Vascular Trauma Revisited

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Trauma with bleeding from named vessels has been treated since antiquity. Many of the techniques used in the modern era to control bleeding, such as manual compression, cauterization, and proximal and distal ligatures, were described before 1000 AD. Even the earliest version of a hemostat, Ambrose Pare's "Bec de Corbin," was described in the 1500s.

With the exception of case reports of vascular repair in 1759, 1762, and 1882, all progress in the clinical repair of injured vessels has been made in the past 117 years. Extraordinary advances in the techniques of operative repair were made in World War I, the Korean War, and the Vietnam War by military surgeons. The significant increase in civilian urban trauma from penetrating wounds since the 1960s in the US has been a major factor in the advances in vascular repair developed by civilian trauma surgeons. These advances have included return of tourniquets to control bleeding from an extremity; improved techniques of resuscitation with blood; recognition of the value of a physical examination and an arterial pressure index to detect a peripheral vascular injury; availability of duplex ultrasonography and CT arteriography (CTA); improved techniques for retrieval of the greater saphenous vein; availability of polytetrafluoroethylene grafts; innovative approaches such as balloon catheter tamponade, use of a temporary intraluminal shunt, and an extra-anatomic bypass; and earlier recognition of compartment syndromes in injured extremities. Even with all these operative advances and the availability of endovascular techniques, patients still present with complex vascular lesions that challenge the modern trauma vascular team.

The presence of a vascular injury in any trauma patient has a significant impact on subsequent management and outcome. With a "hard" sign of a vascular injury such as external hemorrhage, a rapidly expanding hematoma, palpable thrill/audible bruit, or the "6 Ps" of arterial occlusion in an extremity (pulselessness, pallor, paresthesias, pain, paralysis, poikilothermia), control of hemorrhage and restoration of flow are the priorities.[1,2] The sequencing and timing of these will then depend on the patient's physiologic status and presence of associated injuries.

This review will discuss the history of the control of hemorrhage, abbreviated chronological review of the management of vascular trauma since the early 20th century, and case-based management of vascular trauma in the modern era.

CONTROL OF HEMORRHAGE

Aulus Cornelius Celsus (25 BC to 50 AD), thought to be a nobleman in Rome, authored the first textbook (18 volumes) of medicine and surgery, known as De Medicina.[3] This text summarized medical knowledge from "Hippocrates to the beginning of the Christian era," but was ignored for 13 centuries until it was rediscovered by Pope Nicholas V in 1433 and then printed in 1476.[3,4] In the section on wounds caused by trauma in which pressure did not control hemorrhage, he recommended the following: "the bleeding vessels should be taken up, and ligatures having been applied above and below the wounded part, the vessels are to be divided in the interspace…"[3]

Galen of Pergamum (129 to 199 AD) in Asia Minor is considered by medical historian Ira M Rutkow[4] to be "second only to Hippocrates as the most important physician of all antiquity." This is based on the extraordinary volume of his medical writings during his time in Pergamum and for the majority of his career spent in Rome. Many of his observations and conclusions were erroneous, but his writings dominated Western medicine for the next 15 centuries. Galen had extensive experience as a "trauma surgeon," having served as a surgeon to the gladiators for 4 years in Pergamum. His comment on how to control hemorrhage was "by placing a finger on the orifice of a bleeding superficial vessel."[4,5]

Antyllus (second century AD) is described as the "first vascular surgeon," but evidently had experience with a variety of operations in neurosurgery (hydrocephalus), ophthalmology (cataracts), and in performing tracheostomies.[4] In operating on a patient with rupture of a superficial aneurysm, he first applied finger pressure to the area of hemorrhage. Then "we pass underneath the isolated part the needle with the double thread"[4] and proximal and distal ligation was performed.

Albucasis or Abul Quasim (936 to 1013) practiced as a physician and surgeon in Muslim Spain (Western

Table 1. Military Contributions to and Documenters of the Management of Vascular Trauma

First author by war	Year	Contribution(s)
World War I		
Soubbotich[16]	1913	Repair or ligation of vascular injuries
Taylor[17]	1916	Sequential "artery forceps" to control perforated or lacerated inferior vena cava
Weglowski[18,19]	Cited by others: 1985, 1987	Repair or ligation of arterial injuries
Makins[20]	1919	*Gunshot Injuries to the Blood Vessels*
World War II		
Blakemore[21]	1942	Vitallium tube to artery
DeBakey[22]	1946	2,471 arterial injuries
Barr[23]	2016	Review of DeBakey
Elkin[24]	1946	Resection of clavicle for exposure
Shumacker, Jr[25]	1948	Exposure of mediastinal vessels
Elkin[26]	1955	*Vascular Surgery in World War II*
Korean War		
Ziperman[27]	1954	Epidemiology of arterial injuries
Hughes[28]	1954	Aortic balloon catheter
Hughes[29]	1958	304 arterial injuries
Spencer[30,31]	1955, 2006	97 arterial injuries
Howard[32]	1958	*Battle Casualties in Korea*
Howard[33]	1998	Late reminiscence
Vietnam War		
Rich[13,34,35]	1969, 2017	Vietnam Vascular Registry
Hata[36]	2016	Vietnam Vascular Registry
Rich[37-39]	1970	1,000 arterial injuries
Rich[40]	1978	*Vascular Trauma*
Israel-Egypt, etc War		
Eger[41]	1971	Temporary shunts in arteries
Operation Iraqi Freedom		
Rasmussen[42]	2006	Temporary shunts in vessels
Rasmussen[43]	2008	Endovascular capabilities in wartime
Beekley[44]	2008	Pre-hospital tourniquet use
Kragh Jr[45]	2009	Pre-hospital tourniquet use

Titles of books are in italics.

Caliphate). His *Altasrif* was a collection of 30 manuscripts, 3 of which dealt with surgery. Rutkow[6] states that "the *Altasrif* became the leading authority on surgery in the Middle Ages." In the section on "Cauterization in Arterial Hemorrhage" (Book I, Chapter 56, pp 56—57), Albucasis describes 4 methods of controlling hemorrhage: "by cauterization," "by division of the artery," "by firm ligature," and "by the application of remedies."[7]

Ambroise Pare (1510 to 1590), of France, is considered the father of modern surgery, despite the fact that he was only a "master barber-surgeon." He is one of the most famous military surgeons in history (see Battle of Turin, 1536) and was chief surgeon to 4 consecutive kings of France.[8,9] Pare wrote extensively about the control of hemorrhage, particularly during amputations performed

during military conflicts. One of his major contributions in this area was to design an instrument known as the "Crowes beake" ("Bec de Corbin").[10] This curved grasping instrument, looking much like a modern hemostat, was used to grasp actively bleeding vessels that had retracted from view.

Sir Thomas Spencer Wells (1818 to 1897) served in the British military during the Crimean War, where he gained experience in laparotomies. He subsequently became a famous private surgeon in London with a large practice in ovariotomies, for which he developed the modern hemostat (Spencer-Wells clamp).[11] Wells wrote a 2-volume text entitled *Diseases of the Ovaries* and became president of the Royal College of Surgeons in 1881.

Table 2. Civilian Contributions to and Documenters of the Management of Vascular Trauma

First author	Year	Contribution(s)
Carrel[46-48]	1906, 1907	Triangulation for end-to-end anastomosis; end-to-side anastomosis; interposition vein graft; patch technique to encompass branches
Dente[49]	2005	Alexis Carrel (1873–1944) Nobel Laureate, 1912
Cairns[50]	1942	BCAI
Mulloy[51]	1998	BCAI
Yamada[52]	1967	Review of BCAI
Parmley[53]	1958	Nonpenetrating aortic rupture
Morris Jr[54]	1960	First large report of civilian arterial injuries
Taylor[55]	1962	Balloon tamponade for iatrogenic vascular injury
Pearce[56]	1966	Balloon tamponade for injured right pulmonary artery
Dotter[57]	1969	Laboratory origin of endovascular stents
Friedman[58]	2015	Laboratory origin of endovascular stents
Smiley[59]	1971	Balloon tamponade for abdominal vascular injury
Mubarak[60]	1977	Double-incision 4-compartment fasciotomy
Majeski[61]	1979	Temporary shunts in arteries
Matsen III[62]	1980	*Compartmental Syndromes*
Feliciano[63]	1985	PTFE grafts in vascular injuries
Mattox[64]	1989	5,670 cardiovascular injuries at 1 center
Frykberg[65-67]	1989, 1991, 1992	Reliability of exam in diagnosing arterial injuries
Dennis[68,69]	1990, 1998	Nonoperative management of occult arterial injuries
Johansen[70]	1991	Doppler arterial pressure index < 0.9
Lynch[71]	1991	Doppler arterial pressure index < 0.9
Meissner[72]	1991	Duplex ultrasonography for arterial injury
Bynoe[73]	1991	Duplex ultrasonography for arterial injury
Marin[74-76]	1993, 1994, 1995	Endostent grafts for arterial injuries (not thoracic aorta)
Pate[77]	1995	Beta blockers for blunt aortic injury
Fabian[78]	1997	Multicenter review of blunt aortic injury
Kato[79]	1997	Endostent graft into blunt aortic injury
Semba[80]	1997	Endostent graft into blunt aortic injury
Soto[81,82]	1999, 2001	CT arteriography for extremity arterial injury
Biffl[83]	1999	Grading scale for BCAI
Biffl[84]	1999	Denver Health screening for BCAI
Miller[85]	2002	University of Tennessee screening for BCAI
Morizumi[86]	2009	Mobile angiography in trauma room
Demetriades[87]	2009	Multicenter review of blunt aortic injury
Shackford[88]	2013	Multicenter review of surgical specialty in limb salvage

Titles of books are in italics.
BCAI, blunt carotid artery injury; PTFE, polytetrafluoroethylene.

MANAGEMENT OF VASCULAR TRAUMA— ABBREVIATED CHRONOLOGICAL REVIEWS SINCE THE EARLY 20ᵀᴴ CENTURY

The history of early attempts at vascular surgery and repairs after vascular trauma has been well-described by Norman M Rich, MD, in numerous publications and chapters.[12-15] Modeled on the chronological lists of contributors and contributions in several of Rich's publications,[12,14] 2 comprehensive tables on the history of the management of vascular trauma since the early 20ᵗʰ century are included as part of this review (Table 1. Military[16-45]; Table 2. Civilian[46-88]).

MANAGEMENT OF VASCULAR TRAUMA—A CASE-BASED REVIEW

Missed diagnosis of arterial injury

A 22-year-old man was stabbed in the proximal right leg. Emergency medical services personnel reported that there was obvious blood on the rug of the living room where

the injury occurred. On examination in the emergency center of a Level I trauma center, a 1.5-cm stab wound was noted on the medial right calf approximately 10 cm distal to the knee joint. There was no bleeding from the wound, no palpable hematoma, and the dorsalis pedis pulse was readily palpable on the right foot. The right posterior tibial artery was present by palpation, but diminished as compared with the dorsalis pedis pulse. It was decided that the absence of active hemorrhage or an expanding hematoma and the presence of palpable right pedal pulses ruled out the possibility of an arterial injury. No ankle-brachial index or arterial pressure index was measured, and no vascular imaging was performed.[70,71] The patient was not given any specific instructions other than to return if he had any "problems."

Three weeks later, the patient returned to the emergency center with a complaint of swelling of the right leg. The surgical team noted that the proximal right leg was "pulsatile," that the dorsalis pedis pulse was readily palpable, and that the posterior tibial pulse was audible with a Doppler device. An urgent arteriogram (this patient was treated before the availability of CT arteriography) documented the presence of an 8-cm diameter traumatic false aneurysm of the right tibioperoneal trunk approximately 4 cm distal to the origin of the right anterior tibial artery. At operation through a right medial distal popliteal incision, a large pulsatile firm traumatic false aneurysm arising from the right tibioperoneal trunk was present. The tibioperoneal trunk was controlled above the traumatic false aneurysm, which was then opened and evacuated. The orifices of the posterior tibial and peroneal arteries could not be identified in the aneurysm sac, but some small areas of back-bleeding were oversewn. After ligation of the proximal tibioperoneal trunk, the right foot continued to have a palpable dorsalis pedis pulse and continued to be pink and warm.

Comment

The list of physician errors in the management of this patient is impressive. External bleeding is strongly suggestive of a vascular injury, as was the diminished posterior tibial pulse.[1] Based on these, an ankle-brachial index or arterial pressure index (Doppler-derived) at the right posterior tibial artery would have surely been <0.9.[70,71] This would prompt a CTA in the modern era.

Because most missed arterial injuries in the extremities are symptomatic within 10 days, the patient should have been given clear instructions ("the leg should improve, not worsen") and follow-up clinic appointments scheduled at 1 week, 2 weeks, and 2 months.[89]

Preoperative arteriography despite "hard" signs of arterial injury

A 23-year-old man presented to the emergency center after suffering a close range shotgun wound to the medial right thigh. There was a defect in the soft tissue at mid-thigh, pellet holes covered the inferior two-thirds of the thigh, and the ankle-brachial index at the right foot was <0.9. The surgical resident team believed that the patient had enough signs of a major arterial injury in the thigh (large soft tissue defect over usual course of superficial femoral artery and the femoral vein, diminished pedal pulse, multiple pellets in proximity to the femoral vessels) to justify an emergency operation. The attending surgeon pointed out that the patient did not have significant external bleeding and that there was arterial flow to the right foot. In addition, he reminded the team that a blind exploration to encompass the area of pellets in proximity to the vessels would involve one-half of the length of the patient's thigh. A formal arteriogram in interventional radiology documented the presence of 6 clear-cut defects in an 8-cm segment of the left superficial femoral artery. The segment containing the defects was resected, and a reverse autogenous saphenous vein graft from the right groin was inserted as an interposition graft into the superficial femoral artery. Several small venorrhaphies were performed in the femoral vein in the same area. The sartorius muscle covered the saphenous vein graft well, and the 5-cm skin defect mid-incision was allowed to granulate until a split-thickness skin graft was applied.

Comment

This patient had a combination of the previously described "hard" (diminished distal flow) and "soft" (proximity of wound to a named artery) signs of an arterial injury in an extremity.[1,2] There was a strong temptation to perform an emergent operation due to these signs and to the dramatic presentation (large skin defect from close-range shotgun wound, wide dispersal of pellets). There are, however, several clinical scenarios in patients with "hard" signs of an arterial injury in the neck or an extremity (other than external bleeding) in which a preoperative CTA or duplex ultrasonography may be very helpful to the trauma vascular surgeon. These are: wound in the thoracic inlet, shotgun wound to an extremity, and segmental fractures or fractures at 2 levels in an extremity.[90] In each of these complex scenarios, the imaging study will be useful in documenting the presence and location of an arterial injury and in planning the location and length of incision at operation.
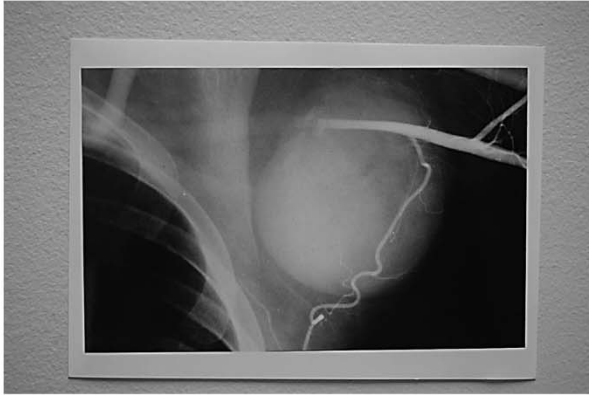
Figure 1. Late pseudoaneurysm and arteriovenous fistula 3 weeks after "negative" exploration of the left axillary artery. The exploration, by an inexperienced surgical team, was hindered by the muscular habitus of the patient and the failure to detach the origin of the pectoralis minor muscle. (Reprinted from Feliciano DV. Vascular Trauma. In: Levine BM, Copeland EM III, Howard JR, Sugerman HJ, Warshaw AL, eds. Current Practice of Surgery. New York: Churchill Livingstone; 1993, with permission from Elsevier.)

Missed arterial injury at operation

A 21-year-old man presented to the emergency center with a gunshot wound to the left lateral pectoralis major muscle. He was hemodynamically stable, the exit wound was in the left upper back, and the left radial pulse was normal. There was some swelling of the left axilla, but this was difficult to assess because of the patient's muscular habitus. A formal arteriogram was performed, which demonstrated a defect in the left mid-axillary artery. An inexperienced surgical team explored the patient through a left infra-clavicular incision extending to the most proximal medial left arm. There was some blood staining of the tissues, but the third portion of the left axillary artery (lateral to the pectoralis minor muscle) was exposed and found to be without an injury. The pectoralis minor muscle was then elevated with a Richardson retractor. This aided in dissection of the lateral aspect of the second portion of the left axillary artery (behind the pectoralis minor muscle). Again, no arterial injury was noted in this area. A decision was reached by the surgical team that the arteriogram must have been a "false positive." The incision was closed, and the patient was discharged on the second postoperative day.

Three weeks later, the patient returned to the emergency center complaining of swelling of the left upper chest and axilla. The surgical team confirmed that this entire area was swollen and also noted the presence of a palpable thrill in the left axilla. An urgent arteriogram documented the presence of a massive traumatic false aneurysm of the mid-left axillary artery with an associated arteriovenous fistula (Fig. 1). In the era before the availability of endovascular stent grafts, an autogenous saphenous vein graft was used to replace the injured segment of left axillary artery at a reoperation. A left axillary venorrhaphy was also performed.

Comment

The obvious error with management was the failure to fully expose the area of probable injury to the left axillary artery. The original surgical team chose to enter the left axilla through the intermuscular groove between the pectoralis major and deltoid muscles, carefully avoiding the cephalic vein. This incision provides excellent access to the third portion of the axillary artery, as noted earlier. The second portion, however, is difficult to visualize in a muscular individual by manual elevation of the pectoralis minor muscle alone. The tendon of this muscle on the coracoid process of the superior scapula should have been divided while preserving the medial pectoral nerve for complete exposure.[91] Trauma surgeons do not make any attempt to reattach this tendon at the completion of the vascular repair.

Because the deltopectoral approach can be somewhat tedious and difficult in a patient with bleeding from the first or second portion of the axillary artery, transverse division of the fibers of the overlying pectoralis major muscle is another approach. Again, transection of the tendon of the pectoralis minor muscle will be necessary to expose the second portion and, if desired, the first portion of the axillary artery.

For the inexperienced trauma surgeon confronted with exsanguinating hemorrhage from either the first or second portions of the axillary artery, there is still another rarely used approach. This is division of the tendon of the pectoralis major muscle from the crest of the intertubercular groove of the humerus. The tendon is divided at least 1.5 to 2 cm from the humerus to allow for reattachment of the tendon at the completion of the vascular repair.

The second error made in intraoperative management of this patient was the failure to perform an arteriogram to localize the "missing" injury. A Cournand disposable arteriogram needle should have been inserted into the third portion of the left axillary artery, with the tip facing medially. After application of a blood pressure cuff inflated to 300 mmHg on the left arm, a retrograde injection of radiologic contrast under fluoroscopy would then be performed.[92] This technique would visualize the proximal axillary-subclavian arterial system with all its major branches and would have demonstrated the area of injury in this patient.

Balloon catheter tamponade × 2 for bleeding at base of skull

A 37-year-old man was stabbed through the left eardrum by his brother. Pulsatile arterial flow was noted
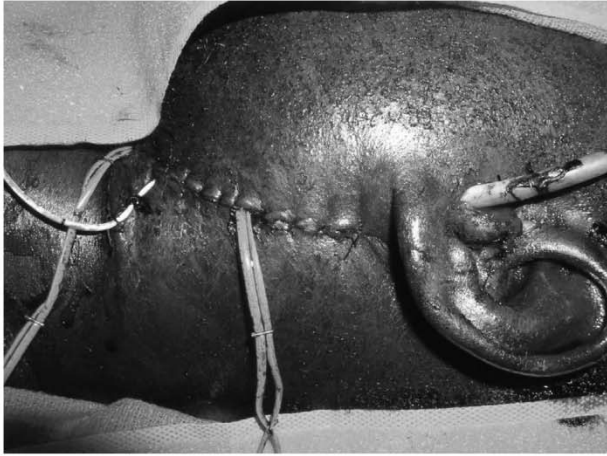
Figure 2. Foley (through external auditory canal) and Fogarty (through internal carotid artery) balloon catheter tamponade after stab wound to internal carotid artery in zone III of left neck.

immediately, and another brother placed his right index finger into the left external auditory canal to control the bleeding. On arrival in the emergency center, a surgical resident's finger replaced that of the patient's brother. In the operating room, an 18-F Foley balloon catheter was advanced into the patient's stab wound track. This was sequentially inflated until there was reasonable control of arterial hemorrhage. Any slight movement of the Foley balloon catheter, however, led to recurrent bleeding from the left ear. The surgical team then made a left oblique cervical incision and exposed the proximal left internal carotid artery. Through a pursestring 6-0 polypropylene suture, a small arteriotomy was made in the proximal left internal carotid artery. A #4 Fogarty balloon catheter (Edwards Lifesciences) was inserted through the arteriotomy, advanced superiorly, and sequentially inflated until all arterial bleeding from the left ear stopped (Fig. 2).

Comment
The internal carotid artery inferior to the base of the skull cannot be exposed quickly because of the overlying mandible. Should external bleeding occur from a penetrating wound in high zone II or zone III of the neck, local compression would be the first step in management.[93] Rapid transfer to the operating room for a vertical ramus osteotomy of the mandible or subluxation of the temporomandibular joint and interdental wiring or interarch fixation in edentulous patients is then performed to expose the internal carotid artery.[94-96]

In the patient described, the volume of arterial bleeding was impressive and packing of the external auditory canal was unlikely to control this. Failure of the Foley balloon catheter to completely control hemorrhage prompted

insertion of a transarterial Fogarty balloon catheter, as well—the only time in my career that 2 separate balloons were needed to control hemorrhage from 1 artery.

Once bleeding is controlled by the balloon catheter, a decision must be reached on whether to expose the injured internal carotid artery and repair it, call an endovascular surgeon for insertion of a stent-graft, or to allow thrombosis to occur around the balloon in the artery. An immediate transfer to radiology for a contrast-enhanced CT of the brain is useful to document whether ischemia of the hemibrain is occurring. Also, a CTA will demonstrate the amount of crossover flow from the contralateral carotid and vertebral artery systems. If crossover flow is adequate, every effort is made to maintain the patient's oxygenation and blood pressure and minimize edema of the hemibrain on the side of the balloon in the ICU. A return to the operating room in 48 hours for removal of the balloon catheter under direct vision is appropriate if the patient has done well. A patient with inadequate crossover flow will need insertion of an endovascular stent-graft or immediate reconstruction of the injured carotid artery with the aid of a "skull base" surgery team.[97] All trauma and vascular surgeons are aware of the multiple other locations in which balloon catheter tamponade can be used to control hemorrhage.[55,56,59,98]

Temporary intraluminal vascular shunt
A 58-year-old woman standing in a parking lot had her right knee and proximal leg crushed between the bumpers of 2 cars. On arrival at a Level I trauma center, her systolic blood pressure was 70 mmHg, temperature 35°C, and arterial pH 7.2. In addition, there was bleeding from a proximal medial laceration of the right leg. A rapid physical examination and x-rays in the emergency room documented a pulseless right foot that was sensate and had motor function, an open dislocation of the right knee, and a mid-shaft fracture of the tibia. Operative findings were transection of the distal right popliteal artery and vein, avulsion of the anterior tibial artery and vein, and the joint-bony injuries, as described. Once the ends of the popliteal artery and vein were isolated, #12-F Argyle (Medtronic) carotid artery shunts were inserted to re-establish arterial inflow and venous outflow. The transected ends of the anterior tibial artery and vein were ligated. The orthopaedic trauma service then scrubbed in, inserted an intramedullary rod into the fractured tibia and relocated the right knee joint. On completion of the orthopaedic procedure, the trauma team scrubbed back in. The patient was hemodynamically stable with a body temperature of 36°C, and a decision was reached to complete vascular reconstruction at that time. Autogenous saphenous vein interposition grafts retrieved from

Table 3. Indications for Insertion of a Temporary Intraluminal Vascular Shunt

Complex repair of the internal carotid artery in zone III of the neck (from the angle of the mandible to the base of the skull)
Gustilo IIIC open fracture of an extremity
Need for perfusion as a complex revascularization after trauma is performed
Perfusion of an amputated part of an upper extremity before replantation
"Damage control" for the patient with near exsanguination from a peripheral vascular injury
"Damage control" for the patient with multiple intra-abdominal injuries including an abdominal vascular injury, a complex abdominal vascular injury, or near-exsanguination from a truncal vascular injury
"Damage control" for the patient with a cervical, truncal, or peripheral vascular injury and a surgical team with an overwhelming number of casualties, limited resources, or limited operative experience with vascular injuries (military triage)

See reference[101] for more information.

the left uninjured thigh were then inserted into the popliteal artery and vein after removal of the shunts. Debridement of frayed and ischemic muscle tissue in the proximal medial superficial posterior muscle compartment of the leg was performed before closure of much of the medial skin wound/incision. Finally, a fasciotomy of the anterior and peroneal muscle compartments of the right leg was performed. Total operative time was 9 hours; blood replacement was 12 units of packed red blood cells. The patient underwent 7 more operations for debridements, bleeding from granulation tissue, and application of split-thickness skin grafts to the anterior-peroneal compartment fasciotomy site and medial popliteal wound. She was discharged 38 days after injury. When seen 3 years later, she had a normal gait, but used a cane for "support." Her major complaint was "aching" in the right knee and leg when the "weather changed."

Comment

Much has been written about temporary intraluminal vascular shunts in recent years.[42,99-101] There are at least 7 indications for a shunt, as outlined in Table 3.[100] In the modern era, shunts are inserted in up to 9% of patients with vascular injuries in civilian reviews.[99] Of interest, the most common indications continue to be a Gustilo IIIC open fracture in an extremity and need for a "damage control" operation.

In the patient described, both classical indications were present. The shunt preserved viability of the right leg and foot during orthopaedic reconstruction and as hypotension, hypothermia, and a metabolic acidosis were corrected.

Use of ringed PTFE graft in peripheral vein

A 21-year-old man was shot in the distal left thigh and presented with a large medial hematoma and a pulseless left foot. In the operating room, the distal left superficial femoral artery and the femoral vein were 80% transected with jagged open ends. After proximal and distal vascular control of both vessels was obtained, the jagged ends were debrided, resulting in a 3.5-cm defect in each vessel. An autogenous reversed saphenous vein graft from the right groin was inserted as an interposition graft into the superficial femoral artery. It was obvious that the saphenous vein was too small to be inserted as an interposition graft into the left femoral vein. Based on my previous tedious and unhappy experiences in creating either a spiral vein graft or a venous panel graft, a 10-mm ringed PTFE graft was inserted as an interposition graft into the left femoral vein (Fig. 3). A venogram of the injured extremity at 2 weeks after injury documented normal flow through the left femoral vein in the thigh. The patient was advised to continue elevation of the left lower extremity when supine, cease smoking, take a "baby aspirin" every 12 hours for 3 months, and follow a daily walking program.

Comment

Repair vs ligation of major injured veins in the lower extremities continues to be a controversial topic. There are significant military and some civilian data documenting the beneficial impact of venous repair on the adjacent arterial repair and in avoiding the need for below-knee fasciotomy and long-term venous sequelae in the injured lower extremity.[102-107] In contrast, there are primarily civilian reports documenting only modest sequelae after ligation of the popliteal, femoral, or common femoral vein in the lower extremity.[108-111]

The recent extensive experience with the use of temporary intraluminal vascular shunts in both military and

Figure 3. Saphenous vein graft in superficial femoral artery and 10-mm ringed PTFE graft in femoral vein. (Reprinted from Feliciano DV. Peripheral vasculature. In: Britt LD, Trunkey DD, Feliciano DV, eds. Acute Care Surgery. Principles and Practice. New York: Springer; 2007, with permission from Springer.)
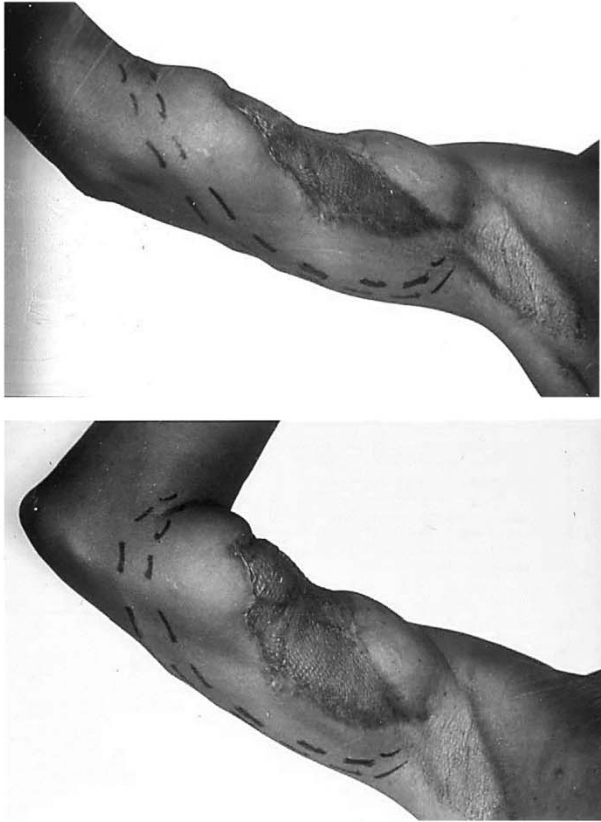
Figure 4. Full range of motion of the right elbow 22 months after blowout of an exposed brachial artery—PTFE suture line and replacement with an extra-anatomic saphenous vein bypass graft (marked with black lines on skin). (Reprinted from Feliciano[112] with permission from Elsevier.)

civilian vascular injuries has convinced me that ligation of a major vein in the lower extremity is no longer appropriate. And with the extended time necessary to construct a spiral or panel vein graft, a ringed PTFE interposition graft is an appropriate second choice to the greater saphenous vein. Patencies of 42 venous repairs by venography or duplex ultrasonography in 1 civilian series at a mean of 10.9 ± 7.1 days after repair were: primary repair, 76.5%; autogenous vein graft, 66.7%; and PTFE graft, 73.7%.[107] If one follows PTFE venous interposition grafts long-term, there is gradual deposition of pseudointima and/or peripheral clot so that thrombosis occurs gradually…if it is to occur. This allows for the gradual development of venous collaterals.

Value of extra-anatomic bypass to treat post-operative blowout of arterial repair
A 23-year-old patient had a 6-mm PTFE graft inserted into the right brachial artery after a gunshot wound to

the distal arm.[112] The operative note described an "inadequate" greater saphenous vein in the right groin. Unfortunately, there was extensive loss of soft tissue over the PFTE graft. The surgical team chose to cover the exposed graft with Vaseline Petrolatum Gauze Dressing (Emergency Safety Supply LLC) under antibiotic-soaked gauze. On the fourth postoperative day, arterial bleeding was noted coming from a partial dehiscence of the proximal PTFE-brachial artery suture line. The patient was returned to the operating room, and the PFTE graft was removed. After exposing healthy proximal and distal brachial artery, a medially placed extra-anatomic interposition graft with autogenous saphenous vein was inserted. Both suture lines were covered by healthy tissue after the small incisions proximal and distal to the defect in soft tissue were closed. The defect in soft tissue was treated with wet-to-dry dressings until a split-thickness skin graft was applied on the 11th post-trauma day. At the time of long-term follow-up at 22 months, the patient had normal right radial and ulnar pulses and full range of motion of the right elbow (Fig. 4).

Comment
The indications for performing an extra-anatomic vascular bypass in an injured extremity are listed in Table 4.[112-114] Although the technique appears somewhat formidable to inexperienced trauma vascular surgeons, the steps in performing the operation are straightforward. First, systemic heparinization with 100 units/kg is initiated. Exposure of healthy proximal and distal artery and/or vein usually mandates separate longitudinal incisions over the vessels outside the area of injury or infection. It is best to mark the saphenous vein or ringed PTFE graft with a straight line to avoid twisting of the graft through the extra-anatomic tunnel. The extra-anatomic tunnel through subcutaneous or muscle tissue is created with a large biliary Bakes dilator. With an adequate tunnel in a gentle curve, the reversed and marked autogenous saphenous vein and/or PTFE graft is pulled through the tunnel in a collapsed fashion. After the proximal healthy artery-to-graft anastomosis is created, flushing through the distal open end of the graft is performed to verify that the graft is not kinked in the tunnel. The proximal artery is reclamped and the area of the graft is compressed to evacuate blood from the entire graft. The graft is then trimmed to an appropriate length. Because the distal graft-to-artery anastomosis is close to completion, proximal and distal flushing are performed. With arterial and/or venous flow restored, both graft-artery suture lines are covered by closing the separate longitudinal incisions mentioned earlier.

Table 4. Indications for Performing an Extra-Anatomic Vascular Bypass in an Extremity

Loss of soft tissue over injured artery or vein
Postoperative infection of the incision with blowout of underlying arterial repair
Infections in both soft tissue and underlying native artery secondary to injection of illicit drugs

See references[113-115] for more information.

Volar-ulnar fasciotomy of the forearm

A 44-year-old bodybuilder had an injection of "steroids" into his right antecubital area by a colleague. Over the next 3 days, he noted progressive edema, erythema, and firmness of the right antecubital area. An emergency room physician in the patient's local hospital diagnosed "cellulitis" and prescribed "antibiotics." The patient's distal right arm, antecubital area, and proximal forearm worsened over the next 2 days. The patient returned to the local emergency room and was seen by the same physician. He told the patient he would need an "amputation." In addition, he was advised to go to a Level I trauma and acute care surgery center in the state capital. After evaluation by an attending surgeon at that center, a diagnosis of a necrotizing soft tissue infection was made. The pressure in the patient's superficial volar muscle compartment of the right forearm was measured and noted to be 25 mmHg. After 12 hours of elevation of the entire right upper extremity in a sling and continued broad-spectrum antibiotics, the patient was re-examined. The patient's right hand was now swollen, and he complained of "tingling" as well. In the operating room, a right volar-ulnar forearm fasciotomy was performed.[115] A transverse incision was made 1 cm distal to the antecubital crease. At the ulnar edge of the volar forearm, the incision was extended in a right angle fashion (Fig. 5). The remainder of the longitudinal volar fasciotomy incision extended down the ulnar side of the forearm with a gentle angle to end at the mid-aspect of the volar wrist. By elevating the proximal right angle flap of skin and subcutaneous tissue proximally, the lateral compartment (mobile wad) muscles (brachioradialis, external carpi radialis longus and brevis) were decompressed. The superficial volar compartment was decompressed through a fasciotomy incision under the longitudinal skin incision. Finally, a space was created between the exposed flexor carpi ulnaris and flexor digitorum sublimis superficial muscles. Carefully avoiding the ulnar nerve and artery in this space, a longitudinal fasciotomy of the deep volar compartment was performed. No fasciotomy of the dorsal (extensor) compartment of the right forearm was thought to be necessary. An intraoperative consult with the Hand Service was obtained, but fasciotomy of the right hand was not thought necessary. The skin, soft tissue, and thrombosed veins in the area of the antecubital necrotizing soft tissue infection were extensively debrided.

After a longitudinal extension of the fasciotomy to decompress the distal right biceps muscle of the arm the next day, modest further debridement was necessary. Elevation of the entire right upper extremity and daily wet-to-dry dressing changes were performed for the next 10 days. A split-thickness skin graft was then applied to the antecubital area and the volar forearm fasciotomy site.

Comment

The volar-ulnar technique to decompress the lateral, superficial volar, and deep volar compartments of the forearm is easy to remember and perform. It is, of course, the same technique used when a compartment syndrome occurs after injury to the subclavian, axillary, or brachial vessels. I perform fasciotomies based on the patient's history (especially if there is a delay in arterial repair), examination (massive swelling or neuromuscular dysfunction), and operative management (ligation of major vein in proximal extremity). To confirm the need for a fasciotomy, a compartment pressure >35 mmHg is a useful number to remember because it exceeds the normal capillary pressure of 20 to 30 mmHg.[62]

Arterial bleeding in an intravenous drug abuser

A 25-year-old woman with a known history of intravenous drug abuse (injections of heroin) presented to the emergency room with a recent history of pulsatile arterial bleeding from the left groin (Fig. 6). A pressure dressing was applied and controlled the bleeding. The patient was questioned and admitted to repeated injections of heroin into the left femoral vein, presumably some of which caused the infected false

Figure 5. Proximal aspect of skin incision used in volar-ulnar approach to decompress the volar and lateral compartments of the forearm. (Reprinted from Dente and colleagues[115] with permission from Elsevier.)

Figure 6. Infected false aneurysm of the left common femoral artery. The patient had a history of repeated injections of heroin into the left groin. Presumably, some injections were into the left common femoral artery.

aneurysm of the left common femoral artery. The pressure dressing was left in place for 24 hours, with careful monitoring of the left pedal pulses, and intravenous broad-spectrum antibiotics were administered. The patient was taken to the operating room on the following day. The proximal left common femoral artery was encircled with a vessel loop by incising the inferior aspect of the left inguinal ligament for a distance of 2 cm. A separate longitudinal incision inferior to the false aneurysm allowed for exposure of the left superficial femoral artery. This, too, was encircled with a vessel loop. After intravenous heparin (100 units/kg) was administered, vascular clamps were applied to the encircled left common femoral and superficial femoral arteries. The mid- and distal left common femoral artery and the proximal superficial femoral and profunda femoris arteries were all infected. By careful elevation of the bifurcation of the common femoral artery, the profunda femoris artery beyond the area of infection was clamped as well. The infected arteries and surrounding soft tissue were excised. The proximal healthy left common femoral artery was oversewn with 2 rows of 5-0 polypropylene suture and was noted to retract under the inguinal ligament. The healthy ends of the superficial femoral and profunda femoris arteries were elevated, another 2 cm was resected from each, and each was oversewn with 2 rows of 5-0 polypropylene suture. The open wound in the left groin was then packed with antibiotic-soaked gauze. The viability of the patient's left lower extremity was monitored in the ICU for 48 hours. Although the left leg and foot were cooler as compared with the right lower extremity, the extremity stayed viable. The patient's left groin was allowed to heal by secondary intention.

Comment

The misadventures of intravenous drug abusers in which arteries rather than veins are injected can result in infected

false aneurysms. These have most commonly occurred in the brachial or common femoral arteries, but have been noted in the carotid artery, as well.[116-118]

The treatment of choice for infected false aneurysms of the groin is excision of the entire femoral artery system involved in the infection.[119] Threatened viability of the involved lower extremity is extraordinarily rare, but is treated with an emergency obturator bypass to the superficial femoral artery.[116-119]

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