

Chapter 12

EXTREMITY, JUNCTIONAL, AND PELVIC TRAUMA

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INTRODUCTION

Recent conflicts have resulted in a high proportion of limb injuries, accounting for 50% to 70% of all injuries treated during Operation Iraqi Freedom.¹ This is reflected in the steady increase in the incidence of traumatic limb amputations reported in military casualties.² Evidence from previous conflicts including Vietnam and Iraq also suggests that exsanguination from these injuries accounts for the greatest proportion of preventable deaths on the battlefield.³ As a result of these experiences, significant advances in hemorrhage control have been developed, implemented, and tested during recent conflicts. In addition, experiences in Afghanistan have revealed an increasing burden of severe extremity, junctional, and pelvic trauma,² which may represent an increased prevalence and evolution in the design of improvised explosive devices (IEDs)⁴ against both military and civilian targets.

IEDs are defined by the US Department of Defense as “devices placed or fabricated in an improvised manner incorporating destructive, lethal, noxious, pyrotechnic or incendiary chemicals, designed to destroy, disfigure, distract or harass.”⁵ These weapons have been responsible for a significant proportion

of deaths in Afghanistan. IED survivors may sustain injuries ranging from relatively minor wounds, with little or no physiological compromise, to multiple traumatic limb amputations with possible pelvic involvement. IEDs contain strong explosives with little primary fragmentation material, thereby giving rise to an injury pattern caused by the primary blast wave with secondary fragmentation. Current combat body armor provides defense to the thorax and abdomen but lacks protection for the limbs and perineum; therefore, highly contaminated junctional trauma with perineal wounds and pelvic fractures are common.^{6,7}

Recent improvements in the design of military helmets and combat body armor, in addition to the relatively high mortality of torso injuries, have also contributed to this changing injury pattern.⁶ Innovations in military medical care, such as the increased use of tourniquets and novel hemostatic treatments, are considered to have improved outcomes in military patients with trauma. Military trauma doctrine now places increasing emphasis on the early identification and treatment of catastrophic hemorrhage,⁸ so military anesthetists must have a thorough knowledge of the challenges posed by these injuries.

CLASSIFICATION OF EXTREMITY, JUNCTIONAL, AND PELVIC TRAUMA

Extremity Injuries

Limb injury and traumatic amputation is common in the current conflicts. In the lower limb, amputation typically occurs through the upper third of the tibia,⁹ although more recent experience suggests an increasing burden of more proximal amputations and junctional injuries. These injuries are associated with other extensive bony fractures, significant soft tissue disruption, and contamination due to separation of fascial planes with embedding of environmental debris. They may occur in isolation, bilaterally, distal, or more proximal, and as a result may present the anesthetist with a range from mild to severe physiological insult and challenges in securing peripheral intraosseous and intravenous access.

Junctional Injuries

Junctional zone trauma, by definition, is an injury occurring at the junction of anatomically distinct zones (Table 12-1). These injuries may be defined as damage to tissues that span the root of an extremity and adjacent body cavity. Such regions include the lower abdomen, groin, axillae, and proximal extremities.¹⁰ The injuries occur as a result of a transfer of energies

from the passage of missiles, energized fragments, or blasts. Junctional areas are traversed by major blood vessels and, when injured, may not be suitable for tourniquet application. Consequently, junctional injuries are frequently associated with profound bleeding that may be difficult to control. Trauma to these areas

TABLE 12-1
CLASSIFICATION OF JUNCTIONAL TRAUMA

Type of Injury	Characteristics	Implications
Type 1	Wound encroaches on a junctional zone but surgical control can be gained without entering adjacent body cavity.	Proximal control requires surgical incision extending across the joint flexure.
Type 2	Wound encroaches on a junctional zone requiring surgical access to gain hemorrhage control.	Body cavity may need to be entered, eg, laparotomy / thoracotomy. Potential for occult blood loss.

may therefore need early and aggressive resuscitation and surgical hemorrhage control; occasionally, limb salvage may have to give way to preservation of life.

Pelvic Injuries

Pelvic injury is associated with civilian mortality rates of 18% to 40%, and deaths within the first 24 hours are often due to blood loss.⁴ Pelvic injury mechanisms involve strong energies and frequently include damage to the pelvic vasculature and organs. The resultant cardiovascular compromise presents a complex challenge to the trauma team.

Pelvic injuries may be categorized according to the forces applied to the pelvis and the degree of ligamentous and bony disruption. Classifying the injury allows the trauma team to predict associated injuries, pathophysiology, and likely transfusion requirements.¹¹ The Young and Burgess system divides injuries into three types:

1. **Anterior posterior compression.** Pubic diastasis disruption with or without sacroiliac disruption. Pelvis is potentially unstable, with damage to pelvic vasculature and bleeding likely.
2. **Lateral compression.** Anterior ring injury with or without sacral compression fracture, posterior ilium, or sacroiliac involvement. Pelvis is usually mechanically stable; therefore, any hemodynamic instability is due to other causes such as intraabdominal pathology.
3. **Vertical shear.** Vertical displacement of hemipelvis. Potentially unstable pelvis associated with intrapelvic, intraabdominal, or mediastinal injury.

Anterior, posterior, and lateral compression have further subtypes I, II, and III with increasing severity. It is also possible to have a combination of the types following a complex mechanism of injury.

PREHOSPITAL CARE

Forward projection of military anesthetic care to aid resuscitation and evacuation of casualties back to field hospitals has gained particular prominence in recent years, in line with civilian practice¹²; examples of such models include the UK-led Medical Emergency Response Team (Enhanced) in Afghanistan.¹³ The degree of medical intervention in the prehospital phase depends on the type and size of platform used for evacuation (eg, helicopter vs land ambulance) as well as the composition and skill mix of the medical team involved.

Initial care is provided by the casualties themselves, followed by other soldiers ("buddy-buddy" system) and combat medical technicians or corpsmen when available. The main aim of care in the field is early control of bleeding in accordance with military trauma doctrine; this begins with the control of catastrophic hemorrhage, prior to assessment and treatment of the airway, breathing, and circulation (the <C>ABC paradigm).⁸ Bleeding from extremities is controlled via application of the combat application tourniquet (CAT), supplemented with direct pressure to the wound and indirect pressure to proximal vessels (eg, femoral artery) where necessary.

Recent conflicts have seen a sharp increase in the use of CATs. A high proportion of casualties with extremity trauma will likely present with at least one tourniquet in place. US data from recent conflicts suggests that CATs were already applied in over 18% of battlefield admissions,^{14,15} with significant vascular injury seen in approximately 6.6% of these cases.¹⁶ Providers must

be aware that CATs may have been applied as part of "care under fire" protocols, and therefore may not be clinically indicated. However, mortality from limb injury exsanguinations in US troops decreased from 9% during the Vietnam conflict to 2% in more recent conflicts in Iraq and Afghanistan, and consensus remains that a well-applied tourniquet can prevent death from catastrophic hemorrhage. The Israeli experience shows a 0% mortality from similar injuries when tourniquets are applied correctly. To prevent unnecessary limb ischemia, it is recommended that when the tactical situation allows, the tourniquet should be loosened after the bleeding is controlled and where appropriate substituted for a pressure dressing and elevation.⁸

Where junctional trauma has created an insufficient proximal stump for tourniquet application, or when the tourniquet fails, direct pressure with topical hemostatic agents will be required. Modern hemostatic products fall broadly into two categories. The first category of products are the chitosan-based preparations (eg, HemCon [HemCon Medical Technologies Inc, Portland, OR]; Chitoflex [HemCon Medical Technologies Inc]; Celox [Medtrade Products Ltd, Crewe, UK]). Chitosan is a nontoxic derivative of the naturally occurring carbohydrate chitin (found in the cell wall of fungi and crustaceans) and has mucoadhesive properties that accelerate hemostasis in the presence of bleeding. The second are zeolite-based preparations (eg, QuikClot [Z-Medica, Wallingford, CT]). Zeolite is a mineral-based material that promotes hemostasis by concentrating clotting factors in an exothermic reaction

initiated by exposure to water (and therefore blood). All these products are widely available to field medics on the modern battlefield and are likely to have been applied to casualties with severe limb bleeding.

The presence of junctional trauma makes adjoining body cavity and bony injury likely, so thoracic, abdominal, and pelvic injury should be assumed. Thorough examination of the body cavity adjoining the injured limbs should be undertaken to exclude pathology such as clinical signs of thoracic and abdominal disruption. All lower limb junctional trauma should be assumed to involve pelvic fractures until proven otherwise. Suspected pelvic fractures should be stabilized with empiric application of a pelvic binder (or a sheets and sand bag improvisation) and correction of lower

extremity external rotation by taping the knees and ankles. The chances of exsanguination and hypovolemia must be mitigated preemptively per current military trauma doctrine.

Major limb trauma is associated with severe pain, and efforts to mitigate pain in the prehospital phase are essential.¹⁷ Splinting fractures to reduce pain and bleeding requires the administration of effective analgesia. Numerous drugs are used in the prehospital environment; the agent chosen will depend on physician familiarity and drug availability. In all cases, the aim is to alleviate pain while minimizing serious adverse effects such as oversedation (loss of verbal contact), respiratory depression, hypotension, nausea, and vomiting.

ROLE 3

When severe extremity, junctional, and pelvic injuries are reported, an appropriately staffed trauma team should be mobilized. Most casualties should receive standard trauma care in the emergency department; however, unstable casualties (eg, in traumatic cardiac arrest with cardiopulmonary resuscitation in progress, or with limb or torso trauma and signs of critical hypovolemia) and those with junctional injuries with incompressible hemorrhage may bypass the emergency department and be taken straight to the operating room (OR) to allow damage control resuscitation and surgery to commence simultaneously.¹⁸ The requirement for large bore intravenous (IV) access is paramount and should be immediately established when the casualty arrives at Role 3 if not already in place. The laboratory liaison should ensure suitable supplies of O Rh-negative, and AB-negative plasma should be requested and used until group-specific agents are available.

All patients will receive a focused assessment with sonography in trauma (FAST) scan, and the majority of blast injury patients will undergo multislice computed tomography (CT) scanning as part of their initial management, to help guide surgery. The decision to scan must balance the risks of delaying the surgical control of significant bleeding with gaining diagnostic information that may allow more appropriate surgery. The use of truncal angiography is gaining in popularity, with the arterial phase often available to the mid lower limb. Approximately 20% of whole body CT scans are extended to include peripheral lower limb angiography. Such preoperative knowledge of arterial damage and collateral vessel “run off” (when accompanied with tourniquet release) greatly assists in assessing hemorrhage sites, determining limb viability, and surgical decision-making (personal com-

munication from Surgeon Commander R Miles, RN, Defence Consultant Advisor, Radiology; Plymouth, UK, August 2011).

Extremity Injuries

Injured limbs associated with potentially catastrophic hemorrhage will have had tourniquets placed in the prehospital phase, and the requirement for these should be reassessed at Role 3. Loosening tourniquets should only be done with the immediate availability of dressings, other hemostatic products, and surgical expertise. If a tourniquet is still required, it should be replaced with a padded pneumatic surgical tourniquet, once the patient is anesthetized. This tourniquet allows more measured application of compression, and the wider dimensions are considered less likely to cause further damage to soft tissues and nerves.

Conscious, physiologically stable patients with extremity trauma should be examined and the extent of injury documented. Digital photographs should be taken of all wounds when possible and with appropriate consent, to aid subsequent reconstructive procedures. The neurovascular integrity of affected limbs should be assessed (with the help of Doppler ultrasound if necessary) and documented to identify any subsequent worsening of the injury. More extensive examination, irrigation, and instrumentation of the wound should be avoided at this stage to prevent further contamination and bleeding. Injured limbs should be carefully redressed with iodine-soaked gauze and secured with a crepe bandage.

Splints applied in the prehospital phase should be reviewed by a surgeon to confirm correct position-

ing when plain radiographs are available. It is likely that improvised splints will be substituted for a more conventional splint (eg, a Thomas splint) by the attending surgeon if the patient is not proceeding to the OR imminently. Appropriate analgesia should be administered to allow the splinting.

Junctional Injuries

The surgeons must consider the approach needed to achieve proximal control, taking into account whether a type 1 or type 2 junctional injury exists. Diagnostic imaging with FAST scanning will aid the surgical decision as to the need for thoracotomy or laparotomy. In the face of physiological instability, a positive FAST scan will encourage urgent surgery for proximal hemorrhage control. If the patient is stable, the investigation of choice to assist in surgical planning is high resolution CT angiography.

OPERATIVE INTERVENTION

In the OR, procedures may be conducted under regional anesthesia, general anesthesia, or a combination of the two. In all cases, the aim is to maintain adequate tissue perfusion, oxygenation, homeostasis, hemostasis, and analgesia.

Generic Considerations

Positioning

It is important that the often numerous surgical teams have adequate access to the injury sites to effectively perform the surgery. The abdomen and chest may need to be prepared and opened to achieve proximal vascular control. Care should therefore be taken to ensure that vascular access sites are accessible and secured. Additionally, it is important to ensure that all limbs, whether injured or otherwise, are adequately padded and joints placed in neutral positions to prevent further neurovascular injury. Placing the patient in the cruciform position addresses these issues while providing good surgical access.

Infection Control

Blast and ballistic wounds are at high risk of bacterial infection due to extensive contamination from environmental debris. The majority of organisms causing life-threatening infections (eg, *Clostridium perfringens* and *Streptococcus pyogenes*) are sensitive to relatively narrow spectrum antibiotics such as benzylpenicillin.

Pelvic Injuries

Life-threatening pelvic hemorrhage remains a source of preventable death in the trauma population and can occur with all pelvic fracture patterns. The three major bleeding sources are fractured cancellous bone and venous or arterial laceration. Priorities are the early identification of fractures and associated bleeding, with early mechanical stabilization and aggressive volume resuscitation. A multidisciplinary approach with coordination of early surgery is key. Pelvic radiographs will guide the surgeon to achieve restoration of the pelvic ring. FAST scanning in the emergency department will assist in diagnosis of abdominal and pelvic blood and inform further treatment.¹⁹ The presence of intraabdominal blood will trigger urgent laparotomy and pelvic fixation, whereas a negative scan will trigger further resuscitation and pelvic fixation if cardiovascular stability is not achieved.

Extensive use of broader spectrum agents has been linked to the increased incidence of multidrug resistant species such as *Acinetobacter* species.^{20,21} Where the tactical situation allows, parenteral antibiotics should be administered during the prehospital phase (eg, benzylpenicillin 1.2 g IV or intramuscular), although the evidence base for this is not extensive.²² In the OR, a suitable choice would be co-amoxiclav 1.2 g IV (clindamycin 600 mg IV if the patient is allergic to penicillin), cefuroxime 1.5 g IV in the presence of fractures, adding metronidazole 500 mg IV with compound fractures and severe soft tissue injury.¹⁸ Those without immunity to tetanus should receive relevant prophylaxis.²³

Communication

The anesthesiologist has a key role in aiding the situational awareness of the surgeon, who is likely to be focused on the surgical field. The anesthesiologist may assist in the coordination of numerous simultaneously operating surgical teams often operating on different anatomical regions of the casualty. It is important to maintain effective communication and convey vital information, including duration of tourniquet inflation, clamping of major vessels, and significant changes in physiological parameters. It may be necessary in the face of significant blood loss for the anesthesiologist to call for a "hemostatic pause," when surgery is halted while blood products and medication are administered to correct coagulopathy and control bleeding.

Regional Anesthesia

Regional procedures can be effectively performed in the emergency department but are usually reserved for the OR. Peripheral nerve blocks may provide excellent anesthesia and analgesia, for both intraoperative and postoperative pain control, avoiding the systemic side effects of many parenteral analgesics and potentially reducing the incidence of postoperative neuropathic and phantom limb pain. Nerve blocks may take the form of single-shot injections of local anesthetic or infusions via peripheral nerve catheters,²⁴ which are increasingly being inserted under direct vision using ultrasound. Such procedures are ideally suited for trauma patients, who may require numerous trips to the OR for staged surgery. Following the correction of coagulopathy, epidural catheters may be considered a more appropriate option in the case of bilateral lower limb injuries.

Tourniquet Use

It is important to avoid the serious and largely dynamic complications associated with tourniquet application and reperfusion (summarized in Table 12-2). Cuff inflation results in rapid increases in systemic vascular resistance, and central blood volume increases following exsanguination of the affected limb. A tachycardia develops as tourniquet pain evolves after approximately 45 minutes, and together these effects lead to increases in cardiac output and mean arterial

blood pressure that may completely conceal an underlying hypovolemia. Careful volume replacement must be instituted preemptively to avoid precipitous hypotension when the cuff is deflated at the end of the procedure. Cuff pain may be severe and often persists for several hours following cuff release as reperfusion occurs. It is characteristically difficult to relieve with systemic analgesics, although because the underlying mechanism is thought to involve *N*-methyl-D-aspartate receptors, ketamine may be more effective.²⁵ Regional anesthetic techniques should be considered by the anesthesiologist to provide adequate analgesia in the perioperative period.

Peripheral nerve injury is uncommon but may be devastating. Rather than ischemic time, it appears that compressive shearing forces across the nerve are likely to be the most important mechanism influencing nerve injury.^{15,26} This problem can potentially be minimized by using wide, contoured cuffs for the minimal necessary time. Excessive cuff pressure should be avoided by targeting the limb occlusion pressure, which is the minimum cuff pressure required to interrupt distal flow (demonstrated by loss of distal pulses, infrared oxygen saturation, or Doppler measurements). After limb occlusion pressure has been determined it is common practice to add cuff pressure as a safety margin to account for surgical changes that may require increased pressure.

Cuff release leads to a predictable reperfusion phenomena characterized by vasodilation, lactic acidosis, hypercarbia, hyperkalemia, hypothermia, and pain.

TABLE 12-2
COMPLICATIONS ASSOCIATED WITH TOURNIQUET USE

System	Responses	Mechanisms	Actions
Respiratory	↑MV, ↑Paco ₂ , hypoxia thromboemboli	Pain, reperfusion, pulmonary embolism	Control ventilation, increase inspired O ₂ fraction as required. Consider imaging and anticoagulation, depending on clinical context.
Cardiovascular	↑SVR, ↑MAP, ↑CO, ↑HR	Occlusion of vessels, ↑central blood volume, catecholamine release	Vasodilators if severe but beware of underlying hypovolemia
Neurological	↑ICP, peripheral nerve damage, pain	↑Cerebral blood volume, nerve compression, ischemia	Ventilate to normocapnia, target cuff pressure (LOP),* minimize cuff time, consider regional anesthesia
Metabolic	↓pH, ↑lactate, ↑K ⁺	Reperfusion of ischemic tissue	Anticipate and treat fluid resuscitation

*to stop the flow of arterial blood into the limb distal to the cuff

↑: increased

↓: decreased

CO: cardiac output; HR: heart rate; ICP: intracranial pressure; LOP: limb occlusion pressure; MAP: mean arterial pressure; MV: minute ventilation; SVR: systemic vascular resistance

This metabolic storm is often only transient (typically 10–15 min) but may be pronounced. In severe cases, myoglobinuria and rhabdomyolysis may combine to precipitate acute renal impairment.

Surgical Considerations

General

Knowledge of surgical approaches to battlefield trauma allows the anesthetist to optimize the condition of the surgical field and preempt any predictable changes in physiology caused by surgery. A number of surgical principles are common to the management of all traumatic injuries (Table 12-3). There may be times when the casualty is so sick that surgery is limited to hemorrhage control only, with the priority being further resuscitation, restoration of physiology, and transfer onward for further debridement at Role 4.

Extremity Injuries

Orthopedic. Stabilization of fractures reduces pain, infection, and further soft tissue damage as well as facilitating bone healing. Strategies for fracture stabilization include:

- Nonoperative
 - Plaster. Suitable for simple or closed fractures. Simple and effective.
 - Traction. Effective and used widely in military and civilian casualties. Its simplicity makes it a particularly attractive option in civilian patients who can be discharged to civilian hospitals with such devices in situ.
- Operative
 - External fixation. Allows more effective elimination of movement at the fracture site, transportation of casualties with open fractures, and access to soft tissue wounds to permit wound care and revascularisation procedures. However, there are some concerns about external fixation; one study suggested that complications requiring revision or removal occurred in 86.7% of cases.²⁷
 - Internal fixation. Inappropriate for the acute management of war injuries because of the unacceptably high risk of infection associated with contaminated wounds.

Vascular. Goals of damage control vascular surgery on extremities are controlling exsanguinating hemorrhage, rapidly restoring blood flow to an ischemic limb,

TABLE 12-3

GENERAL PRINCIPLES OF SURGICAL MANAGEMENT OF BATTLEFIELD WOUNDS

Surgical Principles	Rationale
Hemorrhage control	External then potentially internal proximal control
Damage control surgery	An operative strategy that sacrifices the completeness of the immediate surgical repair in order to address the physiological consequences of the combined trauma (double hit) of injury and surgery. ¹ Integrated and combined with damage control resuscitation
Debridement	Removal of all foreign material and nonviable tissue to leave a bed of healthy tissue on which subsequent reconstruction can be performed. Usually performed with a tourniquet
Wound excision	Excision of no more skin than that sufficient to leave healthy wound edges. Skin must be retained for later reconstruction procedures
Wound extension	Extension of the wound will be necessary to allow adequate examination of the zone of injury, which will extend proximally and distally
Removal of nonviable tissue	Necessary to prevent the establishment of infection. Nonviable tissue is characterized by dark coloration, mushy consistency, lack of capillary bleeding, and lack of muscle contractility when touched with a diathermy probe or crushed with forceps.
Closure	Wounds NOT treated with primary closure

1. Hawley JS, Murray CK, Jorgensen JH. Colistin heteroresistance in acinetobacter and its association with previous colistin therapy. *Antimicrob Agents Chemother.* 2008;52(1):351–352.

and preventing compartment syndrome.²⁸ It may involve clamping a proximal vessel, followed by simple ligation of damaged arteries and veins; limb salvage may be a secondary priority. If the patient is stable and the expertise of the surgeon allows, simple vascular shunts or grafts may be employed to salvage limbs. Coagulopathy often prevents the use of systemic heparin, although with increasingly successful treatment by aggressive targeted administration of blood products, it may still be necessary for surgeons to infuse dilute heparin (1 unit/mL) proximal and distal to the injury. This procedure is supported by anecdotal accounts from Iraq and Afghanistan, when shunts inserted on

the battlefield reportedly clotted during evacuation back to rearward echelons of care.²⁹

Many casualties with vascular injuries will be at risk of developing compartment syndrome, and fasciotomies may be performed. In the civilian extremity trauma population, surgical fasciotomy is performed in less than 1% (upper limb injuries) to 5% (lower limb injuries) of cases, while recent studies have suggested that 16% of casualties evacuated from Iraq and Afghanistan underwent fasciotomies.³⁰ Early clinical diagnosis is key (excessive pain, exacerbated by compression and passive extension, a palpably tense compartment, impaired neurology, and loss of distal pulses are very late signs) and has been shown to be as reliable as invasive compartment pressure monitoring.³¹ A low threshold for fasciotomy therefore stems from a combination of factors including a significant mechanism of injury, the potential for prolonged warm ischemic times, and the use of regional anesthesia techniques to the injured limbs. Another important factor is the prolonged evacuation times to Role 4 in an environment where the clinical monitoring of the limbs is difficult and compartment pressure transducer monitoring is not routinely available. One study of military casualties suggested that 35% of fasciotomies performed were done so without a diagnosis of compartment syndrome.³²

Amputation. Decision to amputate is not always straightforward, and civilian limb salvage scores are not useful. Relative indications to amputate a limb may include severe bone and/or soft tissue loss, extensive arterial injuries, prolonged warm ischemic times, and lack of appropriate surgical experience. Relative indications to salvage a limb may include upper limb injuries, bilateral limb injuries, and injuries in children.³³ If damage is extensive and/or there is questionable circulation to the limb, amputation should be undertaken. Amputations are made at the lowest possible level, with wounds left open (fashioning of flaps should be initially delayed).³⁴

Debridement. Debridement of lower extremity wounds should be performed through inspection of each muscle with transection of necrotic areas. Contamination should be identified, with careful inspection of intermuscular planes for necrosis. Proximal vascular control should be maintained until debridement is completed to allow a clearly visible surgical field.

Junctional Injuries

Type 1 injuries are often unilateral, do not require body cavity exploration, and are associated with less physiological disturbance. Hemorrhage may require an extraperitoneal approach with control at the exter-

nal iliac level. Type 2 injuries are those in which the peritoneal or thoracic cavities must be entered to gain proximal control, commonly seen in bilateral injuries when immediate laparotomy and control at the level of the distal aorta or iliac system is conducted.³⁵ This procedure has the dual effect of limiting blood loss from both the amputation site and from pelvic and perineal injuries. Laparotomy also allows direct visual inspection of abdominal viscera, which may also have suffered as a result of the primary blast wave. Anesthesiologists should be prepared for the surgical invasion of any body cavity and the physiological insults that occur as a result.

The surgical priorities in junctional injuries are continued direct pressure at the wound site, compressing the wound against the underlying axial

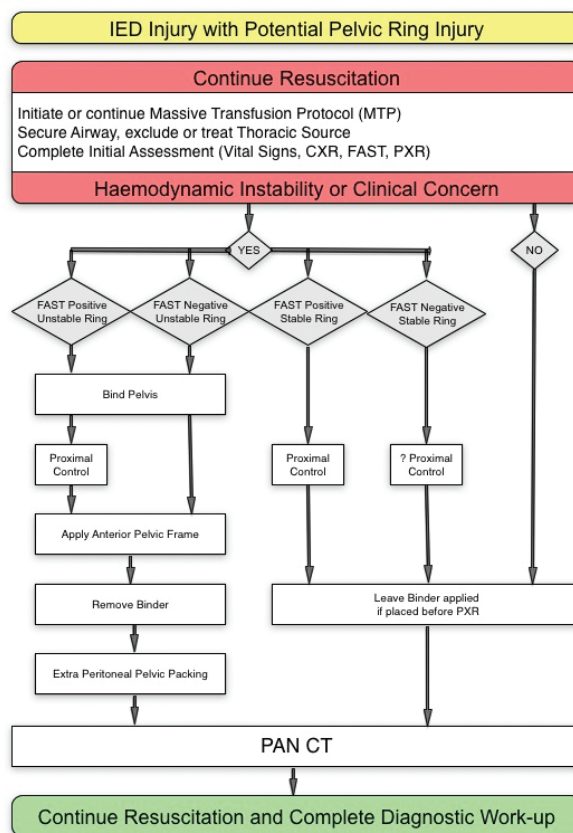


Figure 12-1. A suggested management strategy for pelvic fractures.

CXR: chest x-ray

FAST: focused assessment with sonography in trauma

IED: improvised explosive device

Figure: Courtesy of Lieutenant Colonel SA Adams, Royal Army Medical Corps, Consultant Orthopaedic Surgeon, 16 CS Medical Regiment.

skeleton while preparing for the OR. Once in the OR, manual pressure will be replaced by a sponge stick, held in place until both proximal and distal control have been achieved.

Lower limb junctional injuries can be controlled with femoral or iliac proximal control depending on the site of vessel injury. Whether control is achieved above or below the inguinal ligament will directly affect anesthesia as a result of potential surgical entry into a neighbouring body cavity. Upper limb junctional injuries are less common, but no less challenging to achieve proximal control. Right upper limb injuries may require median sternotomy for proximal aortic arch control compared with thoracotomy for left upper limb injuries; each imposes different challenges to the anesthesiologist. More distal vessel injuries may be accessed by periclavicular incisions and affected vessels ligated with reliance on collateral flow.

Pelvic Injuries

The aim of surgery for pelvic fracture is the restoration of skeletal stability and volume,¹² although further examination in the OR is essential. Pelvic fracture is often associated with damage to the pelvic veins, the pelvic viscera, and the iliac arteries and their divisions. Over 70% of hemorrhage associated with blunt pelvic trauma is venous and may be controlled with maneuvers that reduce the pelvic volume and stabilize the pelvis. The other nearly 30% is arterial and often requires surgical packing or embolization.⁴ Figure 12-1 shows a suggested management strategy for pelvic fractures.

Anteriorly, the urethra and bladder are often threatened, and posteriorly, the lumbosacral and coccygeal nerve plexuses, as a result of their proximity to bone. It is injury to these structures that results in a high morbidity and mortality.

External fixation of the pelvis is often necessary to restore stability using an anterior external fixation frame or a posterior C-clamp. If arterial bleeding continues, ligation or tamponade via catheter balloons may be necessary. Embolization of damaged pelvic vasculature is unlikely to be readily available, but extraperitoneal packing of the pelvic vasculature is a common alternative. This is a simple and potentially lifesaving procedure. It is performed via a midline incision from the umbilicus to the symphysis pubis. Tissues are dissected down to the peritoneum, where clots may be removed and swabs inserted.³⁶ When a laparotomy is indicated in the presence of pelvic fractures, it is performed with the pelvic binder in place, followed by pelvic ring stabilization using iliac crest pins. The binder can then be removed and if necessary the extraperitoneal pelvis packed.¹⁹

Open pelvic fractures and perineal disruption are associated with extremely high mortality although the number of survivors is increasing. These injuries are managed as above but with extensive debridement and antibiotics. Perineal injuries may require selective fecal diversion with a divided sigmoid colostomy. Damage to the bladder, rectum, and small and large bowel and gross soiling of the peritoneum should be anticipated. Vascularized testicular remnants are preserved, scrotal injuries debrided, and urethral injuries managed by urethral or suprapubic catheterization.³⁷

POSTOPERATIVE CARE

The course of the postoperative phase depends largely on the severity and distribution of the casualty's injuries. The physiologically unstable, severely or multiply injured casualty is likely to be transferred sedated to the intensive care unit for further care and stabilization. Particular care should be taken to observe for physiological derangements caused by reperfusion of ischemic limbs following limb salvage procedures. Perfusion of limbs must also be closely monitored and optimized by aggressively treating hypothermia and hypovolemia and avoiding vasopressor drugs. Clinical diagnosis of compartment syndrome must be suspected in all injured limbs and surgeons immediately informed of any concerns.

It is important to liaise closely with intensive care staff when surgeons identify a need to return a patient to the OR for further procedures. Extremity injuries are likely to need repeat debridements and irrigation

at intervals of 24 to 48 hours in the initial stages. Casualties returning to the surgical ward either from the OR or intensive care may require ongoing anesthesia input. When peripheral nerve or epidural catheters are indicated, they should be inserted prior to waking and extubation to allow successful weaning from the ventilator. These catheters may be used for anesthesia for any subsequent surgical procedures, contributing greatly to multimodal analgesia and reducing the need for opioid medications. When using catheters is not possible, a multimodal approach should be taken, and the use of patient-controlled analgesia should be considered.

Casualties with extremity, junctional, and pelvic trauma will require multiple surgical procedures and prolonged rehabilitation in other facilities either within the operational theater or in a Role 4 hospital overseas. This can involve the transportation of critically ill ca-

sualties with complex injuries over many thousands of miles, frequently coordinated by intensive care and

anesthesiology personnel (see Chapter 38, Air Transport of the Critical Care Patient).

SUMMARY

Extensive trauma involving the extremities and junctional and pelvic regions accounts for an increasing burden of trauma on the modern battlefield. It is associated with significant mortality and presents unique challenges to the medical team and anesthesiologists. Initially, treatment will focus on the control of potentially life-threatening hemorrhage; in junctional and pelvic trauma, hemorrhage control is difficult and requires early, clear, and concise discussion among the surgical team. Considerations about how to manage treatment must be made, in the context of the casualty's physiological condition. The anesthesiologist is optimally placed to advise on the patient's physiological

context and inform decision-making.

Operative management of these casualties primarily involves aggressive management of hypovolemia and associated coagulopathy. Communication with the surgical team is paramount to optimize surgical access, maximize limb perfusion, and react to changes in surgical strategy that may occur as wounds are explored. A hemostatic pause should be discussed whenever ongoing bleeding and worsening coagulopathy become apparent. Postoperative anesthetic management focuses largely on pain relief. A body of evidence suggests an increasing role for regional anesthetic techniques in these casualties.

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ATTACHMENT: LIMB INJURY REVASCULARIZATION AND MANAGING REPERFUSION WHEN THE TOURNIQUET COMES OFF

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Introduction

The perioperative management of patients after vascular reperfusion may present a challenge to the anesthesia provider. Presently several methods of vascular occlusion are available to achieve a bloodless field during surgery or control hemorrhage in traumatic injury. With combat injury and trauma, these methods, specifically tourniquets, are often applied preoperatively. The use of vascular occlusion devices produces mechanical, metabolic, and physiologic changes that may be difficult to manage during occlusion and at reperfusion, when the tourniquet is released. While the entire medical team must be aware of these changes, anesthesiologists must specifically understand the type of vascular exclusion employed and the changes the patient will experience perioperatively to avoid the morbidity associated with these devices.

Battlefield and Preoperative Hemorrhage Control

Hemorrhage is a major cause of morbidity and mortality in trauma, and hemorrhage from limb injuries has been recognized as the most important cause of avoidable battlefield death.¹ Important advances in hemorrhage control have been developed, implemented, and tested in the current wartime environment. The US military has mandated medical training for all deployed military personnel focusing on hemorrhage control. Military medics follow specific algorithms to control blood loss and as a result have helped decrease mortality due to exsanguination from major limb trauma.²

The simple application of direct pressure is the primary step in hemorrhage control, and its application is of utmost importance prior to surgical treatment. The failure of direct pressure to stop bleeding usually signifies severe vascular injury or multiple vascular injuries likely requiring surgical intervention. In cases of severe arterial bleeding or other major vascular injury, other methods are utilized to control bleeding. These include pressure dressing, proximal arterial compression, hemostatic agents, tourniquets, and vascular clamps. Compression of proximal arteries including the axillary, brachial, and femoral arteries, can be applied to stop distal arterial bleeding in traumatic limb injuries. Hemostatic agents currently in use include HemCon (HemCon Medical Technologies Inc, Portland, OR) and QuickClot (Z-Medica Corp, Wallingford, CT), which activate the coagulation cascade, forming vascular plugs at sites of hemorrhage. These products are available in powder or dressing form.

When other methods of hemorrhage control have failed to control severe limb bleeding, tourniquets may be applied. These severe injuries often require multiple tourniquets to prevent battlefield exsanguination. In many combat situations tourniquets may be the best option to control bleeding; they require minimal observation, allowing other casualties to be cared for.³

These methods of hemorrhage control are frequently employed in the preoperative setting by lay persons, local emergency services, and medical professionals. The anesthesiologist must be aware of the technique used in the field due to the significant impact it has on anesthetic management.

Tourniquets

The history of tourniquets dates back centuries, but it wasn't until the latter half of the 20th century that the modern pneumatic tourniquet, with pressure control, a timer, and wider cuffs, was invented. These pneumatic cuffs are frequently applied during orthopedic surgery and on trauma patients in the operating room. Intraoperative pneumatic tourniquets, usually applied by technicians, registered nurses, or physicians have a long history and proven track record for safety.

To control hemorrhage on the battlefield, soldiers are currently issued a nonpneumatic tourniquet system, the combat application tourniquet (CAT; Figure Attachment 12-1). Both pneumatic tourniquets and nonpneumatic

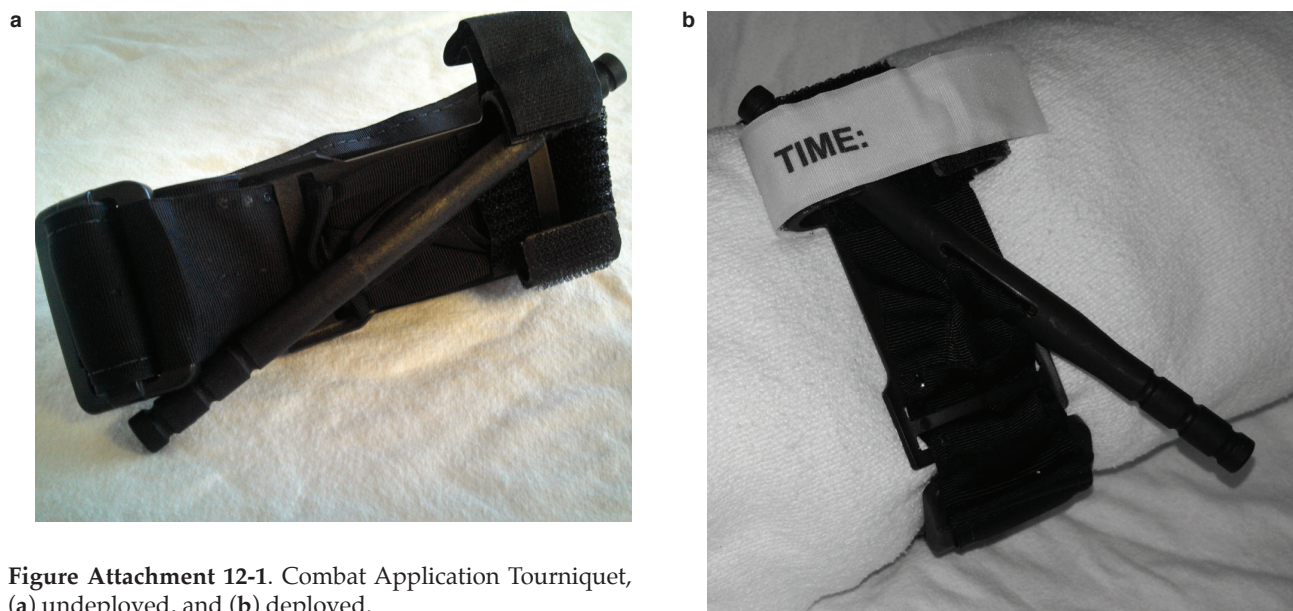


Figure Attachment 12-1. Combat Application Tourniquet, (a) undeployed, and (b) deployed.

tourniquets, similar to the CAT, are in use by local emergency services.⁴ Military tourniquets are frequently applied by a range of people from lay persons to medically trained professionals. Despite training in nonpneumatic tourniquet use, controversy exists on their safety and appropriate use in the prehospital setting.⁵

Limb injuries make up a high percentage of battlefield trauma; some studies suggest that up to 61% of casualties in the current armed conflicts have some form of limb trauma, a majority of these occurring in the lower extremities.⁶ The high incidence of extremity trauma and the issuance of CATs have increased the use of tourniquets to over 18% of battlefield admissions.^{6,7} Significant vascular injury is seen in approximately 6.6% of these admission.⁸

Most clinicians' knowledge of tourniquets is limited and does not extend beyond the mechanism of action and awareness that they should not be inflated for prolonged periods of time.⁹ The anesthesia provider, however, is well aware of tourniquet mechanism and time limits, but also (more importantly) deals with the physiologic result of their use.

Physiologic Effects of Tourniquet Use

Several complex physiologic disturbances occur with tourniquet use, as shown in studies on systemic and local changes during and after tourniquet use.¹⁰⁻¹⁵ These changes are dynamic, usually transient, and drastically different depending on the phase of tourniquet use. These changes can at times have a significant impact on anesthetic management. While most of the changes are well tolerated in the healthy patient undergoing elective surgery, some patients with underlying systemic disease or polytrauma may not tolerate the physiologic insult associated with tourniquets. It is important for the surgical team and especially the anesthesiologist to understand these changes, anticipate complications, and develop practices to minimize complications associated with the use of tourniquets. The anesthesiologist must remain vigilant throughout the perioperative period to prevent serious complications.

Cardiovascular Effects

Initial tourniquet inflation causes immediate and delayed changes in hemodynamic parameters. In non-traumatic surgery, the limb is exsanguinated by the use of gravity or an Esmarch band. This exsanguination initially increases intravascular volume and decreases the vascular bed.¹¹ The immediate increase in central blood volume and decrease in vascular bed increases the mean arterial pressure (MAP), believed to be secondary to increased systemic vascular resistance (SVR). As tourniquet time increases, MAP and SVR continue to increase, likely from increased endogenous catecholamines caused by the tourniquet pressure, limb ischemia,

or tourniquet pain. Initially there may not be a heart rate response to inflation; however, heart rate increases as tourniquet time increases. Additionally, with increased duration of tourniquet use, the elevation in MAP and SVR increase stroke volume and contributes to the elevated cardiac output seen during tourniquet inflation (Figure Attachment 12-2).¹⁰

The dynamic nature of tourniquet use is most evident at deflation. Hemodynamics begin to change instantly, observed as a significant decrease in MAP and SVR. The cause of this is multifactorial and related to vasodilatory effects of metabolic mediators, pain relief, and redistribution of blood flow. Heart rate decreases initially but rapidly returns to baseline.¹⁰ Careful monitoring of the patient is essential at this stage of deflation because of the risk of a sudden release of large venous emboli (although this complication is rare).⁴

Published data on physiologic changes associated with traumatic amputation is limited; however, it is well observed that the hemodynamic changes occurring with tourniquet application in a nontraumatic patient may be less predictable in trauma patients. Tourniquet use in trauma is usually in response to uncontrollable bleeding and vascular injury. The patient may present with severe hemodynamic instability and other physiologic changes that do not produce the predictable hemodynamic changes of elective tourniquet use. These patients often have severe multilimb injuries involving massive blood loss and multilimb amputations. The tourniquet role changes from a bloodless field strategy to a life-saving strategy.

The physiologic and metabolic changes more consistent with a trauma patient include coagulopathy, hypothermia, and acidosis. The role of an anesthesia provider is to direct resuscitation while surgical hemorrhage control is achieved. At times patients will undergo amputation of multiple limbs as a means of controlling hemorrhage, which may lead to a substantial decrease in the vascular bed, followed by increased SVR and the potential for overresuscitation. Vigilance on the anesthesiologist's part in fluid management is important when a large decrease in the vascular bed has occurred.¹⁰

Respiratory Effects

Tourniquet deflation produces a significant and rapid rise in PaCO_2 and partial pressure of end tidal carbon dioxide (PetCO_2), peaking at 2 to 3 minutes postdeflation and returning to baseline within 10 minutes. Minute ventilation increases as PetCO_2 increases, with a peak minute ventilation approximately 2 to 3 minutes postdeflation and returning to baseline within 5 minutes. Spontaneously ventilated patients demonstrate a rapid compensation by increased minute ventilation and fast return to baseline PetCO_2 regardless of the anesthetic type. However, controlled ventilation produces prolonged periods of elevated end tidal carbon dioxide (ETCO_2) unless minute ventilation is increased to compensate for the influx of hypercarbic blood from the ischemic limb (Figure Attachment 12-3).^{12,13}

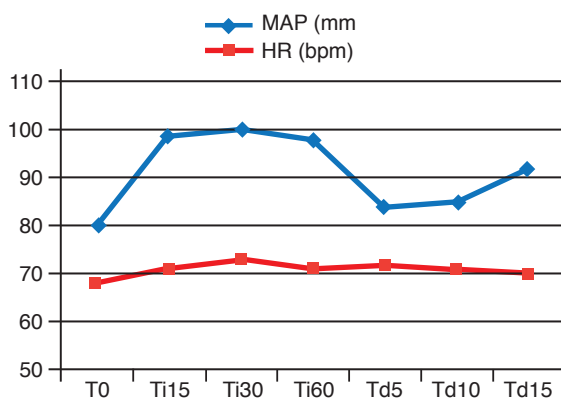


Figure Attachment 12-2. Heart rate (HR) and mean arterial pressure (MAP) changes following inflation and deflation of a tourniquet. Ti: time at inflation; Td: time at deflation; number: the minutes follow each event.

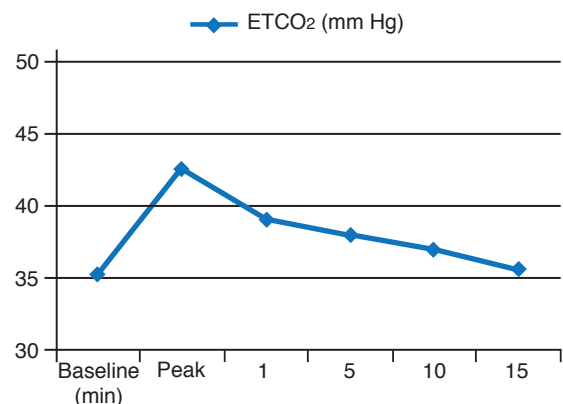


Figure Attachment 12-3. Change in end-tidal carbon dioxide (ETCO_2) after release of tourniquet.

Neurologic Effects

PaCO_2 is an important regulator of cerebral vascular tone and, as mentioned earlier, is elevated above baseline after tourniquet release. At tourniquet release there is also an immediate rise in ETCO_2 , which may last several minutes depending on the specific ventilatory status. The elevation in ETCO_2 is associated with an increase in cerebral flow velocity and increased cerebral blood volume. Hirst's study demonstrated that mean middle cerebral artery blood flow velocity increased 58% from baseline flow rates within 2 minutes of tourniquet deflation (Figure Attachment 12-4).¹⁴ The resulting increase in intracranial pressure (ICP), in combination with an immediate decrease in MAP, can reduce cerebral perfusion pressure to dangerously low levels. The transient increase in cerebral blood flow and ICP is usually tolerated in healthy patients, but may lead to secondary brain injury in patients at risk for cerebral ischemia,¹⁴ including polytrauma patients with underlying traumatic brain injury and elevated ICP.

Although the use of tourniquets in the medical profession is common, it is important to remember that tourniquet use is not benign and is associated with long-term complications and sequelae. Nerve injury is an uncommon injury that may be either minor or devastating. Research on the cause of tourniquet-related nerve injury has shown that neural ischemia related to prolonged tourniquet time is not the key determinant of neural injury, but that compressive shearing forces across the nerve play a major role in nerve injury.^{4,6} Nerves are most vulnerable at the edges of the tourniquet, where pressure differences across the tissue are greatest. These forces stretch the nodes of Ranvier, leading to partial or complete rupture of the stretched myelin and resultant nerve palsy.⁴ Several factors have been found to increase the pressure gradient (and thus decrease the risk of injury), including the use of noncontoured cuffs, narrower cuffs, larger limbs, higher pressure, nonpneumatic cuffs, and increased tourniquet times.⁴

Controversy exists regarding the use of military nonpneumatic tourniquets. Some authors believe this type of tourniquet use has led to preventable nerve injury and unnecessary limb amputation,^{5,6} while other studies consistently show that the appropriate use of combat tourniquets is associated with improved mortality and minor morbidity.⁶ In fact, US mortality from limb injury exsanguinations decreased from 9% during the Vietnam conflict to 2% in the current Middle East conflicts. Israeli literature shows a 0% mortality from similar injuries when tourniquets are applied correctly.⁴ These and other studies report that nerve palsies and limb shortening are infrequent morbidities usually associated with misuse of tourniquets.^{4,6,16}

Tourniquet Pain

The term "tourniquet pain" refers to the observation of increased MAP and heart rate with prolonged tourniquet use. The elevation in systemic blood pressure is often seen after prolonged tourniquet use of over 45 minutes. Tourniquet pain is the most common complication of tourniquet use seen during surgery and is described as a dull, aching pain that increases as tourniquet time increases. It is often difficult to treat, frequently requiring vasodilators to manage blood pressure,¹⁵ may not be fully relieved with narcotics, and can persist for several hours after surgery.¹⁷ After deflation of the tourniquet, a different pain sensation is noted, associated with reperfusion of the limb. This sensation is described as being equal to or greater than the intensity of the discomfort caused by the tourniquet immediately before deflation.¹⁸

The underlying pathophysiology of tourniquet pain is complex and multifactorial, involving mechanical compression, cutaneous neural pathways, and limb ischemia.¹⁴ The noxious stimulus associated with tourniquet use is thought to be mediated by unmyelinated C fibers rather than myelinated delta fibers. Compression of the neural tissue such as myelinated delta fibers

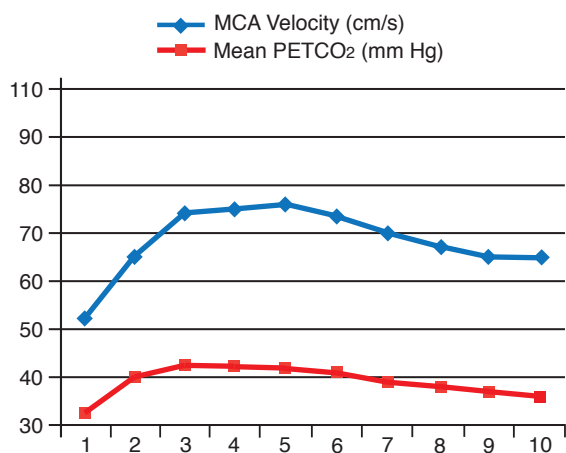


Figure Attachment 12-4. Mean cerebral artery (MCA) velocity and partial pressure of end tidal carbon dioxide (PetCO_2) changes over time in minutes

decreases conduction through the neural fibers, and the neural conduction via these myelinated fibers is blocked, allowing the slower unmyelinated neural tissue, the C fibers, to transmit the dull pain sensation.¹⁵ The C fiber transmission activates *N*-methyl *D*-aspartate receptors, leading to increased blood pressure.¹⁹ In addition to the neural pathway, other processes that may play a role in tourniquet pain are local tissue ischemia and reperfusion of ischemic tissue after deflation, leading to continued pain despite tourniquet release.

Metabolic Changes

Many of the physiologic changes associated with tourniquet inflation and deflation are due to metabolic changes that occur at the cellular level. As stated above, neural injury in the ischemic limb appears to be related to compressive force. Muscular tissue, however, appears to be more sensitive to the duration of ischemia.⁴ After inflation of the tourniquet, anaerobic cellular metabolism predominates, with accumulation of metabolic metabolites including lactate, increased CO₂, and potassium.¹⁹ After release of the tourniquet, the accumulated metabolites are released into the general circulation, and blood levels of lactate increase, PaCO₂ increases, serum bicarbonate decreases, and potassium decreases. The pH decrease can last several minutes; in fact it, appears that many of these metabolic changes last several minutes. Some studies show increased lactate and decreased pH lasting longer than 10 minutes.¹⁹

In addition, core temperature decreases with tourniquet use.^{19,20} In cases of extremely long tourniquet times or multiple limb tourniquets, tissue necrosis may occur and cellular components may be released into the circulation, resulting in myoglobinemia and rhabdomyolysis.¹⁸ These metabolic changes are usually well tolerated during elective surgery in the healthy patient. Patients with significant comorbidities may not tolerate such a systemic insult and require slower release of tourniquets. Trauma patients also may not tolerate immediate release of tourniquets; the release can make management of hypothermia, acidosis, hypotension, and ICP more challenging.

The return of toxic metabolites to the circulation results in systemic metabolic dysfunction, referred to as “myoneuropathic metabolic syndrome” and characterized by metabolic acidosis, hyperkalemia, myoglobulinemia, myoglobinuria, and renal failure. Paradoxically, tourniquet deflation is associated with thrombolytic activity and anoxia, promoting activation of the antithrombin III and protein C pathways, which may be implicated in posttourniquet bleeding.⁴

Safety

In an effort to decrease tourniquet-related injury in the operating room and on the battlefield, guidelines and practices have been proposed by several authors and some organizations. Measurement of limb occlusion pressure before surgery might lead to the use of a lower tourniquet cuff pressure during surgery and thereby reduce the risk of postoperative pain and complications,²⁰ and limb occlusion pressure (LOP) has consistently shown to be lower than traditional tourniquet use.¹⁸ LOP is defined as the minimum pressure required, at a specific time, by a specific tourniquet applied to a specific limb at a specific location, to stop the flow of arterial blood into the limb distal to the cuff. LOP can be determined simply by increasing the tourniquet until distal flow is interrupted, which may be determined by palpation of distal pulses, use of infrared oxygen saturation, or Doppler. Many modern automated tourniquets are equipped with LOP technology. After LOP has been determined, it is common practice to increase cuff pressure by 20 to 50 mm Hg as a safety margin to account for fluctuating blood pressure as a result of painful and noxious surgical stimuli.

There is an inverse relationship between LOP and the ratio of cuff width to limb circumference. A narrower cuff requires higher LOP and increases the pressure gradient across the underlying nerves, as well as the potential for nerve injury. The use of wider or contoured cuffs results in lower pressure gradients and theoretically a decreased risk of nerve injury.⁴

Military combat tourniquets are nonpneumatic, narrow, applied by nonmedical professionals, and can be applied incorrectly, all factors that increase the risk of morbidity. However, the survival benefit of using tourniquets in severe limb trauma cannot be understated. To decrease the risks of injury, all deployed soldiers in the United States, United Kingdom, and several other countries receive training on the appropriate use of tourniquets, including indications, application, and evaluation. Tourniquet use is tracked and training is tailored according to trends in use and morbidity. Once a combat tourniquet is applied, it is important to monitor the injury for continued bleeding; check whether the tourniquet has loosened or moved, especially if placed over clothes; and continue to reevaluate the indication for the tourniquet.^{6,7}

Tourniquet inflation time is another area of uncertainty. It is widely taught that a tourniquet should not be left inflated for longer than 2 hours; however, there are situations when the tourniquet must exceed 2 hours of ischemia in order to complete the surgical procedure. In general, nerves are more susceptible to mechanical pressure, and it is the muscle and other soft tissues that are at increased risk from prolonged tissue ischemia. Many authors suggest that a tourniquet time of 1.5 to 2 hours is an acceptable time for tissue ischemia; however, animal studies suggest that even 1 hour of tissue ischemia can produce muscle weakness and tissue injury lasting up to 7 days.¹⁵ It is generally acceptable to allow a period of reperfusion if the tourniquet is needed for a prolonged period of time, exceeding 2 hours. The optimal duration of reperfusion remains uncertain, but some researchers suggest 10 minutes of reperfusion for every hour of ischemia.¹⁹ In summary, the use of LOP, wider or contoured cuffs, and shorter ischemia intervals or periods of reperfusion may decrease the incidence of neurologic or muscular injury related to tourniquet use.

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