauma.[77] However, EDT for penetrating trauma has been shown to be associated with 14% survival to hospital discharge in patients who have loss of signs of life within sight of a trauma center or within the trauma bay itself.[77,80]

Evidence-based guidelines for EDT in adult trauma patients have been well established for years.[81] Efforts to develop formal evidence-based pediatric practice guidelines for EDT are ongoing,[80] as outcomes after EDT in pediatric patients have been shown to be vastly different than for adult patients and application of those adult guidelines leads to unindicated and unnecessary interventions. Despite the well-demonstrated lack of survival benefit, 65% of all EDTs are performed in children presenting without signs of life and 20% of all EDTs are performed after blunt trauma.[78,80] EDT is indicated only in pediatric patients with signs of life on arrival and should not be performed in patients without signs of life regardless of mechanism.[80] The value of EDT during resuscitation of a pediatric patient presenting with signs of life after penetrating trauma to the chest or abdomen has been well established and is strongly recommended.[77,80,82] Outcomes for pediatric patients presenting after blunt trauma are dismal – regardless of initial presence of signs of life – and EDT is strongly discouraged without compelling evidence of a reversible cause of extremis.[79,82]

## Training opportunities and resources

Maintaining working knowledge and operative skills for vascular trauma exposure and repair can be challenging for pediatric surgeons. The American College of Surgeons Advanced Surgical Skills for Exposure in Trauma (ASSET) course is an invaluable training opportunity for surgeons that may be called upon to manage major torso vascular injury.[83] As previously mentioned, the

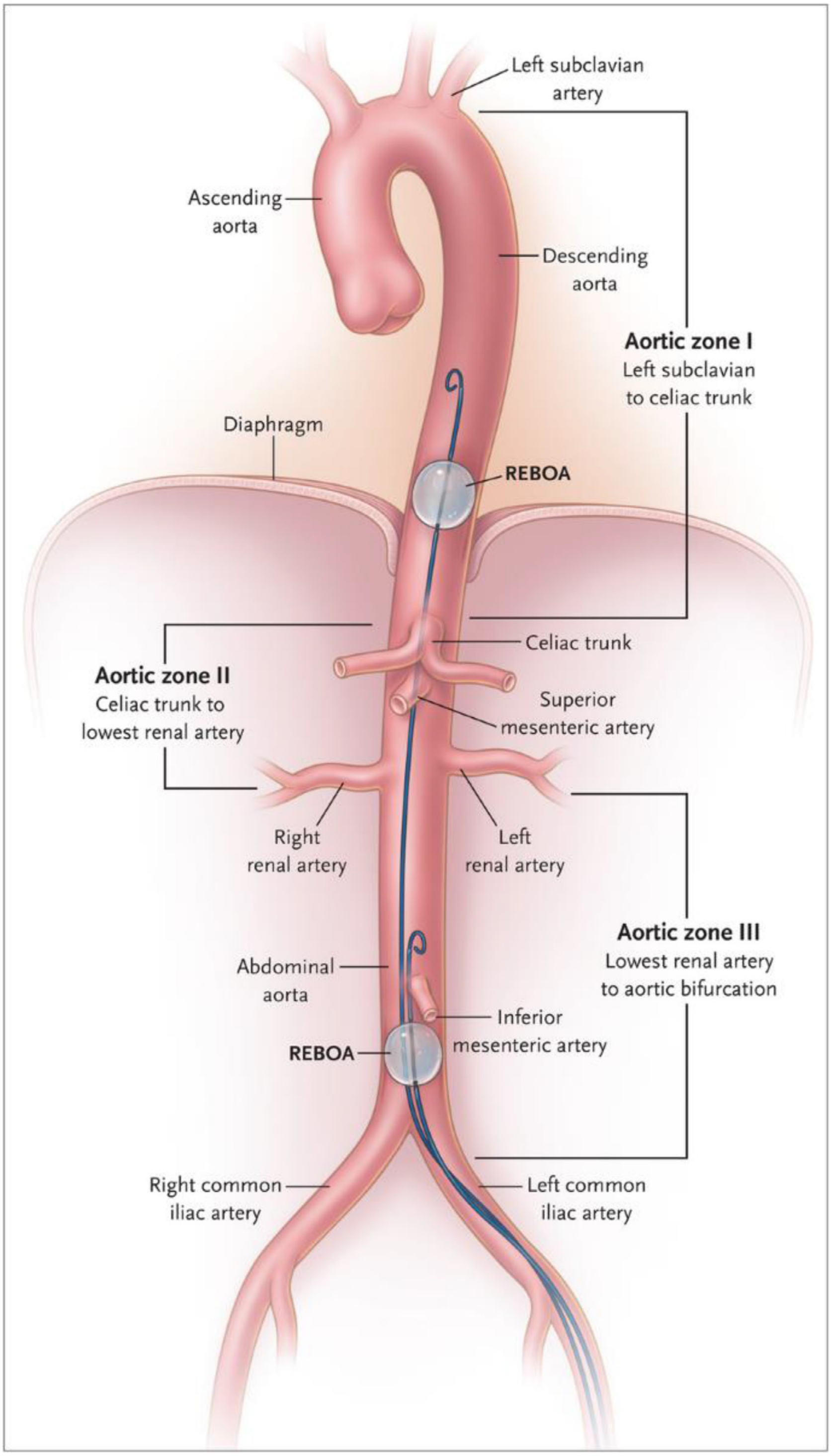


**Fig. 7.** A Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) catheter can be placed through the common femoral artery and used to occlude the aorta in Zone 1 (supraceliac), Zone 2 (visceral segment), or Zone 3. *From King DR.. Initial care of the severely injured patient. N Engl J Med 2019; 380(8):763–70. Copyright © 2019 Massachusetts Medical Society. Reprinted with permission from Massachusetts Medical Society.*

Basic Endovascular Skills for Trauma (BEST) course provides training in REBOA and other basic endovascular skills, but the applicability in children continues to be in evolution. A periodic review of an adult vascular trauma reference[84] or trauma exposure atlas[85] can also be helpful in maintaining working knowledge. The latest edition of the textbook of Trauma[86] includes operative exposure videos available through Access Surgery that can serve as an invaluable resource.

## Declaration of Competing Interest

None of the authors have any personal or financial conflicts to disclose.

## References

1. Barmparas G, Inaba K, Talving P, et al. Pediatric vs adult vascular trauma: a national trauma databank review. *J Pediatr Surg*. 2010;45:1404–1412.

2. Klinkner DB, Arca MJ, Lewis BD, Oldham KT, Sato TT. Pediatric vascular injuries: patterns of injury, morbidity, and mortality. *J Pediatr Surg*. 2007;42:178–182 discussion 182-173.
3. Allen CJ, Straker RJ, Tashiro J, et al. Pediatric vascular injury: experience of a level 1 trauma center. *J Surg Res*. 2015;196:1–7.
4. Allison ND, Anderson CM, Shah SK, et al. Outcomes of truncal vascular injuries in children. *J Pediatr Surg*. 2009;44:1958–1964.
5. Corneille MG, Gallup TM, Villa C, et al. Pediatric vascular injuries: acute management and early outcomes. *J Trauma*. 2011;70:823–828.
6. Bonasso PC, Gurien LA, Smith SD, Gowen ME, Dassinger MS. Pediatric vascular trauma practice patterns and resource availability: a survey of American college of surgeon-designated pediatric trauma centers. *J Trauma Acute Care Surg*. 2018;84:758–761.
7. Branco BC, Naik-Mathuria B, Montero-Baker M, et al. Increasing use of endovascular therapy in pediatric arterial trauma. *J Vasc Surg*. 2017;66:1175–1183 e1171.
8. Eslami MH, Saadeddin ZM, Rybin DV, et al. Trends and outcomes of pediatric vascular injuries in the United States: an analysis of the national trauma data bank. *Ann Vasc Surg*. 2019;56:52–61.
9. Kayssi A, Metias M, Langer JC, et al. The spectrum and management of noniatrogenic vascular trauma in the pediatric population. *J Pediatr Surg*. 2018;53:771–774.
10. Anderson SA, Day M, Chen MK, et al. Traumatic aortic injuries in the pediatric population. *J Pediatr Surg*. 2008;43:1077–1081.
11. Tashiro J, Hannay WM, Naves C, et al. Mechanism and mortality of pediatric aortic injuries. *J Surg Res*. 2015;198:456–461.
12. Parmley LF, Mattingly TW, Manion WC, Jahnke EJ. Nonpenetrating traumatic injury of the aorta. *Circulation*. 1958;17:1086–1101.
13. Rowland SP, Dharmarajah B, Moore HM, Dharmarajah K, Davies AH. Venous injuries in pediatric trauma: systematic review of injuries and management. *J Trauma Acute Care Surg*. 2014;77:356–363.
14. Tran A, Yates J, Lau A, Lampron J, Matar M. Permissive hypotension versus conventional resuscitation strategies in adult trauma patients with hemorrhagic shock: a systematic review and meta-analysis of randomized controlled trials. *J Trauma Acute Care Surg*. 2018;84:802–808.
15. Hughes NT, Burd RS, Teach SJ. Damage control resuscitation: permissive hypotension and massive transfusion protocols. *Pediatr Emer. Care*. 2014;30:651–656 quiz 657-658.
16. Hamner CE, Groner JI, Caniano DA, Hayes JR, Kenney BD. Blunt intraabdominal arterial injury in pediatric trauma patients: injury distribution and markers of outcome. *J Pediatr Surg*. 2008;43:916–923.
17. Heckman SR, Trooskin SZ, Burd RS. Risk factors for blunt thoracic aortic injury in children. *J Pediatr Surg*. 2005;40:98–102.
18. Karmy-Jones R, Hoffer E, Meissner M, Bloch RD. Management of traumatic rupture of the thoracic aorta in pediatric patients. *Ann Thorac Surg*. 2003;75:1513–1517.
19. McLaughlin C, Zagory JA, Fenlon M, et al. Timing of mortality in pediatric trauma patients: a national trauma data bank analysis. *J Pediatr Surg*. 2018;53:344–351.
20. Phillips R, Acker SN, Shahi N, et al. The ABC-D score improves the sensitivity in predicting need for massive transfusion in pediatric trauma patients. *J Pediatr Surg*. 2020;55:331–334.
21. Sartorelli KH, Vane DW. The diagnosis and management of children with blunt injury of the chest. *Semin Pediatr Surg*. 2004;13:98–105.
22. Hamilton NA, Bucher BT, Keller MS. The significance of first rib fractures in children. *J Pediatr Surg*. 2011;46:169–172.
23. Golden J, Isani M, Bowling J, et al. Limiting chest computed tomography in the evaluation of pediatric thoracic trauma. *J Trauma Acute Care Surg*. 2016;81:271–277.
24. American College of Surgeons Trauma Quality Improvement Program. ACS TQIP Best Practices Guidelines in Imaging. https://www.facs.org/-/media/files/quality-programs/trauma/tqip/imaging_guidelines.ashx. Accessed September 9, 2021.
25. Swaroop M, Straus DC, Agubuzu O, et al. Pre-hospital transport times and survival for Hypotensive patients with penetrating thoracic trauma. *J Emerg Trauma Shock*. 2013;6:16–20.
26. McPhee A, Shaikhrezai K, Berg G. Is it safe to divide and ligate the left innominate vein in complex cardiothoracic surgeries? *Interact Cardiovasc Thorac Surg*. 2013;17:560–563.
27. Asensio JA, Demetriades D, Berne JD, et al. Stapled pulmonary tractotomy: a rapid way to control hemorrhage in penetrating pulmonary injuries. *J Am Coll Surg*. 1997;185:486–487.
28. Crestanello JA, Zehr KJ, Mullany CJ, et al. The effect of adjuvant perfusion techniques on the incidence of paraplegia after repair of traumatic thoracic aortic transections. *Mayo Clin Proc*. 2006;81:625–630.
29. Heneghan RE, Aarabi S, Quiroga E, et al. Call for a new classification system and treatment strategy in blunt aortic injury. *J Vasc Surg*. 2016;64:171–176.
30. Fabian TC, Davis KA, Gavant ML, et al. Prospective study of blunt aortic injury: helical CT is diagnostic and antihypertensive therapy reduces rupture. *Ann Surg*. 1998;227:666–676 discussion 676-667.
31. Von Oppell UO, Dunne TT, De Groot MK, Zilla P. Traumatic aortic rupture: twenty-year metaanalysis of mortality and risk of paraplegia. *Ann Thorac Surg*. 1994;58:585–593.
32. Grigorian A, Spencer D, Donayre C, et al. National trends of thoracic endovascular aortic repair versus open repair in blunt thoracic aortic injury. *Ann Vasc Surg*. 2018;52:72–78.
33. Hasjim BJ, Grigorian A, Barrios C, et al. National trends of thoracic endovascular aortic repair versus open thoracic aortic repair in pediatric blunt thoracic aortic injury. *Ann Vasc Surg*. 2019;59:150–157.
34. Nicholas NW, Shaw DR, Puppala S. Pictorial review on the endovascular management of paediatric aortic injuries. *Br J Radiol*. 2020;93.
35. Voigt SL, Bishawi M, Ranney D, et al. Outcomes of carotid-subclavian bypass performed in the setting of thoracic endovascular aortic repair. *J Vasc Surg*. 2019;69:701–709.
36. Demetriades D, Chahwan S, Gomez H, et al. Penetrating injuries to the subclavian and axillary vessels. *J Am Coll Surg*. 1999;188:290–295.
37. Hajarizadeh H, Rohrer MJ, Cutler BS. Surgical exposure of the left subclavian artery by median sternotomy and left supraclavicular extension. *J Trauma*. 1996;41:136–139.
38. Waller CJ, Cogbill TH, Kallies KJ, et al. Contemporary management of subclavian and axillary artery injuries-A western trauma association multicenter review. *J Trauma Acute Care Surg*. 2017;83:1023–1031.
39. Kobayashi L, Coimbra R, Goes AMO, et al. American association for the surgery of trauma-world society of emergency surgery guidelines on diagnosis and management of abdominal vascular injuries. *J Trauma Acute Care Surg*. 2020;89:1197–1211.
40. Yeung KK, Groeneveld M, Lu JJ, et al. Organ protection during aortic cross–clamping. *Best Pract Res Clin Anaesthesiol*. 2016;30:305–315.
41. Bekdache O, Paradis T, Shen YBH, et al. Resuscitative endovascular balloon occlusion of the aorta (REBOA): indications: advantages and challenges of implementation in traumatic non-compressible torso hemorrhage. *Trauma Surg Acute Care Open*. 2019;4.
42. Hoareau GL, Tibbits EM, Beyer CA, et al. Resuscitative endovascular balloon occlusion of the aorta: review of the literature and applications to veterinary emergency and critical care. *Front Vet Sci*. 2019;6:197.
43. Haithcock BE, Shepard AD, Raman SB, et al. Activation of fibrinolytic pathways is associated with duration of supraceliac aortic cross-clamping. *J Vasc Surg*. 2004;40:325–333.
44. Sirinek KR, Gaskill HV, Root HD, Levine BA. Truncal vascular injury–factors influencing survival. *J Trauma*. 1983;23:372–377.
45. Buckman RF, Miraliakbari R, Badellino MM. Juxtahepatic venous injuries: a critical review of reported management strategies. *J Trauma*. 2000;48:978–984.
46. Netto FA, Tien H, Hamilton P, et al. Diagnosis and outcome of blunt caval injuries in the modern trauma center. *J Trauma*. 2006;61:1053–1057.
47. Sullivan PS, Dente CJ, Patel S, et al. Outcome of ligation of the inferior vena cava in the modern era. *Am J Surg*. 2010;199:500–506.
48. Wang TG, Liu RH, Li FS, et al. A temporary stent graft as a new shunt for juxtahepatic vena cava injury. *J Trauma Acute Care Surg*. 2014;77:351–355.
49. Fraga GP, Bansal V, Fortlage D, Coimbra RA. 20-year experience with portal and superior mesenteric venous injuries: has anything changed? *Eur J Vasc Endovasc Surg*. 2009;37:87–91.
50. Asensio JA, Petrone P, Garcia-Nuñez L, et al. Superior mesenteric venous injuries: to ligate or to repair remains the question. *J Trauma*. 2007;62:668–675 discussion 675.
51. Asensio JA, Petrone P, Roldán G, et al. Analysis of 185 iliac vessel injuries: risk factors and predictors of outcome. *Arch Surg*. 2003;138:1187–1193 discussion 1193-1184.
52. Magee GA, Cho J, Matsushima K, et al. Isolated iliac vascular injuries and outcome of repair versus ligation of isolated iliac vein injury. *J Vasc Surg*. 2018;67:254–261.
53. Mulder MB, Maggart MJ, Yang WJ, et al. Outcomes of pediatric pelvic fractures: a level I trauma center's 20-year experience. *J Surg Res*. 2019;243:515–523.
54. DeFrancesco CJ, Sankar WN. Traumatic pelvic fractures in children and adolescents. *Semin Pediatr Surg*. 2017;26:27–35.
55. Banerjee S, Barry MJ, Paterson JM. Paediatric pelvic fractures: 10 years experience in a trauma centre. *Injury*. 2009;40:410–413.
56. Filiberto DM, Fox AD. Preperitoneal pelvic packing: technique and outcomes. *Int J Surg*. 2016;33:222–224.
57. Hak DJ, Smith WR, Suzuki T. Management of hemorrhage in life-threatening pelvic fracture. *J Am Acad Orthop Surg*. 2009;17:447–457.
58. Cullinane DC, Schiller HJ, Zielinski MD, et al. Eastern association for the surgery of trauma practice management guidelines for hemorrhage in pelvic fracture–update and systematic review. *J Trauma*. 2011;71:1850–1868.
59. Burlew CC, Moore EE, Smith WR, et al. Preperitoneal pelvic packing/external fixation with secondary angioembolization: optimal care for life-threatening hemorrhage from unstable pelvic fractures. *J Am Coll Surg*. 2011;212:628–635 discussion 635-627.
60. DuBose J, Inaba K, Barmparas G, et al. Bilateral internal iliac artery ligation as a damage control approach in massive retroperitoneal bleeding after pelvic fracture. *J Trauma*. 2010;69:1507–1514.
61. Gonzalez KW, Dalton BG, Kerisey MC, Aguayo P, Juang D. Pelvic angiography for trauma in children: a rare but useful adjunct. *Eur J Pediatr Surg*. 2017;27:196–199.
62. Gakumazawa M, Toida C, Muguruma T, et al. Transcatheter arterial embolisation is efficient and safe for paediatric blunt torso trauma: a case-control study. *BMC Emerg Med*. 2020;20:86.
63. Vo NJ, Althoen M, Hippe DS, et al. Pediatric abdominal and pelvic trauma: safety and efficacy of arterial embolization. *J Vasc Interv Radiol*. 2014;25:215–220.
64. El-Haj M, Bloom A, Mosheiff R, Liebergall M, Weil YA. Outcome of angiographic embolisation for unstable pelvic ring injuries: factors predicting success. *Injury*. 2013;44:1750–1755.

65. Katayama Y, Kitamura T, Hirose T, et al. Pelvic angiography is effective for emergency pediatric patients with pelvic fractures: a propensity-score-matching study with a nationwide trauma registry in Japan. *Eur J Trauma Emerg Surg*. 2021;47:515–521.
66. Juern JS, Milia D, Codner P, et al. Clinical significance of computed tomography contrast extravasation in blunt trauma patients with a pelvic fracture. *J Trauma Acute Care Surg*. 2017;82:138–140.
67. DuBose JJ, Scalea TM, Brenner M, et al. The AAST prospective aortic occlusion for resuscitation in trauma and acute care surgery (AORTA) registry: data on contemporary utilization and outcomes of aortic occlusion and resuscitative balloon occlusion of the aorta (REBOA). *J Trauma Acute Care Surg*. 2016;81:409–419.
68. Smith AD, Hudson J, Moore LJ, Scalea TM, Brenner ML. Resuscitative endovascular balloon occlusion of the aorta (REBOA) for temporization of hemorrhage in adolescent trauma patients. *J Pediatr Surg*. 2020;55:2732–2735.
69. King DR. Initial care of the severely injured patient. *N Engl J Med*. 2019;380:763–770.
70. Thrailkill MA, Gladin KH, Thorpe CR, et al. Resuscitative endovascular balloon occlusion of the aorta (REBOA): update and insights into current practices and future directions for research and implementation. *Scand J Trauma Resusc Emerg Med*. 2021;29:8.
71. Manzano-Nunez R, Orlas CP, Herrera-Escobar JP, et al. A meta-analysis of the incidence of complications associated with groin access after the use of resuscitative endovascular balloon occlusion of the aorta in trauma patients. *J Trauma Acute Care Surg*. 2018;85:626–634.
72. Hill SJ, Zarroug AE, Ricketts RR, Veeraswamy R. Bedside placement of an aortic occlusion balloon to control a ruptured aorto-esophageal fistula in a small child. *Ann Vasc Surg*. 2010;24:e827–e829 822.
73. Carrillo L, Skibber M, Kumar A, et al. A morphometric model for endovascular occlusion of the retrohepatic vena cava in pediatric trauma. *J Surg Res*. 2019;241:215–221.
74. Sandgren T, Sonesson B, Ahlgren R, Länne T. The diameter of the common femoral artery in healthy human: influence of sex, age, and body size. *J Vasc Surg*. 1999;29:503–510.
75. Norii T, Miyata S, Terasaka Y, et al. Resuscitative endovascular balloon occlusion of the aorta in trauma patients in youth. *J Trauma Acute Care Surg*. 2017;82:915–920.
76. Joseph B, Pandit V, Aziz H, et al. Rehabilitation after trauma; does age matter? *J Surg Res*. 2013;184:541–545.
77. Moskowitz EE, Burlew CC, Kulungowski AM, Bensard DD. Survival after emergency department thoracotomy in the pediatric trauma population: a review of published data. *Pediatr Surg Int*. 2018;34:857–860.
78. Allen CJ, Valle EJ, Thorson CM, et al. Pediatric emergency department thoracotomy: a large case series and systematic review. *J Pediatr Surg*. 2015;50:177–181.
79. Flynn-O'Brien KT, Stewart BT, Fallat ME, et al. Mortality after emergency department thoracotomy for pediatric blunt trauma: analysis of the national trauma data bank 2007-2012. *J Pediatr Surg*. 2016;51:163–167.
80. Prieto JM, Van Gent JM, Calvo RY, et al. Nationwide analysis of resuscitative thoracotomy in pediatric trauma: time to differentiate from adult guidelines? *J Trauma Acute Care Surg*. 2020;89:686–690.
81. Seamon MJ, Haut ER, Van Arendonk K, et al. An evidence-based approach to patient selection for emergency department thoracotomy: a practice management guideline from the eastern association for the surgery of trauma. *J Trauma Acute Care Surg*. 2015;79:159–173.
82. Pearson EG, Fitzgerald CA, Santore MT. Pediatric thoracic trauma: current trends. *Semin Pediatr Surg*. 2017;26:36–42.
83. American college of surgeons committee on trauma. Advanced surgical skills for exposure in trauma (ASSET). American college of surgeons. Chicago, IL. 2000.
84. Rich's Vascular Trauma. *TE Rasmussen and NRM Tai (Eds.)*. 3rd ed. Philadelphia, PA: Elsevier; 2016.
85. Demetriades D, Inaba K, Velmahos G. *Atlas of surgical techniques in trauma*. 2nd Edition. New York, NY: Cambridge University Press; 2020.
86. Trauma. *Trauma*. 9th ed. McGraw Hill; 2021.