no protective material was used in the third group (n = 30). A 140-mm-wide contoured cuff or a 100-mm-wide cylindrical cuff was applied at the discretion of the surgical nurse. Cuff pressure, which was determined by the surgeon, was recommended to be 70 to 100 mm Hg above the patient’s systolic blood pressure for the contoured cuffs and 100 to 150 mm Hg above the systolic blood pressure for the cylindrical cuffs. The two groups with skin protection had fewer skin injuries (p = 0.007), and no patient who received the elastic stockinette had blisters. Skin blisters developed beneath the pneumatic tourniquet in ten patients—seven in the no-tourniquet-padding group and three in the cast-padding group. The duration of the bloodless field was longer for the patients with blisters than it was for those without blisters (mean and standard deviation, 112 ± 29 and 94 ± 21 minutes, respectively; p = 0.04). There were no significant differences in cuff pressure, thigh circumference, or age between the patients in whom blisters developed and those in whom they did not.

Tredwell et al. quantitatively analyzed wrinkling and pinching of the skin at the cuff-limb interface in a study of children. In a series of forty-four trials on the upper arms and thighs of two healthy child volunteers, tourniquet cuffs with dual-layer stockinette limb-protection sleeves in sizes matched to the specific cuffs significantly reduced (p < 0.01) the quantity and maximum height of skin wrinkling when compared with values associated with other forms of limb protection. In a study involving a total of fifty-five trials of five different types of limb protection beneath tourniquet cuffs on the upper limbs and thighs of five adults, it was found that stretched sleeves made of two-layer tubular elastic material and matched to the specific tourniquet cuffs produced significantly fewer, less severe pinches and wrinkles in the skin surface as compared with all other types of limb protection tested (maximum p < 0.01).

**Duration of Tourniquet Use**

Tourniquet-related complications increase as tourniquet time increases. Because there is no completely safe tourniquet time, the concept of accurately monitoring and minimizing tourniquet time to minimize the risk of injury is commonly accepted in surgical, military, and pre-hospital settings. Experimental data have demonstrated that the severity of tourniquet ischemia is dependent not only on tourniquet time but also on tissue type. Serum creatine phosphokinase concentration is elevated in response to muscle damage at and distal to the tourniquet cuff. Furthermore, interruption of blood supply results in cellular hypoxia, tissue acidosis, and potassium release, which, on reperfusion, are eventually corrected in the systemic
circulation. Although we are not knowledgeable of any prospective randomized clinical trial that defined the optimal duration of tourniquet use in lower-limb surgery, two hours is considered to be relatively safe for upper-limb surgery. This is consistent with the findings of a study of lower-extremity surgery by Ostman et al., who used microdialysis to characterize the time course and metabolite levels in skeletal muscle exposed to ischemia and reperfusion in eight patients undergoing arthroscopic-assisted anterior cruciate ligament reconstruction. The ischemia-induced energy metabolic change in the rectus femoris muscle in these patients had almost completely disappeared within two hours after tourniquet deflation.

One way of avoiding ischemic injury to muscle cells may be to employ a so-called tourniquet downtime technique, in which the tourniquet is released for a short period and then is reinflated. However, there is no evidence to support use of this technique, the suggested reperfusion time between successive ischemic periods has ranged from three to twenty minutes, and time limits for subsequent ischemia are unknown. Furthermore, some authors have questioned the benefit of any tourniquet release and reflation if the total tourniquet time does not exceed three hours. In view of this controversy and in the absence of convincing evidence otherwise, we do not recommend a routine tourniquet inflation time of more than two hours. Accurate monitoring and minimization of tourniquet time are recommended.

**Tourniquet Deflation**

Deflation and reperfusion permit replenishment of energy supplies and elimination of toxic metabolites. However, careful monitoring of the patient is essential at this stage of the operation, as pulmonary embolization may occur. Despite the substantial risk of postoperative deep venous thrombosis in orthopaedic extremity surgery, use of a pneumatic tourniquet does not appear to be an independent risk factor. In the setting of intramedullary instrumentation, cementation, or insertion of a prosthesis in the lower limb, deflation of a pneumatic tourniquet adds the risk of a sudden release of large venous emboli, emphasizing the need for careful patient monitoring at that time. The return of toxic metabolites to the circulation results in systemic metabolic dysfunction, referred to as “myonephropathic metabolic syndrome” and characterized by metabolic acidosis, hyperkalemia, myoglobinemia, myoglobinuria, and renal failure. Paradoxically, tourniquet deflation is associated with thrombolytic activity, anoxia promoting activation of the antithrombin-III and protein-C pathways, which may be implicated in post-tourniquet bleeding.

Tourniquet deflation prior to wound closure in knee arthroplasty is associated with greater blood loss and a higher demand for blood transfusion, suggesting that release following wound closure would offer better control. Rama et al. examined the time of tourniquet release in a meta-analysis of eleven randomized controlled trials involving a total of 872 patients and 893 primary knee arthroplasties. They found that early release of the tourniquet to achieve hemostasis increased perioperative blood loss in association with primary knee arthroplasty. However, the risk of a complication requiring additional operative treatment was increased when the tourniquet was left inflated until wound closure was complete. Overall, the surgeon has to balance the potential downside of delayed deflation (namely, increased bleeding) with the risks of prolonging tourniquet inflation times. The final decision regarding when to deflate the tourniquet should be made by the surgeon, after weighing the risks and benefits of delaying tourniquet deflation until closure is complete.

**Future Directions**

The concept of measuring limb occlusion pressure immediately prior to inflation of a surgical tourniquet establishes a basis for setting the optimal tourniquet pressure for each patient. However, a single measurement represents a static limb occlusion pressure to which a margin of safety must be added to account for relevant intraoperative variations in the patient’s physiology during an operation. In the future, safer tourniquet systems using lower tourniquet pressures could perhaps be developed by monitoring those physiologic variations intraoperatively and estimating a dynamic limb occlusion pressure on the basis of those variations and the static limb occlusion pressure, thus eliminating the need to increase the static limb occlusion pressure by an arbitrary predetermined margin of safety.

The risk of tourniquet-related nerve injuries and particularly the increased risk of such injuries as tourniquet pressure levels rise, as pressure gradients under cuffs increase, and as tourniquet time increases are well established. To a large extent, this is addressed in surgical practice by minimizing tourniquet time, by new technology that helps to minimize the tourniquet pressures that are required, and by new types of pneumatic tourniquet cuffs that help to minimize cuff pressure levels and gradients. Given the increasing rate of obesity, new designs of tourniquet cuffs that allow arterial blood flow to be stopped effectively at the lowest possible tourniquet pressures and gradients may be helpful for the increasing numbers of obese patients. Additionally, recent studies suggest that in the future it may be feasible to further reduce the risk of neurological injuries by directly monitoring axonal excitability in nerves beneath tourniquet cuffs. This may allow surgical staff to be alerted promptly to potential nerve-related hazards before injury occurs.

A futuristic concept for further increasing tourniquet safety and effectiveness in orthopaedic surgery may arise from a current military project. The (U.S.) Defense Advanced Research Projects Agency (DARPA) is sponsoring the Deep Bleeder Acoustic Coagulation (DBAC) program with the goal of developing a noninvasive, automated ultrasonic system for the detection, localization, and coagulation of deep bleeding vessels that is operable by minimally trained personnel in the combat environment. A spin-off benefit of the DARPA DBAC program might be the development of low-cost ultrasonic sensor arrays that could be useful for accurately detecting, monitoring, and controlling the occlusion of arterial blood flow beneath surgical tourniquet cuffs.
In the future, to further improve tourniquet safety, efficacy, and reliability, the development and evaluation of surgical tourniquets, military tourniquets, and new pre-hospital tourniquets for both civilian and military applications will be intertwined, and an improved exchange of information about techniques, technology, and outcomes will be possible.

References


Intraoperative Monitoring

Intraoperative monitoring of tourniquet safety parameters reduces the risk of complications. During the procedure, it is important to monitor the patient's blood pressure, tourniquet pressure, and tourniquet time.

Blood Pressure

Monitor the patient's blood pressure for fluctuations and relate this information to the surgeon.

Tourniquet Pressure

Adjust the tourniquet pressure at the physician's request. Monitor the cuff pressure display during surgery and immediately report any changes to the surgeon. Any sudden loss of cuff pressure intraoperatively is a cause for serious concern. If the tourniquet cuff fails for any reason, deflate it fully, and re-exsanguinate the limb before re-inflation. Re-inflation over blood-filled vasculature may lead to intravascular thrombosis.

Tourniquet Time

It is the physician's responsibility to determine when the tourniquet is to be inflated, at what pressure, for how long, and at what point in the procedure the tourniquet should be released. It is customary to prominently note the time of cuff inflation and to notify the physician after a certain time has elapsed and at pre-established intervals thereafter. Modern electronic tourniquet systems have an elapsed time display and an alarm which can be set to sound after a predetermined amount of tourniquet inflation time.

There is no clearcut rule as to how long a tourniquet may be inflated safely, although various investigators have addressed effects of ischemia on muscle and nerve to define a relatively "safe" period of tourniquet hemostasis. In practice, safe tourniquet inflation time depends greatly on the patient's anatomy, age, physical status, and the vascular supply to the extremity. Unless instructed otherwise, report to the surgeon when 60 minutes of tourniquet time has elapsed. There is general agreement that for reasonably healthy adults, 90 minutes should not be exceeded without releasing the tourniquet for a short time.

Releasing the tourniquet allows for removal of metabolic waste products from the limb and nourishment of the tissue with oxygenated blood. During this time, elevate the limb 60 degrees to encourage venous return and apply steady pressure to the incision with a sterile dressing. Tissue aeration periods should last at least 10 and preferably 15 minutes the first time and 15-20 minutes subsequently. To proceed with the surgery, re-exsanguinate the limb before reinflating the cuff. Take care during this procedure to maintain the sterility of the operative field. No known safe limit to the number of aeration intervals during prolonged tourniquet time has been established.

Deflating the Tourniquet

At the surgeon's request, deflate the tourniquet cuff by taking the following steps:

1. Apply pressure dressings over the incision to protect the wound from blood resurgence. Ideally, the final bandage is applied and pressure is exerted over the incision prior to tourniquet cuff deflation, to prevent blood resurgence. Sometimes, however, the tourniquet is deflated before incisional closure in order to better identify and control bleeding.
2. If necessary to prevent blood resurgence, elevate the limb 45-60 degrees. Transient pain upon tourniquet release can also be lessened by elevating the limb.
3. Deflate the tourniquet cuff rapidly to establish immediate venous return and prevent engorgement.
4. Record the time of deflation.
5. Immediately remove the deflated cuff and any underlying limb protection following cuff
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though the application time was relatively short (ie, 45 minutes), alarms are necessary to warn about conditions that may cause patient harm.\textsuperscript{106,110}

Recommendation V

Tourniquet inflation time and patient condition should be monitored while the tourniquet cuff is inflated.

Tourniquet inflation time has a direct correlation to tourniquet-related complications (ie, increased inflation time increases the risk for injury). The patient's systemic response to ischemia is dependent on both tissue type and tourniquet time.\textsuperscript{20} While cardiac muscle has a higher demand for oxygen, skeletal muscle is considered highly susceptible to ischemia.\textsuperscript{106,107} This is because of the higher volumes of skeletal muscle mass releasing toxic substances into the circulatory system when reperfusion occurs, which can then lead to a severe inflammatory response.\textsuperscript{107,108} Excessive tourniquet inflation time (ie, two to three hours) may result in metabolic changes: muscle damage; impaired pulmonary, hepatic, or renal function; neurological complications; or pain.\textsuperscript{106-112}

To determine the efficacy and safety of distally placed pneumatic tourniquets, researchers initiated a retrospective study to review 3,027 procedures during which the surgeons used ankle tourniquets. Following a chart review, the researchers determined that the duration of ankle ischemia was as short as four minutes to as long as 139 minutes. Tourniquet failure was reported in 50 cases. Clinically, five complications were determined (ie, three post-tourniquet syndrome, one sickle cell-related problem, one DVT) and all eventually resolved. Based on the study, the authors concluded that an upper limit of two hours resulted in fewer complications.\textsuperscript{22}

In a prospective study of awake patients, researchers investigated tolerance of intraoperative tourniquet pain. The study was designed to include 1,000 patients undergoing elective foot surgery with a local block, but 12 patients were excluded because the surgeon chose not to use a tourniquet. This left a sample size of 988 patients. The researchers found that 31 patients (3.1\%) expressed pain during the procedure and eight of those experienced symptoms (eg, breakthrough bleeding from reduced tourniquet pressure, oversedation, excessive restlessness) that required the surgeon to interrupt the procedure. Of those eight patients, the anesthesia professional converted four patients to general anesthesia. The maximum tourniquet inflation time was 90 minutes (ie, range two to 90 minutes, median 18 minutes). The researchers concluded that for foot procedures with local blocks and ankle tourniquets, a tourniquet time of up to 90 minutes is tolerated by patients younger than 70 years of age, but 1\% of the patients will report pain for each 11 minutes beyond 30 minutes. They recommended caution when administering local anesthesia to patients older than 70 years, especially if the tourniquet inflation time is expected to be longer than 30 minutes.\textsuperscript{24}

In a retrospective review of more than 1,000 patients who had total knee arthroplasties (ie, primary and revision knee replacements), researchers set out to identify risk factors that contribute to neurological complications. All patients had tourniquet times greater than 120 minutes. The researchers reported that 90 patients (7.7\%) experienced 129 peroneal and/or tibial nerve palsy. They concluded that extended tourniquet times, the patient's age (ie, postoperative neurological dysfunction was associated with younger age), and the presence of preoperative flexion contractions were contributing factors to neurological complications. The authors also reported that total tourniquet time and a reperfusion interval only modestly decreased the risk of nerve injuries.\textsuperscript{111}

Twenty-six patients undergoing arthroscopic anterior cruciate ligament repairs participated in a prospective open randomized study that compared metabolic effects of using wide, curved tourniquet cuffs at a pressure of 250 mm Hg in one group and narrow, straight cuffs at a pressure of 350 mm Hg in the other. The researchers reported a significant correlation between femoral vein lactate levels and tourniquet time. They found the test parameters for measuring muscle injuries and anaerobic metabolism were the same between the two groups for the first hour of tourniquet inflation, but the metabolic changes increased as the tourniquet time increased.\textsuperscript{112}

V.a. Pneumatic tourniquet inflation time should be kept to a minimum. [Likely to be Effective]

Even with relatively short tourniquet inflation times (ie, 26 minutes to eight minutes), researchers have found significant markers of systemic inflammatory response when they were measured 15 minutes after tourniquet deflation.\textsuperscript{26} Inflation times of 60 minutes for an upper extremity and 90 minutes for a lower extremity have been identified as a general guideline for inflation duration.\textsuperscript{22} However, some sources indicate that two hours is a safe time limit for tourniquet inflation.\textsuperscript{26,29} In pediatric patients, inflation times of less than 75 minutes for lower extremities has been recommended.\textsuperscript{113}

Irreversible skeletal muscle damage is thought to begin after three hours of ischemia and is extensive at six hours.\textsuperscript{115} Allowing intermittent reperfusion restores oxygenation and releases toxins.\textsuperscript{115} Deflating the tourniquet every two hours with at least a 10-minute reperfusion time has been identified as a strategy to consider to decrease the risk for tissue damage.\textsuperscript{18} Another approach is to release the tourniquet after 90 minutes for at least 10 to 15 minutes for the first reperfusion period, then 15 to 20 minutes for each subsequent reperfusion period.\textsuperscript{116} However, it has also been reported that implementing reperfusion periods after 60 to 90 minutes of ischemia can contribute to muscle injury.\textsuperscript{22}
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rabbits with damage to skeletal muscle after reperfusion for one hour, following four hours of ischaemia with pneumatic tourniquets on a hind limb.\textsuperscript{10} There was a considerable amount of ultrastructural damage to the anterior tibial muscles accompanied by a rise in circulating creatine kinase activity.

Pretreatment of animals with depot methylprednisolone by a single 8-mg intramuscular injection led to preservation of the structure of tibialis anterior on both light and electron microscopy. High-dose, continuous intravenous infusion with ascorbic acid (80 mg/h) throughout the period of ischaemia and reperfusion also preserved the structure of the muscle. Allopurinol in various doses had no effect.

These findings are fully compatible with a mechanism of ischaemia–reperfusion-induced injury, involving generation of oxygen radicals and neutrophil sequestration and activation. The findings indicate that damage to human skeletal muscle caused by prolonged use of a tourniquet is likely to be reduced by simple pharmacological intervention.

3.3.2 Physical Modification

The practice of using breathing periods represents an attempt to reduce ischaemic injury. This involves releasing the tourniquet after a set period of ischaemia to allow reperfusion, with the aim of returning tissue to its pre-ischaemic state, before subjecting the limb to a further period of ischaemia. Several studies have defined the appropriate breathing periods for the time ischaemia is required.

Newman, on the basis of studies in rats with nuclear magnetic resonance (NMR) spectroscopy, suggested that the biochemical determinant of the speed of recovery after the release of the tourniquet was the level of ATP.\textsuperscript{10} Rapid recovery always occurred in the presence of ATP but not in its absence. He found that hourly ten-minute breather periods prevented the depletion of ATP, and hence during three hours of ischaemia the metabolic demands for chemical energy were met. If the interval was only five minutes, this did not prevent ATP depletion and in addition to causing a deterioration of tissue pH did not shorten the recovery time. Pedowitz, using technetium uptake, found in a rabbit model that with a tourniquet time of four hours, skeletal muscle injury beneath the cuff was reduced significantly by hourly ten-minute reperfusion intervals.\textsuperscript{11} He noted that a ten-minute reperfusion period after a two-hour tourniquet tended to exacerbate muscle injury. Reperfusion intervals could prolong the duration of anaesthesia, increase blood loss, or produce haemorrhagic staining and oedema.\textsuperscript{12} Nevertheless, Sapeg and colleagues recommended on the basis of studies on dogs that ischaemic injury to muscle can be minimised by limiting the initial period of tourniquet time to 1.5 hours.\textsuperscript{13} Release of the tourniquet for five minutes permitted a further period of 1.5 hours. With knowledge of the ischaemia–reperfusion syndrome, the use of breathing periods is not logical, as reperfusion is now recognised as a major cause of damage to limbs after ischaemia. Further damage by free-radical-mediated mechanisms is likely even after the biochemistry of the venous blood returns to normal equilibrium. Work in animals has suggested that allowing reperfusion may actually increase the amount of damage to the ischaemic limb in certain structures.\textsuperscript{14}