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Combat Vascular Trauma Management for the General Surgeon

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Abstract

Purpose of Review This review focuses on the initial management and stabilization of complex vascular injuries for the general surgeon within the combat zone.

Recent Findings Recent conflicts in Iraq, Afghanistan, and Syria demonstrate that general surgeons are responsible for the initial surgical management of combat-related vascular trauma in damage control scenarios. These injuries display a more complex injury pattern and often require different management strategies than seen in civilian trauma.

Summary Vascular trauma in combat settings is often accompanied by a multitude of life- and limb-threatening injuries. Definitive repair operations are often deferred for initial damage control surgery and resuscitation. Resultant strategies to restore perfusion and control bleeding are determined by the patient's underlying physiology and frequently require the use of vascular shunts, ligation, primary anastomosis, or interposition grafting. While general surgeons in the combat zone are not typically responsible for definitive repair during initial damage control surgery, proper initial surgical management in the far-forward setting with an intimate understanding of future repair strategies remains critical aspects in assuring optimal definitive treatment.

Keywords Vascular trauma · Vascular injury · Combat trauma · Penetrating vascular injury · Vascular injury stabilization · Arterial injury

Introduction

Hemorrhage remains a leading cause of death in the combat setting [1]. The widespread use of extremity tourniquets has substantially decreased the amount of exsanguination from extremity trauma [2]. Noncompressible truncal hemorrhage remains the last preventable cause of combat death without an immediate solution offered within the Tactical Combat Casualty Care guidelines [3•]. Use of damage control resuscitation practices and tranexamic acid has further decreased the mortality rate secondary to hemorrhage; however, the definitive correction for all patients with major vascular injury remains surgical intervention [4–8]. The complex injury patterns from significant blunt, penetrating, and blast injuries demonstrated in combat settings result in physiologic derangements unparalleled by civilian trauma. Major vascular injuries requiring prompt evaluation, reestablishment of perfusion, and then reconstruction are significantly more prevalent in the combat environment versus the usual civilian trauma setting. The majority of deployed combat trauma surgeons are general surgeons without additional vascular surgery fellowship training or expertise and who are often deployed within the first 1–2 years after graduating from residency training. As such, military general surgeons at the Forward Surgical Team and Combat Support Hospital levels need to be comfortable and competent with damage control surgery and the accompanying vascular interventions within the critically ill/injured patient. This requirement has been further degraded in recent years by the increasing loss of major open vascular surgical experience among general surgery trainees and even in vascular surgery training programs. Although this may have little impact in the civilian trauma system, where there is almost universal access to vascular surgical specialists, it remains a critical area of concern for military medicine and the delivery of high-quality battlefield trauma care.

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One must pay special attention to limit the amount of distraction caused by the obvious grotesque injury patterns when managing devastating combat polytrauma. This is a major concept that must not be forgotten. As with any trauma, there needs to be an intense focus on maintaining an algorithmic treatment strategy. Control of any obvious exsanguinating hemorrhage, assurance of proper airway management, assessment of respiratory status, hemodynamic and circulatory support, neurologic assessment, and total body exposure should be performed sequentially in all trauma patients. Following the correction of any immediate life-threatening issues, assessment for vascular injury should be performed through physical examination assessing distal pulses, utilizing Doppler signals (if available) and performing bedside Ankle–Brachial Index (ABI) measurements. Extensive orthopedic and soft tissue injury may create difficulty during vascular assessment; however, an important rule of thumb for combat scenarios remains that an extremity without pulse or Doppler signal is never "just spasm," while a palpable pulse and normal ABI rule out any vascular injury that would require any immediate intervention [9]. Hard signs of vascular injury are always a surgical indication and should proceed to the operating room as soon as possible due to the high specificity for vascular injury requiring surgical intervention. This holds especially true in penetrating cervical and extremity trauma where these signs approach a 100% specificity and positive predictive value [10, 11]. Hard signs of vascular injury include external arterial bleeding, rapidly expanding hematoma, palpable thrill, audible bruit, or loss of distal pulse. It is important however to note that the vascular system maintains the unique ability to contest hemorrhage from damaged vasculature that can fool even the most experienced vascular and trauma surgeons. Complete arterial transections tend to spasm and retract into the surrounding tissues causing a decreased initial amount of blood loss despite serious injury. This can lead to troublesome delayed bleeding when not recognized early or to rebleeding from extremities with an incompletely tightened tourniquet. Partial vascular lacerations on the other hand tend to continue bleeding at higher rates due to differences in hemostatic compensatory mechanisms and the inability for the vessel to retract and spasm/clot.

Courses such as the American College of Surgeons Advanced Surgical Skills for Exposure in Trauma (ASSET) and Advanced Trauma Operative Management (ATOM) provide a standardized set of approaches for general surgeons to rapidly gain the appropriate vascular access needed for hemorrhage control. Prior to any surgical deployment, enrollment in these courses should be sought as they provide critical opportunities to practice the multitude of vascular exposures needed for damage control surgery within a controlled environment. These courses further help provide an in-depth knowledge of the appropriate vascular anatomy under ideal conditions as opposed to defining the structures for the first time in a blood filled, distorted field. Adding to this, proper preparation cannot be emphasized enough. There is no excuse for missing, damaged, or an unfamiliarity with the vascular instruments on hand. The middle of a case is never the appropriate time to realize that the required instruments, shunts, or grafts are missing.

Vascular Surgery in the Far-Forward Setting

The challenges associated with forward surgical care remain bountiful. Traditionally, vascular injury within the military setting has been demonstrative of a highly morbid pathology. However, through lessons learned and advances in damage control surgery, the morbidity and mortality associated with these injuries have substantially decreased within recent conflicts (Table 1). The current structure of the military healthcare system in the deployed setting utilizes a series of echelons of care, each of which has increasing capabilities. These echelons are denoted their physical location, medical and surgical capabilities, and timing of patient care. Role I care is dictated by the point of injury provider and battalion aid station. While these providers are the first responders on scene, their capabilities are limited to direct pressure, wound packing, tourniquet application, administration of hemostatic agents, and initiation of the evacuation process. During Role II care, most commonly representative by a derivative of the traditional Forward Surgical Team, surgical capabilities become present. Here, damage control surgery is performed and efforts are focused on resuscitation and the control of life- and limb-threatening injuries. Formal vascular repairs are typically deferred at this stage and replaced by techniques such as temporary shunting, ligation, fasciotomy, and amputation. Role III care is performed in more permanent structures representational of the large Combat Support Hospitals. Role III surgeons are often responsible for the more definitive repairs of vascular injuries using primary repair, patch angioplasty, and interposition or bypass grafts. The most commonly utilized conduits include saphenous vein and synthetic polytetrafluoroethylene depending on the scenario. Finally, Role IV and Role V care, which is representational of fixed structure facilities both overseas and stateside, are responsible for formalized repair or revisions, continued monitoring, and surgical optimization. While the far-forward surgeon at the Role II level may not be performing the vast majority of definitive repairs, it remains critically important to have an intimate knowledge of the capabilities present at each echelon of care to assure no bridges are burned for the next stage in patient care [19•].

It is critically important for the military-deployed trauma surgeon to understand the differences in the wounding patterns and resultant injuries that can occur on the modern battlefield. As the recent conflicts in Iraq and Afghanistan have

Table 1 Epidemiology of combat-related vascular injuries, management, and amputation rates (reprinted with permission from Martin MJ and Long W. Chapter 155—vascular trauma: epidemiology and natural history

Conflict	# injuries	Incidence (%)	Philosophy	Amp rate	Attempted repair[a]	Method of repair	Incidence of repair type[b] (%)	Post-repair amp rate (%)
WWI (Makins) [12]	1202	0.4	Ligate artery and vein (even if uninjured)	19–70%*	39 (3.2%)	Ligation artery	57	28
						Ligation artery + vein	40	20–90
						Lateral suture	3	20
WWII (Debakey) [13]	2471	0.96	Repair only minor injuries, no routine vein ligation	49%	121 (5%)	Ligation	66	50
						Lateral suture	3	35
						1° anastomosis	0.6	50
						Vein graft	1.6	58
Korea (Hughes) [14]	304	2.4	Repair with lateral suture or anastomosis	13%	269 (88%)	Ligation	12	51
						Lateral suture	12	3
						1° anastomosis	48	9
						Artery/vein graft**	27	24
Vietnam (Rich) [15] (McNamara) [16]	1000	2	Vascular repair with vein graft, vein repair	13%	930 (93%)	Ligation	1.5	33
						Lat suture	9	0
						1° anastomosis	38	7.4
						Vein graft	46	13
GWOT (Dua) [17] (White) [18]	1570	12	Vascular repair with vein graft, vein repair, damage control/shunts	14%	339 (65%)[#]	Ligation	35	2
						Lat suture	12.4	2
						1° anastomosis	9.4	0
						Vein graft	38	15
						Prosthetic graft	2.9	21

WW1, World War 1; WW2, World War 2; GWOT, Global War on Terror

[a] Excluding injuries managed with initial ligation

[b*] Totals may not equal 100% due to cases that were uncategorized or labeled as "other"

*The widely reported WW1 amputation rate of 19% (Makins) included up to 70% non-acute lesions, and actual amputation rate appears to be 45–70% based on smaller series

**Wide use of homografts and reported amputation rates 33% with arterial graft versus 12% with vein graft

[#] Among 523 vascular injuries in 497 patients from Dua et al.

In Rutherford's vascular surgery 8th Edition (Cronenwett and Johnston, eds), Elsevier Publishing, 2014)

demonstrated, the two most common mechanisms are blast injuries followed by high-velocity gunshot wounds. Blast injuries are particularly unique in that they often combine aspects of both blunt and penetrating trauma, including injuries from the primary blast wave and any resultant blunt force trauma as well as penetrating injuries from multiple fragments often spread over a larger area of injury versus usual penetrating mechanisms. These patients are particularly difficult to evaluate and rapidly identify all major injuries due to the often multifocal nature of the trauma and the austere environment and evaluation options. However, the basic principles of the vascular trauma evaluation still apply and should focus on a thorough physical examination for hard and soft signs of vascular injury, and particularly a good extremity pulse exam. In the patient with a perfused extremity and palpable pulses, the examiner can be relatively confident that there is no lesion that requires immediate emergent intervention. However, if there are signs of a potential vascular injury, the evaluation and identification of the exact location of the lesion can be more complicated due to the presence of extensive fragment wounds and co-existing soft tissue and bony injuries. This is in contrast to the much more obvious and straightforward evaluation of the patient with a single gunshot wound and hard signs of a vascular injury, where there is little to no mystery about the exact location of the injury and which vessel is injured. For high-velocity gunshot wounds, the major difference that needs to be appreciated (versus low-velocity injuries) is that the amount of resultant tissue destruction/devitalization is typically much greater and that injuries can occur to structures that were not in the direct path of the missile. These remote injuries can be due to trauma from the large temporary cavitation effect of the high-velocity projectile or from the missile deforming and fragmenting into multiple pieces spread over a relatively wider area. A final difference is that the external wounds are often much larger compared to low-velocity gunshot wounds and typically associated with major external hemorrhage that must be controlled at the point of injury in order to stabilize and transport the patient to a facility with surgical capabilities (Fig. 1).

Cervical Vascular Injury

Traditionally, injuries to the cervical region remain difficult to surgically treat and can be associated with devastating aerodigestive and neurologic injuries. Due to the amount of critical structures present, this region has been often referred to as "Tiger Country" by experienced trauma surgeons [20]. Cervical vascular injuries have the unique ability to rapidly occlude the airway from extrinsic compression, and, therefore, a significant focus on assuring a definitive airway is in place needs to be maintained. As with all vascular injuries, any hard signs of injury require surgical intervention, particularly in the battlefield setting where angiography and endovascular adjuncts will not be available. However, in the non-exsanguinating and hemodynamically stable patient, it is not unreasonable to obtain a radiograph of the chest and neck to assess for bullets, fragments, shrapnel, or any other residual debris prior to operative intervention. Immediate bedside interventions that can be very effective for control of hemorrhage and to facilitate further evaluation prior to operation are wound packing with an advanced hemostatic dressing (such as Combat Gauze) or the use of balloon catheter tamponade by placing a Foley catheter into the wound tract and inflating it to compress the injured vessels.

Fig. 1 Extensive soft tissue damage to right cervical region following high-velocity gunshot injury

An intimate understanding of the cervical anatomy and operative exposure is required to successfully obtain adequate vascular exposure and control. A long incision along the anterior border of the sternocleidomastoid from the sternal notch to the base of the ear is commonly required. In scenarios where adequate proximal control is unable to be obtained, the addition of a median sternotomy is warranted. Therefore, the typical full surgical preparation from the neck to the knees utilized in trauma surgery is required. Once the neck has been surgically entered, the internal jugular vein will be the first vascular structure encountered and should be retracted laterally to expose the carotid artery. The common facial vein is a primary landmark as the "gateway" to the carotid bifurcation and should be divided early to obtain access to the internal and external carotid arteries. The omohyoid muscle will often need to be divided for common carotid artery exposure, while division of the digastric muscle is required for adequate internal carotid artery exposure. Anatomically, relevant nerves during this dissection include the vagus nerve which usually lies posterior to the carotid artery and the hypoglossal nerve which will be the first horizontal structure encountered above the carotid bifurcation. Care should be taken to adequately identify these structures during the operation to prevent iatrogenic injury.

Whether experiencing ongoing exsanguination or a contained hematoma, it is important to gain initial proximal control at the base of the neck prior to any deep exploration. Once exposed, a well-placed finger can apply adequate hemorrhage control in most cases of bleeding from cervical vessels. Proximal and distal control of the injured vessels should be obtained via vascular clamps or vessel loops (Fig. 2a). In the situation where there is an inability to adequately expose enough length for a vascular clamp or vessel loop, a Fogarty embolectomy catheter can be inserted into the lumen and inflated to gain hemorrhage control. This can be particularly useful to obtain distal control of high injuries to the internal carotid artery with active bleeding. Injuries to the venous structures or the external carotid artery can be safely ligated in damage control scenarios; however, there is almost no role for ligation of the common or internal carotid artery. Instead, placement of a vascular shunt is the best initial maneuver to control bleeding and restore blood flow between the common and internal carotid arteries (Fig. 2b).

Comfort with vascular shunting is an invaluable tool for the deployed general surgeon and should be used liberally in damage control settings. Often formal vascular shunts are difficult to come by in the deployed setting; therefore, creative measures, such as using pieces of nasogastric tubing, feeding tubes, intravenous line tubing, and small chest tubes, are used for this purpose and have all been successfully utilized in the past as temporary vascular shunts. Prior to placement, one must assure adequate removal of proximal and distal luminal clots via an embolectomy catheter, flush the transected vessel ends with heparinized saline, and assure adequate blood flow

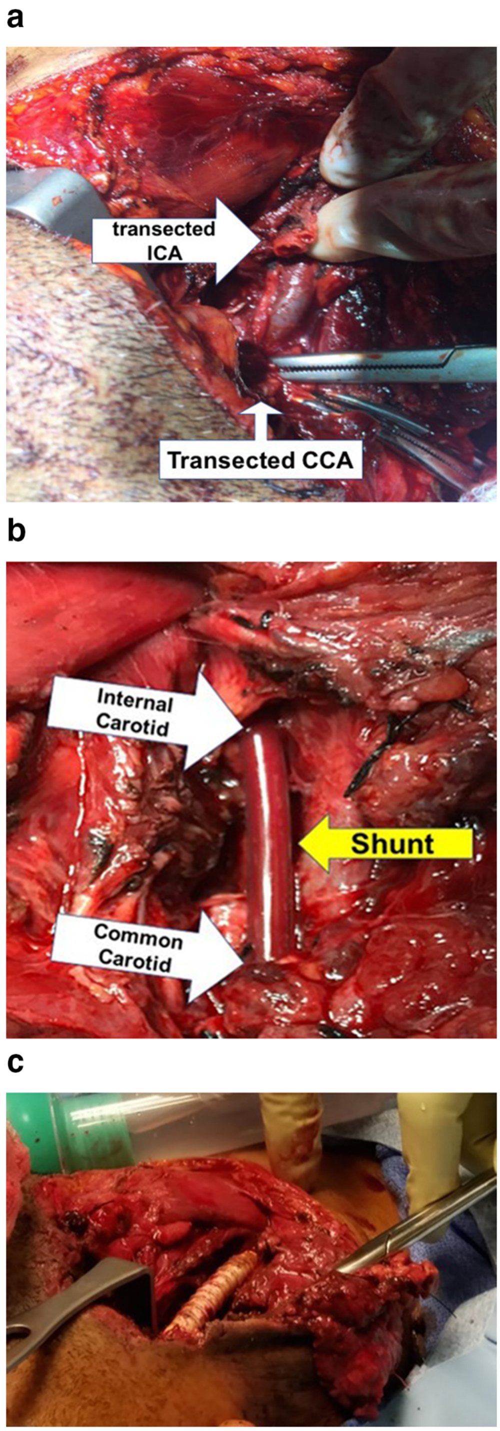

Fig. 2 **a** Example of traumatic carotid artery transection at the transition from the common carotid to the internal carotid artery. **b** Example of temporary intravascular shunt placement to restore flow from the common carotid to internal carotid artery. **c** Example of definitive repair using a polytetrafluoroethylene interposition graft

from the proximal and distal ends of the injured vessel. The largest shunt capable of fitting within the damaged vessel lumen should be utilized with 3–5 cm of inserted shunt on each vessel end. Securement of the shunt via multiple silk ties on the vessel ends, and a long tie placed in the mid-portion of the shunt to facilitate evaluation for any shunt migration is the final critical step required, as any dislodgement during transport can result in devastating exsanguination prior to the definitive repair. Systemic heparinization is not typically required following the placement of a temporary vascular shunt assuming there is strong vascular inflow and outflow, the lumen of the shunt is not inappropriately small, and the shunt remains straight without kinks or bends. Once the vascular shunt has been appropriately secured, a final evaluation of the neck dissection should be performed to assure there are no associated aerodigestive injuries.

Ultimately, patients with temporary vascular shunts require a definitive repair once they are stabilized. This often occurs following transfer to a higher level of care. Prior to repair, CT scan of the head, face, and neck (including CT angiogram if able) should be performed for operative planning and assessment for embolic events, associated infarcts, or evidence of intracranial hemorrhage as these will all affect the surgical timing and any intra or postoperative anticoagulation plan. Definitive repair is accomplished via multiple methods. Injuries without significant segmental loss are amenable to primary repair or patch angioplasty while the use of prosthetic versus saphenous vein graft for more significant repairs requiring interposition or bypass grafts should be based on size, operative time, availability, and local contamination at injury site (Fig. 2c). A general principle that the authors have utilized is to use prosthetic interposition grafts for reconstruction involving the common carotid artery and saphenous vein graft for the internal carotid artery (better size match). In choosing the best conduit, it is important to appreciate that outcomes with prosthetic graft for cervical vascular injuries have been equivalent or even superior to the use of vein. Although there is more concern voiced about infections with prosthetic graft, it is also critical to appreciate that the results of infection of a prosthetic graft are more sub-acute, while infection of a saphenous vein graft often manifests by devastating hemorrhage from disruption of the vein graft. Following repair, intraoperative duplex ultrasound should be performed if available to confirm normal flow without intimal irregularities. Alternatively, a standard angiogram with either fluoroscopy or single-shot plain X-rays can be performed if ultrasound is not available. Finally, all repairs need to be covered with vascularized tissue prior to closure to aid in healing and conduit protection. This is particularly critical if there is any co-existing injury or repair to the aerodigestive tract and vascularized tissue should be utilized to cover and separate the vascular repair from the aerodigestive repair or reconstruction.

Intraabdominal Vascular Injury

Ongoing intraabdominal blood loss in the unstable patient represents a scenario where quick intervention through an exploratory laparotomy is warranted. Rates of blood loss during noncompressible truncal hemorrhage remain prolific and can result in rapid exsanguination if not recognized and appropriately managed displayed mortality rates up to 80% [21, 22]. All efforts should focus on minimizing any delay to operative intervention, establishment of damage control resuscitation techniques, and early administration of tranexamic acid as these injury patterns are not amenable to the same pre-hospital techniques seen with most extremity traumas [23, 24]. In scenarios where surgical capability is not immediately available for the unstable patient, proximal control of the aorta can be obtained via resuscitative thoracotomy with aortic cross clamp or resuscitative endovascular balloon occlusion of the aorta (REBOA) to prevent cardiovascular collapse. While these techniques provide cessation of intraabdominal aortic inflow, they do not correct the underlying problem, nor do they prevent venous loss. As such, prompt surgical exploration is required to define the underlying damage and minimize distal ischemia time from aortic occlusion.

Operative exploration needs to be performed through a generous midline laparotomy extending from the xyphoid process to the pubic synthesis in order to provide optimal visualization of the surgical field. Immediate bowel evisceration followed by subsequent four quadrant packing versus targeted direct control depending on blunt versus penetrating mechanisms should be utilized in an expedient fashion to control and identify sources of blood loss. Once bleeding has been temporized through packing or direct pressure, supradiaphragmatic aortic occlusion (if previously performed) can be converted to supraceliac occlusion via direct pressure at the aortic hiatus through the gastrohepatic ligament. Identification of the injured vessels should be rapidly assessed. In scenarios where the hemorrhage is contained within the retroperitoneum, careful attention should be placed on the underlying mechanism as management is dictated by the etiology and anatomic region of suspected injury. Simplified, all retroperitoneal hematomas from penetrating trauma require exploration whereas only those presenting along the midline (zone 1) from blunt trauma require exploration. Blunt trauma resulting in nonexpanding perinephric/lateral (zone 2) and pelvic (zone 3) retroperitoneal hematomas can be managed without exploration assuming continued stability of the patient [25].

Visualization of the aorta and inferior vena cava can be assessed through a medial visceral rotation commonly referred to as the Mattox or Cattell-Braasch maneuver, respectively. Rapid control of hepatic bleeding should be obtained through occlusion of the hepatoduodenal ligament referred to as the Pringle maneuver. Injuries to the spleen, kidney, and distal pancreas should result in control of the vascular supply with removal of the associated organs; the safest place for these injured organs is often in a bucket next to the operating room table during trauma scenarios. One particularly difficult region to access and gain vascular control remains the confluence of the common iliac veins into the inferior vena cava due to their relationship with the iliac arteries and aortic bifurcation within the pelvis. The veins are deep/posterior to the arteries in the iliac system, and the bifurcation of the inferior vena cava is typically covered directly by the right common iliac artery. Division of the right common iliac artery can provide access to the vena cava bifurcation/left iliac vein; however, this technique should be utilized only when necessary as it requires future definitive repair of the divided iliac artery. Often adequate exposure to the veins can be obtained by circumferential dissection of the overlying iliac artery and retraction superiorly or inferiorly using vessel loops. Injuries to the venous system at or below the infrarenal vena cava can safely be ligated for any signs of physiologic distress or inability to visualize proper anatomy; otherwise, shunting or repair should be attempted [18, 26]. For vascular injuries not resulting in significant segmental damage, primary repair or patch angioplasty may be appropriate; however, it is important to keep in mind the patient's underlying physiologic status as these methods can be time-consuming. The liberal use of shunts for both arterial and venous injuries in these scenarios is another critical tool which expeditiously allow for the control of ongoing hemorrhage and restoration of distal blood flow. Of note, vascular shunts large enough for the iliac vessels/aorta are typically not available in the Role 2 or 3 setting, and small-bore chest tubes can be successfully utilized for this indication.

These injuries frequently present within co-existing contamination from injuries to the small bowel or colon, and, therefore, reconstruction with grafts should not be utilized during the initial stabilizing surgery. Surgeons should focus instead on the principals of damage control surgery in these situations in order to prevent worsening acidosis, coagulopathy, and hypothermia. The initial damage control surgery is not the time or place for complex repairs or reconstructions, particularly in the Role 2 forward surgical setting. Depending on the injury phenotype at presentation, patients should be left in gastrointestinal discontinuity with their injured kidney, spleen, and/or distal pancreas removed as indicated. Temporary abdominal closures should be utilized in all patients to allow for a second look operation after stabilization at that facility or for a repeat exploration at the next echelon of care if the patient is being transferred. The typical battlefield scenario for patients undergoing damage control surgery at a Role 2 facility is to rapidly evacuate the patient to the next echelon of care following initial stabilization. Among the most important actions prior to transfer is to ensure adequate communication of the patient's injuries and procedures that were performed to the receiving surgeon. This can be quite difficult in the combat setting where direct telephone communication may not be possible and paper records are easily lost during transport. One of the most reliable methods is to write the critical information directly on the patient's abdominal dressing, including the procedures that were performed, the date/time of the procedure, the presence of any retained sponges or instruments, and the blood products that have been administered (Fig. 3).

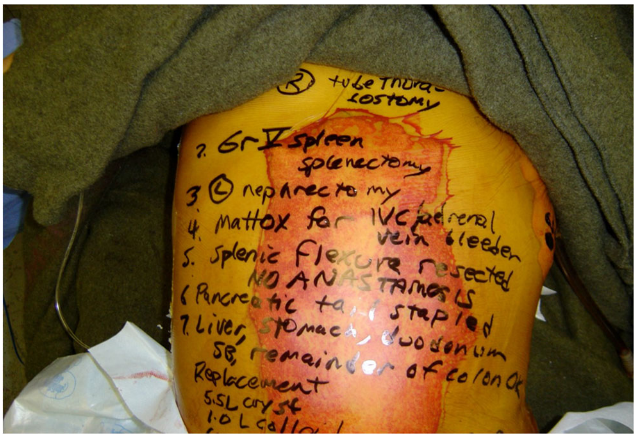

Fig. 3 Temporary abdominal closure with example of extensive surgical notes to assure the receiving surgeon understands the underlying injuries, resultant anatomy, presence of any retained equipment, and medications or transfusions given

Extremity Vascular Injury

The routine use of improvised explosive devices within current conflicts has resulted in an increase in the amount of mangled extremities experienced within military trauma [18, 27]. Both upper and lower extremities often result in significant complex soft tissue, orthopedic, and vascular injuries. Fortunately, the recent widespread use of extremity tourniquets by combat medics and point of injury providers has significantly decreased the mortality associated with extremity exsanguination [2]. Despite this, junctional injuries located in the groin and axilla are not amenable to tourniquet use and still remain a significant concern [1, 28•]. These wounds should be managed initially through wound packing, direct pressure, and possibly through new techniques, such as junctional tourniquets or resuscitative endovascular balloon occlusion of the aorta when available [28•, 29•]. In situations where more proximal control of junctional wounds is necessary, a “hockey stick” incision superior to the inguinal crease will give access to the retroperitoneal iliac vessels while the subclavian artery can be accessed via a supraclavicular incision. Blind clamping with vascular clamps should never be utilized due to significant potential for devastating iatrogenic neurovascular injury.

Patients presenting with ongoing bleeding despite tourniquet use should be managed by tightening the tourniquet, applying a second more proximal tourniquet if needed, and direct application of an advanced hemostatic dressing to the wound. Tourniquets should remain tight and in place until the patient is in the operating room where conversion to a sterile pneumatic tourniquet should be performed if needed [30]. It is not uncommon to see rebleeding from tourniquets that were initially adequately applied when the patient was hypotensive, but then result in re-bleeding following initial resuscitation and elevation of the blood pressure. Access to the groin or axilla should be maintained to allow for exploration to obtain proximal vascular control if needed.

For lower extremity injuries, proximal control should be obtained first via tourniquet or groin cut down to access the femoral vessels and occlude the arterial inflow using proximal vessel loops or clamps. If necessary, the common femoral, profunda femoris, and superficial femoral arteries should be identified and controlled in a similar fashion via a continuation of the longitudinal incision over the medial thigh (Fig. 4a). Despite complete arterial occlusion, bleeding often does not cease entirely due to arterial collaterals. Proximal control should be migrated distally to the level of the injury as soon as possible by extending the initial incision to adequately expose the full extent of the injury. This can be carried down past the level of the calf if necessary and will allow access to the popliteal artery, tibial artery, the tibial trifurcation, and the associated venous structures (Fig. 4b). Injured vessels should be circumferentially dissected and controlled via vessel loops or vascular clamps at the level of the injury. If this is not possible, a Fogarty catheter can be inserted into the open lumen and inflated to provide temporary control and facilitate further dissection in a dry field.

The incidence of combined major extremity arterial and venous injuries is higher in combat trauma, and the managing surgeon should understand the management options and pros/cons of each approach for both the artery and the vein. Although the majority of civilian trauma data has found that repair of major venous injuries does not have a clear benefit (versus ligation), there are several studies from the combat experience indicating an advantage to reconstruction/repairing the vein as well as the artery [31, 32]. Both arterial and venous injuries with segmental loss can be controlled and stabilized using vascular shunts (Fig. 5a). Venous shunts may preserve the option for future repair; however, in situations where there is an inability to accurately define the anatomy or there is uncontrollable venous hemorrhage, ligation of the venous injury is a sufficient option. Ligation of the profunda femoris artery can be tolerated; however, ligation of the common femoral or superficial femoral arteries results in high rates of lower extremity amputation below the level of the ligation [12, 13, 33]. Instead, vascular shunts should be liberally used when segmental arterial loss is identified to help mitigate limb loss [34]. Extremity shunts are performed in a similar fashion to the previously described methods in prior sections. Once a shunt is successfully placed, distal perfusion should be confirmed through audible Doppler signals. If no signals are heard, proximal and distal embolectomies should be performed using a Fogarty catheter and, if able, an on-table arteriogram via a needle or small catheter placed in the proximal femoral artery should be obtained. If there is not significant segmental loss demonstrated within the injury, primary repair or patch angioplasty remains viable options for repair.

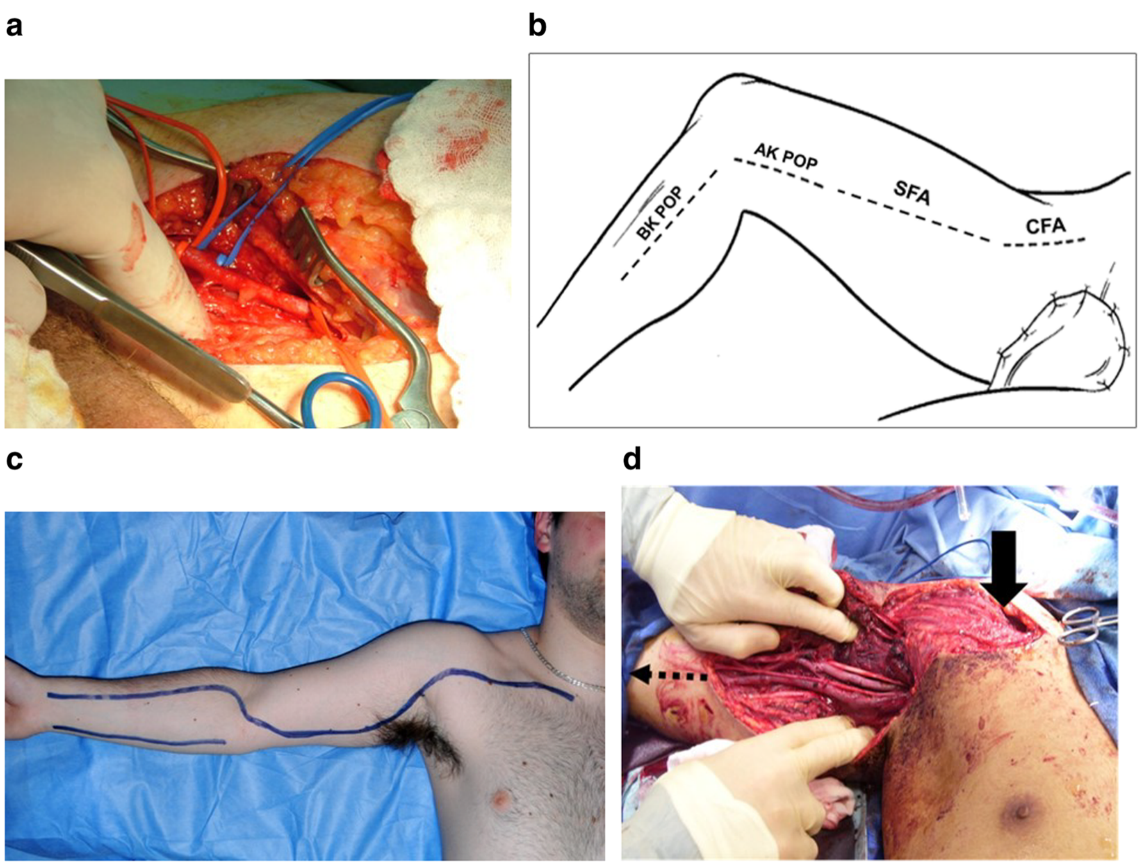

Fig. 4 **a** Femoral artery dissected at the groin level. Blue vessel loop represents the profunda femoris artery which delineates the common femoral artery (proximal) from the superficial femoral artery (distal). **b** Marking representational for incision placement to gain vascular control of major vessels in the lower extremity. **c** Markings representational for incision placement to gain vascular control of major vessels in the upper extremity. **d** Exposure of the axillary artery and vein through the deltopectoral groove. Reprinted with permission from Perry J and Fox CJ, Chapter 22: peripheral vascular injuries in: Front line surgery 2nd edition (Martin, Beekley, Eckert eds). 2017, Springer Publishing, New York, NY

In cases where vascular injury is amenable to interposition or bypass graft for definitive repair, use of a prosthetic versus saphenous vein graft should be considered based on the availability of the graft, size of the graft, and local contamination (Fig. 5b). In general, saphenous vein is the preferred conduit for combat extremity arterial reconstructions, and suboptimal outcomes have been obtained with prosthetic. However, prosthetic reconstruction is a viable option if time is critical, if adequate vein is not available, or as a temporary procedure with a plan for later excision and formal reconstruction with a vein graft. If

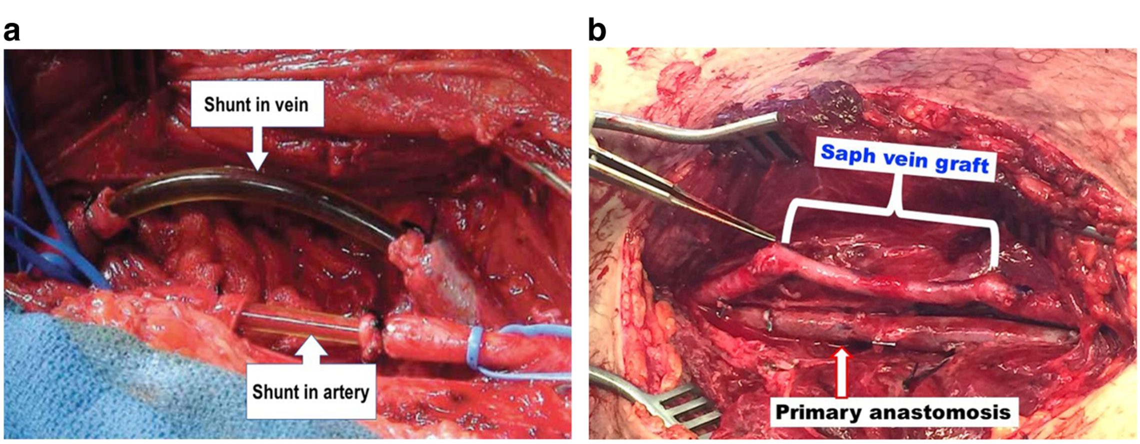

Fig. 5 **a** Lower extremity traumatic arterial and venous transection following damage control surgery and placement of temporary intravascular shunts. **b** Lower extremity traumatic arterial and venous transection following definitive repair which utilized both a saphenous vein graft for the artery and a primary anastomosis for the vein repair

opting for a saphenous vein graft, the donor vein should always be harvested from the uninjured leg as concerns for underlying injury or thrombosis to the deep venous system on the injured leg would result in complete outflow obstruction. For the general surgeon who often has less experience with harvesting saphenous vein, the use of an ultrasound to identify the mark the saphenous vein in the uninjured extremity can be extremely helpful. The vein should be marked along its entire course from the ankle to the groin in case more proximal or distal harvesting is required. This can also be helpful for identifying an inadequate or thrombosed saphenous vein and avoid an unnecessary incision and exposure of this conduit that will not be suitable for use in arterial reconstruction.

Upper extremity injuries should be managed in a similar fashion. Proximal control can be obtained via exposure of the brachial artery by a medial incision within the groove located between the biceps brachii and triceps brachii muscles. If more proximal control is needed, this incision should be extended over the deltopectoral groove with division of the pectoralis minor to give rapid access to the axillary artery and vein (Fig. 4c, d). Iatrogenic injury to the intimately associated brachial plexus should be avoided by proper

Table 2 Patterns of associated musculoskeletal and other structures with specific vessel injury (reprinted with permission from Martin MJ and Long W. Chapter 155—vascular trauma: epidemiology and natural history

Vessel	Musculoskeletal	Other
Carotid artery	Cervical spine	Jugular vein
	Mandible, LeForte 2/3 facial fracture	Carotid artery
	Skull base	Trachea, esophagus
Vertebral artery	Cervical spine (vertebral foramina)	Jugular vein
	Skull base	Carotid artery
Subclavian artery/vein	Clavicle	Thoracic duct (left)
	Sternum/manubrium	Brachial plexus, recurrent laryngeal nerve
Axillary artery/vein	Shoulder/proximal humerus	Brachial plexus, axillary nerve
Brachial artery	Mid-humerus	Ulnar nerve
	Biceps/triceps	Median nerve
Radial/ulnar artery	Elbow fracture or dislocation	Distal radial nerve (sensation only)
	Radius, ulna, wrist Forearm/hand flexor tendons	Ulnar nerve
Thoracic great vessels	Sternum/manubrium	Innominate vein, recurrent laryngeal nerve
Descending aorta	Thoracic spine	Esophagus
	Posterior rib fracture/dislocation	Lung
	Diaphragm	Left subclavian vein (blunt)
Abdominal aorta/vena cava	Thoracic/lumbar spine	Zone 1 retroperitoneal hematoma
Supra-renal	T12-L2 (with or w/o SCI)	Stomach, transverse colon, pancreas
Infra-renal	L2—sacral fractures	Duodenum, small bowel
Portal vein/SMV	Lumbar spine fracture or ligament injury	Zone 4 retroperitoneal hematoma
	Rib fractures	Duodenum (2nd/3rd portion), head of pancreas
		Portal triad (hepatic artery, common bile duct)
Renal artery/vein	Lumbar spine	Zone 2 retroperitoneal hematoma
	Posterior rib fracture/dislocation	Kidney, proximal ureter, adrenal/gonadal vessels
Iliac vessels	Pelvic fracture	Zone 3 retroperitoneal hematoma
	Sacral fracture	Cecum (right), sigmoid colon (left)
	Sacro-iliac joint disruption	Bladder, ureters
Femoral artery/vein	Pelvic fracture	Femoral nerve, sciatic nerve (rare)
	Acetabulum	Inguinal ligament
	Proximal to mid femur	Spermatic cord
Popliteal artery/vein	Dislocated or "floating" knee	Tibial nerve
	Distal femur, proximal tibia	Calf compartment syndrome
Tibio-peroneal vessels	Tibia, fibula	Tibial nerve, peroneal nerve (foot drop)
	Ankle fracture or dislocation	Calf compartment syndrome

In Rutherford's vascular surgery 8th Edition (Cronenwett and Johnston, eds), Elsevier Publishing, 2014) identification of underlying anatomy and avoidance of blind vascular clamping. When dissecting the brachial artery, careful identification of the median and ulnar nerves should be performed. If more distal exposure is required to expose the radial and ulnar arteries, the medial incision should be extended toward the forearm and the bicipital aponeurosis should be divided. For injuries distal to the brachial artery bifurcation, arterial inflow to the hand is only needed by one of the two major vessels to maintain adequate perfusion. In most patients, the dominant inflow to the hand is through the ulnar artery and thus surgical focus should remain on the dominant vessel via restoration of its flow through shunting or bypass if amenable. Following restoration of distal blood flow through the dominate vessel as demonstrated by Doppler signals at both radial and ulnar arteries within the wrist and palmar arch of the hand, ligation of the nondominant artery can be tolerated if needed. If the decision to utilize a bypass graft is made, saphenous vein, cephalic vein, and prosthetic grafts have all been utilized with success; however, saphenous vein graft remains the conduit of choice [35]. As with all vascular grafts in trauma, coverage with well-perfused tissue following repair should be obtained. If this is not possible, alternative routing of the graft through extra-anatomic locations to ensure tissue coverage should be pursued.

Associated orthopedic injuries are common among this cohort [36, 37•]. In general, the initial restoration of distal blood flow should be obtained by vascular shunting followed by external fixation and definitive vascular repair. If external fixation is not performed, then vascular repair to restore distal perfusion must be performed prior to any orthopedic repair. In far-forward settings, external fixation may be the responsibility of the general surgeon, and, therefore, familiarity with these devices is critical for the deployed setting. Furthermore, associated soft tissue damage, prolonged ischemia time, combined arterial and venous injuries, and the inability to assure close monitoring should prompt the early use of complete fasciotomies to alleviate any concerns for compartment syndrome [38]. In the deployed setting, there is no role for partial or limited fasciotomy incisions. Full-compartment release is recommended through full-length incisions to prevent worsening in physiology and limb loss [39•]. A standard lower extremity 4-compartment fasciotomy is performed through two incisions on the medial and lateral component of the tibia allowing the adequate release of the anterior, lateral, superficial posterior, and deep posterior compartments of the lower limb. Upper extremity fasciotomy, while less commonly needed, should be performed through a lazy S incision over the volar forearm extended through the carpal tunnel to release the superficial and deep forearm compartments and a longitudinal incision over the dorsal forearm to release the extensor forearm compartment. Although prophylactic fasciotomies are not commonly performed within civilian trauma due to adequate resources for frequent examinations with immediate intervention being readily available, far-forward and austere settings create scenarios where patients remain unexaminable for prolonged periods of time; thus, a properly performed prophylactic fasciotomy can have drastic limb-saving implications [38, 39•]. In situations where fasciotomies are not performed, careful assessment for subtle changes in serial exams as evidenced by increases in compartment pressures, pulse differences, or worsening pain, accompanied by laboratory analysis suggesting rhabdomyolysis, myoglobinuria, or renal injury is all representative of the need for fasciotomies due to the impending development of compartment syndrome.

Conclusions

Exsanguination remains the most common cause of death on the battlefield. As such, the deployed general surgeon needs to be comfortable with the initial management and stabilization of complex vascular injuries and their associated injuries (Table 2). Damage control surgery and resuscitation remain the key components of the initial treatment algorithm until patients are stabilized. Proximal control should initially be performed well outside the field of injury and subsequently migrated distally into the operative field. Usage of shunts should not be underutilized in these scenarios as they can be rapidly performed to achieve hemostasis, restore distal perfusion, maintain healthy tissue for future repair, and allow for more time to harvest vein, stabilize fractures, or prepare vascular conduits. Systemic heparinization is typically not required when using a temporary vascular shunt assuming there is good vascular inflow and outflow through a large caliber shunt without kinking. Both arterial and venous injuries can be shunted and repaired; however, major venous injury can be ligated if dictated by anatomical or physiologic derangements. Once their physiology stabilizes, a definitive repair can be made during a later surgery which often occurs at the Role III level. A general rule of thumb for conduit choice is to utilize prosthetic grafts for injuries proximal to the shoulder or groin and autologous vein for injuries distal to those landmarks. Following graft or repair, coverage with vascularized tissue is critical for protection of all conduits while non-anatomic rerouting of vascular grafts should be performed if the surrounding anatomy is not amenable for tissue coverage. All patients should be maintained on at least an antiplatelet agent to prevent conduit thrombosis following definitive surgery. Finally, familiarization with vascular instruments, enrollment in ASSET and ATOM courses, and performance of vascular cases under controlled scenarios cannot be overemphasized as increased comfort and competency will directly aid in decreasing the morbidity and mortality of the severely injured warfighter.

Compliance with Ethical Standards

Conflict of Interest The authors have no conflict of interests to declare.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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