Use of Tourniquets in Limb Trauma Surgery

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KEYWORDS

• Tourniquet • Exsanguination • Orthopedic limb trauma • Tourniquet design • Cuff pressure • Cuff width

KEY POINTS

- Tourniquets are frequently used in both upper and lower extremities, usually without significant complications.
- Optimal pressure is still unknown, but using limb occlusion pressure rather than systolic blood pressure may be better for decreasing the risk of injury.
- No specific tourniquet design has been proven superior, but recent data points to assessing limb circumference when choosing a tourniquet.
- Protocols and guidelines for tourniquet use, taking patients and the type of procedure into consideration, are needed.
- Tourniquets are not benign and have been associated with fatalities, so the surgeon must remain vigilant and knowledgeable about their risks and benefits.

INTRODUCTION

A tourniquet is a device used to halt blood flow to an extremity. In the modern surgical theater, tourniquets of various designs are used in more than 15,000 procedures every day.[1] The goal of tourniquet application is most often to create a bloodless field; it is, however, also used to assist with limb anesthesia (ie, Bier block), venipuncture (to enlarge blood vessels), and control of catastrophic blood loss in an acute setting.[2]

The historical use of tourniquets dates back to the ancient Romans who used them in amputations,[3] but the actual term was coined in the 1700s by Jean Louis Petit from the French term *tourner* ("to turn").[1] His simple device was a screw-type mechanism that was revolutionary in not requiring an assistant to keep the pressure constant. Lister performed the first nonamputation surgeries with a tourniquet, combined with limb elevation for exsanguination. Later, Esmarch created the flat rubber bandage that now bears his name. In the early 1900s, Cushing developed the pneumatic tourniquet, a variant of which is still used today.[1,3] This design was perfected in the 1980s by McEwen, who invented the modern microcomputer tourniquet, which monitored not only pressure but also leakage, inflation time, and other parameters. It also estimated the limb occlusion pressure (LOP) (the minimal pressure required to halt blood flow) and protected from both depressurization and overpressurization.[2]

Although tourniquets have been in use for many decades, definitive protocols are still lacking; physicians' knowledge of the risks and benefits of this device remains subpar. A study of residents and operating room (OR) assistants used a questionnaire that assessed their knowledge of tourniquet use, including repositioning, correct cuff size and

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shape, contraindications, safe inflation time, and other facts. The average test score for residents was 41.3% and 46.7% for assistants. The investigators cautioned that surgeons must be knowledgeable in the application and indications for tourniquets, particularly for medicolegal reasons.[4] It is also important to note that most tourniquets are placed by assistants and not by the surgeons themselves, further divorcing the tourniquet from being an essential part of the case.

Formal protocols on tourniquet use in the United States vary greatly in scope and application, particularly in the prehospital setting. Eighty-four percent of states have statewide emergency medical systems (EMS) exsanguination protocols; only 35% have very clear, detailed instructions on when and how to use tourniquets. This factor likely results in suboptimal and sporadic use.[5] The Eastern Association for the Surgery of Trauma has published a management guideline for penetrating lower extremity trauma that contains a section on tourniquets and states that a tourniquet can be used if direct pressure fails to control bleeding.[6] However, this guideline is listed as level 3, which is defined by a lack of formal evidence.

Generally, no standard exists for tourniquet use; the decision rests with the individual surgeon. This decision is largely based on personal preference and several factors, including procedure duration, technical difficulty, blood loss, and the location of the injury on the body. Recently published articles summarize the various issues in tourniquet application.[1,7] The goal of this work is to review the current literature on indications, technique points, and complications of tourniquets in limb trauma, both in the acute and elective setting.

PREHOSPITAL AND EMERGENCY TOURNIQUET USE

Although most of the literature on tourniquets in trauma focuses on elective procedures, some studies deal specifically with the prehospital setting. Much of what we know of tourniquet use in this setting comes from military experience. In the 1600s, French army surgeon Etienne Morel was one of the first to use tourniquets on the battlefield to treat extremity wounds.[8] In the 1950s and 1960s, Vietnam War casualties often died of massive limb hemorrhage, leading to an increased interest in tourniquets as a lifesaving measure.[9] The explosive weapons of modern warfare in Iraq and Afghanistan also added to the experience of tourniquet use in soldiers.[6,10]

On the battlefield, the Combat Application Tourniquet (CAT; www.combattourniquet.com) involves a simple windlass mechanism that can be applied one-handed with good results. A 4-year study of military prehospital tourniquet use in 550 patients at an average ischemic time of 83 minutes showed 78% overall effectiveness, 94% in upper limbs and 71% in lower limbs. No patient died of hemorrhage.[9] Another prospective observational study of both civilian and military casualties in a Baghdad hospital assessed tourniquet use in the prehospital versus the emergency department (ED) setting. In 232 patients, the mortality rates were 11% in the prehospital group (n = 194) and 24% in the ED group (n = 38). Transient nerve palsies occurred in 1.7%. Prehospital use of the tourniquet was weakly associated with survival; the absence of shock with tourniquet use was also associated with survival. The study also matched a group of patients for the Injury Severity Score and Abbreviated Injury Scale scores. Patients who had a tourniquet placed were matched with those who had compressible limb injuries and would have benefited from a tourniquet but did not get one because of availability or medic decision. All patients in the latter group died (0% vs 77% survival rate).[11]

The frequency of tourniquet use in the military has not translated to the civilian sector, largely because of the faster access to definitive care in the case of civilian trauma.[12] Some investigators state that a tourniquet should never be used as a first-aid measure,[3] but literature exists to counter that position. Civilian settings where tourniquets may be useful include penetrating trauma, such as stab and gunshot wounds, terrorism incidents, rural or wilderness medicine, limb entrapment with an inaccessible bleeding site, industrial or machinery accidents, and extreme or life-threatening situations.[8] One study examined injury patterns and outcomes in 14 civilians who died of exsanguination of an isolated extremity injury. It showed that only one patient had some attempt at bleeding control before EMS arrival, and intravenous (IV) access was not obtained in 71%. This study suggested that aggressive attempts to control limb hemorrhage, such as with a tourniquet, may prevent death from exsanguination.[13]

A retrospective review of 87 civilian patients looked at tourniquet use (primarily with the CAT) in the prehospital, ED, and OR settings. Half of the cohort had tourniquets applied in the prehospital time period, mostly on upper extremities. The Mangled Extremity Severity score and the rate of limb loss did not differ between

the groups. No major complications occurred as a result of tourniquet use, except one case of compartment syndrome. In that patient, however, limb ischemia due to arterial transection was documented before tourniquet placement, and the tourniquet's role in precipitating the complication was unclear.[12]

Despite promising data, prehospital tourniquet use remains rare. A study from 2 Canadian centers over a 10-year period of patients with arterial injuries yielded only 8 patients who had tourniquets placed for isolated extremity injury. Only 4 had the tourniquet placed before arrival at the hospital; all of these patients survived, despite being more hypotensive and acidotic than those whose tourniquets were placed in the trauma bay. The investigators compared this group with a group who did not get a tourniquet and who died. All patients who died did so from hemorrhage. The study also showed no statistically significant difference in transfusion rates between the tourniquet and no tourniquet groups but did show a trend toward less transfused blood in the tourniquet group.[14]

Technical points of tourniquet use in the acute limb trauma setting include the understanding that less severe measures, such as direct pressure and pressure dressings, should always comprise the initial attempts to control bleeding.[6] If a tourniquet is applied, it should not be loosened until patients reach the hospital because incremental exsanguination may occur. If bleeding is still not controlled, a second tourniquet can be applied.[8] Frequent reassessment is indicated as the patients are resuscitated; changes in blood pressure may affect tourniquet effectiveness.[10] Pain control is also paramount because a properly applied tourniquet is extremely uncomfortable and will often require IV analgesia.[8] For cases of prolonged transport, limb cooling helps to slow metabolism and protect muscles from ischemia. A study in pigs showed that hypothermic limbs had a faster recovery immediately after tourniquet deflation and 10 days later. The hypothermic pigs also had lower lactate levels, less glycogen breakdown, and a smaller decrease in blood pH, which all served as protection against the inflammatory response.[15]

LIMB TRAUMA SURGERY: GENERAL CONSIDERATIONS

Application

The tourniquet should be placed on the limb as distally as possible, but at least 5 cm proximal to the area of injury, avoiding joints (Table 1).[8,10] Prep solutions, such as povidone iodine, can pool under the tourniquet and cause friction or chemical burns, so a barrier is necessary to prevent liquid from pooling.[16] A surgical glove or another impenetrable drape can be used for this purpose.[17]

Table 1
Tips for tourniquet use

Application	Keep the tourniquet at least 5 cm proximal to area of injury.
	Use a barrier to prevent prep liquid from pooling under tourniquet.
	Curved/wider tourniquets require less pressure to stop the blood flow.
Inflation	Use a fast inflation rate to avoid venous pooling.
	The inflation pressures are 250 mm Hg for the upper extremity and 300 mm Hg for the lower extremity or use LOP + 50–100 mm Hg.
Deflation	Monitor the physiologic changes during deflation.

Inflation should take place over a short period of time, as slow inflation rates or incorrect application will block venous flow before arterial flow, causing venous congestion and possibly more bleeding.[8,18] Simple elevation is effective in cases when pressure is contraindicated, such as sickle cell anemia.[2] Tourniquet use is also contraindicated in malignancy and infection.[1,19]

The timing of antibiotic administration has been controversial, with some investigators advocating that a period of at least 5 minutes is necessary before tourniquet inflation to allow antibiotics to penetrate the limb.[2] However, a randomized controlled trial of 106 patients compared infection rates in 2 groups: one with antibiotic administration 5 minutes before tourniquet inflation and one with antibiotic administration 1 minute after tourniquet inflation. Contrary to the expected result, the group who had preinflation antibiotics actually had higher infection rates.[20]

Pressure

Published recommendations on tourniquet pressure use a variety of markers to achieve an optimal bloodless field while avoiding high pressures that can lead to nerve injury. These parameters, which can be easily obtained intraoperatively, include systolic blood pressure and mean arterial pressure.[19] A review article

lists the currently accepted parameters; the general recommendation is to stay less than 250 mm Hg in the upper extremity and less than 300 mm Hg in the lower extremity.[7]

Another guide for optimal pressure is the limb LOP, which is the minimum pressure needed to stop arterial blood flow in a given patient or situation. It is calculated before surgery by assessing when a Doppler signal disappears from the distal extremity as the tourniquet is inflated.[1] Many modern tourniquets can calculate the LOP, and a 50- to 100-mm Hg safety margin is frequently added to account for intraoperative physiologic changes. The LOP has been the subject of several studies and is suggested as an alternative in cases when high pressures must be avoided, such as in patients with arterial calcification.[2] Today, however, it remains an infrequently used parameter; a study showed that only 7% of polled physicians (podiatrists) considered the LOP when selecting cuff pressure.[21]

Time

A general recommendation for continuous cuff inflation time ranges from 2.0 to 2.5 hours.[7] The concept of tourniquet time is based on the idea that adenosine triphosphate is depleted during the period of ischemia, and a time limit allows patients' tissues to recover.[22] Despite recommendations, it is important to understand that a safe tourniquet time does not exist and any amount of time can potentially cause damage to the limb.[8] To minimize complications, a deflation interval has been used since the 1950s; its optimal duration, however, remains unclear.[3] One article recommends a 10-minute interval at 2.5 hours of surgery, with further reperfusion intervals at each additional hour.[7] The concept of reperfusion as a means of protection seems to be supported by at least one randomized controlled trial, in which patients undergoing ankle surgery with a tourniquet deflated at the end of the procedure were compared with patients who underwent staggered release (initial tourniquet release followed by 2 cycles of reinflation/deflation, with each cycle occurring over 3 minutes). The staggered-release group experienced decreased metabolic changes reflected in the lactate level and end tidal carbon dioxide. These changes were deemed to be protective to the soft tissues because of less buildup of metabolites indicating tissue damage.[23]

During deflation, it is important to monitor for changes in oxygen parameters, particularly during intramedullary nailing, cementing, or prosthesis insertion. Deflation can release large venous emboli, adding to the patients' already increased clot burden.[1] The surgeon must also balance the need for decreased tourniquet time with the risk of increased bleeding if the tourniquet is released too quickly. Investigators disagree on whether release of the tourniquet before wound closure is recommended.[7]

Cuff Width and Design

Much interest in the type and width of the tourniquet has surfaced in the last decade, particularly with the increase of obesity in the United States. Cuff design becomes important in this population because of the relationship between optimal pressure and limb circumference. A study of healthy volunteers showed an inverse relationship between the LOP and the ratio of the cuff width/limb circumference, meaning that for a given limb, a narrower cuff requires much higher pressure to stop the blood flow.[24] This pressure causes a higher gradient and predisposes to nerve injury. Notably in this study, the relationship of LOP and blood pressure predicts that the LOP will be subsystolic for normotensive patients when the cuff width/limb circumference ratio is greater than 0.3:1.0. Another study of 26 volunteers explored the concept of fitted tourniquets to account for the conical shape of most human limbs. The investigators found that the use of curved and wider tourniquets resulted in lower occlusion pressures: a mean of 183 mm Hg in the arm and 208 mm Hg in the leg. They recommended adding 75 mm Hg to the LOP to account for changes in blood pressure.[25]

With regard to design, the silicone ring tourniquet (SRT) has been introduced to the market as a sterile alternative to the standard pneumatic tourniquet. It consists of a silicone ring encased within a stockinette; the ring is placed over the fingers or toes and rolled up the extremity proximally, achieving compression and exsanguination. A study of 536 patients, with 63% being fracture cases, showed several advantages to the silicone ring design, which was most frequently used on the femur.[26] These advantages include sterility; the ability to access places, such as the groin where a regular tourniquet would not be possible or practical; and a one-step exsanguination process.[27] Limitations of the SRT include injuries that may hinder the roll-on application, including open fractures and the presence of external fixation.[28] No particular design, however, has been 100% proven to be better than another; the choice remains with the surgeon.[7]

UPPER EXTREMITY

Tourniquet Use

The use of tourniquets in the upper extremity has been gaining popularity, both in the hand and trauma literature. One review of 505 patients with upper extremity tourniquets found no immediate or delayed adverse events, even in patients with medical comorbidities. Most of these patients had pressures of 250 mm Hg or less and a tourniquet time of about 30 minutes. This study deemed tourniquets as safe to use in commonly performed hand procedures.[22] However, another study found some disadvantages. In a randomized trial of closed forearm fractures, the pressure ranged from 200 to 250 mm Hg; the visual and verbal pain scores were assessed in patients without a tourniquet, a tourniquet used for less than 1 hour, and a tourniquet used for 1 to 2 hours. The nontourniquet group had less overall pain on postoperative days 1 and 2, particularly in older and male patients.[29]

Technique Points

The optimal position of the tourniquet on the arm is controversial and was evaluated in a study of patients undergoing carpal tunnel release.[30] Either a forearm or upper arm cuff was placed, and outcomes included surgeon assessment of the bloodless field. No major differences stood out in the groups, except the forearm tourniquet often made fingers curl involuntarily and sometimes blocked the surgeon's view. Based on this, upper arm tourniquets were deemed preferable in the study.

In the case of finger tourniquets, the application can be with a rubber catheter held with a hemostat or a finger of a glove rolled up onto the base of the finger.[31] However, such tourniquets provide variable, nonstandard pressures and are often obscure enough to be left in situ accidentally. All-purpose digital tourniquets provide a better option because of their bright colors, but correct sizing is problematic.

The exsanguination method in the upper limb has also been explored, particularly in healthy volunteers. One randomized trial assessed 26 patients who had arm elevation versus esmarch exsanguination before tourniquet inflation at 250 mm Hg for a maximum of 20 minutes. Although there was no difference in recovery after deflation, the pain scores during the time of inflation were in favor of exsanguination.[32] Another randomized study in 100 patients evaluated the elevation for 5 seconds, the squeeze method (manually squeezing the blood out of the limb from distal to proximal), and the esmarch in effectiveness of stopping blood flow. No difference was seen between the latter two, but both were better than elevation.[33] In another study using labeled erythrocytes to assess exsanguination in healthy volunteers, the following reductions in blood volumes were found: elevation 5 seconds, 44% and 4 minutes, 42%; esmarch 69%; gauze bandage 63%; pomidor roll cuff 66%; squeeze method 53%; and Urias bag 57%.[34] This finding suggests that no method is completely effective and that the time of elevation may not be significant beyond 5 seconds.

The tourniquet choice in the upper limb includes the standard pneumatic cuff (PT) or the SRT. The two options do not seem to differ greatly in outcomes. One study of SRT versus a forearm tourniquet in carpal tunnel surgery showed that the mean final pain during the surgery was higher and had a more rapid increase with the conventional tourniquet.[27] However, another randomized study assessed areas of nerve compression in SRT versus PT on the upper arm. Visual analog scale (VAS) pain scores were obtained, and MRI of the radial and ulnar nerves provided the basis for measuring nerve diameters. No differences were found in the two groups.[28] The SRT may have smaller pressure gradients at the cuff edges than the wide tourniquet, causing less chance of nerve injury. This finding seems to be confirmed by another study, in which a wider cuff caused more severe changes in nerve conduction (by 10%) than a narrow cuff.[35]

Complications

Tourniquet nerve injury occurs 2.5 times more commonly in patients with an upper rather than a lower extremity tourniquet,[36] likely because of less soft tissue in that area, with the radial nerve being most susceptible. Complications are mentioned in several published case reports and include arm paralysis lasting 5.5 months after a digital amputation, possibly involving a malfunctioning tourniquet pressure gauge.[37] Posterior interosseous nerve palsy has been known to develop after a forearm tourniquet.[38] Another possible, though rare, complication is upper arm deep venous thrombosis (DVT).[18] Retaining a digital tourniquet after a dressing is more common and has pushed the need for more colorful tourniquets that are removed as part of the postoperative checklist.[39]

LOWER EXTREMITY

Tourniquet Use

The use of tourniquets in the lower extremity during elective trauma surgery has had support

in the literature. One retrospective study of 603 patients undergoing ankle open reduction internal fixation (ORIF) with and without a tourniquet looked at opioid use during the first day after surgery. The tourniquet group had a 20% increase in opioid consumption; but in reality, the difference was only 3 mg of opiate, a clinically insignificant amount.[40] Another study randomized 132 patients undergoing ORIF of extra-articular tibia fractures into tourniquet and nontourniquet groups. At the 1-year follow-up, no tourniquet complications were noted. The investigators noted less pain (by one VAS point), less drainage (by 2 mL), and longer OR time (by 6 minutes) in the nontourniquet group, all clinically negligible differences.[41] A systematic review of 4 foot and ankle articles also showed limited differences and few complications with and without the use of tourniquets.[42]

Other investigators, however, are less enthusiastic about tourniquet use in the lower extremity because of concerns about poor visibility of blood vessels, the lack of a cooling effect of circulating blood, time restriction, and other issues.[43] Wound healing problems and erythema with a tourniquet have been documented in at least 3 studies: one in a randomized trial of 54 patients undergoing ankle fixation,[44] another in a randomized trial of tibia fractures,[43] and the third in a randomized trial of distal fibula fractures, which also noted a 1-week longer return to work in the tourniquet group.[45] Another study of thigh tourniquets assessed electromyography (EMG) changes and functional differences in the leg at 6 weeks postoperatively, showing that 71% of patients in the tourniquet group had evidence of denervation on EMG (vs none in control group) and functional capacity of 40% of normal (vs 79% of normal in control group). Interestingly, in the tourniquet group, pressures were similar in patients with and without EMG changes and thigh sizes varied; this suggests that other tourniquet-related factors may be responsible.[46] Lastly, tourniquets in the lower limb are associated with pulmonary morbidity. In a retrospective study of 72 patients undergoing reamed femoral nailing who also had tibia or ankle fractures, patients were grouped according to tourniquet use for the tibia/ankle injury and matched for injury severity. Ventilator-dependent days and intensive-care-unit days increased with increasing tourniquet time. This study suggests that the combination of reamed femoral nailing and tourniquet ischemia may cause increased susceptibility to pulmonary events.[47]

Technique Points

Optimal pressure and the use of thigh tourniquets is contested. In a survey of 140 American Orthopedic Foot and Ankle Society members, common cuff pressures included 301 to 350 mm Hg for the thigh and 201 to 250 mm Hg for the ankle. Only 11% of surgeons used less than 250 mm Hg for the thigh, which, from assessment of the LOP, would be enough for most patients with a safety margin. Only 9% of surgeons used LOP to set pressure. Forty-six percent were concerned with hazards, especially nerve injury, whereas 17% were not concerned at all.[48]

One study attempted to use the LOP to understand optimal pressure in different thigh tourniquets. In this randomized controlled trial, standard versus wide cuffs were used, with LOP set as the pressure in addition to a safety margin. Outcomes included quality of the bloodless field and were acceptable in both types of cuff, although the surgeon was not blinded. Mean pressures that achieved a good bloodless field were 178 mm Hg and 142 mm Hg for narrow and wide cuffs, respectively, far less than the usually used 300 to 350 mm Hg. Using the LOP decreased the average pressure by 33% to 42%. Systolic blood pressure did not correlate well with LOP. The recommendations from this study for the safety margin to be added to LOP were 40 for LOP less than 130, 60 for 131 to 190, and 80 for greater than 190.[49]

Another area of research in leg tourniquets deals with preconditioning of the extremity before tourniquet inflation. This preconditioning requires extra surgical time, but at least one study has shown good results. A randomized trial divided 30 healthy patients scheduled for lower extremity surgery into 2 groups: a control group who had a regular inflated tourniquet and a preconditioning group who had 3 cycles of 5 minutes of ischemia and 5 minutes of reperfusion before inflation of the tourniquet. The outcomes were the levels of inflammatory markers and oxygen exchange up to 24 hours postoperatively. No pulmonary complications occurred in either group, but the preconditioning group had less increase in inflammatory markers and less change in arterial P_{O_2} and alveolar-arterial oxygen tension ratio. This finding suggests that ischemic preconditioning may decrease pulmonary morbidity in patients at risk.[50]

Complications

Complications specific to lower limb tourniquets are similar to those in the upper extremity. Nerve injury to the femoral[51,52] and saphenous[51]

nerves can occur. One study detailed a permanent femoral palsy after patella fracture fixation without prolonged tourniquet time or excessively high pressure, suggesting that our understanding of this phenomenon is still limited.[52] One complication that seems to be more prevalent in the lower limb is compartment syndrome due to ischemia. A case report of 2 patients who developed this complication after a tourniquet warned that tourniquets should be used with caution, particularly in obese and athletic patients. Notably, both patients in the report had high tourniquet pressures, 350 mm Hg and 450 mm Hg.[53] This finding underscores the need for optimal guidelines to reduce excessive pressure.

OTHER CONCERNS

Tourniquet problems not specific to a particular extremity include nerve injury (both transient and permanent),[1] pain, and weakness defined as "post-tourniquet syndrome,"[2] metabolic changes,[54] muscle injury,[2] Volkmann contracture,[3] and systemic complications, such as pulmonary embolism (PE).[55] Fortunately, these remain rare, with an incidence of 0.024% in one Norwegian study.[56]

The highest concern for surgeons is for permanent nerve injury and fatal PE. It is difficult to understand changes to nerves because much of the data used to study nerve function are in animals and uses pressures of 1000 mm Hg, much higher than what is clinically used in humans.[7] However, certain basic science work has improved our understanding of how tourniquets affect nerve tissue. One study assessed conduction of peripheral nerves in baboons. The investigators found that direct pressure on the nerve results in displacement of the node of Ranvier with respect to the Schwann cell junction. Maximal damage occurs at cuff edges, greater at the proximal edge. The study concluded that it is pressure, and not nerve ischemia, that comprises the main issue in nerve injury. Timing is also important, as the number of total affected nodes decreases with less tourniquet time.[57]

Multiple case reports of fatal PE in the setting of tourniquet use have been published,[55,58–61] a rare but grave complication in a routine procedure. A study of clot burden in knee arthroscopy patients using a transesophageal echocardiogram showed that PEs occur within minutes of release and that their number depends on tourniquet time.[62] Another study suggests that rolling and squeezing motions to achieve exsanguination, as with an esmarch or SRT, can release thrombi and potentially result in fatal consequences.[55] Examination of several trauma case reports of fatal PE show that, in many of these cases, the patients were bedbound for a prolonged period,[58,61] had no DVT prophylaxis[55] or were off their DVT prophylaxis,[60] or were of advanced age.[61] When choosing to use a tourniquet, the surgeon must be aware of this serious complication and weigh the need for a bloodless field against the risk of injury and possibly death.

REFERENCES

1. Noordin S, McEwen J, Kragh JF, et al. Surgical tourniquets in orthopaedics. J Bone Joint Surg Am 2009;91(12):2958–67.
2. Oragui E, Parsons A, White T, et al. Tourniquet use in upper limb surgery. Hand (N Y) 2011;6(2):165–73.
3. Klenerman L. The tourniquet in surgery. J Bone Joint Surg Br 1962;44-B:937–43.
4. Sadri A, Braithwaite IJ, Abdlu-Jabar HB, et al. Understanding of intra-operative tourniquets amongst orthopaedic surgeons and theatre staff - a questionnaire study. Ann R Coll Surg Engl 2010;92(3):243–5.
5. Ramly E, Runyan G, King DR. The state of the union: nationwide absence of uniform guidelines for the prehospital use of tourniquets to control extremity exsanguination. J Trauma Acute Care Surg 2016;80(5):787–91.
6. Fox N, Rajani RR, Bokhari F, et al. Evaluation and management of penetrating lower extremity arterial trauma: an Eastern Association for the Surgery of Trauma practice management guideline. J Trauma Acute Care Surg 2012;73(5 Suppl 4):S315–20.
7. Fitzgibbons PG, Digiovanni C, Hares S, et al. Safe tourniquet use: a review of the evidence. J Am Acad Orthop Surg 2012;20(5):310–9.
8. Lee C, Porter KM, Hodgetts TJ. Tourniquet use in the civilian prehospital setting. Emerg Med J 2007;24(8):584–7.
9. Lakstein D, Blumenfeld A, Sokolov T, et al. Tourniquets for hemorrhage control on the battlefield: a 4-year accumulated experience. J Trauma 2003;54(5 Suppl):S221–5.
10. Rush RM, Arrington ED, Hsu JR. Management of complex extremity injuries. Tourniquets, compartment syndrome detection, fasciotomy, and amputation care. Surg Clin North Am 2012;92(4):987–1007.
11. Kragh JF, Walters TJ, Baer DG, et al. Survival with emergency tourniquet use to stop bleeding in major limb trauma. Ann Surg 2009;249(1):1–7. https://doi.org/10.1097/SLA.0b013e31818842ba.

12. Inaba K, Siboni S, Resnick S, et al. Tourniquet use for civilian extremity trauma. J Trauma Acute Care Surg 2015;79(2):232–3.
13. Dorlac WC, DeBakey ME, Holcomb JB, et al. Mortality from isolated civilian penetrating extremity injury. J Trauma 2005;59(1):217–22.
14. Passos E, Dingley B, Smith A, et al. Tourniquet use for peripheral vascular injuries in the civilian setting. Injury 2014;45(3):573–7.
15. Irving GA, Noakes TD. The protective role of local hypothermia in tourniquet-induced ischaemia of muscle. J Bone Joint Surg Br 1985;67(2):297–301.
16. Ellanti P, Hurson C. Tourniquet-associated povidone-iodine-induced chemical burns. BMJ Case Rep 2015;2015. https://doi.org/10.1136/bcr-2014-208967.
17. Tomlinson PJ, Harries WJ. The use of a surgical glove in the prevention of tourniquet-associated chemical burns. Ann R Coll Surg Engl 2008;90(3):255.
18. Desai K, Dinh TP, Chung S, et al. Upper extremity deep vein thrombosis with tourniquet use. Int J Surg Case Rep 2015;6:55–7.
19. Cox C, Yao J, Flatt AE, et al. Tourniquet usage in upper extremity surgery. J Hand Surg Am 2010;35(8):1360–1.
20. Akinyoola AL, Adegbehingbe OO, Odunsi A. Timing of antibiotic prophylaxis in tourniquet surgery. J Foot Ankle Surg 2011;50(4):374–6.
21. Kalla TP, Younger A, McEwen JA, et al. Survey of tourniquet use in podiatric surgery. J Foot Ankle Surg 2003;42(2):68–76.
22. Drolet BC, Okhah Z, Phillips BZ, et al. Evidence for safe tourniquet use in 500 consecutive upper extremity procedures. Hand (N Y) 2014;9(4):494–8.
23. van der Velde J, Serfontein L, Iohom G. Reducing the potential for tourniquet-associated reperfusion injury. Eur J Emerg Med 2013;20(6):391–6.
24. Graham B, Breault MJ, McEwen JA, et al. Occlusion of arterial flow in the extremities at subsystolic pressures through the use of wide tourniquet cuffs. Clin Orthop Relat Res 1993;286:257–61.
25. Pedowitz RA, Gershuni DH, Botte MJ, et al. The use of lower tourniquet inflation pressures in extremity surgery facilitated by curved and wide tourniquets and an integrated cuff inflation system. Clin Orthop Relat Res 1993;237–44. https://doi.org/10.1097/00003086-199302000-00038.
26. Drosos GI, Ververidis A, Mavropoulos R, et al. The silicone ring tourniquet in orthopaedic operations of the extremities. Surg Technol Int 2013;23:251–7.
27. Drosos GI, Ververidis A, Stavropoulos NI, et al. Silicone ring tourniquet versus pneumatic cuff tourniquet in carpal tunnel release: a randomized comparative study. J Orthop Traumatol 2013;14(2):131–5.
28. Kovar FM. Nerve compression and pain in human volunteers with narrow vs wide tourniquets. World J Orthop 2015;6(4):394.
29. Omeroğlu H, Uçaner A, Tabak AY, et al. The effect of using a tourniquet on the intensity of postoperative pain in forearm fractures. A randomized study in 32 surgically treated patients. Int Orthop 1998;22(6):369–73.
30. Odinsson A, Finsen V. The position of the tourniquet on the upper limb. J Bone Joint Surg Br 2002;84(2):202–4.
31. Brewster MBS, Upadhyay PK, Hill CE. Finger tourniquets: a review of National Patient Safety Agency recommendations, available devices and current practice. J Hand Surg Eur Vol 2015;40(2):214–5.
32. Lees DA, Penny JB, Baker P. A single blind randomised controlled trial of the impact on patient-reported pain of arm elevation versus exsanguination prior to tourniquet inflation. Bone Joint J 2016;98-B(4):519–25.
33. Blønd L, Jensen NV, Søe Nielsen NH. Clinical consequences of different exsanguination methods in hand surgery. A double-blind randomised study. J Hand Surg Eur Vol 2008;33(4):475–7.
34. Blønd L, Madsen JL. Exsanguination of the upper limb in healthy young volunteers. J Bone Joint Surg Br 2002;84(4):489–91.
35. Mittal P, Shenoy S, Sandhu JS. Effect of different cuff widths on the motor nerve conduction of the median nerve: an experimental study. J Orthop Surg Res 2008;3:1.
36. Lowe JB 3rd, Sen SK, Mackinnon SE. Current approach to radial nerve paralysis. Plast Reconstr Surg 2002;110(4):1099–113.
37. Aho K, Sainio K, Kianta M, et al. Pneumatic tourniquet paralysis. Case report. J Bone Joint Surg Br 1983;65(4):441–3.
38. Maguiña P, Jean-Pierre F, Grevious MA, et al. Posterior interosseous branch palsy following pneumatic tourniquet application for hand surgery. Plast Reconstr Surg 2008;122(2):97e–9e.
39. Selvan D, Harle D, Fischer J. Beware of finger tourniquets: a case report and update by the National Patient Safety Agency. Acta Orthop Belg 2011;77(1):15–7.
40. Kruse H, Christensen KP, Møller AM, et al. Tourniquet use during ankle surgery leads to increased postoperative opioid use. J Clin Anesth 2015;27(5):380–4.
41. Saied A, Zyaei A. Tourniquet use during plating of acute extra-articular tibial fractures: effects on final results of the operation. J Trauma 2010;69(6):E94–7.
42. Smith TO, Hing CB. The efficacy of the tourniquet in foot and ankle surgery? A systematic review and meta-analysis. Foot Ankle Surg 2010;16(1):3–8.

43. Salam AA, Eyres KS, Cleary J, et al. The use of a tourniquet when plating tibial fractures. J Bone Joint Surg Br 1991;73(1):86–7.
44. Konrad G, Markmiller M, Lenich A, et al. Tourniquets may increase postoperative swelling and pain after internal fixation of ankle fractures. Clin Orthop Relat Res 2005;(433):189–94.
45. Maffulli N, Testa V, Capasso G. Use of a tourniquet in the internal fixation of fractures of the distal part of the fibula. A prospective, randomized trial. J Bone Joint Surg Am 1993;75(5):700–3.
46. Dobner JJ, Nitz AJ. Postmeniscectomy tourniquet palsy and functional sequelae. Am J Sports Med 1982;10(4):211–4.
47. Pollak AN, Battistella F, Pettey J, et al. Reamed femoral nailing in patients with multiple injuries. Adverse effects of tourniquet use. Clin Orthop Relat Res 1997;(339):41–6.
48. Younger ASE, Kalla TP, McEwen JA, et al. Survey of tourniquet use in orthopaedic foot and ankle surgery. Foot Ankle Int 2005;26:208–17.
49. Younger ASE, McEwen JA, Inkpen K. Wide contoured thigh cuffs and automated limb occlusion measurement allow lower tourniquet pressures. Clin Orthop Relat Res 2004;428(428):286–93.
50. Lin LN, Wang LR, Wang WT, et al. Ischemic preconditioning attenuates pulmonary dysfunction after unilateral thigh tourniquet-induced ischemia-reperfusion. Anesth Analg 2010;111(2):539–43.
51. Kornbluth ID, Freedman MK, Sher L, et al. Femoral, saphenous nerve palsy after tourniquet use: a case report. Arch Phys Med Rehabil 2003;84(6):909–11.
52. Mingo-Robinet J, Castañeda-Cabrero C, Alvarez V, et al. Tourniquet-related iatrogenic femoral nerve palsy after knee surgery: case report and review of the literature. Case Rep Orthop 2013;2013:368290.
53. Hirvensalo E, Tuominen H, Lapinsuo M, et al. Compartment syndrome of the lower limb caused by a tourniquet: a report of two cases. J Orthop Trauma 1992;6(4):469–72.
54. Murphy CG, Winter DC, Bouchier-Hayes DJ. Tourniquet injuries: pathogenesis and modalities for attenuation. Acta Orthop Belg 2005;71(6):635–45.
55. Feldman V, Biadsi A, Slavin O, et al. Pulmonary embolism after application of a sterile elastic exsanguination tourniquet. Orthopedics 2015;38(12):e1160–3.
56. Odinsson A, Finsen V. Tourniquet use and its complications in Norway. J Bone Joint Surg Br 2006;88(8):1090–2.
57. Ochoa J, Fowler TJ, Gilliatt RW. Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet. J Anat 1972;113(Pt 3):433–55.
58. Pollard BJ, Lovelock HA, Jones RM. Fatal pulmonary embolism secondary to limb exsanguination. Anesthesiology 1983;58(4):373–4.
59. Araki S, Uchiyama M. Fatal pulmonary embolism following tourniquet inflation. A case report. Acta Orthop Scand 1991;62(5):488.
60. Hofmann AA, Wyatt RW. Fatal pulmonary embolism following tourniquet inflation. A case report. J Bone Joint Surg Am 1985;67(4):633–4.
61. Darmanis S, Papanikolaou A, Pavlakis D. Fatal intraoperative pulmonary embolism following application of an Esmarch bandage. Injury 2002;33(9):761–4.
62. Hirota K, Hashimoto H, Kabara S, et al. The relationship between pneumatic tourniquet time and the amount of pulmonary emboli in patients undergoing knee arthroscopic surgeries. Anesth Analg 2001;93:776–80.