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Current Concepts Review

Surgical Tourniquets in Orthopaedics

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- Higher levels of tourniquet pressure and higher pressure gradients beneath tourniquet cuffs are associated with a higher risk of nerve-related injury.
- Measurement of limb occlusion pressure can help to minimize tourniquet pressure levels and pressure gradients for individual patients and individual surgical procedures.
- Selective use of pneumatic, wider, and contoured tourniquet cuffs reduces tourniquet pressure levels and the applied pressure gradients.

The modern pneumatic tourniquet traces its roots to the time of the Roman Empire (199 BCE-500 CE), when non-pneumatic bronze-and-leather devices (Fig. 1) were used to control bleeding from limb amputations during war. The goal was to save a life without regard for the limb. The term "tourniquet," coined by Jean Louis Petit, is a derivation of the French verb "tourner," meaning to turn. Petit described a new screw-like device that tightened a belt to stop arterial blood flow[1].

With the advent of general anesthesia, Joseph Lister was the first to use a tourniquet to create a bloodless surgical field[2], in 1864. At the end of the nineteenth century, Friedrich von Esmarch advanced tourniquet design by devising a flat rubber bandage for exsanguination and to stop blood flow[3]. In 1904, Harvey Cushing introduced the first inflatable (pneumatic) tourniquet, thereby permitting tourniquet pressure to be monitored and manually controlled[4,5].

Elements of Modern Pneumatic Tourniquet Systems

Within the last thirty years, there have been important improvements in the technology of tourniquet instruments and tourniquet cuffs. The resulting improved safety, efficacy, and reliability allowed the U.S. Food and Drug Administration to classify pneumatic tourniquets as Class-I medical devices (indicating that they present minimal harm to the user and do not present a reasonable source of injury through normal use). Pneumatic tourniquets are used in an estimated 15,000 orthopaedic and non-orthopaedic surgical procedures daily in the United States and elsewhere, facilitating operations by reliably establishing a bloodless surgical field with a high level of safety[6].

The modern microcomputer-based tourniquet system was invented in 1981 by one of us (J.A.McE.)[7]. The elements of that first automatic tourniquet system are depicted in Figure 2. A microcomputer-controlled pressure regulator typically maintains cuff pressure within 1% of the set pressure, allowing lower tourniquet pressures to be safely and reliably used, and an automatic timer provides an accurate record of tourniquet inflation time. Audiovisual alarms are often included to prompt the operator if hazardously high or low cuff pressures are present. Automatic detection and monitoring of potentially hazardous air leakage from pressurized tourniquet cuffs is often included, and self-test capabilities are typically included to provide automatic checks of calibration, audiovisual alarms, and hardware and software integrity at each start-up of the tourniquet instrument. A backup power source is often included to allow such instruments to continue to operate normally during an unanticipated power interruption.

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Also shown in Figure 2 are additional safety features of the most modern tourniquet systems[8]. These include a cuff hazard interlock to prevent a user from inadvertently powering off a tourniquet instrument while the cuff is still inflated and an intravenous regional anesthesia safety interlock to help prevent a user from inadvertently deflating the wrong cuff during intravenous regional (Bier block) anesthesia and during bilateral limb procedures by requiring a separate confirming user action. Most modern tourniquet systems now include automated estimation of the limb occlusion pressure of each patient, permitting individualized setting of safer tourniquet pressures as described below. To facilitate measurement of limb occlusion pressure and the adaptation of tourniquet operation during surgery, some modern tourniquet systems include a provision for connection of the tourniquet instrument to physiologic monitors.

Tourniquet-Related Nerve Injuries: History and Pathogenesis

The complications and relative contraindications of tourniquet use have been well described and summarized by others[5,9,10]. However, the risk of tourniquet-related nerve injury remains a particular concern. In an early study, before the introduction of automatic tourniquet systems and before the routine use of lower tourniquet pressures, electromyographic evidence of peripheral nerve injury was found in a high percentage of limbs after tourniquet use[11]. In prospective randomized studies conducted in the 1980s, when mechanical tourniquets and higher tourniquet pressures were in common use, there was evidence of denervation in 71% (seventeen) of twenty-four patients after lower-extremity tourniquet use[12] and in 77% (twenty-four) of thirty-one patients after upper-extremity tourniquet use[13]. The prevalence of electromyographic abnormalities was reported to increase with tourniquet time, and evidence of denervation typically lasted from two to six months. Electromyographic abnormalities correlated with impaired postoperative function and delayed recovery, suggesting that tourniquet-induced neuropathy played a causal role in impaired rehabilitation[14].

On the basis of a questionnaire survey in Norway, the incidence of neurological complications associated with tourniquet use was estimated to be one per 6155 applications to the upper limb and one per 3752 applications to the lower limb[15]. Other estimates have varied, and it has been suggested that the actual incidence of so-called tourniquet paresis may be underreported[7,16]. Such nerve injuries range from a mild transient loss of function to permanent, irreversible damage and are a potential source of litigation. To minimize risk and potential litigation, an understanding of both the mechanism of injuries and possible preventive measures is important. Ochoa et al.[17-19] showed that most cases of nerve damage were limited to the portion of the nerve beneath and near the edges of the cuff. They found that compressive neurapraxia rather than ischemic neuropathy or muscle damage was the underlying cause of tourniquet paralysis and demonstrated that compression of the large myelinated fibers involves a displacement of the node of Ranvier from its usual position under the Schwann-cell junction. This was accompanied by stretching of the paranodal myelin on one side of the node and invagination of the paranodal myelin on the other. The nodal axolemma was sometimes identified as far as 300 μm from its original position under the Schwann-cell junction, causing partial or complete rupture of the stretched paranodal myelin (Fig. 3). The nodal displacement was maximal under the edges of the cuff, where

Fig. 1

A thigh tourniquet used by the Romans to control bleeding, especially after traumatic amputations. The tourniquet is made of bronze with engraved patterns and is covered with leather to help protect the patient's thigh and reduce pain[58]. (Printed with permission of Science and Society Picture Library. http://www.scienceandsociety.co.uk/.)

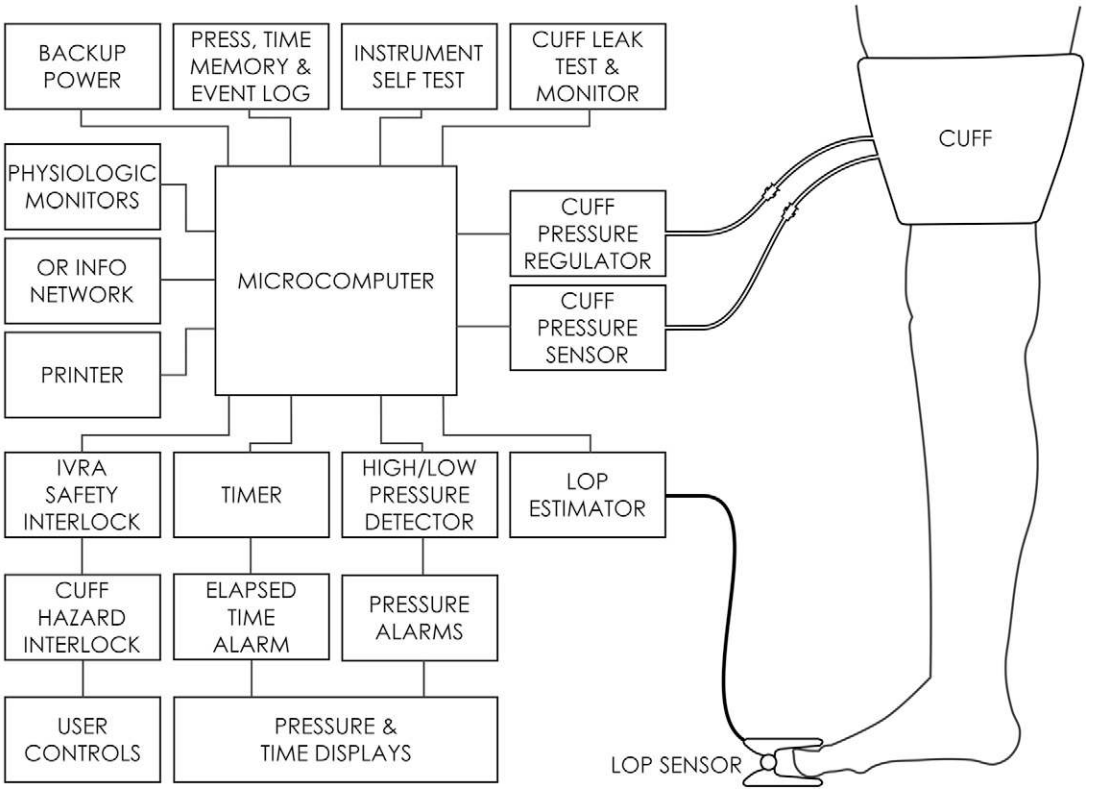

Fig. 2

Modern tourniquet system with elements that have improved safety, accuracy, and reliability[8]. Microprocessor technology allows precise sensing and regulation of the actual cuff pressure, enables accurate indications of cuff pressure and elapsed time to be provided visually, produces audiovisual alarms automatically in the event of a wide range of hazardous conditions, and allows automatic estimation of limb occlusion pressure (LOP). Improved cuff designs allow cuff pressure to be applied effectively to encircled limbs with a wide range of sizes and shapes[24-27,41,42]. IVRA = intravenous regional anesthesia, OR = operating room.

the applied pressure gradient was greatest. There was relative or complete sparing under the center of the cuff, and the direction of displacement was away from the cuff toward the uncompressed tissue.

Tourniquet Cuff Design

The actual levels of pressure applied by a pneumatic tourniquet cuff to the underlying limb and soft tissues vary widely in comparison with the pneumatic inflation pressure within the tourniquet cuff. McLaren and Rorabeck[20] measured the distribution of tissue pressures under pneumatic tourniquets in canine limbs. The peak pressure, which was 97% of the cuff inflation pressure, was in the subcutaneous tissue just proximal to the midposition along the tourniquet width. Tissue pressures decreased progressively as they became closer to the cuff edges, with a decrease of about 90% from the midpoint of the cuff width to the cuff edge. Pressures were lower in deeper tissues as well, but the decrease from the limb surface to the center was only about 2%. At the midpoint of the cuff width, surface tissue pressure was 95% of the cuff inflation pressure. Shaw and Murray[21] also showed a decrease in tissue pressure with increasing depth, midway along the width of a cylindrical pneumatic tourniquet cuff on the lower extremities of human cadavers. They noted that the pressure measured in the soft tissue was consistently lower than the pneumatic pressure in the tourniquet cuff and that the level of tissue pressure varied inversely with the thigh circumference. All such studies suggest that higher tourniquet inflation pressures and higher applied pressure gradients on the limb surface correspond to higher pressures and higher pressure gradients in the underlying soft tissues.

The distribution of perineural pressures under the cuff is described by a parabolic curve (Fig. 4), with peak levels at the midpoint of the cuff and much lower pressures at the proximal and distal edges[22]. The difference between soft-tissue pressures at the cuff midpoint and those at the cuff edges increases at higher levels of cuff inflation, establishing a direct relationship between the level of the cuff inflation pressure and the pressure gradient in the underlying soft tissue. There is an inverse relationship between limb occlusion pressure and the ratio of the cuff width to the limb circumference[23]. This relationship is shown in Figure 4, indicating that, for a given limb circumference, a narrower cuff requires a much higher tourniquet pressure to stop blood flow (higher limb occlusion pressure). This is associated with higher applied pressure gradients and

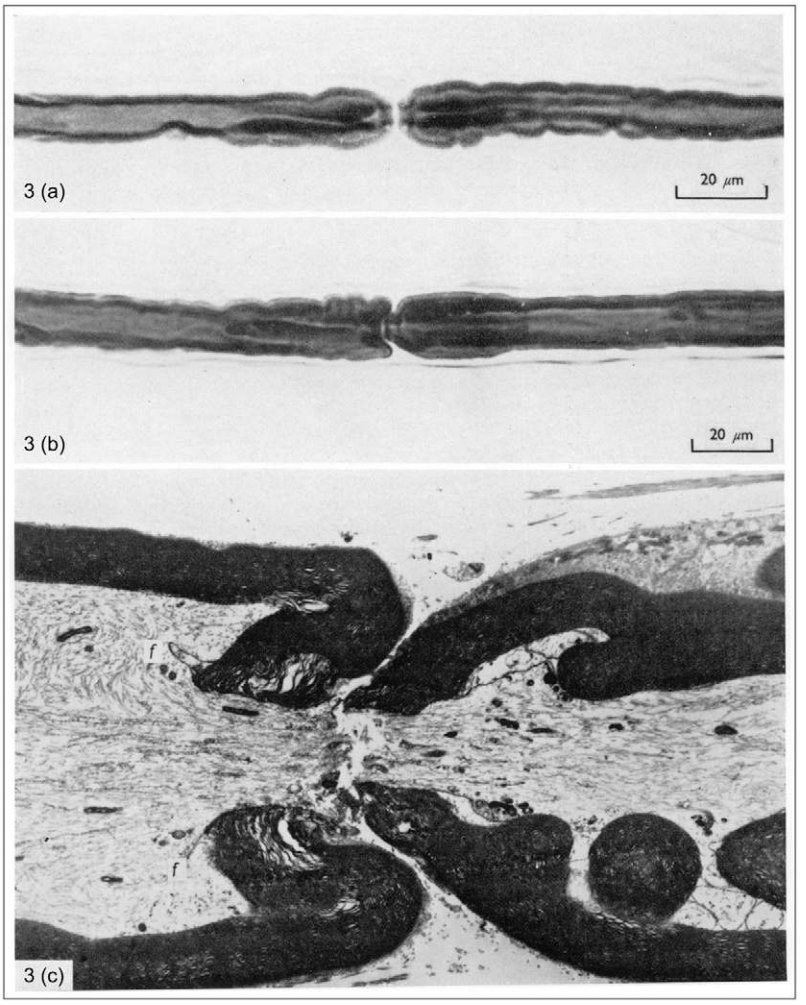

Fig. 3

a: A normal node of Ranvier of a nerve in a limb, showing a nodal gap 1 to 2 μm in width. *b:* An abnormal node of Ranvier four days after compression of the limb and nerve by a tourniquet cuff. *c:* A low-power electron micrograph of the node shown in *b*[18]. This nodal lesion is followed by breakdown of the paranodal myelin. Repair may be delayed by intramyelin and periaxonal edema, resulting in localized swelling found in diminishing amounts for several months and possibly responsible for a delay in functional recovery. (Reprinted, with permission of Blackwell Publishing Ltd., from: Ochoa J, Fowler TJ, Gilliatt RW. Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet. J Anat. 1972;113 (pt 3):433-55.)

a greater risk of neurological injury. Conversely, for the same limb circumference, a wider cuff requires a lower tourniquet pressure to stop blood flow. Additionally, a contoured tourniquet cuff occludes blood flow at a lower inflation pressure than does a straight (cylindrical) cuff of equivalent width[24,25]. This may be attributable to a better fit of the cuff to the limb and thus more efficient transmission of pressure to the underlying tissue. These facts have motivated the development and increasing use of wider, variable-contour cuffs that conform to a wide range of limb shapes, stopping blood flow at pressures that are lower than are necessary with narrower, cylindrical cuffs.

Tourniquet Limb Occlusion Pressure

Limb occlusion pressure is defined as the minimum pressure required, at a specific time by a specific tourniquet cuff applied to a specific patient's limb at a specific location, to stop the flow of arterial blood into the limb distal to the cuff. Setting tourniquet pressure on the basis of limb occlusion pressure thus minimizes the pressure and pressure gradients applied by a cuff to an underlying limb and helps to minimize the risk of nerve-related injuries. The currently established guideline for setting tourniquet pressure on the basis of limb occlusion pressure is that an additional safety margin of pressure is added to the measured limb occlusion pressure to account for physiologic

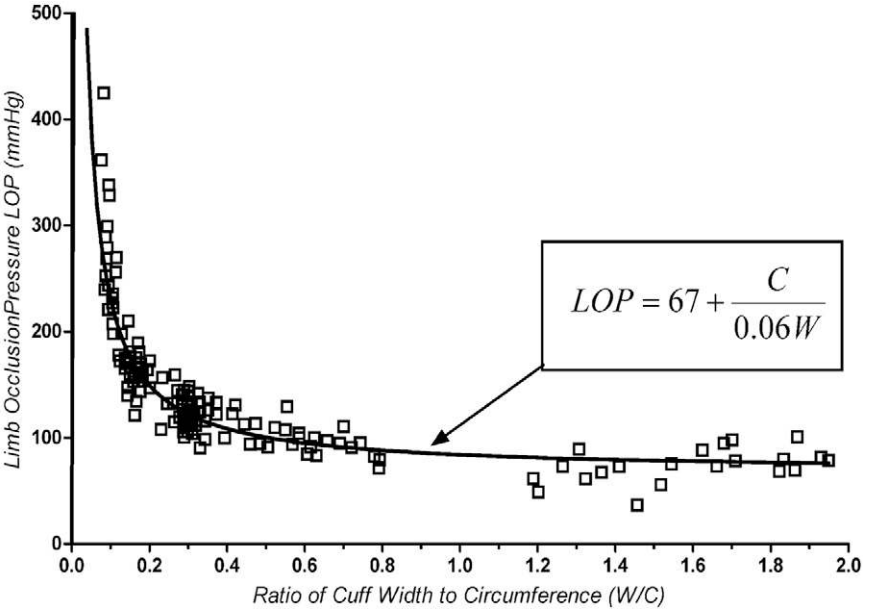

Fig. 4

Limb occlusion pressure (LOP) versus the ratio of tourniquet cuff width to limb circumference. For any given limb circumference, the tourniquet pressure required to stop arterial blood flow decreases inversely as the width of the tourniquet cuff increases. (Reproduced, with modification, from: Graham B, Breault MJ, McEwen JA, McGraw RW. 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. Reprinted with permission of Lippincott Williams and Wilkins.)

variations and other changes that may be anticipated to occur normally over the duration of a surgical procedure. Limb occlusion pressure usually is determined by gradually increasing tourniquet pressure until distal blood flow is interrupted[26]. Previous studies[23-27] have shown that cuff inflation pressures based on limb occlusion pressure measured for each patient before cuff inflation were generally lower than a predetermined generic cuff inflation pressure but were sufficient to maintain a satisfactory operative field.

Limb occlusion pressure inherently accounts for variables such as systolic blood pressure, tourniquet cuff design, cuff application method, limb circumference and shape, and tissue characteristics at the cuff site. Some advanced surgical tourniquet systems include means with which to measure limb occlusion pressure automatically. After limb occlusion pressure is measured, tourniquet pressure is typically set by adding to the limb occlusion pressure an additional pressure safety margin that is selected to be greater than the magnitude of any increase in limb occlusion pressure normally expected during the operation.

An automated plethysmographic system built into the tourniquet that measures limb occlusion pressure in about thirty seconds at the beginning of an operation was developed by one of us (J.A.McE.) and colleagues[25,27]. This system was used to determine how much the pressure could be reduced by applying a wide contoured cuff instead of a standard cuff[26]. Patients undergoing foot and ankle surgery with a thigh tourniquet were randomized into two groups of twenty patients each: one was treated with a standard cuff, and the other was treated with a wide cuff. Pressure was set at the automatically measured limb occlusion pressure plus a safety margin. The safety margin was defined as 40 mm Hg for limb occlusion pressures of <130 mm Hg, 60 mm Hg for those between 130 and 190 mm Hg, and 80 mm Hg for those of >190 mm Hg. Use of the new automated plethysmographic technique for measurement of limb occlusion pressure reduced the average thigh tourniquet pressures by 19% to 42% as compared with the typical 300 to 350 mm Hg. The standard cuff maintained an acceptable bloodless field in eighteen of the twenty patients, at an average pressure of 242 mm Hg. The wide cuff maintained an acceptable bloodless field in nineteen of the twenty patients, at an average pressure of 202 mm Hg. The final cuff pressure did not correlate with the systolic blood pressure in either the standard or the wide-cuff group, suggesting that basing cuff pressure on systolic blood pressure alone does not lead to an optimum cuff pressure. Therefore, earlier heuristic recommendations such as adding 50 to 75 mm Hg and 100 to 150 mm Hg above the systolic arm blood pressure for the tourniquet pressure during upper and lower-limb surgery, respectively[9], may not be ideal. However, recommendations for estimating arterial occlusion pressure with a formula combining systolic blood pressure and a "tissue padding coefficient"[28] also may not adequately account for all of the above-described variables that are known to affect limb occlusion pressure.

Reilly et al.[29] conducted a blinded prospective randomized controlled study of children ten to seventeen years old who were undergoing anterior cruciate ligament repair. These

patients were block randomized to either a control group treated with a standard cuff (4 in [10.2 cm] wide) and a pressure of 300 mm Hg or an experimental group treated with a wide-contour cuff (6 in [15.2 cm] wide) in conjunction with measured limb occlusion pressure. The quality of the bloodless operative field did not differ between the groups ($p = 0.053$). There was a significant difference in the mean cuff pressure between the control group (300 mm Hg) and the limb-occlusion-pressure group (151 mm Hg) ($p < 0.001$). The average limb occlusion pressure was 133 mm Hg in the control group, in which the standard cylindrical cuffs were used, and 100 mm Hg in the limb-occlusion-pressure group, in which wide contoured cuffs were used ($p = 0.01$).

In its 2009 Recommended Practices for the Use of the Pneumatic Tourniquet, the (U.S.) Association of periOperative Registered Nurses (AORN) recommended that tourniquet pressure for normal adults be set at the limb occlusion pressure, as measured with any validated method, plus a safety margin of 40 mm Hg for limb occlusion pressures of <130 mm Hg, 60 mm Hg for those of 131 to 190 mm Hg, and 80 mm Hg for those of >190 mm Hg[30]. The 2009 AORN Recommended Practices notes that adding 50 mm Hg to the measured limb occlusion pressure has been recommended for children.

Military and Surgical Tourniquets

Tourniquets are deployed in combat and in civilian emergency settings. Non-pneumatic military tourniquets are commonly used by both medical personnel and lay soldiers, and pneumatic tourniquets are commonly used in war hospitals. Both types are designed for rapid, one-handed self-application in the field. Early use of both types of military tourniquets (pneumatic and non-pneumatic) in the absence of shock has been strongly associated with the saving of lives[31]. Battlefield use is also associated with saved lives, particularly in the absence of shock, and in one study no limbs were lost as a result of use of these military tourniquets[32]. In another study of the same cohort, pneumatic military tourniquets were rated 92% effective and non-pneumatic tourniquets were rated 79% effective[33].

However, the use of non-pneumatic Petit (belt) tourniquets and Esmarch (elastic) tourniquets in non-military surgical procedures other than amputations in the nineteenth century resulted in continuing reports of permanent and temporary limb paralysis, nerve injuries, and a variety of other soft-tissue injuries[7]. This motivated the development of safer types of pneumatic tourniquets for surgery, in which applied pressures and pressure gradients could be measured, controlled, and minimized. Figure 5 shows a comparison of applied pressures and pressure gradients produced by a pneumatic surgical tourniquet cuff, by a non-pneumatic non-surgical military tourniquet designed for self-application on the battlefield, and by a non-pneumatic elastic ring designed to combine exsanguination and tourniquet functions. As can be seen in this figure, both the non-pneumatic, non-surgical military tourniquet and the non-pneumatic elastic ring tourniquet produced pressure levels and gradients that were higher than those associated with the surgical tourniquet cuff. Higher pressure levels and gradients are associated with higher probabilities of nerve injuries during operations, as described above. However, in modern warfare, the most common cause of preventable death is exsanguination from limb hemorrhage[32]. The indication for emergency tourniquet use on the battlefield is any compressible limb bleeding that the rescuer deems to be life-threatening[34]. Anatomic indications are tissue lesions with limb bleeding that could cause death, such as a midthigh gunshot wound with transection of the femoral artery. Anatomic indications are defined medically and can be confirmed during an operation. Situational indications are predicaments in which a tourniquet is chosen as the best treatment for reasons other than the lesion itself (e.g., care under fire on the battlefield[35]) and are defined and determined by rescuers. Both types of indications influence the rescuer's decision regarding when to use tourniquets instead of alternatives such as pressure dressings. Civilians may encounter both indications, but in general they are rare or uncommon in the civilian setting. In war, both indications are common and can be present simultaneously. A rescuer who rapidly controls bleeding and transports a casualty and himself or herself to safety can save two lives in war. Narrower and smaller devices of lighter weight that can be carried by and applied by the injured soldier or a close companion and that do not require electrical or battery power to regulate and minimize applied pressure may be required in such warfare situations because of their portability and ability to rapidly control hemorrhage, regardless of their association with a higher risk of nerve injuries. In these situations, careful manual monitoring of tourniquet function is essential for safety.

There have been reports of the use of non-pneumatic tourniquets, including elastic bandages, elastic rolls, and non-elastic straps similar to those used in the eighteenth and nineteenth centuries, in some non-military settings[36,37]. We stress that the uncritical use and acceptance of non-pneumatic tourniquets for extended periods, without measurement of applied pressure levels and gradients, may increase the incidence of tourniquet-related adverse events, exposing patients and surgical staff in civilian settings to unnecessary risks[6].

Limb Exsanguination and Underlying Limb Protection

External compression in addition to elevation has been shown to improve the degree of limb exsanguination at the time of tourniquet application. However, it is contraindicated for patients who have a suspected infection or malignant lesion. Use of an Esmarch bandage or hand-over-hand manual exsanguinations[38] are more effective than elevation alone[39]. Exsanguination and the use of tourniquets are both controversial in patients with sickle cell disease[39].

Olivecrona et al.[40] confirmed that an elastic stockinette under a pneumatic tourniquet cuff protected against the development of blisters during total knee arthroplasty. They randomized ninety-two patients to one of three groups. In the first group, the limb underneath the pneumatic tourniquet cuff was protected by a two-layer elastic stockinette ($n = 33$). In the second group, it was protected by cast padding ($n = 29$), and

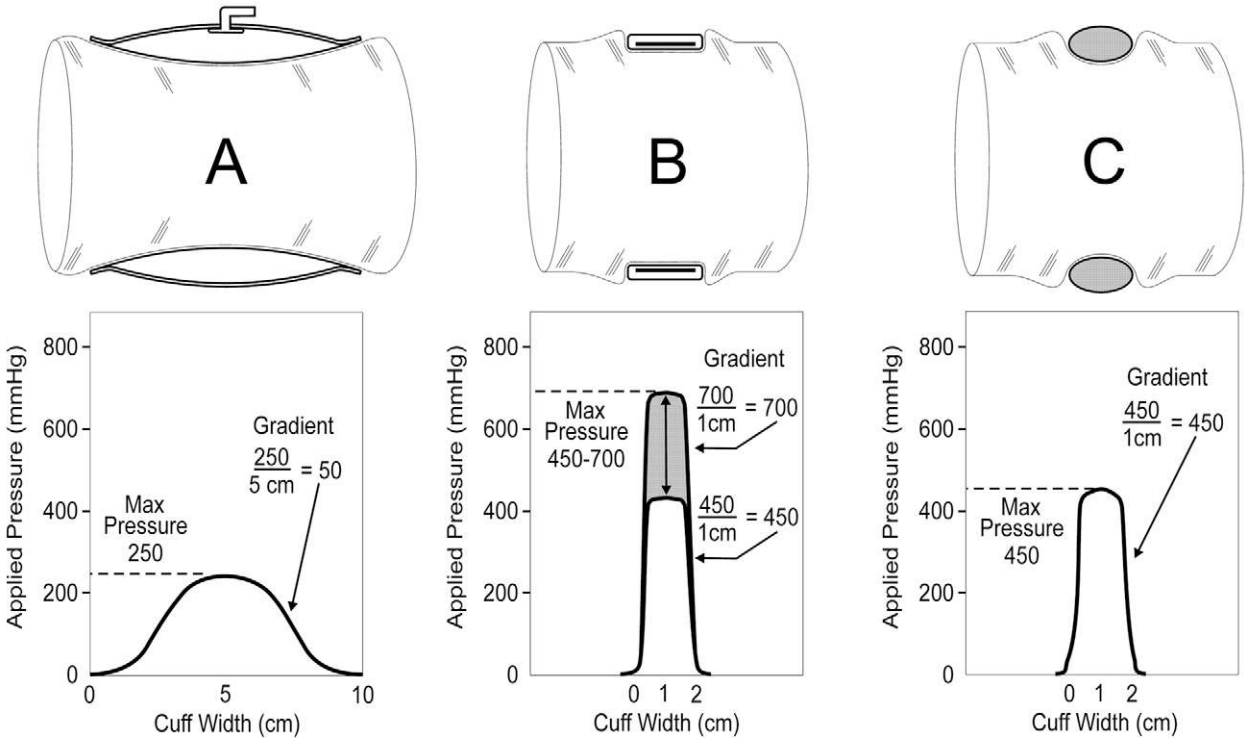

Fig. 5

A comparison of applied pressures and pressure gradients typically produced by a modern pneumatic surgical tourniquet cuff (A); a non-pneumatic, non-elastic, belt-type military tourniquet designed for self-application on the battlefield (B); and a non-pneumatic ring made of elastic material, designed to be rolled from a distal location to a proximal location on a limb and to remain there for surgery, thereby combining exsanguination and tourniquet functions (C). Each tourniquet was selected and applied as recommended by the respective manufacturer to stop arterial blood flow in an upper limb. Higher levels of pressure and higher pressure gradients are associated with higher probabilities of patient injuries[6].

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.[41] 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 $p < 0.01$)[42].

Duration of Tourniquet Use

Tourniquet-related complications increase as tourniquet time increases[43-45]. 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[39], which, on reperfusion, are eventually corrected in the systemic

circulation. Although we are not aware of any prospective randomized clinical trial that has defined the optimal duration of tourniquet use in lower-limb surgery, two hours is considered to be relatively safe for upper-limb surgery[9]. This is consistent with the findings of a study of lower-extremity surgery by Ostman et al.[46], 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[47], and time limits for subsequent ischemia are unknown. Furthermore, some authors have questioned the benefit of any tourniquet release and reinflation if the total tourniquet time does not exceed three hours[48]. 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[49]. 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[50]. 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[49]. 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, myoglobulinemia, myoglobinuria, and renal failure[9]. 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[51]. Rama et al.[52] 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[8,28,53,54].

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[55,56]. 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[57]. 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. ■

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