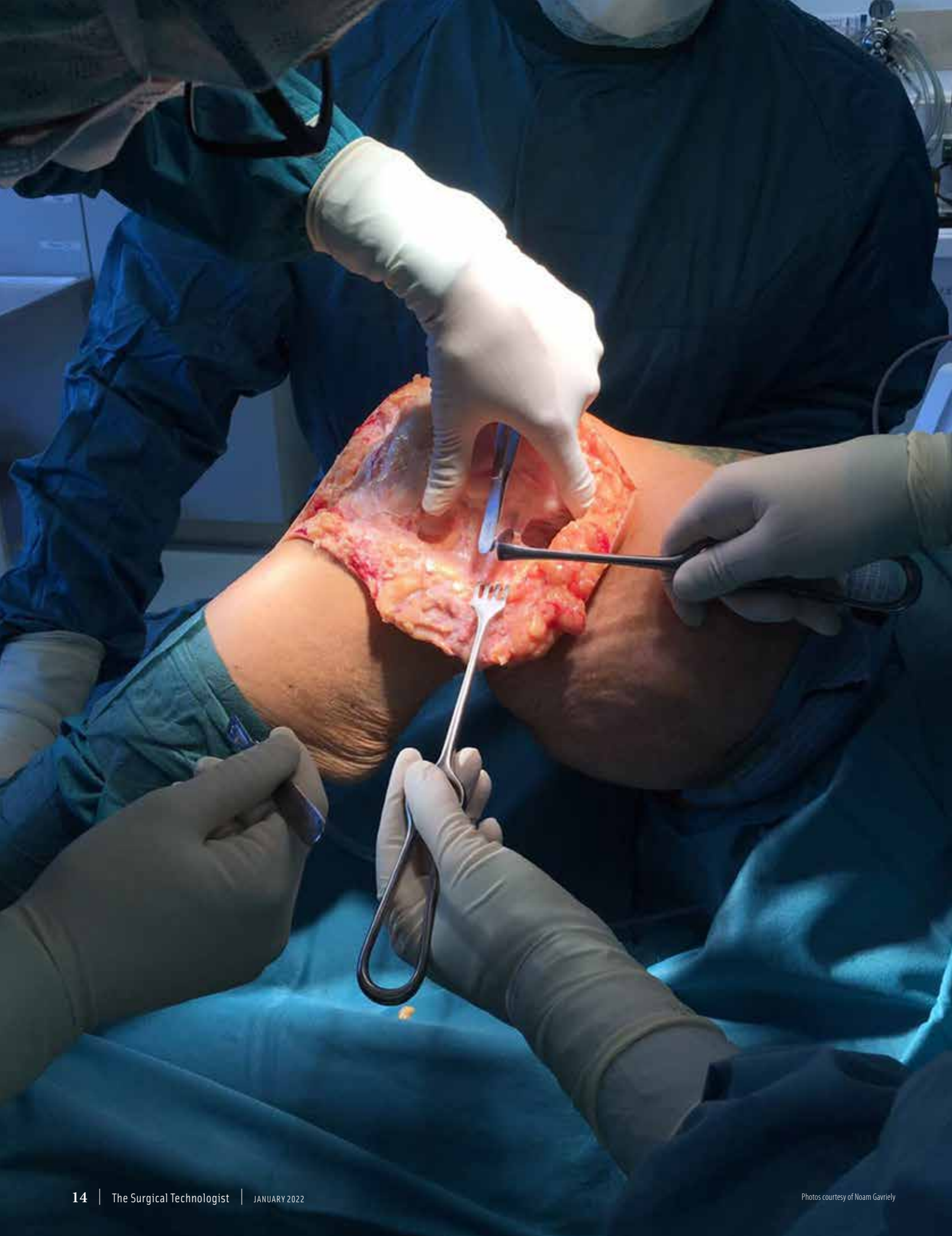

Photos courtesy of Noam Gavriely

Optimizing the Bloodless Surgical Field in Limb Surgery

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Limb surgery under a bloodless field is performed approximately 3,000,000 times a year (10,000 cases a day) in the US. The historical method of using an Esmarch bandage and a pneumatic tourniquet, first introduced in 1873 and 1904, respectively, dominates the practice, despite a high rate of adverse events and complications.

The incidence of post-operative skin injuries and blisters is reported[8] in 20.7% of TKA cases using a state-of-the-art pneumatic tourniquet. The same study reports 39.7% of patients having significant thigh pain on day 4 post-operatively and one case of nerve injury among the 160 patients. A concerning practice is the re-use of non-sterile cuffs in many of the US hospitals and ASCs that perform limb operations which likely contribute to the incidence of SSIs. An alternative safe and effective Surgical Exsanguination Tourniquet (SET) is now used in over 500 hospitals in the US with superior exsanguination, simpler OR logistics and most importantly, an impeccable patient safety track record. Multiple investigator-initiated studies published in peer-reviewed journals report no skin or nerve damage, significantly less pain, much reduced intra-operative blood loss, less SSI, less DVT and longer auto-graft harvesting for ACL reconstruction.

LEARNING OBJECTIVES

- Read about the history of bloodless limb surgery
- Explain the different tourniquet styles mentioned in this article
- Review how the pathophysiology of the skin, muscles and nerve compression are impacted by tourniquets
- Describe the importance of completely exsanguinating the limb before a tourniquet is used
- Compare and contrast patient safety with economic advantages between the two tourniquet styles

This article is intended to provide the surgical technologist the knowledge on the correct application of the SET, model selection, documentation of pressure and the contraindications as well as with the Esmarch bandage and comparison of both. The article also reviews the biomechanics and physiology of applying a tourniquet (SET or pneumatic) to a limb. The decision on which tourniquet to use is the surgeon's, but the surgical technologist should be prepared to safely assist in applying the SET if this option is requested.

HISTORY

Performing bloodless limb surgery was first described in 1873 by Johannes Friedrich August von Esmarch (1823-1908)[1] using a long bandage, now called the Esmarch bandage. Still used to date, when wrapped tightly around the limb from distal to proximal, it expels the blood from the limb into the central circulation. This procedure is called exsanguination. In its original application, the Esmarch bandage was wrapped several additional times at the proximal end of the limb to also block the return of arterial blood into the limb to act as a tourniquet. While this method is still occasionally used in ORs, it is now recognized to apply inconsistent, often excessive, pressure on the soft tissues. In 1904, Harvey Cushing, the well-known neurosurgeon who was concerned about tissue damage from the tight Esmarch bandage, first described the pneumatic tourniquet using compressed gas source.[2] Despite many shortcomings and complications,[3, 28, 29] the Esmarch bandage together with the pneumatic tourniquet are the most widely used method for achieving bloodless surgical field in the US and globally. Recently, a review of the use of pneumatic tourniquets and military tourniquets,[19] advanced the hypothesis that individualizing the cuff pressure can reduce the incidence of tourniquet-induced adverse events including nerve damage. This article aims to broaden the surgical technologist's knowledge and understanding on the newer methods of safely and effectively providing a bloodless limb surgical field for orthopedic, plastic and vascular surgeries, as well as the biomechanics and physiology of tourniquet-tissue interactions.

In recent years, more hospitals and surgical centers in the US are using a novel device that expels the blood from the limb, blocks the blood re-entry and provides a sterile surgical field in one action. The generic name of this free-standing elastic device is the Surgical Exsanguination Tourniquet (SET).[4]

THE SET AND ITS APPLICATION ON THE OPERATED LIMB

The SET is supplied sterile-packed in dual peel-back pouches. The device consists of a silicone circular ring (torus) wrapped around with an elastic tubular stockinet made from woven cotton and spandex and with straps that end with a plastic handle (Figure 1). The SET is placed on the tips of the fingers or toes while an assistant stabilizes the hand/foot. When the handles are pulled proximally along the axis of the limb, the torus rolls upon itself along the limb while the sterile stockinet unrolls on the limb.

Figure 1. *The application of the SET.*

Once the SET has been rolled up the limb to reach its final position, the straps either can be cut away or wrapped around the limb. The correct sequence of preparation for applying the SET is to first disinfect the skin to about 10 cm (4") above the anticipated final position of the ring and drape the proximal portion of the limb so that the edge of the drape is about 4-5 cm below the anticipated final ring position. After a timeout is performed and the patient is properly draped for the procedure, the SET is applied, typically by the surgeon with the help of one or two assistants.

MODEL SELECTION

There are four basic SET sizes: small, medium, large and extra large. In addition, there are two special models: Model F for the forearm and Model A for the ankle. The medium and the large SET models are available at 3 levels of tightness; the least tight models are suitable for patients with low blood pressure, ie, <130 mm Hg systolic (typically children) and the tightest models are suitable for patients whose BP may rise up to 190 mm Hg. The medium tightness is for patients whose highest anticipated systolic BP during the operation is not more than 160 mm Hg.

With each SET unit there is a small envelope with a color-coded measuring tape. Measuring the limb circumference at the site the surgeon decides to place it will immediately show which size to use. SET sizes range from 14 cm to 85 cm. The best practice is to base model selection on the ruler and sizing. If sizes overlap, it is recommended to

use the larger model. SET also is very suitable for placement on the forearm, typically 10 cm above the wrist line and on the ankle, 10-15 cm above the malleolus. This is because it does not trap the ligaments leading to the fingers/toes. If a pneumatic tourniquet is placed on the forearm or on the ankle, the ligaments cannot move and the fingers/toes are frozen. The distal placement of SET has great advantage since distal placement means less tissue is under ischemic conditions for the duration of the case.

The SET is removed by cutting the ring with a scalpel. To do so, the pointed plastic card included with each product is inserted under the ring from its distal side. The rest of the stockinet is best cut with a bandage scissors.

CASES IN WHICH SET CAN BE USED AND ITS CONTRAINDICATIONS

SET can be used in all patients for whom an Esmarch bandage and a pneumatic tourniquet can be used. To date, more than 1.5 million cases were operated on with SET globally, of which about a third were in the US. The breakdown of cases in the US is approximately 48% for leg trauma, TKA and knee arthroscopy, 37% in upper extremity, 7% in pediatric orthopedics, 5% in foot and ankle surgery and 3% in miscellaneous cases such as vascular access for dialysis shunts, plastic surgery and in ER for suturing of hand lacerations. More recently, hand surgeons have been using SET in procedure rooms and clinics for office-based minor procedures such as carpal tunnel release and trigger finger. These clinics are usually not equipped with pneumatic tourniquet pumps, so SET may be the only viable alternative for a dry field.

SET has particular benefits in cases of upper arm (elbow and humerus) surgery where the space is limited. Same is true for thigh cases (eg, ORIF of femoral fractures). SET is also preferred for TKA on obese patients (eg, BMI greater than 32) in cases of TKA revision[36] and in pediatric orthopedic cases. These categories are known to be problematic due to the taper of the thigh that often causes migration of the pneumatic tourniquet distally when it is inflated. Other cases where SET is preferred include patients with low pre-op hemoglobin, patients with bleeding disorders (eg, hemophilia) and patients with weakened immunity (eg, patients on chemotherapy, hemodialysis, steroids and patients with diabetes mellitus).

When SET is used in knee arthroscopy for ACL reconstruction, the length of hamstring autograft is significantly larger, particularly in short patients with conical thigh, where the use of allografts becomes necessary. Allografts are not needed when SET is used.[6]

Note 1: SET and patient's blood pressure. Once a particular model of SET is placed on the patient, the pressure remains constant for the entire duration of the case. There is no "upping" or "downing" of the pressure as is often done with the pneumatic tourniquet. As such, it is imperative to maintain the patient's systolic blood pressure below the designated SET maximal systolic pressure. In general, it is the anesthesia personnel who are responsible for monitoring and maintaining the blood pressure. It is, however, useful for the technical team to know the factors that cause blood pressure to rise during surgery. Pain is the most important cause of BP rise. Premature stopping of the analgesics at the (presumed) end of surgery is not helpful. Also, bringing SET up a leg quickly (i.e. in a few seconds) shifts >500 cc of blood (over 1.1 pints) from each leg to the core. This can easily cause a temporary spike of BP. "Tourniquet Pain," which is common with pneumatic tourniquet, but is not seen when SET is placed in the correct designated sites, is a well-known cause of BP rising during surgery with pneumatic tourniquet, but not with SET. Finally, taking frequent BP readings (eg, every 3-5 minutes) is the best way to notice early that BP is creeping upwards. Paying attention to these details by the entire OR team helps prevent mishaps resulting in rising BP and blood seeping under the SET ring.

CONTRAINDICATIONS AND WARNINGS

The use of SET is contraindicated in the same cases where the use of Esmarch bandage is contraindicated, namely:

1. Active deep vein thrombosis (DVT) in the operative limb; use the Wells Criteria to screen for DVT.*
2. Infection in the operated limb.
3. Cancer in the operated limb.

In addition, the use of SET is limited to 120 minutes (same as for pneumatic tourniquet and military tourniquet). It is also recommended to wrap the limb with an elastic bandage prior to applying the SET if the skin is damaged or paper-thin.

*The issue of DVT deserves special attention. The use of Esmarch bandage[20,21,23,24,25] as well as SET[22] has been associated with dislodging of a thrombus into the circulation causing fatal pulmonary embolus. As such, any patient with even a low level of DVT suspicion must be evaluated carefully using clinical examination, D-dimers, ultrasound or venography to rule out DVT before Esmarch or SET are applied. Using a pneumatic tourniquet without exsanguination is strongly discouraged.

Note 2. SET used during the cementing of an implant (eg, in TKA). Some surgeons prefer to inflate the pneumatic tourniquet only during the application and setting of the cement (with or without Esmarch bandage exsanguination). Likewise, SET can be applied only for this part of the operation. The instruments are removed, the incision is covered with a lap-pad and the SET is applied. The exsanguination guarantees dry field which improves the penetration of the cement into the cut-bone trabeculae. The SET can be cut away as soon as the surgeon feels it is time to do so.

HOW IS SET SKIN PRESSURE DETERMINED?

It is customary to document tourniquet pressure in the patient's OR/anesthesia chart. With the pneumatic tourniquet the cuff pressure is read from the pump's display, assuming that it is properly calibrated. The SET pressure is determined by measuring the limb circumference at the site of the SET ring placement and the distance from the toes/fingers to the ring. A look-up table showing the circumference versus the distance is used to determine the pressure in mm Hg. The pressure tables such as the one shown in is used to determine the exact skin pressure. The measurement of the circumference determines exactly how much the SET is stretched (expanded), and the distance from the toes/fingers tells how much of the stockinet has been removed from the ring thereby reducing the force.

BIOMECHANICS AND PHYSIOLOGY OF APPLYING A TOURNIQUET TO A LIMB

All tourniquets – including blood pressure cuffs, pneumatic tourniquet, the SET and the first aid/military tourniquets used to stop bleeding – exert pressure on the surface of the limb in order to collapse the arteries leading into it and block the inward blood flow. To do so, the pressure applied to the arteries must be greater than the systolic blood pressure over a short segment of the vessel. In normal arteries, just a few mm Hg are sufficient to collapse the artery, but if the arteries are calcified and stiff, the pressure should be much greater in order to overcome the stiffness. In some patients the arteries are so stiff that it is not possible to collapse them at all. Such arteries can usually be visualized on X-ray due to the radiopacity of the atheromatic calcifications. This X-ray finding is not a contraindication to using a tourniquet, including SET, but the surgeon must be aware of the possibility that the artery may not be occluded, and observe the color of the skin, before making the first incision.

A great deal of debate has been held over the issue of tourniquet width. When measuring blood pressure, it is recommended that the cuff needs to be wide enough to ensure that the pressure in the tissues beneath the cuff is uniform and the same as the cuff pressure. This guarantees accurate BP measurement. Unfortunately, this notion of the use of surgical tourniquets has not been proven with proper scientific evidence. In fact, biomechanical analysis of the pressures beneath wide and narrow surgical tourniquets show that it is exactly the opposite. A finite element analysis of the stresses (pressure) and strains (deformations) of tissues beneath tourniquet[5] shows the pressure field in the tissue beneath a wide pneumatic tourniquet and a narrow SET ring (Figure 2). The analysis shows that, as expected, the pressure beneath a wide pneumatic tourniquet (left panel) is uniform and high with steep gradients at the two ends of the compressed segments. On the other hand, the pressure field beneath the SET is the same at the surface of the limb (ie, skin pressure) of the pneumatic tourniquet, but it dissipates

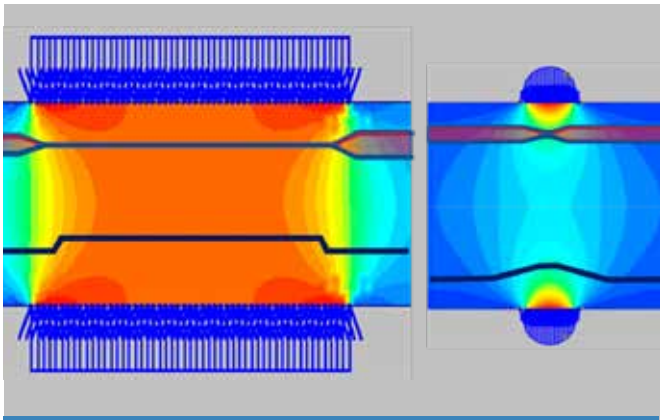


Figure 2. *Pressure fields beneath a pneumatic tourniquet (left) and SET ring (right) obtained from finite element analysis of the forces and pressures in the tissues of a limb.*

gradually as tissue is penetrated deeper (right panel). In normal BMI patients, the artery is about 1 cm deep in the upper arm and about 2.5 cm deep in the thigh. This means that higher skin pressure is needed when SET is applied to the thigh than to the arm. Similarly, in obese or very muscular patients, the artery passes deeper inside the limb and as such, higher skin pressure is required to collapse it and block the blood flow. Figure 2 also shows an artery (top) and a nerve (bottom). The artery beneath a pneumatic tourniquet is collapsed over a larger distance. The nerve is abruptly deformed at the two ends.

PATHOPHYSIOLOGY OF SKIN, MUSCLE AND NERVE COMPRESSION BY PNEUMATIC TOURNIQUET AND SET

Compressing a limb in order to block arterial flow applies pressure and deforms the tissues. This is an inevitable result of applying any tourniquet. However, when applying a wide pneumatic tourniquet, a much larger amount of tissue is compressed than is needed. The compressed tissues tend to migrate toward the distal and the proximal ends of the cuff. This is particularly detrimental when the nerves are concerned, as reported by Ochoa et al in 1973.[7]

Ochoa and co-workers applied tourniquets to baboons' limbs and noted an interesting phenomenon: the nerves that were compressed beneath the tourniquet elongated and telescoped into themselves and the Nodes of Ranvier, causing axonal disruption. Ochoa found these nerve telescoping events only proximally and distally to the cuff, and concluded that the wider the cuff, the higher the risk of nerve damage associated with pneumatic tourniquet. Ochoa also pointed to the steep pressure gradient at the two ends of the cuffs causing transverse shearing effect on the nerves, presenting another potential cause of nerve damage by the wide cuff. The rate of pneumatic-tourniquet-associated nerve damage is between 1:4000 to 1:1000 and is presenting as the leading cause of malpractice litigation in joint replacement surgery.[26] The narrow ring of the SET is not wide enough to cause nerve elongation and the gradients at its two ends are shallower, making for less of a chance for nerve damage.

Skin damage and blister formation is another adverse effect of using pneumatic tourniquet. In a study performed in Stockholm[8] it was found that despite individualization of tourniquet pressure by using LOP, 20.7% of the patients had blisters on their thigh four days after a state-of-the-art pneumatic tourniquet was used to provide a bloodless surgical field during TKA. The mechanism of these blisters is often blamed on chemical effect on the skin beneath the tourniquet cuff. However, the cause is the uneven inflation of the inner surface of the cuff, causing pinching and mechanical detachment of the epidermis and blisters.

Review of FDA depository of medical devices-related problems[27] revealed hundreds of entries related to malfunctions and injuries caused by pneumatic tourniquets. There are two SET-related Maude reports from 2011; one on skin-tear caused by dragging (pushing) the SET up an arm of a hemodialysis patient, instead of rolling it by pulling the straps; the other was a complaint on pain listed by a sales associate who trialed SET without anelgesia.

Perhaps the most concerning and common aspect of using pneumatic tourniquets is the post-operative tourniquet pain. For many patients this pain is more debilitating after surgery than the incisional pain. This is noticed in all uses of pneumatic tourniquets, and often becomes the limiting factor in early discharge of patients after TKA ("fast track"). If a patient has too much pain to ambulate to toilet and requires narcotic drugs, they may be less likely to be discharged early, adding to the cost of surgery and to patient dissatisfaction. In the same Stockholm study[8] it was found that 39.7% of post TKA patients done with the pneumatic tourniquet with individualized tourniquet pressure and curved cuff had significant thigh pain four days after surgery. Other studies done with pneumatic tourniquets have shown similar results.[28-31] Studies comparing post-op pain with pneumatic tourniquet and with SET have all shown significantly reduced post-op pain when SET was used.[30]

The pathophysiology of tourniquet pain can be understood from observing the MRI of a limb done while the subject had an inflated pneumatic tourniquet on the patient's thigh. In addition to the skin and muscle compression and displacement, it is possible to see the fascia of the muscle as a dense white line. The fascia had been deformed and stretched. Pain receptors are mostly present in the fascia. The pain sensation is conducted by the thin, poorly myelinated slow C fibers leading from the fascia to the spinal cord, leading the pain sensation to the brain. This case further illustrates the reason as to why placing tourniquets directly on major muscles is not recommended. It also explains why the use of SET is associated with less tourniquet pain (if any) when placed at the recommended positions. These positions are chosen to be over parts of the limb where there are fewer (or no) muscles and as such less fascia. The specific positions are: 10 cm above the wrist, distal to the forearm muscles groups;

on the upper arm above the biceps and below the deltoid muscle; on the ankle below the calf muscles and in the groin area very high up on the thigh, above the upper pole of the quadriceps muscle.

PHYSIOLOGY AND BIOCHEMISTRY OF TISSUE ISCHEMIA AND TISSUE COMPRESSION BY PNEUMATIC TOURNIQUET AND SET

Whenever a tourniquet is placed on a limb it intentionally causes ischemia. Unlike the heart and the brain that have very little reserves before loss of function (eg, loss of consciousness, cardiac arrest) and irreversible damage occurs, the tissues of the limbs can withstand a relatively long period with no oxygen supply. The muscle has energy reserves in the form of creatine phosphate that can rapidly release its high energy phosphate stores to create ATP directly. These stores are not large, and the cells continue to consume the dissolved oxygen until its level is too low to generate ATP from glucose or fat. At this point, anaerobic metabolism kicks in to generate ATP by glycolysis with the end products being lactic acid and pyruvic acid instead of CO2. This anerobic metabolism is less efficient than the aerobic one and the lactic acid causes acidity (reduced pH). This process continues until there is no more substrate (glucose) and at this point depletion of ATP causes cell membrane disruption and necrosis. The muscle of a fit person with normal blood supply can withstand longer periods of ischemia than in a person suffering from chronic poor blood supply such as in peripheral vascular disease (PVD). Likewise, a person with chronic lung disease may start the ischemia period with less O2 in the limb. The temperature of the limb also influences the metabolic rate. It is recommended that 120 minutes is the maximal duration of safe limb ischemia in all patients. If the case is longer, the tourniquet/SET must be removed for enough time to restore oxygen and ATP stores (typically 15-20 minutes) before ischemia is induced again. If SET is used, it needs to be completely removed and a new one placed. If a pneumatic tourniquet is used, the pressure must be completely reduced to zero to avoid venous occlusion, and excessive bleeding and swelling of the limb. Before the tourniquet pressure is restored, the limb should be exsanguinated again to the greatest extent possible. Excessive tissue hypoxia is thought to be associated with generation of reactive oxygen species[9] and limb swelling.

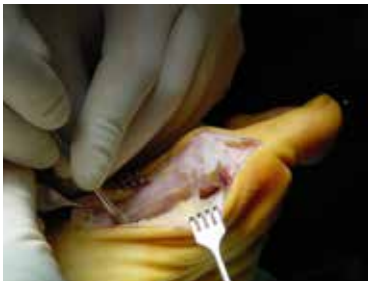
The other unavoidable effect of applying pressure to soft tissue is the compression of the tissues beneath the tourniquet. This is sort of a localized "crush injury" and its effects should be taken into consideration. When a muscle is compressed for an extended period, biochemical substances may leak from the muscle cells, either by diffusion through cell membrane or due to disruption of the cells' walls. Muscles contain enzymes and large molecules such as creatine phosphokinase (CPK), lactic dehydrogenase (LDH) and myoglobin, but also leak small molecules and ions such as potassium (K+) and lactate. One study measured nerve conduction speed with a wide vs. narrow tourniquets in normal volunteers, showing significantly slower conduction with the wide tourniquet.[11]

THE IMPORTANCE OF COMPLETE EXSANGUINATION THE LIMB BEFORE A TOURNIQUET IS USED

From early on, it was customary to empty the limb from blood as much as possible before a pneumatic tourniquet is applied. The two methods commonly used are limb elevation and tight application of Esmarch bandage from distal to proximal. Blond et al used radioactively tagged red blood cells and a gamma camera to obtain quantitative data on the quality of limb exsanguination with these methods.[12] They found that limb elevation, irrespective of elevation duration from 0.5 to 10 minutes, removed approximately 45% of the blood, while applying an Esmarch bandage removed 67% of the blood. In other words, at least half or a third of the blood remained in the limb for the duration of the tourniquet time with no flow.

However, the clinical importance of incomplete exsanguination is different. In 1979, it was shown that after 15-20 minutes stagnant blood coagulates to form soft-fresh clots.[13] In 1993, Parmet et al[35] used a transesophageal Doppler probe to track the blood flow in the right atrium, at the time a pneumatic tourniquet is deflated at the end of a primary TKA. They observed showers of echogenic material starting 15 seconds after the deflation and continuing for as long as 15 minutes in all patients. This study was repeated by multiple researchers with the same results. The debate whether the echogenic material was blood clots, bone debris, fat, air bubbles, or cement was finally settled by inserting catheters into the femoral veins and pulmonary artery of patients undergoing TKA and aspirating blood right after the tourniquet was deflated. Microscopic examination of the aspirated blood showed only fresh clots and no other types of granular material that could give echo in ultrasonic Doppler examination. The conclusion from these studies is that upon pneumatic tourniquet deflation at the end of surgery, clots migrate from the patients' leg veins to

the right atrium and from there to the pulmonary circulation causing multiple small pulmonary emboli. The physiological consequences of such interference with pulmonary blood flow is a rise in pulmonary arterial blood pressure and a drop in left ventricular output, which contribute to the drop in systemic blood pressure.



This pulmonary embolization, however, is not the worst part of this sequence. In about a quarter to a third of the population,[14] the embryonic foramen ovale is not completely fused and is only closed with a flap that acts as a one-way valve, preventing blood to pass from the left atrium to the right. However, when the pressure in the right atrium is higher than in the left, right-to-left shunting of blood occurs. If this blood contains clots, the clots will also cross over into the left heart and from there to the systemic circulation, with preference to the carotid arteries that are first to emerge from the aortic arch. It is not surprising that in 1999 Sulek et al,[15] who used transcranial Doppler to monitor blood flow in the Circle of Willis which supplies the entire cerebral circulation, found echogenic material in over 50% of the patients undergoing TKA within 20 seconds after the deflation of the tourniquet.

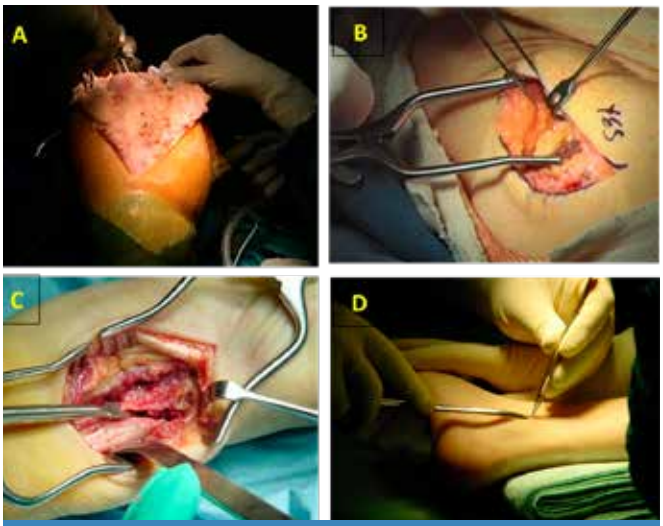


Figure 3. *Images from cases done with SET showing the level of field dryness. A – TKA in an obese patient; B – Elbow surgery in a child; C – ORIF of distal radius fracture in an elderly woman; D – Ankle ligaments lengthening in an 18 years old female CP patient.*

In yet another study, David et al[16] performed MRI studies on TKA patients, once before surgery and again two days after surgery. In five of the patients (23%), they detected cerebral infarcts in the post TKA images that were not present before surgery. Other researchers suggested that these infarcts are the cause of the well-known post-TKA Cognitive Dysfunction Syndrome.

Given the fact that limb exsanguination is 95% complete when SET is used[19] (Figure 3), with the only remaining blood being in the bone marrow, it is unlikely that intravascular clots will be formed during the period of stagnation. While there are no studies that have been performed to date on the incidence of echogenic material after SET is removed, there are also no reports of post TKA cognitive issues when SET is used.

DEFLATING PNEUMATIC TOURNIQUETS AND REMOVING SET AT THE END OF SURGERY

Stopping the blocking of arterial blood flow at the end of surgery is done by deflating the pneumatic tourniquet or by cutting the SET ring with a scalpel. Once this is done, blood returns to the empty blood vessels of the limb. In fact, more blood returns to the limb than was originally removed because of the physiological phenomenon called "reactive hyperemia." This is a normal compensatory vasodilatation of the limb blood vessels after a period of ischemia. It can easily be seen as redness of the skin which lasts from a few minutes to a half hour. If suturing and compression-dressing of the limb is delayed until after tourniquet/SET removal to facilitate meticulous hemostasis, the reactive hyperemia contributes to increased blood loss. It is imperative to deflate the tourniquet completely in order to avoid venous occlusion, which may further increase blood loss and can cause swelling of the limb, and in rare cases compartment syndrome. The removal of the pressure of SET is complete when it is cut with a scalpel.

Systemic blood pressure falls when pneumatic tourniquet is deflated and when SET is removed. This is primarily due to the return of blood from the central circulation to the limb.

SUMMARY AND CONCLUSIONS

SET is a viable safe and effective alternative to the use of pneumatic tourniquets with Esmarch bandage to provide bloodless surgical field during limb surgery. Tables 1-2 compare side-by-side the effects of using each of the methods on patient safety and on OR workflow. Table 3 summarizes the cases categories where using the SET is most advantageous.

Table 1. Patient safety and outcome advantages with SET vs. pneumatic tourniquet

Category	SET	Pneumatic Tourniquet	Comments
Sterility	Always; the ring is cut at the end of surgery	Often re-used as non-sterile	Reprocessed (sterile) pneumatic tourniquets are also available
Intra-operative blood loss	Negligible	May be as much as few hundred CC	
Intra-op tourniquet pain	None	Frequent	Causes rise in BP and need for anesthetics
Post-op tourniquet pain	Seldom	Frequent (39.7% of patients)8	SET needs to be placed on the designated positions
Use of pain medications	Less	Significantly more	
Skin damage	None	Frequent (blisters in 20.7%)8	
Long-lasting nerve damage	None	1:4000 to 1:1000	Also known as Neuropraxia
Use for upper arm surgery	The narrow ring CAN be placed high up on the arm; broader incision space	Often takes too much space, even if sterile	ORIF of humerus without tourniquet may require 1-2 pints of blood
Use for femur/thigh surgery	Easy to place SET all the way up to the groin	Often takes too much space, even if sterile	ORIF of Femur fracture often requires blood transfusion
Exsanguination	95%	45% with limb elevation, 67% with Esmarch Bandage	See text for significance
Tourniquet time	8-10% shorter than with PT		Most important in pediatrics
Tourniquet failure	Occasional, when BP rises	Happens when air leaks or pump fails	
Postop Deep Vein Thrombosis (DVT); Pulmonary Emboli (PE)	Significantly less than with pneumatic tourniquet	3-7% of patients	Mechanism of reduced DVT/PE with SET not known

Table 2. Effects of using SET on OR workflow and logistical considerations

Item	SET	Pneumatic tourniquet	Comments
Pump	Not needed	Pump needs to be bought or leased	Pump pressure must be calibrated periodically
Tubes	Not needed	Tubes need to be replaced periodically	Tubes connection to PT occasionally fails
Positioning	SET never rolls down if placed in the correct sites	Cuff often migrates distally on conical limb when inflated	Distal migration of non-sterile tourniquet requires re-draping
Space ("real estate")	SET is narrow and when placed proximally on the limb, gives optimal space and exposure	Pneumatic tourniquet is wide, limiting incision space	Important when working on the upper arm/elbow and thigh and when revision knee is performed
Mobility	SET does not trap the ligaments or the muscle beneath it, permitting full ROM of fingers, toes and knee	When pneumatic tourniquet is placed on the forearm/ankle, it splints the ligaments, limiting toes/fingers motion	Trying to forcibly flex the knee with pneumatic tourniquet at mid-thigh on the quadriceps muscle may cause muscle fibers tears.
OR air quality due to use of electrocautery	Less frequent use of cautery due to dry field;	Cautery is frequently used.	Cautery pen/forceps can be opened on demand when SET is used
Use on obese patients	XL Model readily used, never rolls distally	Often migrates distally when inflated	PT requires tech repositioning under drapes
Need for cell saver/ autotransfusion	Not needed	Often used in bilateral TKA, trauma	
Preparations for case	Single item needed for a case	Cuff, padding, stockinet, Esmarch bandage, pump setting and manning	
Cleanup after case	SET is discarded, no additional handling	Cuff reprocessing requires handling and cleaning by tech	
Pressure documentation	Requires measuring circumference and distance from toes/fingers	Read directly from pump display	
Timer	No built-in timer; needs an OR clock/timer	Timer built into pump	

Table 3. Cases of clinical importance and/or economic advantage of SET

Type of case	Clinical importance	Economic advantage
Surgery of upper arm and femur	Not enough space for PT, even if sterile, full, free ROM	No intra-operative blood loss, reduced need for transfusion
Knee arthroplasty revision	Larger operative space	Faster procedure, never need to re-do drapes
Bilateral TKA	Less blood loss; can work simultaneously on both knees	
Knee arthroscopy ACL reconstruction	Longer harvested hamstring autograft	Obviates need for allograft
Obese patient; eg, BMI>32	Optimal exsanguination, quicker procedure	Never need to re-do drapes
Pediatric cases; eg, four years old and younger	No migration of tourniquet, larger real estate, no skin injury, shorter case	
Patients with low pre-op hemoglobin; eg, Hb < 9 g%	No intra-op blood loss, reduce the need for blood transfusion	No need for cell saver or auto-transfusion20
Patients with bleeding disorders; eg, hemophilia	No intra-op blood loss, reduce the need for blood transfusion	No need for cell saver or auto-transfusion20
Patients in which blood transfusion is not possible; eg, Jehovah Witnesses, rare blood type, organ transplant candidates	No intra-op blood loss, reduce the need for blood transfusion	No need for cell saver or auto-transfusion20
Patients with immune deficiency; eg, steroids, HIV, diabetes	Lower risk of infection due to SET sterility, less need for cautery, suctioning, pulse lavage	Lower risk for Surgical Site Infection (SSI)

DISCLOSURE

Noam Gavriely is the founder, shareholder and executive of Oneg HaKarmel Ltd., manufacturer of HemaClear® Surgical Exsanguination Tourniquet.

ACKNOWLEDGEMENTS

Ana E. Puig, Certified Surgical Specialists lll, Ortho Trauma - Ortho/Neuro Spine prompted the preparation of this manuscript, read it and commented. Larry Murdock, RRT, assisted in preparing the paper and proofreading it. Both are affiliated with OHK Medical Devices Inc., the distributor of SET (HemaClear®) in USA.

REFERENCES

1. 1911 Encyclopædia Britannica/Esmarch, Johannes Friedrich August von - Wikisource, the free online library
2. Cushing, H. *Pneumatic tourniquets: with especial reference to their use in craniotomies.* Medical news; 1904. p. 577.
3. Saied, Alireza, et al. Tourniquet in Surgery of the Limbs: A Review of History, Types and Complications. *Iran Red Crescent Med J.* 2015 Feb; 17(2): e9588. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4353220/
4. Surgical Exsanguination Tourniquet (SET) www.hemaclear.com
5. Levenberg, E. The Mechanical Response of Limbs to a Tourniquet Application Part 1: Axisymmetric and Plane-Strain Analysis and Part 2: A Study of the Interaction between the Auto-Transfusion Tourniquet and a Limb. OHK Medical Press, April 2002.
6. Mehmet, Faruk; Catma M. F.; and A. Ozturk. The effect of tourniquet type and thigh conicity on the length of hamstring autograft. *J of Ortho Surg.* 2019: 26(3) 1–6.
7. Ochoa J., Fowler T. J., Gilliat R.W. *Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet.* J Anat 1972: 113(3): 433-455.
8. Olivecrona, C; Ponzer, S; Hamberg, P; Blomfeldt, R. Lower Tourniquet Cuff Pressure Reduces Postoperative

Wound Complications After Total Knee Arthroplasty - A Randomized Controlled Study of 164 Patients. *Bone Joint Surg Am*. 2012; 94:2216-21.
9. Clanton TL. Hypoxia-induced reactive oxygen species formation in skeletal muscle. *J Appl Physiol.* 102: 2379–2388. https://journals.physiology.org/doi/full/10.1152/japplphysiol.01298.2006
10. Parul Mitta*; Shweta Shenoy; Jaspal S Sandhu. Effect of different cuff widths on the motor nerve conduction of the median nerve: an experimental study. *J of Ortho Surg and Res* 2008, 3:1-6.
11. Blond L, et al. Exsanguination of lower limbs in healthy male subjects. *Acta Orthop Scand*. 2002; 73 (1):89–92.
12. Miller SH, et al. Intravascular coagulation and fibrinolysis within primate extremities during tourniquet ischemia. *Ann Surg.* 1979;190:227-230.
13. P T Hagen, D G Scholz, W D Edwards doi: 10.1016/s0025-6196(12)60336-x. Incidence and size of patent foramen ovale during the first 10 decades of life: an autopsy study of 965 normal hearts. Mayo Clinic Proc. 1984 Jan;59(1):17-20.
14. C A Sulek [1], L K Davies, F K Enneking, P A Gearen, E B Lobato. Cerebral microembolism diagnosed by transcranial Doppler during total knee arthroplasty: correlation with transesophageal echocardiography. *Anesthesiol.* 1999 Sep;91(3):672-6.
15. Peter, David. SAFE-TKR Study Group; the SAFE-TKR study group. Tourniquet use in total knee replacement surgery: a feasibility study and pilot randomised controlled trial (SAFE-TKR study). *BMJ.* Open. 2021 Jan 22;11(1).
16. Gavriely O, Nave T, Sivan S, Shabtai-Musih Y, Gavriely N. Auto Transfusion and Blood Pressure Elevation by Elastic Leg Compression in Normal Subjects. Rappaport, Technion. Haifa: Israel Institute of Technology; 2000. http://www.emergencyeed.com/ uploads/1/9/1/4/19141635/study_-_auto_transfusion_mk0036200_ compressed_2.pdf. Accessed October 20, 2013.
17. B. Borghi, E. Pignotti, M. Montebugnoli, A. Bassi, M. Corbascio, N. de Simone, K. Elmar, U. Righi, A. M. Laguardia, S. Bugamelli, F. Cataldi, R. Ranocchi, M. A. Feoli, T. Bombardini, G. Gargioni, A. G. Franchini and G. C. Caroli. Autotransfusion in major orthopedic surgery: experience with 1785 patients *Brit J of Anaesthe*. 1997; 79: 662–664 Also, http://www.aetna.com/cpb/medical/data/600_699/0639.html
18. Masri B.A., Eisen A, Duncan C.P., and James A. McEwen. Tourniquet-induced nerve compression injuries are caused by high pressure levels and gradients - a review of the evidence to guide safe surgical, pre-hospital and blood flow restriction usage. *The Surg Technol*. 2021, Vol 53 p 67-74.
19. Darmanis S, Papanikolaou A, Pavlakis D. Fatal intra-operative pulmonary embolism following application of an Esmarch bandage. *Injury.* 2002; 33(9):761-764.
20. Desai S, Prashantha PG, Torgal SV, Rao R. Fatal pulmonary embolism subsequent to the use of Esmarch bandage and tourniquet: a case report and review of literature. *Saudi J Anaesth*. 2013; 7(3):331-335.
21. Viktor Feldman, MD; Ahmad Biadsi, MD; Omer Slavin, MD; Benjamin Kish, MD; Israel Tauber, MD; Meir Nyska, MD; Yaron S. Brin, MD Pulmonary Embolism After Application of a Sterile Elastic Exsanguination Tourniquet. *Ortho.* 2015; 38(12):e1160-e1163
22. Lu, Chen-Wei MD*; Chen, Yi-Sharng MD†; Wang, Ming-Jiuh MD, PhD‡ Massive Pulmonary Embolism After Application of an Esmarch Bandage Anesthesia & Analgesia. 2004. 98(4):1187-1189.
23. M Páez , E Herrero Gento, F Buisán Garrido Rev Esp Anestesiol Reanim. Pulmonary embolism after placement of an Esmarch bandage for ankle surgery. 2003. 50(4):192-6.
24. A case of pulmonary embolism associated with pneumatic tourniquet deflation. Tsubota S, Watanabe T, Hamaura M, Miyamoto Y. Masui, *The Japanese J of Anesthe*. 2001 Mar; 50(3): 293-5.
25. Ashish Upadhyay, Sally York, William Macaulay, Brian McGrory, Jennifer Robbennolt, and B. Sonny Bal. Medical Malpractice in Hip and Knee Arthroplasty. *The J of Arthroplasty*. 2007. 22(6):2-7.
26. FDA Maude Depository of Medical Device Malfunctions and Adverse events. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfmaude/textResults.cfm
27. David Liu, FRACS,[1] David Graham, MBBS,[2] Kim Gillies, M Hlth.Sc,[3] and R. Mark Gillies, PhD[4] . Effects of Tourniquet Use on Quadriceps Function and Pain in Total Knee Arthroplasty. *Knee Surg Relat Res.* 2014 Dec; 26(4): 207–213.
28. Tourniquet pain in upper thigh. Discussion "Concerns after knee surgery." September 2017. https://bonesmart.org/forum/threads/tourniquet-pain-in-upper-thigh.5622/
29. 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 Dec;12(8):848-52.
30. Estebe JP, LeNaoures A, Chemaly L, Ecoffey C. Tourniquet pain in a volunteer study: effect of changes in cuff width and pressure. Anaesthe. 2000 Jan;55(1):21-6.
31. Sanjay Bhalchandra Londhe, Ravi Vinod Shah, Shubhankar Sanjay Londhe, Pritesh Omprakash Agrawal, Nicholas A Antao, Sushil Churhe. Comparison of local pain and tissue reaction between conventional pneumatic tourniquet and disposable silicone ring tourniquet during Total Knee Arthroplasty. J Clin Orthop Trauma. 2020 Sep 9; 15:152-155.
32. Vicente J. León-Muñoza,*, Alonso J. Lisón-Almagroa, César H. Hernández-Garcíaa, Mirian López-Lópezb Silicone ring tourniquet versus pneumatic cuff tourniquet in total knee arthroplasty surgery: A randomized comparative study. J of Orthopae. (2018) 15:545–548.
33. Ismail Demirkale, Osman Tecimel, Hakan Sesen, Kasim Kilicarslan, Murat Altay, and Metin Dogan. Nondrainage Decreases Blood Transfusion Need and Infection Rate in Bilateral Total Knee Arthroplasty. The J of Arthroplasty. 2014. 29(5):993-997.
34. J L Parmet 1, A T Berman, J C Horrow, S Harding, H Rosenberg Thromboembolism coincident with tourniquet deflation during total knee arthroplasty. Lancet. 1993. 341(8852):1057-8.
35. Ved A, Kempshall PJ, Sharma H, Morgan-Jones RL. A comparison of operative field space between sterile single use and re-useable pneumatic tourniquets in revision total knee arthroplasty. *Inter J of Orthopae Scien.* 2015. 1(1): 01-03.

Optimizing the Bloodless Surgical Field in Limb Surgery

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1. **Complete removal of blood from the limb (exsanguination) prior to occluding the blood flow is important because:**
   a. To prevent intra-vascular clotting of stagnant blood during surgery
   b. To avoid post-operative embolization of the lung and brain when the tourniquet is removed
   c. To facilitate a dry field and minimize cauterization
   d. All of the above

2. **The true statement(s) about post-operative thigh pain after TKA is:**
   a. Thigh pain is caused by stretching and deforming fascia beneath the pneumatic tourniquet
   b. Placing SET in areas where muscles and fascia are minimal help avoid post-operative pain
   c. Opiates are optimal for treating post-operative tourniquet pain
   d. Both a and b

3. **The recommended tourniquet time, irrespective of which tourniquet is used is:**
   a. 120 minutes
   b. 150 minutes
   c. 220 minutes
   d. 240 minutes

4. **Who first described the usage of a pneumatic tourniquet:**
   a. Harvey Cushing
   b. Johannes Friedrich August von Esmarch
   c. Christian Doppler
   d. None of the above

5. **Optimal placement of SET is:**
   a. By pulling the straps to the sides, perpendicular to the limb
   b. In the middle of thigh
   c. On the elbow
   d. None of the above

6. **Which statement about limb exsanguination is false?**
   a. Limb elevation removes about 45% of the blood
   b. Esmarch bandage exsanguinates 67% of the blood from the limb
   c. It is safe to inflate a pneumatic tourniquet without exsanguination
   d. Blood that remains in the limb for the duration of the case clots

7. **Contraindications for use of Esmarch and SET are:**
   a. Pre-existing deep vein thrombosis in the operated limb
   b. Infection in the operated limb
   c. Cancer in the operated limb
   d. All of the above

8. **When does right-to-left shunting of blood occur?**
   a. When blood passes from the right atrium to the left atrium
   b. When pressure in the right atrium is higher than in the left
   c. When the right atrium is higher than the left atrium
   d. When clots form in the left atrium

9. **The correct statement regarding tourniquet pressure is:**
   a. Pneumatic tourniquet applies pressure and compresses a larger volume of tissue
   b. SET skin pressure is the same as with pneumatic tourniquet, but is 30-40% lower inside the limb
   c. The pressure on the artery must be greater by at least 50-100 mm Hg to stop the blood flow
   d. It is necessary to collapse at least 5 cm of the artery in order to block the blood flow

10. **Tourniquet time should be limited to 120 minutes to:**
    a. Prevent surgeon fatigue
    b. Avoid complete depletion of all ATP in the muscle in all types of patients
    c. Be able to reuse the tourniquet another time
    d. Only b and c

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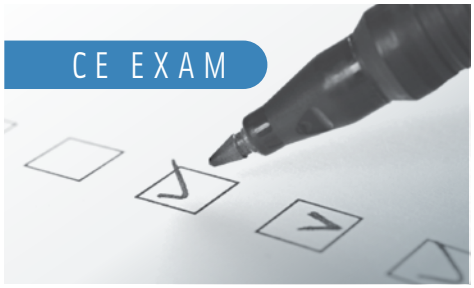

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