

# Tourniquet use in upper limb surgery

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**Abstract** Tourniquets are compressive devices that occlude venous and arterial blood flow to limbs and are commonly used in upper limb surgery. With the potential risk of complications, there is some debate as to whether tourniquets should continue to be routinely used. In this review, we first look at the different designs, principles, and practical considerations associated with the use of tourniquets in the upper limb. The modern pneumatic tourniquet has many design features that enhance its safety profile. Current literature suggests that the risk of tourniquet-related complications can be significantly reduced by selecting cuff inflation pressures based on the limb occlusion pressure, and by a better understanding of the actual level of pressure within the soft tissue, and the effects of cuff width and contour. The evidence behind tourniquet time, placement,

and limb exsanguination is also discussed as well as special considerations in patients with diabetes mellitus, hypertension, vascular calcification, sickle cell disease and obesity. We also provide an evidence-based review of the variety of local and systemic complications that may arise from the use of upper limb tourniquets including pain, leakage, and nerve, muscle, and skin injuries. The evidence in the literature suggests that upper limb tourniquets are beneficial in promoting optimum surgical conditions and modern tourniquet use is associated with a low rate of adverse events. With the improvement in knowledge and technology, the incidence of adverse events should continue to decrease. We recommend the use of tourniquets in upper limb surgery where no contraindications exist.

**Keywords** Tourniquet · Upper limb · Limb occlusion pressure · Complications

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Tourniquets are compressive devices that occlude venous and arterial blood flow to limbs and their use has been described in antiquity. The term tourniquet derives from the French verb “tourner” that means to turn, and was coined by the French Surgeon Jean Louis Petit (1,674–1,750) who described a belt like device that was used to reduce blood loss in limb amputations. The belt was pulled tight around a limb with a screw sited over the main artery, and the screw subsequently turned to compress the artery [35].

Tourniquets are commonly used in surgery to create a bloodless field, to engorge vessels for venepuncture, and in rare instances to control bleeding in life or limb threatening situations. They are also used in Bier's block as an adjunct to regional anesthesia whereby a tourniquet is applied to the limb and local anesthetic administered intravenously at a site distal to the tourniquet to anesthetize the entire distal limb.

The use of tourniquets reduces the incidence of technical difficulties during surgery but there is no conclusive evidence that it influences pain perception or lessens duration of surgery [74]. This lack of conclusive evidence coupled with well-publicized few adverse events have led to some debate as to whether tourniquets should continue to be routinely used in upper limb surgery.

### Modern Pneumatic Tourniquets

The modern pneumatic tourniquet was invented by James A McEwan in the early 1980's and consists of an inflatable cuff, a compressed gas source, and a microprocessor-controlled pressure regulator that maintains cuff pressure within 1% of the set pressure [42]. The cuff pressure and inflation time are displayed on a monitor that can be easily read by clinical staff. The design protects against over-pressurization or sudden de-pressurization, and an audiovisual alarm is usually incorporated and triggered by cuff leaks, excessively high or low cuff pressures, or a prolonged tourniquet time.

A number of additional design features enhance its safety profile such as the dual-line cuff that facilitates the detections of kinks or occlusions in the line, and a back-up battery that ensures normal function in the event of a power-supply failure. The modern tourniquet system allows the judicious administration of lower tourniquet pressures than was hitherto advocated and used [5, 19] achieving a better safety profile while still maintaining a blood-less field.

Manufacturing guidelines advise on how to achieve good tourniquet care [42], and these should be supplemented by local hospital policy. Gauges and valves should be checked regularly to avoid malfunction that can lead to dangerously high inflation cuff pressures. Frequent calibration checks and intraoperative monitoring of tourniquet function can ensure that actual cuff pressures are accurate to the specified set pressure.

Manufacturing guidelines and local hospital policy should be followed for decontamination. At our hospital, the cuff, tubing and tourniquet unit are checked for soiling and are cleaned between cases with a neutral hospital detergent diluted in warm tap water to prevent cross infection. The open end of the tubing however should not be immersed in water as it could alter the pressure distribution of the cuff. The equipment is then dried with a clean disposable cloth following decontamination.

### Limb Occlusion Pressure

The concept of Limb Occlusion Pressure (LOP) is important in safe and effective tourniquet use. It is the

pressure at which arterial blood flow is occluded past a specific tourniquet cuff at a specific time in a specific limb. It considers the anatomical and physiological characteristics of a patient's limb and the physical properties of the tourniquet in question. Current literature suggests that the risk of tourniquet related complications can be significantly reduced by measuring the LOP and selecting cuff inflation pressures accordingly [24, 41, 60, 86].

Conventionally LOPs are determined manually by inflating the tourniquet and recording the pressure at which the distal arterial pulsation ceases, usually verified by a doppler stethoscope. A margin of error of 50–100 mmHg is added in consideration of changing conditions during surgery. These values are based on the results in the literature where bloodless fields have been consistently achieved [14, 60]. The manual process however is both time consuming and labor intensive and despite its proven safety benefit, has not been readily accepted in clinical practice. Another option is to use systolic blood pressure plus a standard margin of error to obtain a safe cuff inflation pressure [10, 85]. However the results of this estimation are suboptimal because of the variable relationship between LOP and systolic blood pressure [41, 71].

More recently, advanced tourniquet systems have been developed that are able to measure the LOP automatically. These systems are based on the photoplethysmographic principle that uses a light transducer to deduce blood flow and calculate the cuff inflation pressure at which distal circulation is occluded [43]. The accuracy of this device is comparable to the standard doppler technique and has been shown to significantly reduce the tourniquet pressure used in a clinical setting [86].

Current guidelines from the Association of peri-Operative Registered Nurses [9] recommends that for adults, a safety margin of 40 mmHg be added for LOP less than 130 mmHg, 60 mmHg be added for LOP 131–190 mmHg, and 80 mmHg be added for LOP greater than 190 mmHg. In children a standard safety margin of 50 mmHg is recommended for all LOPs.

### Tourniquet Design

Studies have shown that the actual level of pressure applied in the pneumatic cuff varies widely in comparison to the pressure within the encircled soft tissue [23, 66, 71]. Peak pressure occurs in the subcutaneous tissue just proximal to the mid-position along the tourniquet width, and decrease from this point towards the center and towards the cuff edge. There is a direct relationship between cuff inflation pressure, peak pressure in subcutaneous tissue and the pressure gradient in underlying soft tissue. The probability of tourniquet-related complications increases as the peak

pressure and pressure gradient increase [44, 53, 71], thus it is desirable to achieve vascular occlusion with the lowest possible cuff inflation pressure.

Crenshaw et al. (1988) measured tissue pressure in cadaveric limbs at four depths following the application of a pneumatic cuff [10]. They found that wide cuffs had a more gradual pressure profile at all tissue depths, with relatively smaller changes between the peak pressures at the mid-position of the tourniquet width and lowest pressures at the periphery of the tourniquet width. They also found that wide cuffs required lower inflation pressures to stop the flow of arterial blood distal to the tourniquet. Graham et al. (1993) showed an inverse relationship between LOP and the ratio of the cuff width to the limb circumference [22]. They showed that the occlusion pressure reached sub-systolic levels when the cuff width to limb circumference ratio exceeded 0.5.

Contoured cuffs have been proven to occlude blood flow at lower pressures than standard straight cuffs and, when used with LOP, can significantly reduce the necessary cuff pressures to maintain a bloodless surgical field in both the adult and paediatric population [22, 60]. This has led to the development of variable-contour cuffs that are suitable to a wide range of limb sizes and shapes. Thus a wide and contoured tourniquet is favored to achieve the lowest possible limb occlusion pressure.

### Non-pneumatic Tourniquet

Non-pneumatic tourniquet devices typically produce applied pressures and pressure gradients that are significantly higher than the LOP, and at levels associated with significantly higher rates of morbidity. Previously these non-pneumatic tourniquets were used in hospitals but the transition has been made to pneumatic tourniquets for safety reasons. Non-pneumatic tourniquets still serve a purpose in the military due to their ability to stop arterial bleeds, their ease of use and their proven life and limb salvage potential [38].

### Practical Considerations

**1. Duration of Tourniquet Use** There is no completely safe duration of tourniquet use, and it is important to minimize tourniquet time to minimize the chances of any potential complications. Historical studies did not show any post-operative complications

where tourniquet time exceeded 2 h [6, 18], and in clinical practice 2 to 3 h was considered a safe upper limit for tourniquet use. Excessive tourniquet time however increases the rate of tourniquet-related ischemic complications and more recently human studies have shown that significant ischemia and muscle dysfunction occurs after 2 h [57]. The issue of temporarily tourniquet deflation during prolonged surgery to allow tissue reperfusion is not supported by evidence in the literature [74]. Tourniquet inflation should occur at least 5 min after any intravenous antibiotic administration to allow adequate tissue perfusion of antimicrobial agents [3].

**2. Tourniquet Placement** Tourniquets are conventionally placed on the upper arm in upper limb surgery, but there has been an increasing trend of using forearm tourniquets supported by literature evidence of their efficacy and safety [80]. In Bier block, forearm tourniquets have the advantage of requiring a lower dose of local anesthetic [73]. Hutchinson and McClinton (1993) have shown that, for minor surgical procedures under local anesthetic lasting less than 30 min, patients reported less pain and tolerated tourniquets placed on the forearm better than those on the upper arm [29]. Odinson and Finsen (2006) concurred with these findings but found that surgeons experienced greater difficulty with more distally placed tourniquets [55].

**3. Limb Exsanguination** Mechanical limb exsanguination can be performed prior to applying the tourniquet and commencing surgery to facilitate the creation of a blood-less field. The Esmarch bandage is a rubber bandage devised by the German

surgeon, Johann von Esmarch that is tied around the limb for exsanguination or as a tourniquet. Its efficacy in exsanguination is well described but its use as a tourniquet is controversial as it achieves greater pressure and has been associated with higher rates of complication. Alternatively a Rhys-Davies exsanguinator can be used [64]. This consists of an inflated elastic cylinder that is rolled over a limb to produce exsanguination. It is highly effective and has a very good safety profile. Simple elevation can achieve a good result where mechanical limb exsanguination is contraindicated e.g. in sickle-cell. Warren et al. (1992) recommend upper limb elevation for 5 min at 90° before tourniquet application [83].

Tourniquet use in the presence of arterial calcification such as in people suffering with diabetes mellitus should be carried out judiciously. Theoretical risks are failure to achieve a blood-less field leading to inadequate visualization during surgery, systemic toxicity from anesthetic agents as a result of a failed regional intravenous block, and an increased risk of tourniquet-related complications due to the higher cuff inflation pressures that may be needed to achieve arterial occlusion. Jeyaseelan et al. (2007) report on the case of a patient with Mönckeberg's calcinosis in whom a limb tourniquet failed due to calcification of the femoral artery wall [31]. Excessive bleeding at the surgical site was observed due to failure to achieve arterial occlusion but a very effective venous occlusion.

As discussed above, LOP is the directly measured minimum pressure required to stop the flow of blood for a specific situation,

and is generally lower than a predetermined generic pressure, e.g., 250 mmHg. In situations where the arterial calcification hinders adequate arterial occlusion, the use of LOP is likely to avoid the use of higher predetermined generic pressures.

There have been reports of crises precipitated by the use of tourniquets in surgery in sickle cell disease and, conversely, successful procedures carried out with minimal adverse events. Clinical decisions regarding tourniquet use should be made on the basis of risk versus benefit to the patient, and supplemented with careful exsanguination technique and good general principles of sickle cell patient management [1, 75, 84].

Obese patients often present a problem in tourniquet application due to their excessive subcutaneous tissue. A wide and appropriately sized tourniquet should be selected and contoured. Tourniquets have been found to be extremely useful. Its efficacy is improved by having an assistant draw the skin and subcutaneous tissue distally before fastening the tourniquet [37].

## Complications

There are a variety of local and systemic complications that may arise from the use of upper limb tourniquets in the surgical or anesthetic settings. Localized physiological changes can result from the direct effect of cuff compression or tissue hypoperfusion due to vascular occlusion. Systemic complications appear related to tourniquet inflation and deflation [33].

Studies suggest that tourniquet associated complications remain fairly rare. Reports in Australia in the 1970's showed adverse events related to tourniquet use in one in 5,000 and one in 13,000 procedures on the upper and lower limb respectively [46]. More recent studies in Norway showed 26 complications in approximately 63,484 surgical procedures using tourniquets [55].

## 4. Special Medical Considerations

Most clinical and animal based research suggests that tourniquet-related complications increase with time [16, 32, 40] and this has led to the widespread practice of limiting tourniquet use to less than 2 h [3, 82].

1. Pain Pain may be experienced with tourniquet use on the upper limb and tolerance depends upon a number of variables such as patient pain threshold, duration of use, cuff pressure and cuff diameter [13].

When tourniquets are inflated, patients experience a vague, dull pain in the limb and there is an associated increase in blood pressure [20, 76]. A prospective study showed overall good tolerance of tourniquets up to 20 min and suggested an idiosyncratic relationship between pain perception and tourniquet use [56]. Prolonged tourniquet inflation results in an increase in heart rate and blood pressure, and the anesthetist often increases the depth of anesthesia to counteract this [36]. The duration of pain tolerance improves in sedated patients [11, 36]. Hagenouw et al. (1986) demonstrated that higher cuff pressures with narrower tourniquet diameters can cause less pain than wider cuffs with lower pressures [11], whereas Estebe (2000) showed that a wide-cuff pneumatic tourniquets improve arterial occlusion and are less painful than narrow cuffs when pressure is limited to arterial pulse loss [17, 25].

There is a complicated multifactorial aetiology for tourniquet pain. Tourniquet pain is thought to be nerve fiber related with pain transmitted along slow-conducting unmyelinated C-fibers. It is suspected that fast conducting myelinated A- $\delta$ -fibers, that under normal circumstances inhibit this C-fiber related pain transmission, are blocked by mechanical compression through ischemia [32, 36]. Another explanation of tourniquet pain is that during compression there is an increase in spontaneous firing activity and expansion of the receptive fields of nociceptive dorsal horn neurones around the area of tourniquet application [12]. Limb reperfusion pain has also been described after tourniquet deflation when blood flow is restored and toxic metabolites removed [11, 36, 63].

2. Leakage Leaks are important because of the risks local anesthetic agents pose during Bier block anesthesia if they reach the systemic circulation, and the effect ooze may have on the

surgical field. Leakage in upper limb tourniquets is affected by a variety of factors. Blood pressure, cuff pressure and width, and cannula location in the arm have all been described as having a bearing on movement of anesthetic agents into systemic circulation and oozing of blood through arterial leakage into the surgical field.

Studies using radiolabeled isotopes have tried to quantify leakage in upper limb surgery of substances reaching systemic circulation. Hoffmann et al. (1995) revealed a mean leak of  $15\pm 5\%$  of radiolabeled compound from distal to an upper arm tourniquet to the systemic system [27]. Coleman et al. (1999) described leakage of  $10\pm 20\%$  of radiolabeled compound from distal to an upper arm tourniquet to the systemic system, and of  $6\pm 12\%$  for a forearm tourniquet [8]. Arterial leakage has proved more difficult to measure accurately.

Interosseous, especially biosseous, routes have been implicated as a source of leakage since such vessels are not readily compressed by tourniquets, but such evidence is yet to be clinically quantified and substantiated [8, 65]. There is an increased risk of leakage in hypertensive patients. As there is an inverse relationship between the LOP and the ratio of tourniquet cuff width to limb circumference [22], any increase in limb circumference increases the pressure required to prevent a leak. Limb congestion thus may increase the risk of local anesthetic agent leaking past the tourniquet into the systemic circulation.

3. Nerve Injury There have been numerous publications on tourniquet-related nerve damage. The incidence varies in the literature but nerve complications appear uncommon ranging from 1 in 750 [18] to 1 in 11,000 [46] in upper limb surgery. The radial nerve is most prone to injury [32, 46].

A number of factors have been implicated in tourniquet related nerve damage including longer durations of tourniquet application [28] and higher tourniquet pressure gradients [45, 47]. Studies performed prior to the use of lower pressures in tourniquets demonstrated a



higher incidence of neuromuscular dysfunction [51]. Tourniquet related nerve complications exist on a spectrum from minor transient loss of function to permanent irreversible damage. The typical duration of reversible denervation ranges from 2 to 6 months [47, 55, 66] with irreversible damage being rare [66].

The pathophysiology of nerve damage relates to direct compressive forces under the tourniquet and at its edges. Compression causes stretching of myelin sheaths, displacement of nodes of Ranvier from their normal position, microvascular damage, edema and ischemia related tissue nutrition depletion [32, 67, 68]. There is associated partial to complete rupture of the paranodal myelin promoting axonal degeneration. Nerve constituent displacement occurs in the direction of non-compressed tissue and is greatest at the tourniquet edge, i.e., the area of highest pressure gradient [21, 53, 54].

**4. Muscle Injury** As with tourniquet related nerve damage, muscle tissue injury beneath and distal to tourniquet sites have been shown in clinical and animal studies to be directly correlated to application times and pressures [32, 61]. Inflammatory changes, focal and regional necrosis and hyaline degeneration take place following microvascular compression and superoxide free radical endothelial damage. The extent depends on muscle location in relation to the tourniquet and duration of ischemia [49, 62].

There are cellular, metabolic and microvascular changes that take place as a result of anaerobic metabolism during tourniquet application. The reduced tissue perfusion during tourniquet application leads to a depletion of the intracellular nutrients creatine phosphate, glycogen and adenosine triphosphate, while lactate and carbon dioxide levels increase and intracellular pH decreases. Tissue nutrition appears depleted after 2 to 3 h of ischemia [26, 32, 69].

After deflation further cellular injury can ensue due to microvascular congestion. This is related to “Post-tourniquet syndrome” where the patient may expe-

rience weakness, stiffness and numbness of the affected limb, which tends to recover on average 3 weeks postoperatively. Recovery time is proportional to ischemic duration. After 3 h of cuff inflation the recovery time may be significantly increased [32, 49, 61, 69, 70]. Rhabdomyolysis due to prolonged tourniquet application is well-documented [58, 72, 81].

**5. Skin Injury** This is a rare complication related to pressure necrosis or friction burns due to tourniquet movement [7]. Chemical burns can be caused when solutions used for operative preparation pass under the tourniquets and remain there under pressure during surgery [15].

**6. Deflation** Deflation and reperfusion allow nutritional replenishment of the affected limb and metabolite removal. This stage of the operation requires close patient monitoring [48, 67]. Myoneuropathic metabolic syndrome has been described when toxic metabolites enter systemic circulation. Clinically it is characterized by metabolic acidosis, hyperkalemia, myoglobulinaemia, myoglobinuria, and renal failure [48, 59]. Post-tourniquet bleeding may occur after deflation, related to increased activation of protein-C and antithrombin-III thrombolytic pathways [62].

## Discussion

The use of epinephrine, and other vasoconstrictive drugs, provides an alternative to the use of tourniquets. The effectiveness of local anesthetics is improved by the addition of a epinephrine, and provides an increased duration of action and decreased local bleeding. The addition of epinephrine to the local anesthetic has been shown to cause sufficient vasoconstriction to maintain a dry field and allow carpal tunnel decompression procedures without the need of a tourniquet [79]. In arthroscopy procedures, 10 ml of 1:10,000 epinephrine may be mixed in 3 L irrigation fluid to control hemostasis [39]. Tourniquets may however still need to be applied in a standby manner, in more extensive or higher risk procedures, and where there is a history of coagulopathy. Epinephrine use has limitations due to potential cardiac and local toxic effects.

Adverse effects due to tourniquet use are well-documented but remain reassuringly uncommon. With the

improvement in knowledge and technology, the incidence of adverse events should continue to decrease. Many methods have been described and continue to be developed that aim to reduce adverse events. These include the use of lower inflation pressures [47, 60], entire limb cooling to extend ischemic time [34], alternately inflated two tourniquet cuffs to avoid prolonged compression under the cuff [50] and anesthetic techniques to improve cuff use and tolerance [2, 4, 30, 77, 78]. There nevertheless remains an absence of convincing scientific evidence to support any of these techniques. Noordin et al. stated that accurate monitoring and minimization of tourniquet time was the most important factor in preventing adverse events [52].

The risks and benefits associated with the use of an arterial tourniquet should be assessed by the clinician performing the procedure, and the patient should be appropriately informed and consented. Accurate procedural and patient assessment prior to surgery will help optimize upper limb tourniquet use and individualize the technique. The clinician using the tourniquet should give clear instructions regarding the appropriate choice of cuff and gauge pressure, decide when to inflate and deflate the tourniquet, and ensure good communication.

The evidence in the literature suggests that upper limb tourniquets are beneficial in promoting optimum surgical conditions and modern tourniquet use is associated with a low rate of adverse events. We recommend the use of tourniquets in upper limb surgery where no contraindications exist.

### Summary for Safe Tourniquet Use

- The use of well-maintained wide modern contoured pneumatic tourniquets reduces the pressures applied to the underlying tissues and improves their safety profile.
- The measurements of LOP can potentially reduce the tourniquet pressures used.
- There is no completely safe duration of tourniquet use, and it is important to minimize tourniquet time to minimize the chances of any potential complications.
- Higher tourniquet pressures and durations are associated with higher risk of pain, and skin, muscle and nerve-related complications.

**Conflicts of Interest** The authors declare that they have no conflict of interest.

### References

1. Adu-Gyamfi Y, Sankarankutty M, Marwa S. Use of a tourniquet in patients with sickle-cell disease. *Can J Anaesth*. 1993;40:24–7.
2. Al-Metwalli RR. Evaluation of the tourniquet leak during forearm intravenous regional anesthesia-manual vs automatic pump injection. *Mid East J Anesth*. 2009.
3. Bannister GC, Auchincloss JM, Johnson DP, Newman JH. The timing of tourniquet application in relation to prophylactic antibiotic administration. *J Bone Joint Surg Br*. 1988;70:322–4.
4. Bonnet F, Diallo A, Saada M, et al. Prevention of tourniquet pain by spinal isobaric bupivacaine with clonidine. *Br J Anaesth*. 1989;63:93–6.
5. Boyd HB. Surgical approaches. *Campbell's Operative Orthopaedics*, 5th Ed, St. Louis, Mosby Co. 1971;58.
6. Bruner JM. Time, pressure and temperature factors in the safe use of the tourniquet. *Hand*. 1970;2:39–42.
7. Choudhary S, Koshy C, Ahmed J, Evans J. Friction burns to thigh caused by tourniquet. *Br J Plast Surg*. 1998;51:142–3.
8. Coleman MM, Peng PW, Regan JM, et al. Quantitative comparison of leakage under the tourniquet in forearm versus conventional intravenous regional anesthesia. *Anesth Analg*. 1999;89:1482–6.
9. Conner. AORN Perioperative Standards and Recommended Practices. Association of periOperative Registered Nurses (AORN). 2010.
10. Crenshaw AG, Hargens AR, Gershuni DH, Rydevik B. Wide tourniquet cuffs more effective at lower inflation pressures. *Acta Orthop Scand*. 1988;59:447–51.
11. Crews JC, Denson DD, Hilgenhurst G. Tourniquet Pain: The response to the maintenance of tourniquet inflation on the upper extremity of volunteers. *Reg Anesth*. 1991;16:314–7.
12. Crews JC, Cahall MA. An investigation of the neurophysiologic mechanisms of tourniquet related pain: changes in spontaneous activity and receptive field size in spinal dorsal horn neurons. *Reg Anesth Pain Med*. 1999;24:102–9.
13. Deloughry, Griffiths. Arterial tourniquets. *Contin Educ Anaesth Crit Care Pain*. 2009;9:56–60.
14. Diamond EL, Sherman M, Lenet M. A quantitative method of determining the pneumatic ankle tourniquet setting. *J Foot Surg*. 1985;24:330–4.
15. Dickinson JC, Bailey BN. Chemical burns beneath tourniquets. *BMJ*. 1988;297:1513.
16. Edwards S, Harper G, Giddins G. Efficacy of forearm versus upper arm tourniquet for local anaesthetic surgery of the hand. *J Hand Surg*. 2000;25B:573–4.
17. Estebe JP, Le Naoures A, Chemaly L, et al. Tourniquet pain in a volunteer study: effect of changes in cuff width and pressure. *Anaesthesia*. 2000;55:21–6.
18. Flatt AE. Tourniquet time in hand surgery. *Arch Surg*. 1972;104:190–2.
19. Flewellen E, Jarem B. Pneumatic tourniquets. *Anesthesiol Rev*. 1978;5:31–4.
20. Gielen MJ, Stienstra R. Tourniquet hypertension and its prevention: a review. *Reg Anaes*. 1991;16:191–4.
21. Gilliatt RW, Ochoa J, Rudge P, Neary D. The cause of nerve damage in acute compression. *Trans Am Neurol Assoc*. 1974;99:71–4.
22. Graham B, Breault M, McEwen J, McGraw R. Occlusion of arterial flow in the extremities at subsystolic pressures through the use of wide tourniquet cuffs. *Clin Orthop Relat Res*. 1993;286:257–6.
23. Griffiths JC, Heywood OB. Bio-mechanical aspects of the tourniquet. *Hand*. 1973;5:113–8.
24. Guay J. Adverse events associated with intravenous regional anesthesia (Bier block): a systematic review of complications. *J Clin Anesth*. 2009;21:585–94.
25. Hagenouw RR, Bridenbaugh PO, Egmond J, Stuebing R. Tourniquet Pain: a volunteer study *Anesth Analg*. 1986;65:1175–80.
26. Haljamäe H, Enger E. Human skeletal muscle energy metabolism during and after complete tourniquet ischaemia. *Ann Surg*. 1975;182:9–14.

27. Hoffmann AC, van Gessel E, Gamulin Z, et al. Quantitative evaluation of tourniquet leak during i.v. regional anaesthesia of the upper and lower limbs in human volunteers. *Br J Anaesth.* 1995;75:269–73.
28. Horlocker TT et al. Anesthetic, patient, and surgical risk factors for neurologic complications after prolonged total tourniquet time during total knee arthroplasty. *Anaesth Analg.* 2006;102:950–5.
29. Hutchinson DT, McClinton MA. Upper extremity tourniquet tolerance. *J Hand Surg.* 1993;18A:206–10.
30. James NK, Khoo CTK, Fell RH. The ‘Mini-Bier’s Block’: a new technique for prevention of tourniquet pain during axillary brachial plexus anaesthesia. *J Hand Surg.* 1994;19B:347–9.
31. Jeyaseelan S, Stevenson T, Pfitzner J. Tourniquet failure and arterial calcification. *Anaesthesia.* 2007;36:48–50.
32. Kam PC, Kavanagh R, Yoong. The arterial tourniquet: pathophysiological consequences and anaesthetic implications. *FF Anaesthesia.* 2001;56:534–45.
33. Kam PC. Uses and precautions of tourniquets. *Surg (Oxford).* 2008;26:70–2.
34. Kelly C, Creagh T, Pierce A, Bouchier-Hayes G, Bouchier-Hayes D. Regional hypothermia protects against tourniquet neuropathy. *Eur J Vasc Surg.* 1992;6:288–92.
35. Klenerman L. The tourniquet in surgery. *J Bone Joint Surg Br.* 1962;44:937–43.
36. Klenerman L. *The tourniquet manual: principles and practice.* London: Springer; 2003.
37. Krackow KA. A manoeuvre for improved positioning of a tourniquet in the obese patient. *Clin Orthop Relat Res.* 1982;168:80–2.
38. Kragh Jr JF, Walters TJ, Baer DG, et al. Survival with emergency tourniquet use to stop bleeding in major limb trauma. *Ann Surg.* 2009;249:1–7.
39. Law BK, Yung PS, Ho EP, et al. Review of knee arthroscopy performed under local anesthesia. *Sports Med Arthrosc Rehabil Ther Technol.* 2009;1:3.
40. Malanjum L, Fischer B. Procedures under tourniquet. *Anaesthetic Int Care Med.* 2009;10:14–7.
41. Massey KA, Blakeslee C, Martin W, et al. Pneumatic ankle tourniquets: physiological factors related to minimal arterial occlusion pressure. *J Foot Ankle Surg.* 1999;38:256–63.
42. McEwen JA. Complications of and improvements in pneumatic tourniquets used in surgery. *Med Instrum.* 1981;15:253–7.
43. McEwen JA, Jameson M. Physiologic Tourniquet. US Patent No. 5,607,447, March 4 1997.
44. McGraw R, McEwen J. In: McFarlane RM, editor. *The Tourniquet. In unsatisfactory results in hand surgery.* NY: Churchill Livingstone; 1987. p. 5–13.
45. McLaren AC, Rorabeck CH. The pressure distribution under tourniquets. *J Bone Jt Surg.* 1985;67A:433–8.
46. Middleton RW, Varian JP. Tourniquet paralysis. *Aust N Z J Surg.* 1974;44:124–8.
47. Mohler LR, Pedowitz RA, Lopez MA, et al. Effects of tourniquet compression on neuromuscular function. *Clin Orthop.* 1999;359:213–20.
48. Murphy CG, Winter DC, Bouchier-Hayes DJ. Tourniquet injuries: pathogenesis and modalities for attenuation. *Acta Orthop Belg.* 2005;71:635–45.
49. Neimkin RJ, Smith RJ. Double tourniquet with linked mercury manometer for hand surgery. *J Hand Surg.* 1983;8A:938–41.
50. Newman RJ. Metabolic effects of tourniquet ischaemia studied by nuclear magnetic resonance spectroscopy. *J Bone Jt Surg.* 1984;66B:434–40.
51. Nitz AJ, Dobner JJ. Upper extremity tourniquet effects in carpal tunnel release. *J Hand Surg.* 1989;14A:499–504.
52. Noordin S, McEwen JA, Kragh Jr JF, Eisen A, Masri BA. Surgical tourniquets in orthopaedics. *J Bone Jt Surg.* 2009;91A:2958–67.
53. Ochoa J, Danta G, Fowler TJ, Gilliatt RW. Nature of the nerve lesion caused by a pneumatic tourniquet. *Nature.* 1971;233:265–6.
54. Ochoa J, Fowler TJ, Gilliatt RW. Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet. *J Anat.* 1972;113:433–55.
55. Odinson A, Finsen V. Tourniquet use and its complications in Norway. *J Bone Joint Surg Br.* 2006;88:1090–2.
56. Ogufero WE, Giddins GEB, Thom JS. Upper arm tourniquet pain in local anaesthetic surgery. *J Hand Surg.* 1995;20B:413–4.
57. Ostman B, Michaelsson K, Rahme H, Hillered L. Tourniquet-induced ischemia and reperfusion in human skeletal muscle. *Clin Orthop Relat Res.* 2004;418:260–5.
58. Palmer SH, Graham G. Tourniquet-induced rhabdomyolysis after total knee replacement. *Ann R Coll Surg Engl.* 1994;76:416–7.
59. Patel AJ, Choi CS, Giuffrida JG. Changes in end tidal CO<sub>2</sub> and arterial blood gas levels after release of tourniquet. *South Med J.* 1987;80:213–6.
60. Pedowitz RA, Gershuni DH, Schmidt AH, et al. Muscle injury beneath and distal to a pneumatic tourniquet; a quantitative animal study of effects of tourniquet pressure and duration. *J Hand Surg.* 1991;16A:610–21.
61. Pedowitz RA, Gershuni OH. 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.* 1993;287:237–44.
62. Petaja J, Myllynen P, Myllyla G, Vahtera E. Fibrinolysis after application of a pneumatic tourniquet. *Acta Chir Scand.* 1978;153:647–51.
63. Prodhomme G, Mouraux D, Dugailly PM, et al. Tolerance of upper extremity pneumatic tourniquets and their effect on grip strength. *J Hand Surg.* 2008;33B:266–71.
64. Rhys-Davies NC, Stotter AT. The Rhys-Davies exsanguinator. *Ann R Coll Surg Engl.* 1985;67:193–5.
65. Rodolà F, Vagnoni S, Ingletti S. An update on intravenous regional anaesthesia of the arm. *Eur Rev Med Pharmacol Sci.* 2003;7:131–8.
66. Rorabeck CH, Kennedy JC. Tourniquet induced nerve ischaemia complicating knee ligament surgery. *Am J Sports Med.* 1980;8:98–102.
67. Rydevik B, Nordborg C. Changes in nerve function and nerve fibre structure induced by acute, graded compression. *J Neurol Neurosurg Psych.* 1980;43:1070–82.
68. Rydevik B, Lundborg G, Bagge U. Effects of graded compression on intraneural blood flow. An in vivo study on rabbit tibial nerve. *J Hand Surg.* 1981;6A:3–12.
69. Santavirta J, Mandracchia V, Niinikoski J. Effect of the pneumatic tourniquet on muscle oxygen tension. *Acta Orthop Scand.* 1978;49:415–6.
70. Sapega AA, Heppenstall B, Chance B, Park YS, Sokolow D. Optimizing tourniquet application and release times in extremity surgery. *J Bone Jt Surg.* 1985;67A:303–14.
71. Shaw JA, Murray DG. The relationship between tourniquet pressure and underlying soft-tissue pressure in the thigh. *J Bone Joint Surg Am.* 1982;64:1148–52.
72. Shenton DW, Spitzer SA, Mulrennan BM. Tourniquet induced rhabdomyolysis. *J Bone Jt Surg.* 1990;72A:1405–6.
73. Singh R, Bhagwat A, Bhadoria P, Kohli A. Forearm IVRA, using 0.5% lidocaine in a dose of 1.5 mg/kg with ketorolac 0.15 mg/kg for hand and wrist surgeries. *Minerva Anestesiol.* 2010;76:109–14.
74. Smith TO, Hing CB. Should tourniquets be used in upper limb surgery? A systematic review and meta-analysis. *Acta Orthop Belg.* 2009;75:289–96.
75. Stein R. Use of the tourniquet during surgery in patients with sickle cell haemoglobinopathies. *Clin Orthop Relat Res.* 1980;151:231.



76. Tetzlaff J, O'Hara J, Yoon H, Schubert A. Tourniquet-induced hypertension correlates with autonomic nervous system changes detected by power spectral heart rate analysis. *J Clin Anaes.* 1997;9:138–42.
77. Tsai YC, Lai YY, Chang CL. Comparison of the effect of EMLA cream, subcutaneous ring anaesthesia and a double cuff technique in the prevention of tourniquet pain. *Br J Anaesth.* 1993;70:394–6.
78. Turan A, White P, Karamanlioglu, Pamukcu Z. Premedication with Gabapentin: the effect on tourniquet pain and quality of intravenous regional anesthesia. *AA.* 2007;104:97–101.
79. Tzarnas CD. Carpal tunnel release without a tourniquet. *J Hand Surg Am.* 1993;18:1041–3.
80. Vlassakov KV, Bhavani K. The forearm tourniquet Bier block. Logic and authority versus science and experience. *Minerva Anesthesiol.* 2010;76:91–2.
81. Vold PL, Weiss PJ. Rhabdomyolysis from tourniquet trauma in a patient with hypothyroidism. *West J Med.* 1995;162:270–1.
82. Wakai A, Winter DC, Street JT, Redmond PH. Pneumatic tourniquets in extremity surgery. *J Am Acad Orthop Surg.* 2001;9:345–51.
83. Warren P, Hardiman P, Woolf V. Limb exsanguination. I. The arm: effect of angle of elevation and arterial compression. *Ann R Coll Surg Engl.* 1992;74:320–2.
84. Willinsky JS, Lepow R. Sickle cell trait and the use of the pneumatic tourniquet. *J Am Podiatr Assoc.* 1984;74:38–41.
85. Worland RL, Arredondo J, Angles F, Lopez-Jimenez F, Jessup DE. Thigh pain following tourniquet application in simultaneous bilateral total knee replacement arthroplasty. *J Arthroplasty.* 1997;12:848–52.
86. Younger AS, McEwen JA, Inkpen K. Wide contoured thigh cuffs and automated limb occlusion measurement allow lower tourniquet pressures. *Clin Orthop Relat Res.* 2004;428:286–93.