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Pediatric peripheral vascular injuries and associated orthopedic considerations

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ABSTRACT

Pediatric peripheral vascular trauma is a rare but highly morbid injury in children and is frequently associated with concomitant orthopedic injuries. These children require multidisciplinary care by pediatric, vascular, and orthopedic surgery. In this review, we describe elements of the complex care required for children with peripheral vascular trauma.

Introduction

Traumatic injuries are the leading cause of death in children and adolescents aged 1-19 years in the United States. Traumatic causes represent approximately 60% of childhood deaths. Within this category, motor vehicle accidents, bicycle accidents, pedestrian strikes, sports injuries, falls, burns, drownings, and penetrating injuries are included[1]. Approximately 1% of pediatric trauma patients have a vascular injury with a 13% mortality rate[2]. External hemorrhage from uncontrolled extremity bleeding is increasingly recognized as being a potentially preventable cause of death after severe trauma[3].

We examine peripheral vascular trauma in the pediatric population focusing on the work-up and management of upper and lower extremity penetrating and blunt vascular injuries. Therapy for patients with concomitant vascular and orthopedic injuries will also be discussed. Complex pediatric vascular trauma is generally treated by "adult" vascular surgeons in association with pediatric surgeons. There is no formal additional training pathway for pediatric vascular surgery. Injuries in the pediatric population are handled very similarly to adults with a few key differences which will be discussed.

Pediatric vascular trauma includes blunt, penetrating and burn injuries. For our purposes, penetrating and blunt injuries will be discussed, as less than 1% of documented vascular injuries in the pediatric population are the result of burns. An estimated 60% of pediatric vascular injuries are from penetrating mechanisms and approximately 40% are blunt in nature[4]. Most pediatric vascular injuries are to the extremities. Due to the scarcity of pediatric vascular injuries, most studies have a relatively small number of patients.

Exsanguination prevention: stop the bleed campaign

The American College of Surgeons Committee on Trauma led "Stop the Bleed" Campaign has been instrumental in training civilians with the basic skills of hemorrhage control in a prehospital setting. The national campaign was organized in 2015. The campaign first demonstrated improved bleeding control skills and knowledge in the adult population and has been increasingly examined in the pediatric population. The "Stop the Bleed" tourniquet use has its roots in military experience. The wars in

Abbreviations: (PTS), Pediatric Trauma Society; (ABI), Ankle Brachial Index; (IEI), injured extremity index; (API), arterial pressure index; (CTA), computed tomography angiography; (DSA), Digital subtraction angiography; (GSV), Great Saphenous Vein; (PTFE), polytetrafluoroethylene; (ACT), activated clotting time; (PT), posterior tibial artery; (AT), anterior tibial artery; (TEVAR), Thoracic endovascular aortic repair; (ASA), Aspirin; (AVF), arteriovenous fistula; (SH), Salter-Harris; (MESI), system, Mangled Extremity Syndrome Index; (MESS), Mangled Extremity Severity Scoring System; (PSI), Predictive Salvage Index; (LSI), Limb Salvage Index; NISSSA, (Nerve Injury, Ischemia, Soft Tissue Injury, Skeletal Injury, Shock, and Age of Patient).

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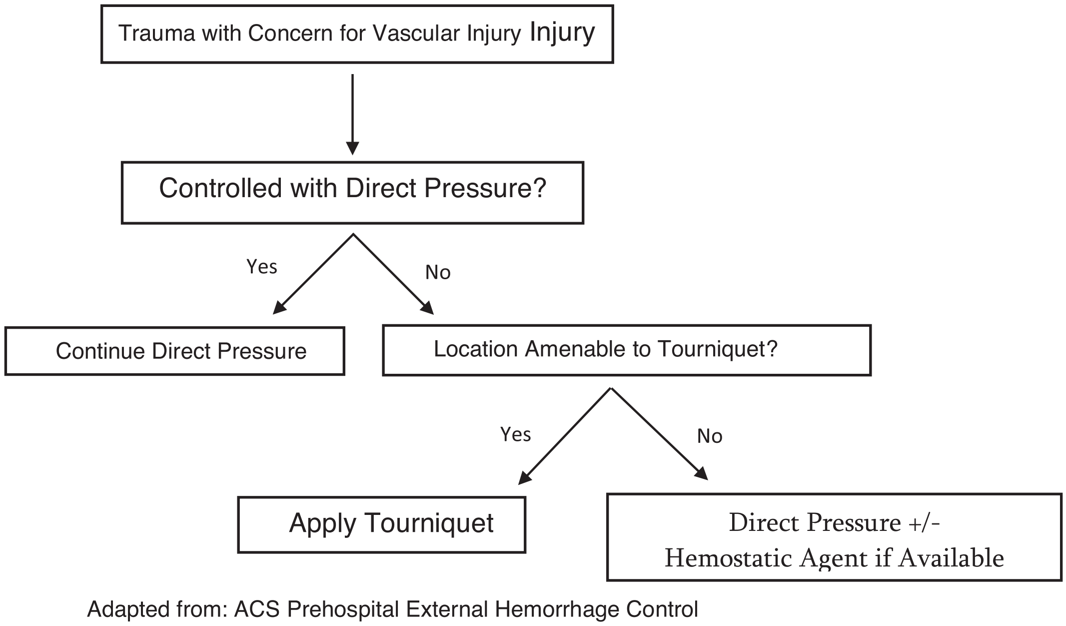

Fig. 1. Pre-hospital extremity injury vascular assessment and intervention.

Afghanistan and Iraq led to identification and improved treatment of hemorrhage outside the hospital setting. Prior to these conflicts, tourniquet use was widely discouraged due to the concern for ischemic tissue injury and limb loss. We now know the opposite to be true – that tourniquet use does indeed have survival benefits. During the conflicts in the Middle East from 2006-2011, mortality from external hemorrhage was reduced to 2.6% of all battlefield fatalities[5]. This corresponds to the availability of tourniquets and implementation of the Tactical Combat Casualty Care guidelines[6].

Training the public in traumatic hemorrhage control should be performed through in-person sessions. Studies have demonstrated laypersons are more likely to assist a severely bleeding person if they have had formal training[7,8]. Formal training also leads to improved proper tourniquet usage and retention of a learned application skill[7].

Adult combat tourniquets are effective in children as young as 6 years old. It has been shown that tourniquet use is greater than 90% effective in controlling hemorrhage in both the upper and lower extremities[9]. Like adults, high school students with a hemorrhage control curriculum were more successful at placing a tourniquet than those without formal in-person training[10,11]. Unfortunately, few states require hemorrhage control kits in public schools. However, some states have introduced bills that would require “Stop the Bleed” training for students and faculty in public schools. While this is a great step, most states do not have such a requirement.

Pre-hospital care

Uncontrolled hemorrhage in the pre-hospital setting is best managed with a tourniquet proximal to the injury. The Pediatric Trauma Society (PTS) supports the ACS “Stop the Bleed” campaign and tourniquet use in children. In addition to the pre-hospital setting, the PTS supports tourniquet use during the resuscitation phase of pediatric trauma patients[12]. Definitive vascular repair is paramount after resuscitation and tourniquet time must be limited to the shortest duration possible. Recommendations by the American College of Surgeons in 2015[3] for external hemorrhage control were designed and studied in adult patients but the principles can be applied to pediatric patients as well (Fig. 1).

Work-up and diagnostic approach

Timely extremity revascularization is most important for improved functional and growth outcomes in children after vascular and orthopedic trauma. Full primary and secondary surveys should be performed on pediatric patients in the emergency department. If a tourniquet is present, this should be released for a pulse examination and for signs of uncontrolled hemorrhage. If there is uncontrolled hemorrhage, the tourniquet should be re-applied with prompt transfer to the operating suite.

Hard signs of extremity vascular injury include absent distal pulses, active hemorrhage, expanding or pulsatile hematoma, thrill or bruit over a hematoma, and the additional 5P’s of distal ischemia (paresthesias, pallor, pain, poikilothermia, and paralysis). In a patient with one hard sign of injury, immediate surgical consultation with a provider capable of vascular repair (pediatric and/or vascular surgery) should be sought as there is a high likelihood of vascular injury requiring repair[13]. Soft signs of vascular injury (Table 1), if present, should heighten the suspicion for vascular injury.

Pulse discrepancy between two extremities is a soft sign of vascular injury. Plain film radiography should be performed in the emergency department in hemodynamically stable patients. Fractures and dislocations should be reduced as quickly as possible to decrease morbidity to the extremity. Post reduction, the vascular exam should be repeated. Table 2 describes common orthopedic injuries and their associated arterial injuries.

Previously healthy pediatric patients should have palpable distal (radial, dorsalis pedis or posterior tibial) pulses at baseline. If there is any discrepancy between laterality, the index of suspicion for a vascular injury should be heightened. Ankle Brachial Index (ABI) is often used after reduction of fractures in the emergency department. An ABI less than 0.9 is concerning for limb ischemia and vascular injury. However, in infants and toddlers less than 2.5 years of age, a normal ABI is often less than 0.9 and therefore not an accurate diagnostic tool[14]. In these younger patients, the injured extremity index (IEI) or arterial pressure index (API) should be utilized. The IEI is the ratio of the highest systolic occlusion pressure in the injured extremity at the level of the dorsalis pedis/posterior tibial arteries (or radial/ulnar arteries in upper extremity) divided

Table 1
Hard & soft signs of vascular injury.

Hard signs	Soft signs
Pulsatile Bleeding	History of arterial bleeding on scene
Expanding Hematoma	Proximity of penetrating wound to major artery
Bruit or Thrill	Diminished unilateral distal pulse
Pulseless	Small nonpulsatile hematoma
Pallor, Paresthesia, Pain, Poikilothermia, Paralysis	Neurologic deficit
	ABI, IEI < 0.9

Table 2
Common orthopedic injuries and associated vascular injury.

Orthopedic injury	Artery
Anterior Shoulder Dislocation	Axillary
Supracondylar Humerus Fracture	Brachial
Elbow Dislocation	
Supracondylar Femur Fracture	Popliteal
Posterior Knee Dislocation	
Tibial Plateau Fracture	Popliteal, Tibioperoneal Trunk

Table 3
Arterial injury and management.

Artery	Repair vs Ligate
Axillary	Repair
Brachial	Repair
Radial and Ulnar	Repair. Can ligate single vessel if intact palmar arch
Common Femoral	Repair
Superficial Femoral	Repair
Profunda Femoris	Ligate if Hemodynamically Unstable
Popliteal	Repair. Most often requires interposition graft
Tibial Vessels	Repair. Can ligate single vessel

by the systolic pressure in a proximal vessel in an uninjured extremity (most often the brachial artery).

With an IEI or ABI less than 0.9 in an older pediatric patient, the patient warrants further workup. This usually consists of duplex ultrasound or computed tomography angiography (CTA). At most institutions, CTA is the next imaging modality of choice. Duplex is user dependent and often not as readily available as computerized tomography. CTA is available at most institutions; it is rapid, standardized, and noninvasive. Digital subtraction angiography (DSA) is the gold standard for the diagnosis of arterial injuries. It can be used for therapeutic interventions as well[15]. However, CTA has largely replaced DSA in almost all large hospital systems. DSA is still warranted in select cases in patients with soft signs of injury and metal implants or shrapnel which will cause artifact with computerized tomography.

Operative management

Management of traumatic arterial injuries of the upper and lower extremities in the pediatric population is similar to that of adults (Table 3). However, the small size and future growth of pediatric vessels must be considered. An injured artery should be debrided to viable tissue. Repair options include primary repair with resection and re-anastomosis, interposition grafting with autologous vein or synthetic graft (polytetrafluoroethylene (PTFE) or Dacron) and vein patch angioplasty. If resection and anastomosis is performed, the artery must be mobilized both proximal and distal to allow for a tension free repair. If an interposition graft is necessary for a tension free repair, an autologous vein graft is best and reversed Great Saphenous Vein (GSV) is most commonly used. If the injury is to the lower extremity, contralateral GSV should be used for the conduit. Contralateral vein is believed to be superior to ipsilateral graft to avoid decreasing venous outflow in an already injured extremity. Patch angioplasty is used if there is a dissection flap or an incomplete transection of the vessel. The majority of repairs (~60%) consist of resection and re-anastomosis and ~40% are performed with a venous interposition graft[16]. Vascular anastomoses in children are performed by spatulating both ends of the vessels to be joined and performing an anastomosis using interrupted non-absorbable monofilament suture. Interrupted repair allows for later circumferential growth of the vessel[17]. Procedural heparin is widely used and accepted unless there is a contraindication to anticoagulation. Systemic heparinization should be initiated once hemorrhage is controlled. A weight-based dosage of 50-100 units of heparin per kilogram is used. Adequate anticoagulation is measured using a goal activated clotting time (ACT) of approximately 250 seconds. The ACT should be rechecked until the goal ACT is reached and then each hour until limb reperfusion is achieved.

For injuries of the forearm, a Doppler Allen's test must be performed to confirm both radial and ulnar contribution to the palmar arch. If only one artery is injured and there is an intact palmar arch via Doppler Allen's test or intra-operative DSA, the injured artery can safely be ligated. If the palmar arch is not intact, the injured vessel should be repaired via one of the approaches discussed earlier. With injuries to both arteries, the ulnar artery should be preferentially repaired since the majority of the population is ulnar dominant. After repair of the ulnar artery, an on-table angiogram should be performed to confirm an intact palmar arch and arterial flow to all 5 digits. If the patient is radial dominant, a second repair to the radial artery is then performed. Forearm arterial injuries are often amenable to resection to healthy tissue and primary anastomosis if the injured artery can be mobilized proximally and distally. If the artery is unable to be reapproximated without tension, a size-matched autogenous interposition graft should be used. Reversed great saphenous, cephalic or basilic veins are commonly used for this.

Tibial vessels are most often treated with interposition grafts. Single tibial vessel runoff to the foot is adequate. Either the posterior tibial (PT) or anterior tibial (AT) artery can be ligated in a single vessel injury. If both are transected, a single repair to either artery is often adequate[18]. The peroneal artery alone is not adequate runoff.

One should liberally employ the use of 4-compartment fasciotomies for lower extremity arterial injuries. Forearm fasciotomy is rarely necessary for upper extremity vascular injury and not routinely performed. Young, healthy patients are accustomed to having normal blood flow to their extremity prior to trauma and often have significant swelling and re-perfusion injury after ischemia. Liberal use of fasciotomies likely plays a role in limb salvage. Post-operative patients should be monitored for rhabdomyolysis. Aggressive crystalloid resuscitation is necessary and serum Creatine phosphokinase and urine myoglobin should be trended. Normal saline is most commonly used with an initial bolus of 20cc/kg and a continuous rate of 2 times normal maintenance rate (Maintenance: 4-2-1 Rule per hour. 4cc/kg for <10kg, 10-20kg 40cc + 2cc/kg for every kg >10, >20 kg is 60cc + 1cc/kg for every kg >20). Resuscitation is based on goal urine output of approximately 3cc/kg body weight/hr. In cases of rhabdomyolysis resulting in renal failure, intermittent hemodialysis (renal replacement therapy) is required.

Postoperative patients with hemodynamic instability and coagulopathy must be brought to the intensive care unit (ICU) for resuscitation and warming. Performing an abbreviated operative procedure in pediatrics is acceptable. This involves shunting of the arterial or venous injury such as when orthopedic surgery is applying an external fixator. Shunting is often performed using an Argyle shunt (carotid shunt) or a pediatric feeding tube. The shunt should be size matched to the injured artery. If an Argyle shunt (8, 10, 12, 14Fr) is not available, a small-bore feeding tube, foley catheter or chest tube can be used. The shunt is typically left in place for 12-24 h prior to definitive repair. Shunted larger vessels have greater patency rates than smaller vessels in the forearm or tibial vessels[19]. Systemic anticoagulation is not needed while a shunt is in place. In addition, anticoagulation is used during resuscitation and reversal of a coagulopathy. Definitive repair is performed shortly after correction of the coagulopathy.

Endovascular therapy

Endovascular therapy in traumatic arterial injuries has been increasing in frequency but may not be available for use in all pediatric patients. Thoracic endovascular aortic repair (TEVAR) and internal iliac artery embolization for pelvic injuries are the most commonly reported uses of endovascular therapy in vascular injuries in adolescent patients[16]. Small intimal injuries or dissection flaps in blunt extremity trauma can be treated with angioplasty or with therapeutic anticoagulation with a heparin drip and serial clinical examination. Small dissection flaps managed conservatively should be transitioned to 6 months of aspirin therapy. Balloon angioplasty has been performed in pediatric patients successfully for traumatic popliteal occlusion[22]. Endovascular embolization using coils or gel can be efficacious in treating small pseudoaneurysms and arteriovenous fistulas within deep femoral artery branches[23,24]. A peroneal or PT/AT injury identified on CTA can be embolized under DSA[25] in the absence of hard signs of vascular injury with adequate runoff to the foot via a PT or AT artery. This should be considered if there is concern for re-bleeding as opposed to traditional open exploration and ligation.

Many endovascular devices can be used for adult-sized adolescent patients. Currently, there are no stent grafts on the market for the smaller vessels in young pediatric patients. Widely available sheath sizes of 6Fr or greater are used for delivery of the endoprosthesis with a covered stent diameter starting at 5mm. In addition, stent grafts do not grow when a child grows, which further limits the potential for use in children. While bioabsorbable stents are currently being studied, there are no currently approved devices available on the market for use in adults or children[26]. However, this technology may impact endovascular therapy in pediatric patients in the future, especially in difficult to expose arteries such as the subclavian and iliac.

During interventional radiologic or cardiologic procedures in children, utilization of sheath sizes greater than 6Fr has been associated with iatrogenic injury[20]. Iatrogenic injury is likely caused by spasm in the artery after catheterization. Spasm can lead to thrombosis or persistent spasm that can last for several hours[21]. Papaverine (30mg slow IV push over 1-2 minutes or 30mg in 250cc in saline infusion), systemic and topical nitroglycerine and warming the patient will assist with spasm reversal.

Venous injuries

The intervention of choice for venous injuries of the extremities depends on the hemodynamic stability of the patient. In hemodynamically unstable patients with an isolated venous injury, the vein should be ligated. Ligation is the technique of choice for small caliber veins such as the posterior tibial or anterior tibial veins. In concomitant larger vessel arterial and venous injuries, the vein (femoral or axillary) should be repaired to reduce tissue compartment pressures and allow for adequate venous return after the arterial repair[27]. Similarly, if arterial shunting is used in a damage control setting to allow for resuscitation, the concomitant vein can be shunted and either repaired or ligated at the definitive operation. Options for venous repair range from venorrhaphy with or without a vein patch, resection and primary anastomosis, or saphenous vein grafting. All repairs should be performed in an interrupted manner to allow for vessel growth in the future[27].

Post-operative and long-term follow-up

After arterial or venous repair, low dose (ie 81mg) Aspirin (ASA) daily should be given for $\geq$ 3 months post-operatively. The endothelium takes several days to bridge the anastomosis leaving it prone to platelet aggregation until complete. The role of ASA is to prevent platelet aggregation, intimal hyperplasia at the anastomosis and within the venous bypass graft[28,29].

Patients should be followed at regular intervals post-operatively: 2 weeks, 3 months, 6 months, 12 months and annually thereafter. A complete physical exam, especially a pulse exam, should be performed during follow-up visits. If the patient has not finished growing, monitoring for limb length discrepancy should be performed in follow-up. Children and younger adolescents benefit from annual monitoring for progressive limb length discrepancy. Patients approaching skeletal maturity (age 14 in females, age 16 in boys) at the time of injury do not require growth surveillance. Duplex ultrasound should be performed at 3 months, 6 months, and 12 months post-operative and then annually thereafter. This should be performed for the lifetime of the graft.

Long-term risks include claudication, functional impairment, and limb length discrepancies[30]. Surveillance for anastomotic stricture and aneurysmal degeneration of venous grafts must be performed yearly. Anastomotic stricture can be treated with graft/anastomotic revision or endovascular therapy. Limb lengthening procedures are sometimes required in pediatric patients with limb length discrepancy. Rarely, unidentified traumatic arteriovenous fistula (AVF) can lead to high flow cardiac failure over years. Traumatic AVF can be independent of prior arterial repair. High flow AVF can lead to high-pressure venous and ischemic arterial ulcers in the affected limb[31,32]. This is often identified with CTA and treated with endovascular embolization or open surgical repair.

Peripheral vascular trauma cannot be discussed without discussing concomitant orthopedic injuries. As will be discussed, fracture severity, treatment, and soft tissue management is vital for long term vascular repair success.

Associated fracture and/or dislocation

In the setting of a grossly deformed limb with poor perfusion, it is imperative to immediately perform a gentle reduction of associated fractures and/or dislocations to relieve potential kinking or compression of the vasculature Grossly deformed limbs should be repositioned after expedient administration of pain medication. Formal reductions are performed without excessive force under sedation. After the limb realignment, perfusion should be reassessed. Vascular studies such as a CTA should not be performed until restoration of normal limb alignment has been performed, correcting obvious deformity from a fracture or dislocation.

If there is persistent abnormal perfusion after realignment of the limb, the patient should be taken emergently to the operating room. Immediate arterial repair may precede skeletal stabilization if a fracture is stable and will not require manipulation. However, rapid bony stabilization should be performed first for an injury that is unstable, displaced, shortened, or extensively comminuted if the expected total ischemia time is less than 2.5 h. Limb stability can be rapidly achieved with external fixation, pin fixation, or plate and screw fixation to allow for subsequent revascularization. Skeletal stabilization provides a normal resting position of the limb, improving the exposure of the vascular injury and allowing the vascular repair to be of adequate length. Subsequently, this will help protect the vascular repair during the manipulation required at the time of definitive fracture repair[33].

External fixation can be rapidly applied and requires minimal imaging. Care should be taken to place the external fixator in a position that does not interfere with access to the pertinent vasculature or subsequent management of complex associated wounds. Additionally, temporary pin fixation of certain fractures or dislocations can stabilize the limb alignment to allow for urgent revascularization. Specific pediatric fractures may be appropriately managed definitively with pin fixation, and this can be performed rapidly. Definitive fracture fixation with a plate and screw construct may be appropriate prior to revascularization, but the orthopedic surgeon should be cognizant to only consider this option if this can be performed rapidly while avoiding excessive ischemia time. Otherwise, a temporizing strategy such as external fixation or pin fixation is the preferred option.

When there has been prolonged ischemia of the injured limb, restoring arterial flow becomes the highest priority. As previously stated, temporary intraluminal vascular shunting should be considered prior to skeletal stabilization[34-36]. This strategy provides rapid restoration of perfusion and allows time for detailed examination of the limb, debridement of bone and soft tissue injuries, and skeletal stabilization prior to formal vascular repair.

Compartment syndrome

Compartment syndromes frequently occur in closed fractures, open fractures, or crush injuries without fracture. Swelling and tense compartments are typically present. Early symptoms may include paresthesias and decreased sensation in the injured limb. Progressive pain is the most important symptom when assessing for the diagnosis. Pain is typically out of proportion to the injury and is exacerbated by passive stretch of muscles in the involved compartment. Decreased active movement may be noted but it is often difficult to differentiate true paralysis from muscle guarding due to pain from the injury. Capillary refill and peripheral pulses are typically normal in acute compartment syndrome unless there is an associated vascular injury.

Due to limitations in the ability of children to communicate and cooperate with examination, there may be a delay in the diagnosis of compartment syndrome. The classic signs and symptoms of pain, pallor, paresthesia, paralysis, and pulselessness have been noted to be relatively unreliable in children[37]. For pediatric patients, the three *As* – agitation, anxiety, and increasing analgesic requirements, may herald the development of compartment syndrome and should elevate the clinical concern[38].

Compartment pressure measurements serve as an adjunct to the diagnosis and should be interpreted with the overall clinical scenario. An intra-compartmental compartment pressure (ICP) of greater than 30 mm Hg is considered abnormal. Some have advocated that ICP greater than 30 - 45mm Hg serve as a threshold for the diagnosis, but there is variation in the individual tolerance of elevated ICP linked with systemic blood pressure or perfusion pressure. Others have suggested that limb perfusion would be adequate if the diastolic blood pressure (DBP) is 30 mm Hg greater than the measured ICP. Fasciotomy is then indicated if the ΔP (ΔP = DBP – ICP) is less than 20-30 mm Hg. A complicating factor is that ICPs are frequently measured in children under general anesthesia where the diastolic blood pressure may be artificially depressed.

The traumatized extremity with vascular injury is at risk for compartment syndrome. Reperfusion injury may increase this risk after restoration of arterial inflow and subsequent interstitial fluid leakage that may increase compartment pressures If there has been prolonged ischemia of $\geq$ 6 h or excessive swelling, fasciotomy should be strongly considered after revascularization. A fasciotomy should always be performed after revascularization of any mangled extremity [39-41]. Early fasciotomy in patients with extremity vascular injury has been shown to decrease the risk of adverse outcomes such as amputation [42]

Growth plate fractures

Physeal fractures are classified using the Salter-Harris (SH) system (Fig. 2) described in 1963[43]. SH Type 1 fractures are transphyseal with separation of the physis from the metaphysis through the zone of hypertrophic cells. Growth often continues normally unless there is disruption of the epiphyseal circulation, as may occur with proximal femoral epiphyseal separation. SH type 2 fractures traverse across the physis and exit through the metaphysis. This the most common physeal fracture pattern and growth disturbance is unusual. SH type 3 fractures extend across the physis and exit through the epiphysis, resulting in an intraarticular fracture. Growth disturbance is more common with this fracture pattern. These fractures must be reduced anatomically to restore joint congruity and minimize the risk of growth arrest. SH type 4 fractures extend through the metaphysis, physis and epiphysis. The risk of growth arrest is high and anatomic reduction is necessary to align the joint and reduce the risk of growth disturbance. SH type 5 fractures are characterized by a crushing or compression injury to the physis. These are rare injuries and are sometimes recognized retrospectively after a growth disturbance has been diagnosed. Lawnmower and other high energy mechanisms may result in partial physeal loss and have been described as a type 6 injury[44]. This is associated with a high rate of premature physeal closure.

Open fractures

If the extremity vascular injury is associated with an open fracture, appropriate antibiotic therapy should be instituted upon as early as possible after arrival in the emergency room. Open fractures are stratified using the Gustilo and Anderson classification system (Table 3)[45]. Type 1 and type 2 open fractures should be treated with a first-generation cephalosporin (cefazolin) for 24 h. Type 3 open fractures or highly contaminated open fractures should receive piperacillin and tazobactam for 48 to 72 h. (Table 4 and 5)

Thorough debridement and lavage of an open fracture is critical to reduce the risk of infection. In highly contaminated wounds, irrigation with a large volume of sterile saline should be performed prior to prepping and draping the limb. Pulsatile irrigation is no longer recommended as this can drive contamination deeper into the tissues and provoke greater swelling. The operative debridement is a systematic removal of foreign material, avascular tissue, and contaminated hematoma. This is followed by additional lavage with a large volume of sterile saline.

Primary wound closure may be considered following adequate debridement and lavage. In the setting of high energy injuries or severely contaminated wounds, it is advisable to plan for serial debridement before definitive wound closure or soft tissue coverage. Negative pressure wound therapy ("wound vac") is an excel-

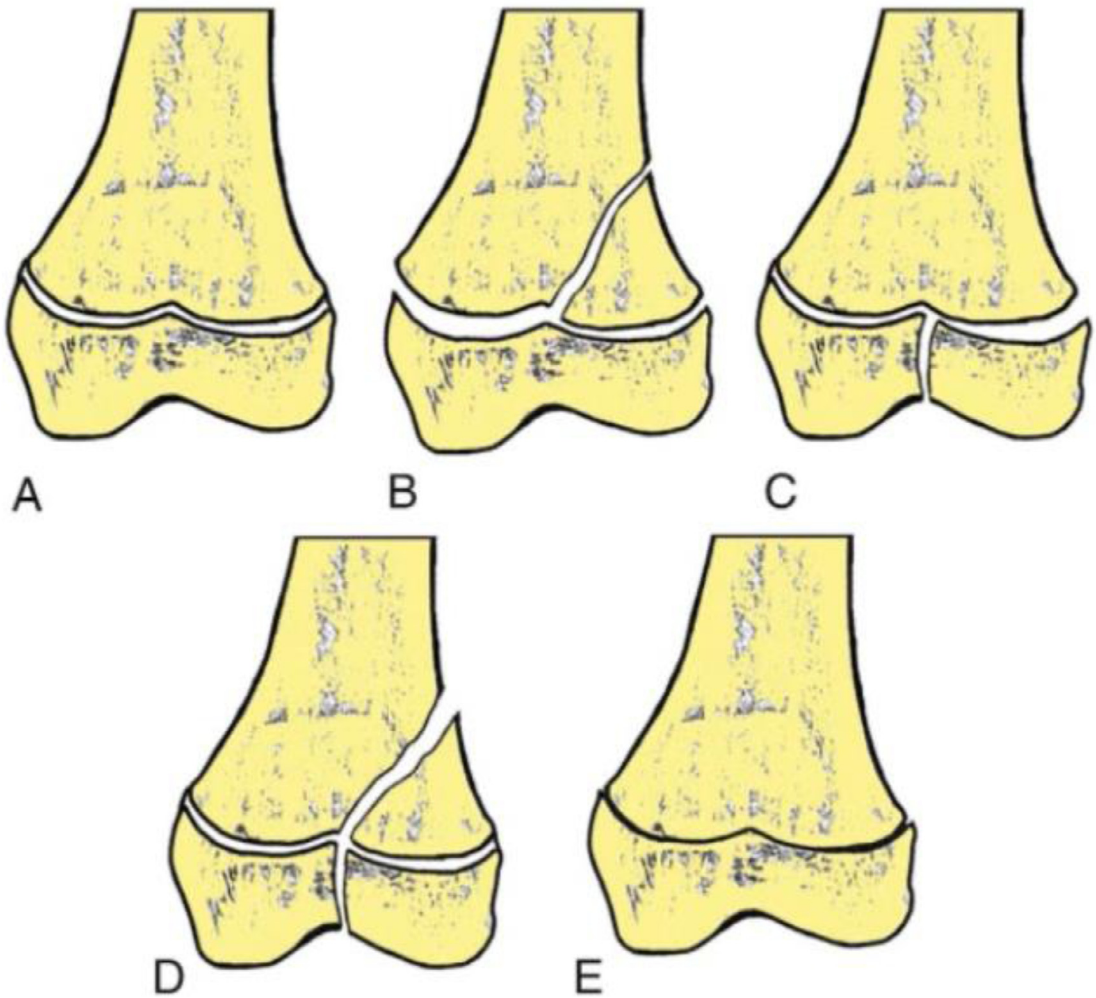

Fig. 2. Salter-Harris (SH) fracture classification system.
A. SH Type 1 fractures are transphyseal with separation of the physis from the metaphysis through the zone of hypertrophic cells.
B. SH type 2 fractures traverse across the physis and exit through the metaphysis.
C. SH type 3 fractures extend across the physis and exit through the epiphysis, resulting in an intraarticular fracture.
D. SH type 4 fractures extend through the metaphysis, physis and epiphysis.
E. SH type 5 fractures are characterized by a crushing or compression injury to the physis.

Table 4
Classification of open fractures.

Type	Description
I	Laceration of $\leq$ 1 cm
II	Laceration of >1cm and < 10 cm
III	Laceration of $\geq$ 10 cm with extensive soft tissue damage including skin, muscle, and neurovascular structures
IIIA	Type III open fracture with adequate soft tissue coverage
IIIB	Type III open fracture with extensive soft tissue damage requiring flap coverage
IIIC	Open Fracture associated with arterial injury requiring repair

Table 5
Prophylactic antibiotic protocol for open fractures.

Open Fracture Type	Primary Antibiotic	Secondary Antibiotic
Type 1 or Type 2	Cefazolin	If Cefazolin allergy, then give Clindamycin If Cefazolin and clindamycin allergy, then give Vancomycin
Type 3 or Highly Contaminated Open Fracture	Piperacillin and Tazobactam	If Piperacillin and Tazobactam allergy, then administer the following 3 antibiotics: (Clindamycin or Vancomycin) and (Ciprofloxacin or Gentamicin) and (Flagyl)

lent method of wound management when immediate soft tissue coverage is not possible. Contraindications to placement of a negative pressure appliance include an exposed vascular anastomosis or major neurovascular bundle. Wet to dry dressing changes may be utilized for wound management if negative pressure wound therapy is not appropriate.

The mangled extremity

A mangled extremity is a severe extremity injury where limb salvage may not be possible, and an amputation may be considered. These high energy injuries result in large, contaminated wounds with skin loss, degloving, and extensive muscle injury. Complex comminuted open fractures are common and there are frequently associated vascular, tendon, and nerve injuries.

The decision for limb salvage or amputation of a severe injury is challenging. Microsurgical soft tissue reconstruction and advanced skeletal repair techniques allow for salvage of extreme injuries in some circumstances. The decision for salvage should be carefully considered so that a patient is not subjected to numerous operative procedures with prolonged hospitalization and recovery if an amputation will ultimately provide a better *functional* outcome. Multiple criteria for immediate amputation exist:

- Excessive limb ischemia time (>6 h lower extremity, >8 h upper extremity)
- Vascular injury that is nonrepairable without collateral flow on arteriogram
- Multisystem trauma with injury severity score $\geq$ 25 where limb salvage may provoke multiorgan dysfunction syndrome or mortality
- Preexisting comorbid conditions where extensive operative procedures for limb salvage would pose the possibility for mortality
- Severe soft tissue loss without flap reconstruction options
- Severe bone injury without the possibility for reconstruction
- Injury severity indicates that ultimate function after salvage will be worse than with a prosthesis

Investigators have developed multiple limb salvage scoring systems with a goal to guide clinicians in the decision making for limb salvage or amputation. These include the Mangled Extremity Syndrome Index (MESI), Mangled Extremity Severity Scoring System (MESS), Predictive Salvage Index (PSI), Limb Salvage Index (LSI), and a modification of the MESS termed NISSSA (Nerve Injury, Ischemia, Soft Tissue Injury, Skeletal Injury, Shock, and Age of Patient) scoring system[35,46-49]. These scoring systems highlight factors important in limb salvage, however, each has limitations and fails to provide high specificity and sensitivity across the spectrum of injury and patient specific characteristics, limiting effectiveness in clinical care.

After the initial debridement and stabilization of a mangled extremity that does not require immediate amputation, the clinical care team should engage the patient and family in a thorough discussion in the option of continued limb salvage as compared to delayed amputation. The care team may be diverse and include pediatric surgery, orthopedic surgery, plastic surgery, and physical medicine and rehabilitation. An objective description of the magnitude of the injury is critical. The team should outline the treatment course and the expected clinical outcomes with limb salvage as compared to amputation. It is important to that the patient and family is engaged and committed to the final treatment decision.

Conclusion

The care of patients with pediatric peripheral vascular trauma with orthopedic injuries requires a multidisciplinary team of surgeons performing initial resuscitation followed by appropriate diagnostic and therapeutic measures. This often can take the work of coordinated teams working simultaneously or sequentially. It's important to remember that once the acute injury has been repaired that long term close monitoring must occur with medical therapy, vascular exams, studies, and potential interventions.

Declaration of Competing Interest

The authors have nothing to disclose.

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