Understanding and Mitigating Tourniquet Risks

(Tourniquet Pain, Skin Injury and Neuropraxia can be Mitigated by Using Sterile Silicone Exsanguination Tourniquet (SET))

March 2018

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Key words

Pneumatic Tourniquet, Esmarch bandage, exsanguination tourniquet, tourniquet-pain, tourniquet-burn, tourniquet-neuropraxia

Conflicts

The authors are executives and stakeholders in Oneg HaKarmel Ltd., manufacturer and distributor of HemaClear® (www.hemaclear.com).

Abstract

The majority of limb operations are performed with a bloodless surgical field, obtained by removing the blood from the limb (exsanguination) and blocking its re-entry (tourniquet). During the past 100+ years this has been achieved by using an elastic band (Esmarch bandage) and a wide cuff Pneumatic Tourniquet. This practice is associated with frequent and sometimes severe adverse effects. A recent JBJS (Am) study in 164 patients undergoing TKA using a Pneumatic Tourniquet (Zimmer, AST 4000) in Karolinska Institute (Stockholm, Sweden (6)), 20.7% of the patients had skin injuries at the tourniquet site on the thigh, 39.6% reported thigh pain on day 4 postop and 1 patient had tourniquet paralysis. Multiple other studies report similar results.

This review article analyzes the biomechanical processes leading to these adverse effects. In particular, (a) the effects of friction and pinching of skin folds by the inflating Pneumatic Cuff, leading to skin injuries and blisters; (b) the deformations and shear forces applied by a wide cuff on the muscles and specifically on the deep fascia where the pain slow C-fibers are located; and (c) the effect of nerve elongation and telescoping at the Nodes of Ranvier, leading to axonal disruption at the distal and/or proximal edges of the wide Pneumatic Tourniquet, causing nerve damage.

The article also discusses reasons why using the narrow elastic ring exsanguination tourniquet to achieve a bloodless field has not been associated with skin or nerve damage (0 cases in >1,100,000 uses) and significantly less post-op tourniquet pain. The narrow footprint, symmetric circumferential stretching when rolled up the limb, optimized subcutaneous pressure distribution and ability to place it at sites where there is less muscle and fascia, all contribute to its vastly improved safety track record.

When patient safety is of concern, it is apparent that using the sterile elastic exsanguination tourniquet is far safer than using the wide-cuff Pneumatic Tourniquet.

Introduction

The benefits of using a tourniquet during limb surgery are often offset by their adverse effects, namely tourniquet pain, tourniquet “burn” and less frequently tourniquet neuropraxia (2). Nevertheless, the majority of orthopedic surgeons use tourniquets during limb surgery to reduce intra-operative blood loss and in order to improve operative visibility, which lead to more accurate and shorter procedures. Studies and meta-analyses on the benefits and side effects of the use of tourniquets (1) show that their use reduces intra-operative blood loss, but overall hemoglobin levels drop and transfusion rate is not different, while post-operative tourniquet pain and skin damage are not seen when a tourniquet is not used. This essay explores the available data on the mechanisms of wide Pneumatic Tourniquet adverse effects and on the enhanced safety of using a Sterile Silicone Exsanguination Tourniquet – SET (HemaClear®, Oneg HaKarmel Ltd., Tirat Carmel, Israel) in upper and lower extremities surgery.

Tourniquet Pain – (TP)

There are two kinds of tourniquet pain (TP): intra-operative and post-operative. The intra-operative TP is described as an anesthesia challenge characterized by gradually increasing arterial blood pressure and heart rate that are poorly responsive to standard analgesics and anesthesia (2, 3, 4, 5). This kind of TP typically subsides upon release of tourniquet pressure. Speculations concerning the cause of intra-operative TP implicate nerve compression and ischemia that stimulate unmyelinated C-fibers. Their action potentials are perceived as pain. It is believed that slow conduction C-fibers, which are typically less responsive to local anesthetic blockade are the source of the pain. The pain increases over the first 45-60 minutes of tourniquet inflation so that regional blocks that are normally sufficient for surgical anesthesia for the surgical incision itself are not enough to block the tourniquet pain. Additional analgesia or even general anesthesia become necessary and even with those, sympathetic responses of blood pressure and heart rate may become excessive and require premature tourniquet pressure release.

Postoperative TP

Postoperative TP is pain experienced by the patient following the operation at the site where the tourniquet was placed. When Pneumatic Tourniquet is used this pain is in the quad muscles in the leg and on the biceps in the upper arm. The following paragraph was copied from a patients group blog (8) as is (including photograph). It best depicts the symptoms in a most authentic way:

“Tourniquet pain is a consequence of lower limb surgery that is not much talked about. It's a pain that occurs in the upper thigh because of the tourniquet the surgeon uses to both restrict blood loss and make the surgical field bloodless so he can carry out the procedure with greater accuracy and speed.

The tourniquet is usually pumped up to around [three] times the patient's blood pressure - 350mg/Hg for an adult leg. If this is maintained for a couple of hours, the patient may experience a burning pain for some hours or even days after the surgery. It can range from a slightly bruised feeling to an intense burning pain which restricts movement and makes it difficult to do straight leg raises and walking.”

Figure 1 Pneumatic Tourniquet placed on a patient’s thigh (8)

Several studies that looked into the incidence of postoperative tourniquet pain (6, 7, 9, 10, 11) have been published in recent years. The most focused one is the study by Olivecrona et Al from Karolinska Institute in Sweden, published in JBJS in 2012 (6). This study’s primary outcome was the effect of tourniquet inflation pressure on postoperative tourniquet pain. Curved thigh Pneumatic Tourniquet (Zimmer) was applied on 161 patients who were divided into two groups, based on the method of pressure selection (Limb Occlusion Pressure method (LOP) and surgeon-determined pressure). The pain was assessed using a standardized questionnaire (WOMAC) on day 4 postoperatively. On that day, 20.7% of patients had developed blisters or other pressure-related injuries underneath the tourniquet cuff and 39.6% of patients reported they had pain in the quadriceps muscle beneath the tourniquet cuff. There were no differences between the two groups, (p = 0.400). All patients also received infiltration of local analgesic into the incision site at the end of the surgery by injecting it into the fascia, muscles, and subcutaneous tissue, regardless of whether they had spinal or general anesthesia. In 147 of the patients, a catheter was also inserted into the knee joint for post-op pain treatment with a local anesthetic. It was used during the day following the surgery and was then withdrawn.

This study clearly shows the discrepancy between the well-controlled incisional pain by the infiltration of long-acting local anesthetics vs. the extent of thigh muscle tourniquet pain. Other studies (7, 10, 11) also found that postoperative thigh pain was prevalent after TKA and often required parenteral narcotics (e.g. morphine).

Factors that Influence Pneumatic Tourniquet Pain and Other Adverse Effects

When compressive mechanical load is applied to a limb to block blood flow, the tissues beneath it are deformed macroscopically and microscopically. First off, the load has to be sufficient to collapse the arteries in order to stop the circulation. This means that the pressure just outside of the artery must be greater than the highest intravascular pressure, namely the systolic blood pressure. The artery must be collapsed over a length of no more than a few millimeters in order to block it. The actual complete collapsing transmural pressure on the artery is a complex function of the systolic pressure and the arterial wall thickness and flexibility (http://www.academia.edu/13977055/General_Tube_Law_for_Collapsible_Thin_and_Thick-Wall_Tubes (Kozlovsky, P., et al., General tube law for collapsible thin and thick-wall tubes. Journal of Biomechanics (2014)). The applied external pressure must overcome the systolic blood pressure, as well as the mechanical resistance to complete folding of the arterial wall at the two edges of the buckled artery (Figure 2)

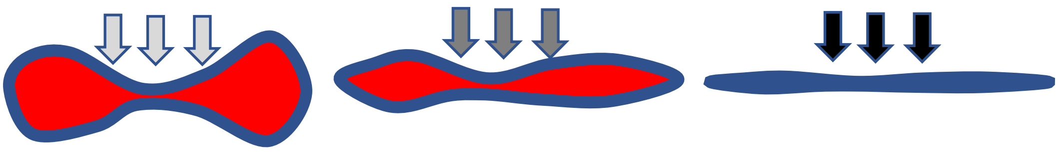


Figure 2 Left, low sub critical pressure causes partial collapse with significant side-lobes; Middle, higher pressure compresses the side-lobes, but closure is still incomplete; Right, the pressure needed to completely collapse the artery and block blood flow is somewhat higher than the systolic pressure. The extra pressure needed to completely fold the artery is small relative to the systolic blood pressure except in patients with arterial calcification and sclerosis.

To achieve the needed pressure just outside of the arterial wall the pressure applied by a tourniquet to the patient's skin should be at least as high. When a wide Pneumatic Cuff is used, such as when measuring blood pressure by the Riva Rocci sphygmomanometer the skin pressure and the internal pressure are identical. This is true also when applying a wide surgical Pneumatic Tourniquet to a limb. However, when the tourniquet is narrow relative to the limb diameter such as when a too narrow cuff is used to measure blood pressure or when the Silicone Exsanguination Tourniquet – SET (HemaClear®, Oneg HaKarmel Ltd., Tirat Carmel, Israel) is used to provide a bloodless surgical field, the tissue pressure outside the arterial wall is significantly less than the skin pressure.

When a wide Pneumatic Tourniquet cuff is applied to a limb, e.g. the thigh over the quadriceps or the upper arm over the biceps/triceps, in addition to the compression of the arteries, a large volume of soft tissue comes under stress and deformed. MRI images taken during tourniquet application (figure, 6 from Dr. Estebe Personal communication) show the deformed tissues and the extent of the deformation. Clearly the skin, subdermal tissues, the muscles and the deep fascia are deformed and displaced. The nerve(s) running along the limb are compressed and deformed as well.

The factors that play a role in this process are as follows:

1. Tourniquet skin pressure
2. The pressure field and distribution of pressure in the tissues
3. Tourniquet width which determine the volume of tissue and skin surface area beneath the tourniquet
4. Limb diameter and thickness of adipose layer

5. Duration of tourniquet application and patient-related factors (e.g. preoperative tissue oxygen storage, arterial stiffness, tissue vascularization etc.)
6. Location of tourniquet placement

The following chapters analyze the contribution of each factor to the risk of developing postoperative tourniquet pain.

Tourniquet Skin Pressure

There are many empiric clinical protocols to determine the skin pressure that will be sufficient to block the blood flow into a limb. The use of 200-250 mm Hg on the upper arm and 300-350 mm Hg for the thigh is common among surgeons and seem to work for the vast majority of patients, but may actually be excessive. Some researchers who felt that these pressure levels are too high and may be the cause of adverse effects sought to find a formula for "dialing in" tourniquet pressures that are tailored to the individual patient. They proposed using the patient's pre-operative systolic blood pressure and add a fixed value to it (e.g. 50 mm Hg for the arm and 100 mm Hg for the thigh). Another method is to determine the patient's pre-operative Limb Occlusion Pressure – LOP, which is the tourniquet pressure where pulsations in the toe/finger cease as determined by a photocell or a pulse oximeter. This value which is circa the systolic blood pressure is then used as basis for adding a fixed value. In both cases the reason for setting the tourniquet pressure higher than the pre-op systolic pressure/LOP is because blood pressure can rise during the operation. Most common reasons for this rise are (i) the shifting of blood from the limb (leg in particular) to the core during the pre-inflation limb exsanguination and (ii) surgical or tourniquet pain that is not countered sufficiently by analgesics. In a recent study (6) Olivecrona et Al suggested using 225 mm Hg as the highest tourniquet pressure in patients undergoing TKA who have a BMI not greater than 35. In a post-hoc analysis of their data they found a significantly lower rate of complications when tourniquet pressure was less than 225 mm Hg.

Pressure Distribution Inside a Limb

The origin of the Pneumatic Tourniquet is from the Riva-Rocci method of blood pressure measurement (Figure 3a) (http://en.wikipedia.org/wiki/Scipione_Riva-Rocci), or sphygmomanometer. The force applied to the soft tissues by a circumferential Pneumatic Cuff or tourniquet pressurizes and deforms the tissue. However, although the soft tissues of limbs (muscle, skin, fat) are elastic and flexible, they are not compressible. As a result, the applied forces cause elements of the tissue to move (displacement). Already in 1977, Alexander et Al calculated the pressure field within a limb model beneath a cuff and determined that in order for the pressure inside the limb at the middle of the width of a cuff to be equal to the cuff pressure throughout from the skin level to the center of the limb the cuff width must be 1.2 times larger than the diameter of the limb at the cuff site (Figure 3b). This is very important in order for blood pressure determination by the Riva-Rocci method to be accurate (red arrow). However, if the tourniquet is narrow (e.g. its width is only 0.5 (50%) of the limb diameter (green arrow), the tissue pressure at the midpoint of the tourniquet may be as low as 0.75 (75%) of the surface pressure (green arrow).

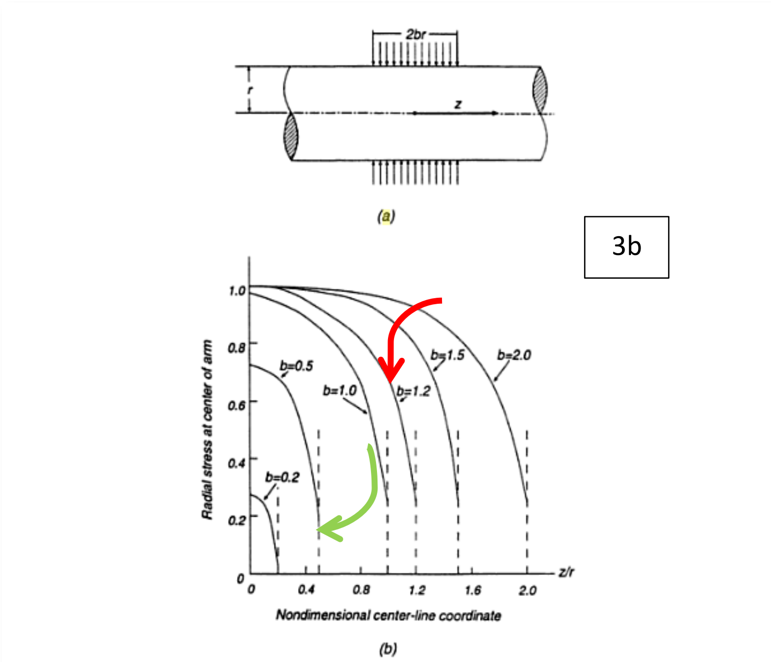


Figure 2.45 A simplified model of the arm (**A**), and calculated radial stress distribution at the arm axis (**b**). (From Alexander, H. et al., *Med. Biol. Eng. Comput.*, 15, 2, 1977. With permission.)

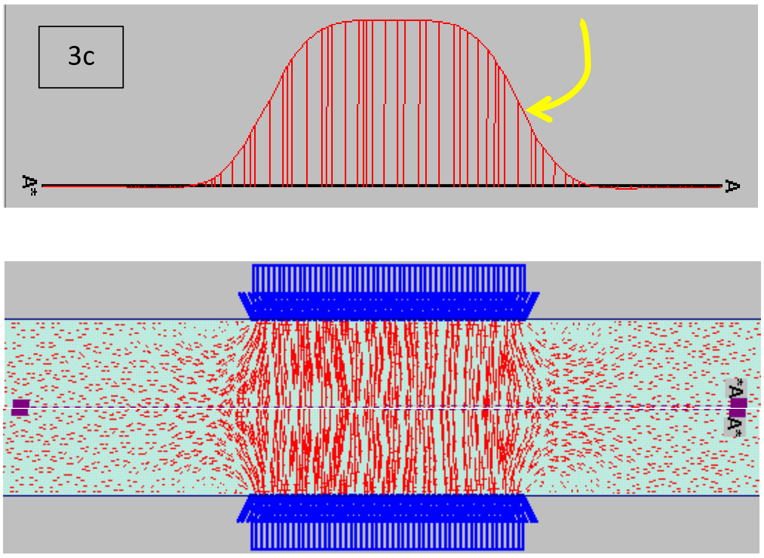


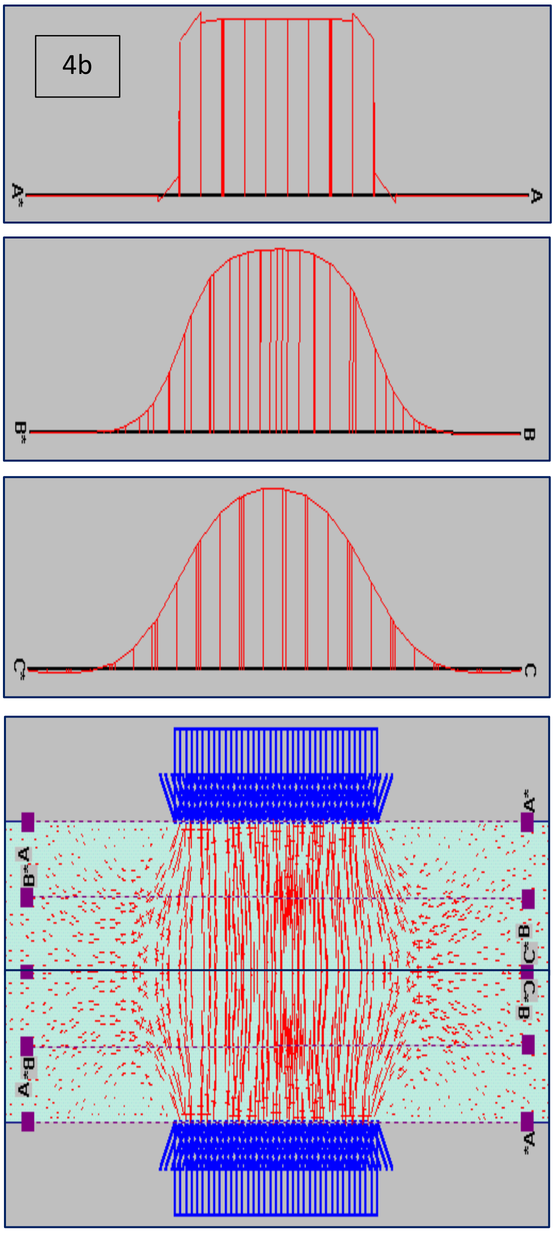
Figure 3a-c

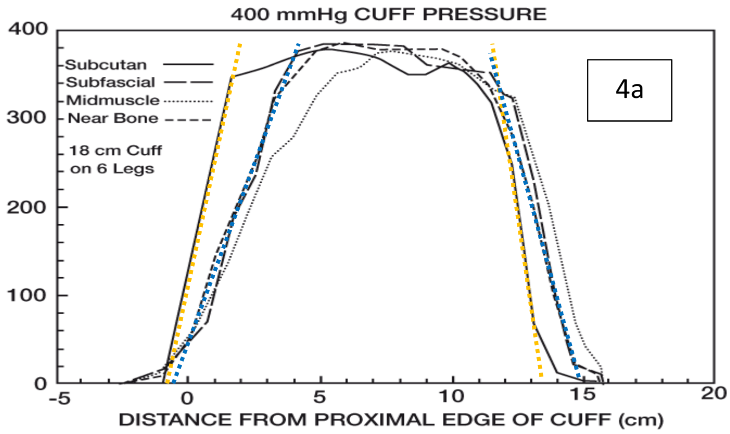
3a. Top left: blood pressure measuring device (sphygmomanometer)

3b. Top right: Calculated radial stresses in a limb at its midline from Alexander et al, Med. Biol. Eng. Comput 1977. See text for explanation.

3c. Left: Distribution of principal stresses (pressure, lower panel) and a plot of the radial stresses at the axis of symmetry (upper panel) when a wide tourniquet (width = 1.5 X limb diameter) is applied [from Levenberg E. OHK Archives 2002].

Note the rather steep gradient of pressure drop along the axis of the limb at the edges of the tourniquet (yellow arrow).



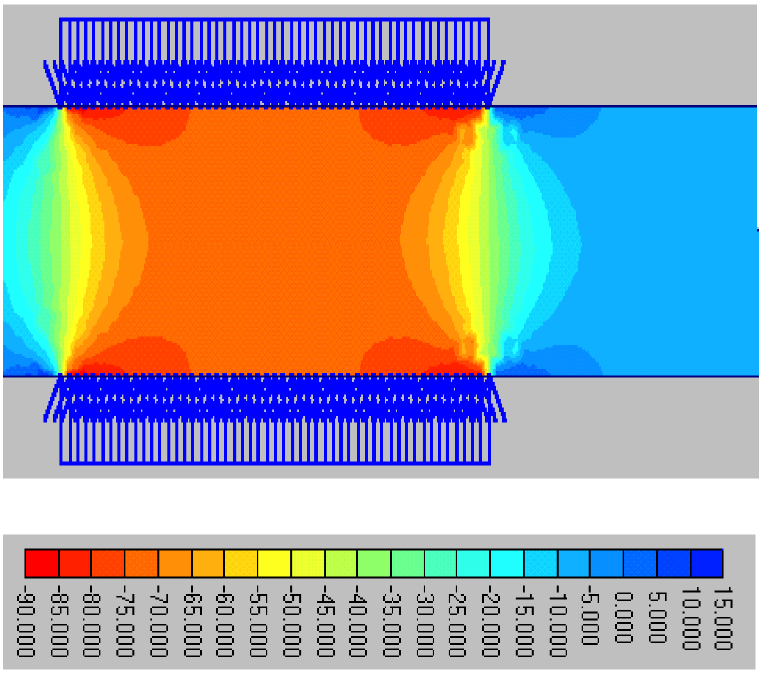


<u>**Figure 4a-b**</u>

4a. Top: Data from Crenshaw AG, Hargens AR, Gershuni DH, Rydevik B. Acta Orthop Scand 1988; 59(4): 447-451. **showing the pressures measured <u>inside</u> a cadaver limb beneath a cuff of a Pneumatic Tourniquet. The pressure profiles at four levels beneath the skin are shown. While the peak pressures in all the profiles are the same, it is possible to see that the subcutaneous profile is wider, nearly as wide as the cuff width, and the gradients at its two ends are very steep (orange dashed lines). The profiles deeper into the limb and near the bone are narrower and the gradients are less steep (blue dashed lines).**

4b. Left: Computational finite elements analysis of the same situation showing the limb model with the tourniquet (here the tourniquet width is the same as the limb diameter). Panel A is right under the cuff, panel B is half way to the midline and panel C is at the midline. Note that here also the peak pressure is nearly the same as the tourniquet pressure and that deeper into the limb the pressure gradients at the two ends become less sharp.

The similarity between the computational model results and the experimental data indicates a positive validation of the model.

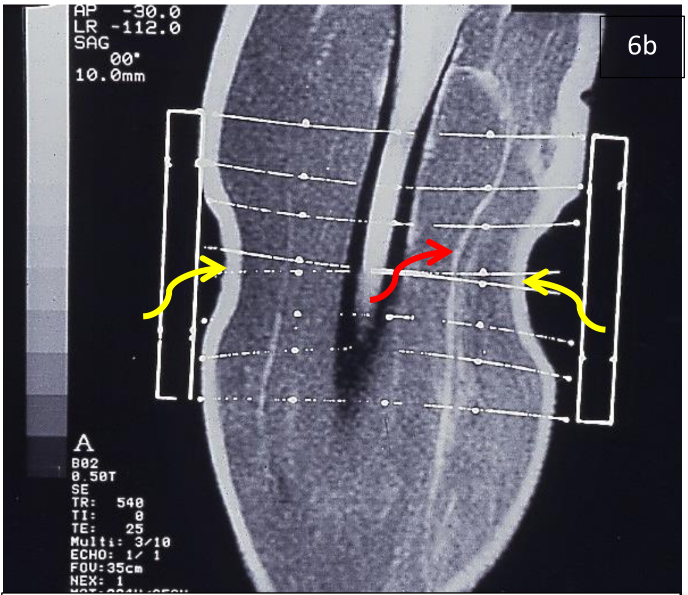


<u>Figure 5</u>

The pressure field inside the limb can also be shown as colored isobars (left). Isobars are areas where the pressure is about the same and are shown in percent of the skin pressure according to the color scale below. In this computational model of the pressures, it is possible to see that with a wide tourniquet (in this case the tourniquet width is X1.5 the limb diameter) the tissue pressure is uniform across the limb cross-section almost under the entire width of the tourniquet and is approximately equal to the tourniquet skin pressure. The gradient at the two ends of the tourniquets is steep, full scale over less than 0.5 limb diameter.

Soft Tissue Deformation Beneath a Cuff.

When a Pressure Cuff (tourniquet or sphygmomanometer) is pressurized around a limb, the soft tissues (skin, fat, muscle etc.) change their shape (deform). [Calling this deformation "compression" is incorrect since tissues, like solids and liquids are essentially incompressible materials. This is different from gases which can change their volume when pressurized and are therefore called "compressible"]. The MRI image on the right (Figure 6a) (courtesy of Prof. Estebe, Rennes, France, who had taken an MR image of his own thigh while a Pneumatic Tourniquet was inflated for 20 minutes) shows the deformation of the tissues. The cuff base is shown as two rectangles and the indentation of the skin (yellow arrows) is where the inflated bladder pushed and deformed the thigh. It is also possible to see that the muscle (gray) and the fascia (red arrow) are displaced, deformed and stretched.



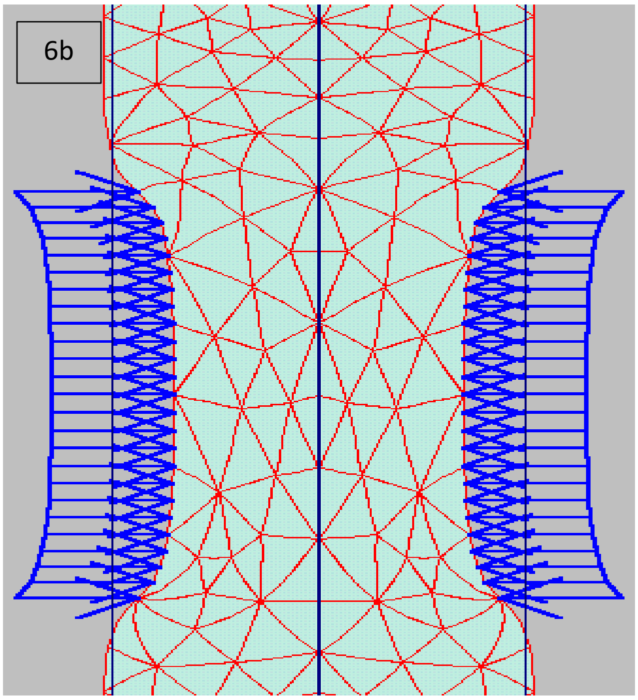


Figure 6a-b

6a. Top: MRI of the thigh under a pressurized Pneumatic Tourniquet (Estebe, personal communication, Rennes, France).

6b. Left: Computational finite elements analysis (red strings) showing the deformation (strain) of a limb under circumferential pressure by a Pneumatic Cuff. From Levenberg E. OHK Archives 2002.

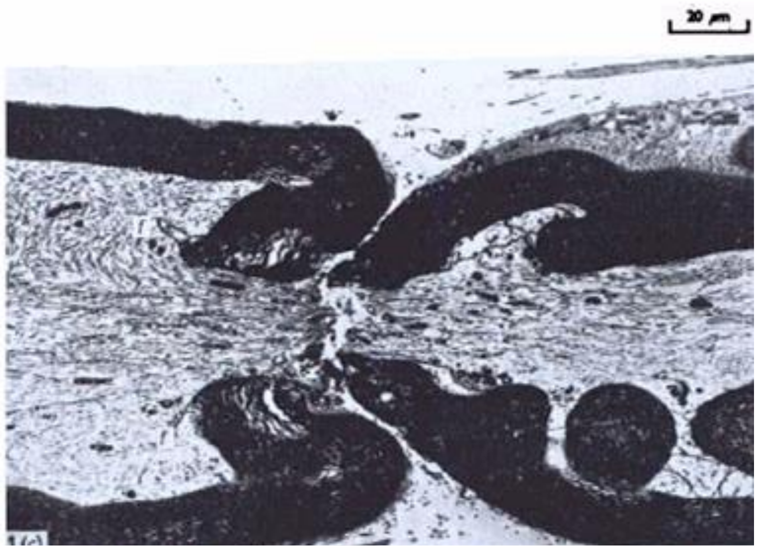
Note the similarities between the model results and the MR image of the limb above.

It is important to understand that the changes observed in the shape of the tissues are all related to motion or dispacement of tissue elements squeezed from the pressurized area beneath the cuff distally and proximally towards the un-pressurized areas. The only actual volume reduction is due to the closing shut of the blood vessels.

Consequences of Soft Tissue Deformation by a Tourniquet

Clearly, when circumferential force is applied to a limb, the resulting pressure field causes deformation and displacement of the soft tissues. The extent of deformation (or "strain") is not negligible and is different in various components of the tissue, depending on their elastic properties (also called the Young's Modulus). Fat is the softest element and muscle properties are different if deformed along the fibers or perpendicular to them. Fascia can be bent, but not shifted. A special case is the nerve, which, when compressed is elongated (see below). The difference in elasticity can cause adjacent tissues to move differently resulting in sheer forces between them, stretching beyond the elastic range and possible tears.

The radial forces that deform the limb radially cause longitudinal motion of tissues along the limb axis. This was noted already in the early 1970s by Ochoa et al who sought a mechanistic understanding of the cause of tourniquet-induced nerve damage ("tourniquet neurpraxia"). They applied pressurized Pneumatic Tourniquets to primates' limbs for several hours and after sacrificing the animals dissected the nerves for electron microscopy.



Changes in nerves compressed by tourniquet 441

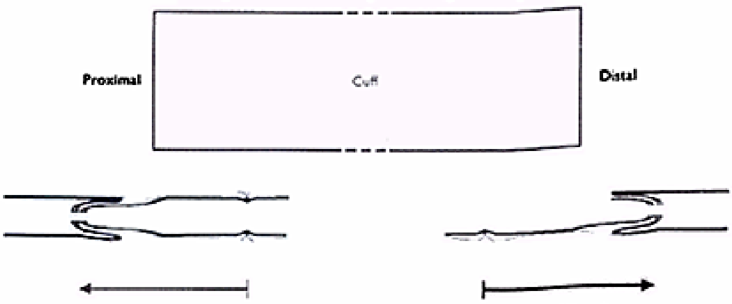


Fig. 6. Diagram to show the direction of displacement of the nodes of Ranvier in relation to the cuff.

They found that the nerves were damaged in a characteristic fashion – they telescoped into themselves at their weakest point, namely the Nodes of Ranvier (Figure 7). At these nodes the Schwan Cells sheet that envelopes the nerve is interrupted for a few microns so that only the axons are continued. The electron micrograph on the left shows an example with a disruption of the axons. To their surprise, the damaged nerves were only seen just proximal and just distal to the Pneumatic Tourniquet cuff as depicted on the two lower panels on the left.

The researchers concluded that the lateral compression of the nerve, which caused it to deform and elongate is the primary cause of the damage, rather than a direct effect of the pressure under the cuff.

The computational analysis by Levenberg depicted below (Figure 8) clearly shows the direction (arrows orientation) and the extent (arrows size) of tissue deformation caused by tourniquet pressure. Areas of excessive axial deformation just before and just after the edges of the tourniquet are marked by yellow arrows.

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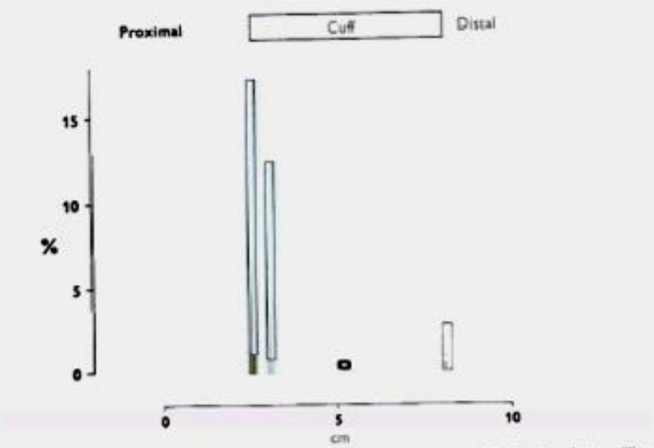
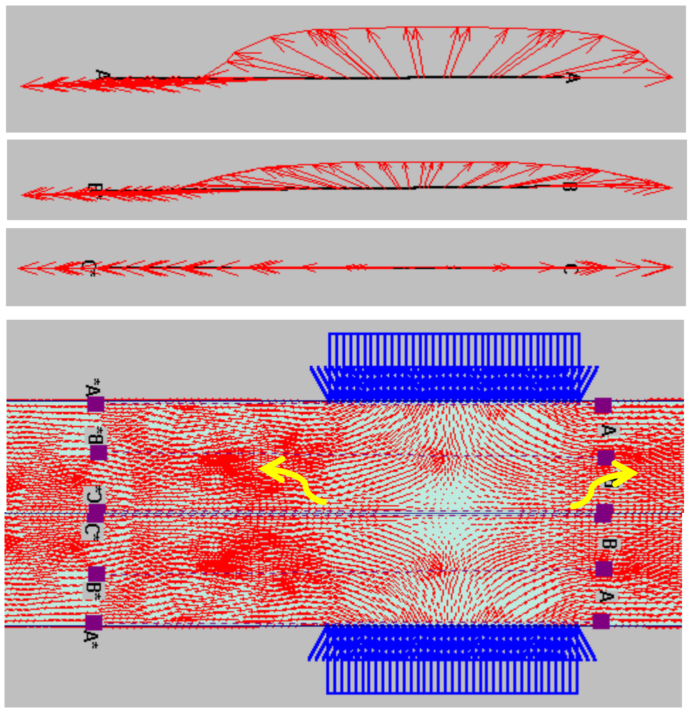
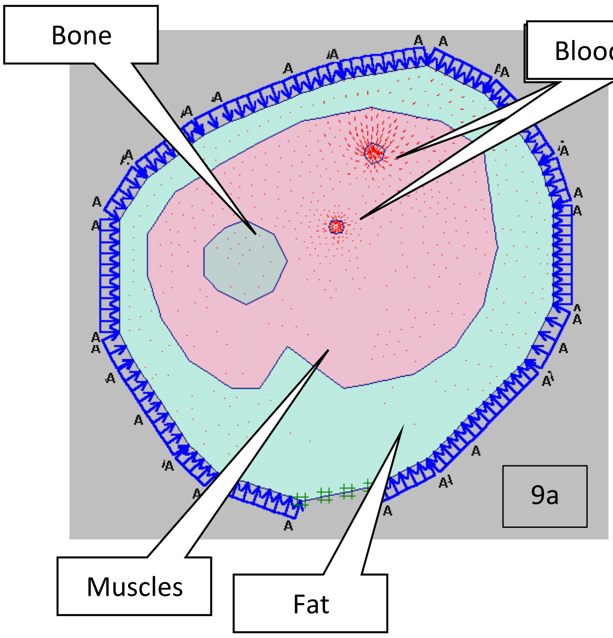


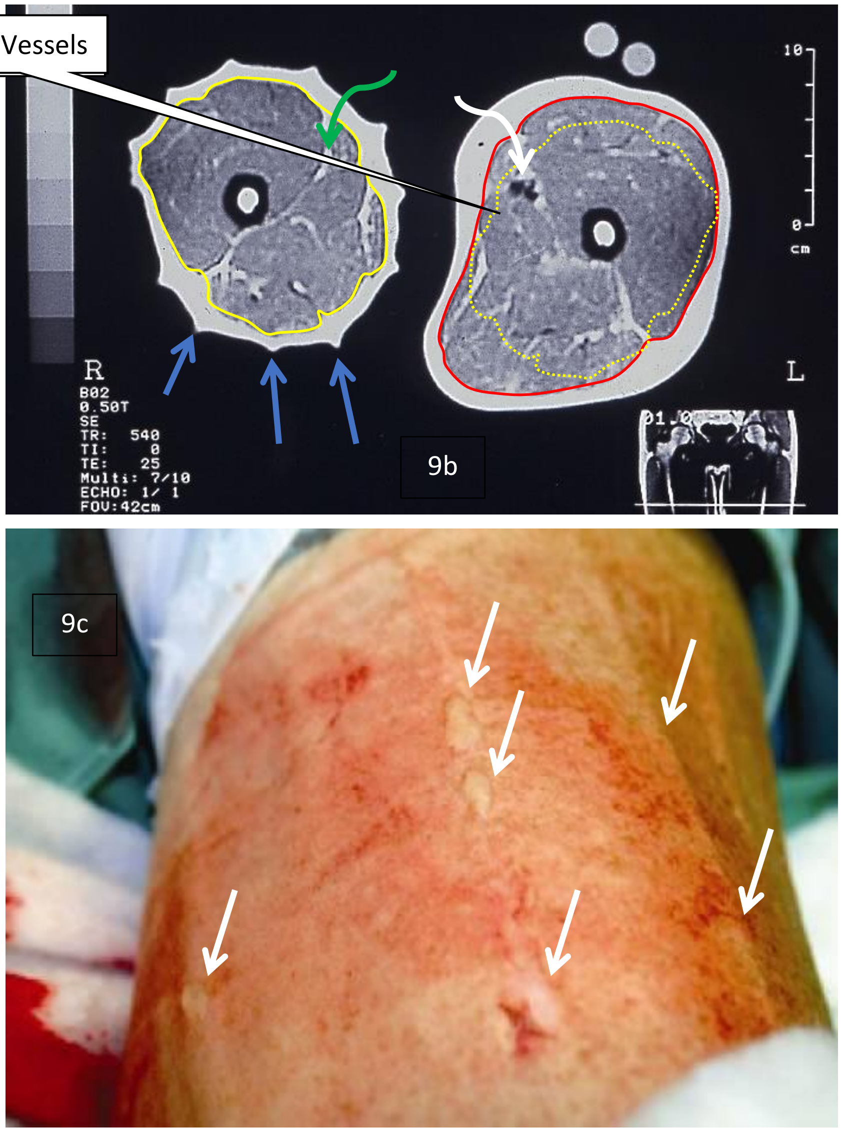
Fig. 7. Medial popliteal nerve, 4 days after compression at 1000 mm Hg for 90 minutes. The histogram shows the proportion of abnormal fibres in transverse sections at different levels under the cuff, the abnormal fibres being expressed as a percentage of the large myelinated fibre population at each level. For further details see text.



Additional Effects of Tissue Deformation

Two additional adverse effects of the use of wide Pneumatic Tourniquets are also related to tissue deformation, rather than to direct pressure effects or to ischemia. These are (A) skin injury, primarily in the form of blisters; and (B) tourniquet pain. In addition, tissue element motion is also responsible for the desired effect of using a tourniquet, namely the collapsing of the blood vessels beneath the cuff. Below are pictures that illustrate these effects and side effects as MRI (courtesy of Prof Estebe), photo of the skin of a patient who developed tourniquet-related blisters and a computational image showing the closure of the blood vessels by the applied tourniquet pressure.





<u>Figure 9a-c</u> Clockwise from top:

a. Computational model of a limb under circumferential pressure. Note the tissue motion around the blood vessels leading to their closure

b. MRI of the thighs. The left leg (marked L; on the right) is unpressurized, the right leg (marked R on the left) is under Pneumatic Tourniquet pressure. The femoral artery is open and clearly seen in the left thigh (white curved arrow) and is closed in the right thigh (green arrow). The extent of deformation can be appreciated from the difference between the red and the dotted yellow perimeters. Note the creases of the skin where the inflated tourniquet pinched the excess skin (blue arrows).

c. These creases correspond to the longitudinal elevations and linear blisters seen in the photo of the post tourniquet skin damage (white arrows). These so called "tourniquet burn" have been attributed to chemicals used in disinfecting the skin. Obviously the main cause is mechanical and associated with the pinching of the skin by the inner surface of the Pneumatic Tourniquet.

Biomechanics of the Elastic Exsanguination Tourniquet

The Elastic Exsanguination tourniquet (HemaClear®, Oneg HaKarmel Ltd., Tirat Carmel, Israel is an elastic ring (torus) which, when stretched, applies circumferential tension around the limb that results in radial force and displacement of the tissue. The relationships between the circumferential force, the radial force and the tissue pressure are explained in Section 2.3.

Ring-induced pressure in the tissue

The Elastic Exsanguination Tourniquet exerts its maximal force on the skin surface where the force is perpendicular to the limb. Further into the limb the force (a vector) principal direction shifts a bit axially and as such the pressure becomes smaller. This results in two pressure gradients, one in the radial direction where the pressure becomes smaller deeper into the limb and the other is in the axial direction. In fact, in a thin limb (e.g. an arm) if the surface pressure is 250 mm Hg, the pressure near the artery may be less than 200 mm Hg. This radial gradient is even greater when the limb is wider (e.g. thigh) and the artery is further away from the skin surface.

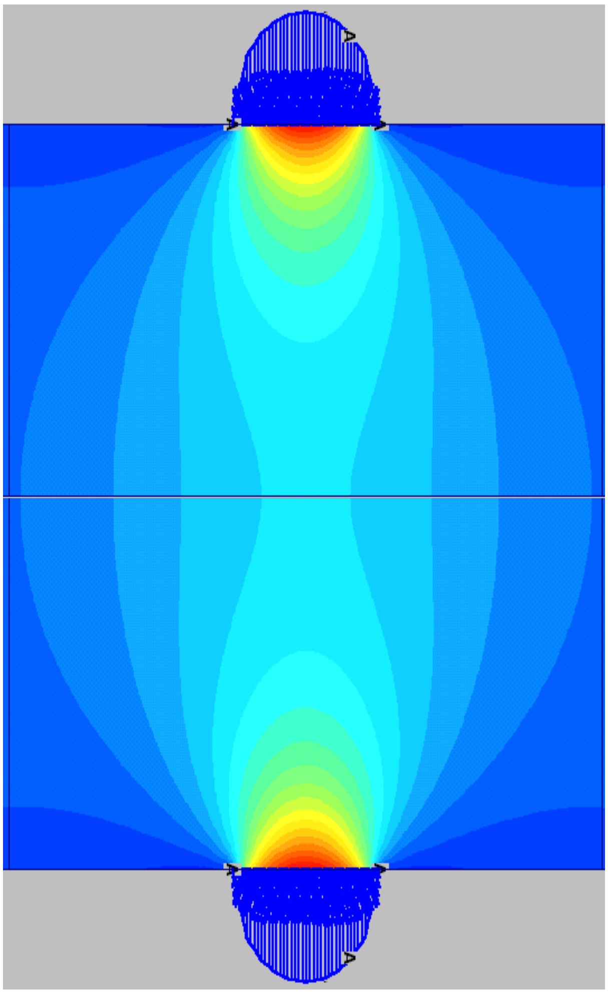
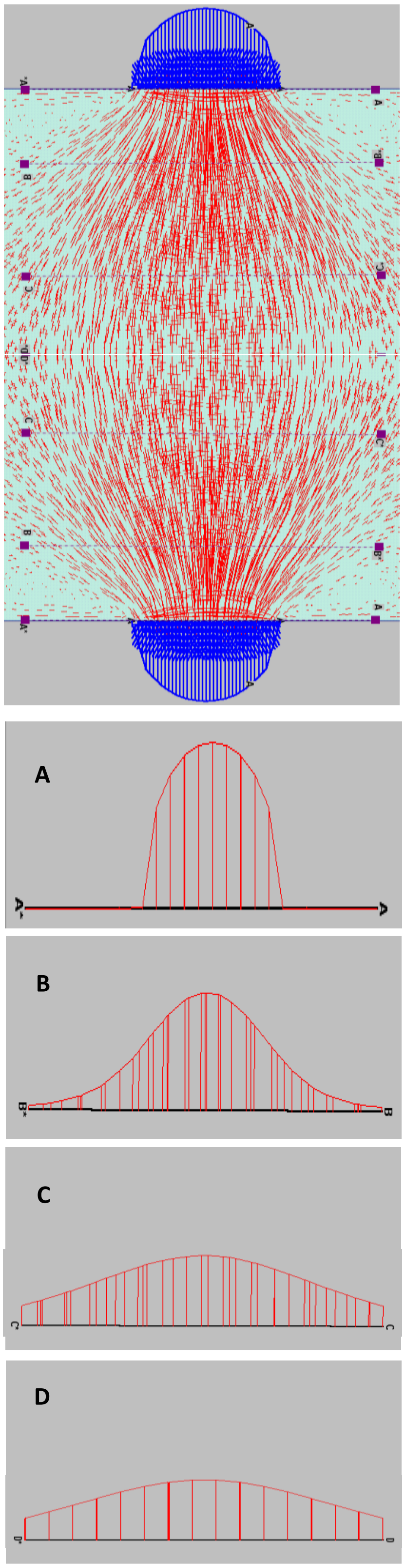


Figure 10

The figure on the right shows the pressure profiles at 4 levels: (A) immediately under the skin, (B) two thirds of the limb radius, (C) third of the limb radius, and (D) at the midline. Note that level B, which is about 68% of the maximum, represents a typical depth of the artery.

Note that the pressure dissipates beyond the width of the Elastic Exsanguination Tourniquet.



Soft Tissue Deformation by the Elastic Exsanguination Tourniquet

Applying equivalent radial force (stress) on the soft tissue of a limb by an Elastic Tourniquet causes approximately the same level of deformation or strain. This is so because the ratio of Stress/Strain is equal to the Young's modulus, which is a constant depending only on the properties of the tissue and not on the

mechanism by which the tissue is acted on. The images shown below for the Elastic Exsanguination Tourniquet should be compared to those for the Pneumatic Tourniquet shown in Sections 3.2 - 3.4.

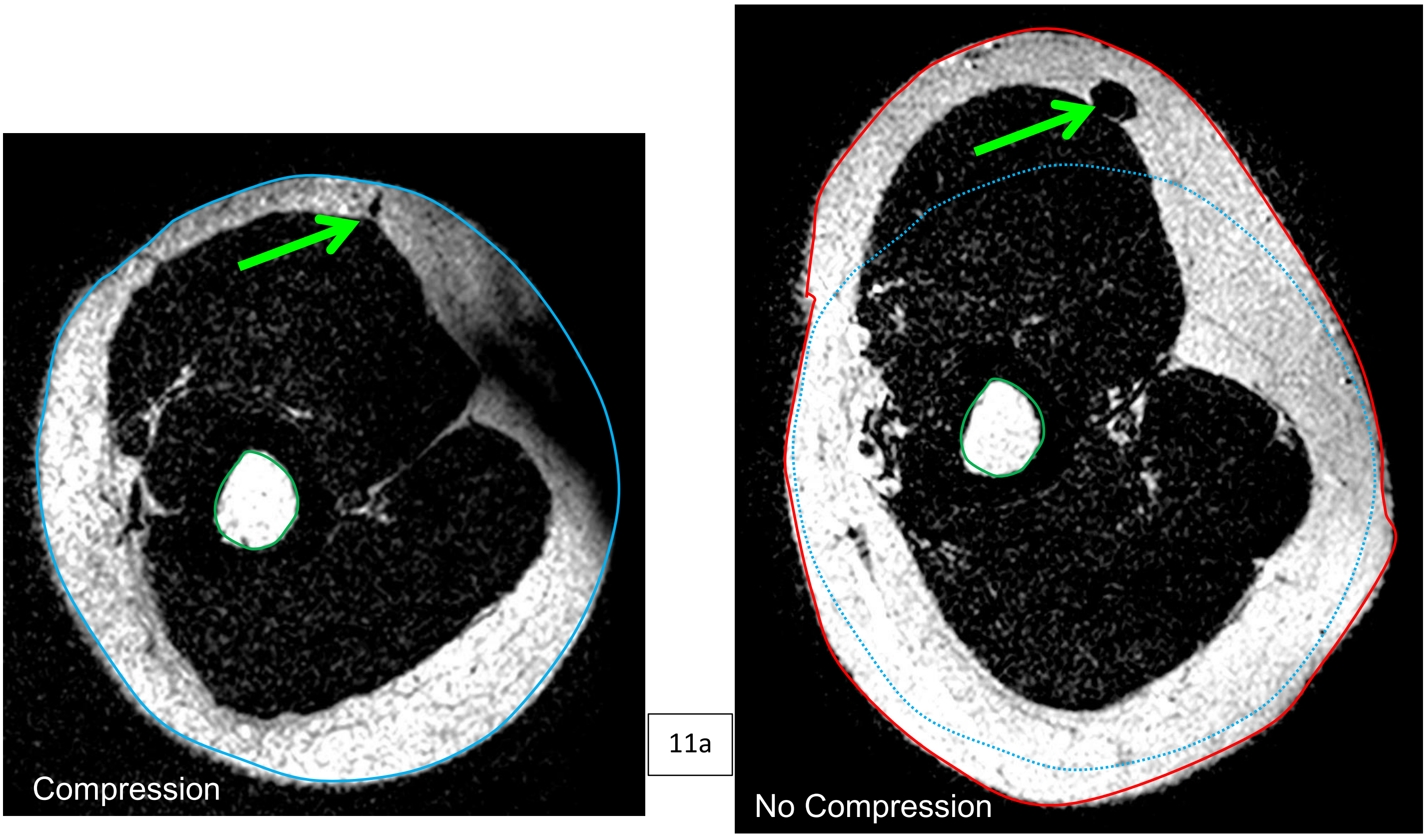
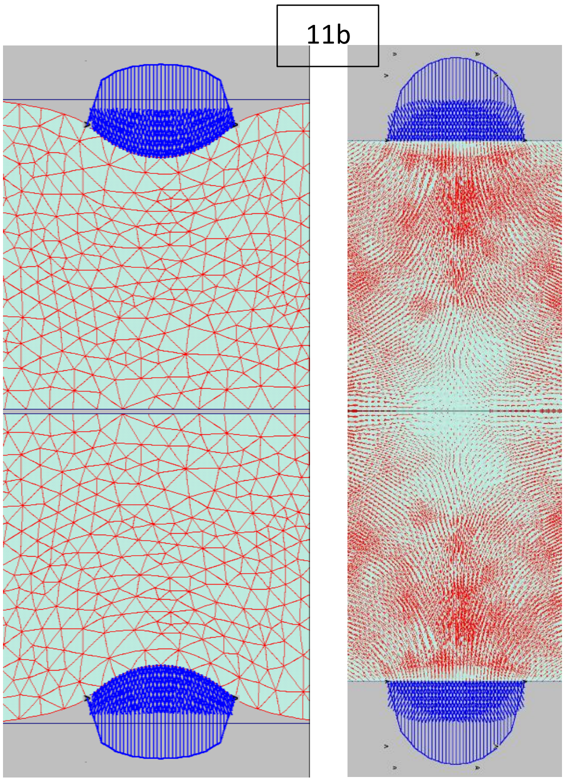


Figure 11 a-b

11a Top: MRI of an arm without (right) and with (left) an Elastic Exsanguination Tourniquet in place (courtesy of Dr. Kovar and Prof. Herzenberg, personal communication). The intra-medullary canal (white spot, perimeter marked in green) was used to verify dimensions. The elastic ring closed the blood vessels (green arrows) and deformed the muscles and fat. The extent of deformation is comparable to that by a Pneumatic Tourniquet, but into a smoothly rounded shape without the pinching side-lobes seen with the Pneumatic Tourniquet.

11b Right: Computational model of the tissue deformation beneath an Elastic ring. The extent of surface and elements deformation can be appreciated from the left-hand panel, while the extent actual motion can be seen in the direction and size of the small arrows shown in the right panel.



Tourniquet Width and the Volume and Surface Area of Tissue Under Compression Force Beneath the Tourniquet and the External Work Applied to the Tissue

We shall now calculate the volume and skin surface area beneath a tourniquet. If we call the cuff width "H" and the limb radius "R" than the volume of tissue beneath the tourniquet "V" can be calculated as

$$V = \Pi * R^2 * H$$

and the skin surface area beneath the tourniquet "A" is given by

$$A = 2\Pi * R * H$$

To calculate the Compression Force "F" we need to recall that the Tourniquet Skin Pressure "P" is given by the applied force divided by the surface area beneath the tourniquet:

$$P = F / A = F / (2\Pi * R * H)$$

This equation can be re-written as a calculation of Force for a given pressure and limb surface area:

$$F = P * A = P * (2\Pi * R * H)$$

When a tourniquet is placed on a limb, it compresses it and causes a change in volume ΔV. External work or applied energy "W" is defined as the product of the pressure applied and the displaced volume ΔV that can be estimated from the MRI images as $\Delta V = \Pi * R^2 * H - \Pi * (R- \Delta R)^2 * H \sim= 2\Pi * R * \Delta R * H$ so that:

$$W = P * \Delta V =\sim P * 2\Pi * R * \Delta R * H$$

Pneumatic Tourniquets cuffs widths vary between 75 mm ("narrow") to 120 mm ("dual bladder") and are typically 100 mm. The SET width is typically 15 mm. For this analysis we shall assume a normal adult upper thigh with a radius R = 100 mm (circumference of 62.8 cm). Table 1 shows the calculated V, A, F and W for a Pneumatic Tourniquet cuff and SET. Both with skin pressure of 250 mm Hg [= 0.33 atmosphere = 0.33 kg/ cm^2).

	Pneumatic Cuff	SET
Volume under constriction [ml]	$V = 3.14 * 10^2 * 10 =$ 3140 ml	$V = 3.14 * 10^2 * 1.5 =$ 471 ml
Skin area beneath tourniquet [cm^2]	A = 6.28 * 10 * 10 = 628 cm^2	A = 6.28 * 10 * 1.5 = 94 cm^2
Force applied to the volume of tissue	F = 0.33 * 628 = 209 kg	F = 0.33 * 94 = 31 kg
External Work	W = 0.33 * 3.14 * 5 *1 * 10 = 50 Atm-cm^3	W = 0.33 * 3.14 * 5 * 1 * 1.5 = 7.5 Atm-cm^3 if we assume internal pressure is uniform. Since the internal pressure is lower than the skin-pressure, the external work is even smaller.

It is clear that the constricting force of over 200 kg applied by a Pneumatic Tourniquet on the volume of tissue beneath is excessive. This force has two direct effects: (A) it deforms the tissues beneath the tourniquet and given the fact that the soft tissues of the limbs are essentially non-compressible, the force is primarily causing the tissue to move and when possible to migrate away from the volume under force; and (B) the force is applied as nearly a step change at the two edges of the cuff, thereby creating a steep gradient, also called shear stress at the two edges of the cuff.

Another way to characterize the effect of applying a tourniquet to a limb is by determining the External Work into the tissue. External Work is force times displacement when applied in a unidirectional fashion (e.g. lifting a weight), or pressure time change in volume in three-dimensional compression as with the tourniquet. External Work is equivalent to energy input into the pressurized element and at ~50 Atm-cm is excessive.

The Effect of the Duration of Blood Flow Occlusion by a Tourniquet

When blood flow to a limb is stopped, the supply of oxygen and metabolite substrate (e.g. glucose) is stopped. This results in a quick drop in PO2 and the onset of consumption of alternative sources of ATP. Initially from the muscle stores of creatine phosphate, followed by onset of anaerobic metabolism that results in accumulation of its metabolites such as lactic acid. The graphs below show the kinetics of PO2 levels (top panels), quantity of anaerobic metabolites (e.g. lactate) in the intracellular compartment and the corresponding concentration. The occlusion of blood flow is indicated by the onset of PO2 drop.

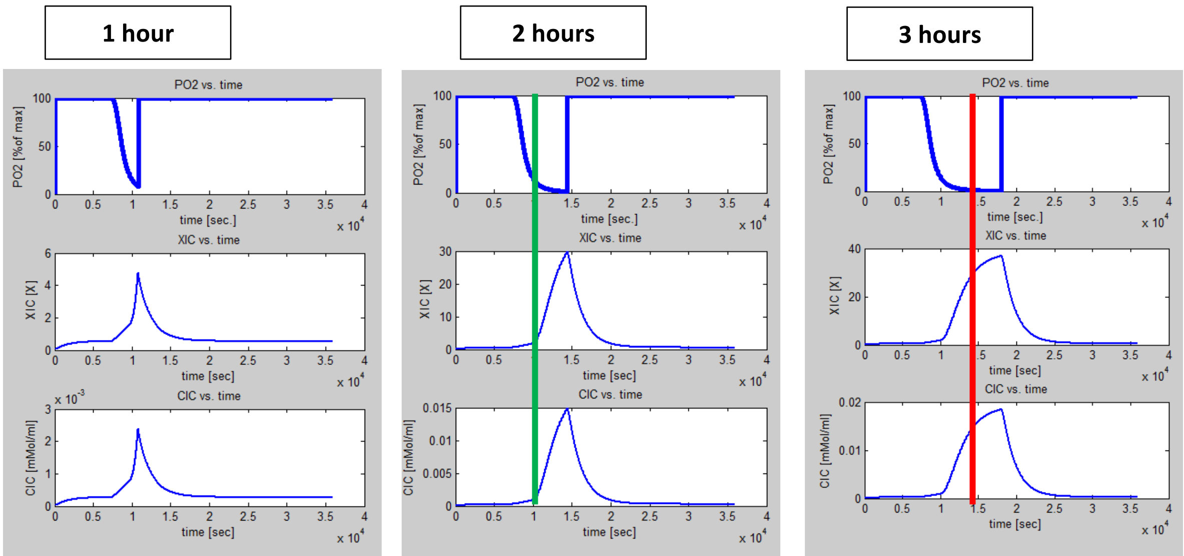


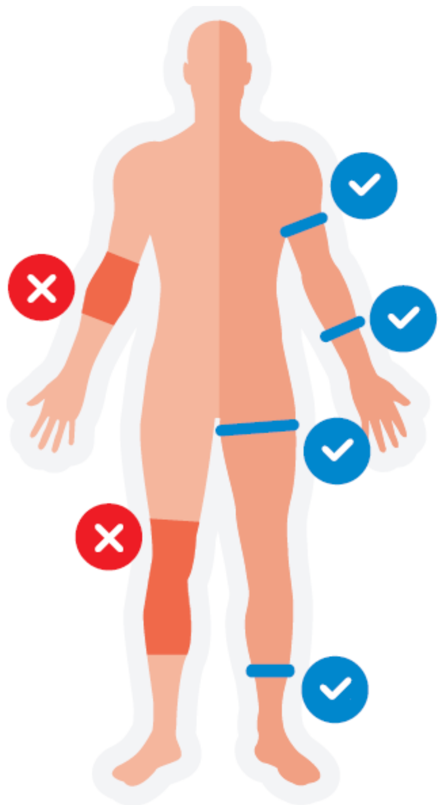
Figure 12 The effect of Tourniquet Time on PO2, quantity of metabolite (e.g. lactate) in the intra-cellular compartment (XIC) and its concentration (CIC). Left panel – 1-hour, Middle panel 2-hours, Right panel 3-hours. Note that the Y-axis is not the same in all the panels; time axis is in seconds X 10^4. (Gavriely, N. unpublished data)

In this example it is possible to see that when intracellular PO2 reaches a critically low level, the anaerobic metabolites start to accumulate (green vertical line). However, when the substrates for the anaerobic metabolism is depleted, the slope of the metabolites accumulation changes (red line). This is when ATP availability to the tissues becomes critically low and ischemic injury is imminent. In this model, the onset is at about 7000 sec after tourniquet onset =~ 2 hours. The situation is reversed when the blood flow occlusion is removed where PO2 returns to normal and the metabolites are washed out.

This model is helpful in pointing out the importance of pre-occlusion conditions and in particular the tissues oxygen levels and the stores of ATP and metabolic substrates. These are typically low in patients with co-morbidities such as peripheral vascular disease, cardio-pulmonary ailments and diabetes.

Location of Tourniquet Placement

An important factor in preventing tourniquet adverse effects is the locations where the tourniquet is placed. The options with the Pneumatic Tourniquet are limited to the thigh (mid or upper), or upper arm. Placing a Pneumatic Tourniquet on the wrist or on the ankle splints the ligaments and result in marked limitation of the motion of the fingers and toes, thereby interfering with the surgical procedures of hands and toes. These sites are associated with marked deformation of the underlying muscles and fascia and cause significant post-operative pain.



The SET, on the other hand, can be placed away from major muscle masses as shown in the diagram on the right (Figure 12). On the upper limb it is placed over the insertion of the deltoid, just above the biceps or on the wrist, 10 cm above the wrist skin fold. The wrist placement of the SET is possible because it does not splint the ligaments and allows full free passive and active motion of the fingers. The same is true when the SET is placed 10 cm above the lateral malleolus on the ankle. If on the upper leg, the SET should be placed at the groin level (i.e. where the leg connects to the pelvis). In all these sites the underlying muscles and fascia are the least and the result is much less post-op pain.

Summary and Conclusions

This manuscript reviews the biomechanics of tourniquets use and the known adverse effects of the wide Pneumatic Tourniquets including tourniquet neuropraxia, tourniquet pain and tourniquet-related skin injuries and blisters. It is apparent that all are attributed to the width of the tourniquet. An outcome of the analysis is the clarification that the wide tourniquet applies very large force and external work on a large volume the limb's tissues, which are unnecessary in order to occlude the blood flow. The superiority of the narrow elastic SET are brought to light with the markedly better safety track record – no neuropraxia, no skin damage and much less pain in more than 1.1 million cases, which are due to its narrow footprint, the uniform skin pressure, the optimized internal pressure and the ability to place it in optimal positions. The metabolic consequences of tourniquet use are briefly presented. Those are common to all tourniquets (wide, narrow or trauma types) and show the biochemical foundation for the empiric time limit of 120 minutes of continuous tourniquet use.

References

1. References on surgery with and without tourniquet
2. Klenerman L. the Tourniquet Manual.
3. https://www.openanesthesia.org/upper_extremity_tourniquet_pain_prevention/ intraoperative tourniquet pain
4. Cherng CH, Wong CS, Chang FL, Ho SJ, Lee CH. Epidural morphine delays the onset of tourniquet pain during epidural lidocaine anesthesia. Anesth Analg. 2002;94:1614–6.
5. Viscomi CM, Friend A, Parker C, Murphy T, Yarnell M. Ketamine as an adjuvant in lidocaine intravenous regional anesthesia: a randomised, double-blind, systemic control trial. Reg Anaesth Pain Med. 2009;34:30–3.
6. Charlotta Olivecrona, RN, Sari Ponzer, MD, PhD, Per Hamberg, MD, PhD, and Richard Blomfeldt, MD, PhD **Lower Tourniquet Cuff Pressure Reduces Postoperative Wound Complications After Total Knee Arthroplasty - A Randomized Controlled Study of 164 Patients** Department of Orthopaedics, S¨odersjukhuset Karolinska Institutet, Stockholm, Sweden J Bone Joint Surg Am. 2012;94:2216-21
7. 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.
8. Tourniquet pain in upper thigh https://bonesmart.org/forum/threads/tourniquet-pain-in-upper-thigh.5622/ Discussion in 'Concerns after knee surgery' started by Josephine, Sep 13, 2017.
9. 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.
10. Estebe JP, LeNaoures A, Chemaly L, Ecoffey C. Tourniquet pain in a volunteer study: effect of changes in cuff width and pressure. Anaesthesia. 2000 Jan;55(1):21-6.
11. Kerr DR, Kohan L. Local infiltration analgesia: a technique for the control of acute postoperative pain following knee and hip surgery: a case study of 325 patients. Acta Orthop. 2008 Apr;79(2):174-83.
12. Ochoa J, Fowler TJ, and Gilliatt RW. Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet. J Anat (1972), 113, 3, 433-455.