The Pressure Distribution under Tourniquets*

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ABSTRACT: We measured the detailed pressure distribution under pneumatic tourniquets and Esmarch bandages in canine limbs. The results showed that pressure concentration can occur in the tissue under the tourniquet. The Esmarch-bandage tourniquet was shown to be capable of producing pressures in excess of 1000 millimeters of mercury immediately beneath the tourniquet. There is a wide variation between cuff pressure and the pressures in the underlying tissues.

CLINICAL RELEVANCE: Because pressure concentration can occur in certain situations, the pressure on nerves underlying a tourniquet may be higher than expected. Although the precise relationship has not been determined, a wider tourniquet relative to limb diameter will generally lead to greater pressure concentration in the deep tissues. In these situations, the risk of nerve injury is increased.

Compression of the tissues under tourniquets used in extremity surgery is associated with varying degrees of soft-tissue injury. These injuries involve muscle[12,19], artery[4], and, most importantly, peripheral nerves[1-3,5-7,10,11,14-16]. The incidence and severity of the nerve injuries are a function of the pressure[3,6,7,10,11,14] and the duration of tourniquet application[1,6,14]. No combination of pressure and time has been proved to be safe; however, the lowest effective pressure (systolic blood pressure, thirty to 100 millimeters of mercury)[6,8] for ninety to 120 minutes[6,7,14] has been thought to be associated with an acceptable risk. The temporal component is easily controlled, and with modern pneumatic tourniquets it is possible to accurately determine and control the inflation pressure. However, the pressure in the soft tissues under a tourniquet may vary widely from the inflation pressure of a pneumatic cuff[1,5,15,17,18]; therefore, the actual pressure to which the nerves under the tourniquet are subjected is unknown. When the Esmarch bandage is used an unknown pressure is applied to the limb, resulting in further uncertainty as to the tissue pressure. If the etiology of tourniquet-induced nerve palsies is to be understood, an accurate knowledge of the pressure distribution in the tissues under the tourniquet is essential.

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This investigation was carried out to determine the pressure distribution in the tissues under two different tourniquets: a pneumatic tourniquet (Kidde) that incorporates a plastic insert to maintain its shape, and an Esmarch bandage of a similar width. We specifically used a model with a mismatch in shape between the pneumatic tourniquet (a cylinder) and the limb (a cone)[15], to determine if a stress concentration would result. We also were concerned with whether or not fascial planes or bone may cause shielding or concentration of stresses[1,5].

Materials and Methods

The hind limbs of anesthetized large mongrel dogs were chosen for the experimental model. They provided a large conical muscle mass surrounding a single osseous support and a diameter similar to that of an adult human arm. The animals were kept alive throughout the experiment in order to provide limbs with normal tissue turgor; however, direct monitoring of tissue perfusion was not carried out. The left thighs were used for pressure measurements under the 8.5-centimeter-wide pneumatic tourniquet, which was inflated to a pressure of 200 millimeters of mercury. The right thighs were used for pressure measurements under eight-centimeter-wide red rubber Esmarch bandages. The Esmarch bandage was wrapped around the thigh six times at approximately fifty newtons of tension. The tension of fifty newtons, measured with a tensiometer, is the tension that was achieved on application by minimally stretching the bandage.

The application of the Esmarch bandage was repeated for six wraps at two higher tensions: approximately 125 newtons, which is the average tension that is achieved on routine application of an Esmarch bandage, and approximately 175 newtons, which is near the tensile limit of the bandage. Application of the Esmarch bandage at the 125-newton tension was repeated with three, four, five, and seven wraps. Deep-tissue measurements were made under the pneumatic tourniquet and under the Esmarch bandage for the six-wrap, fifty-newton tension only. For all other applications of the Esmarch bandage, only subcutaneous pressures were measured.

The slit catheter and monitoring system (Howmedica) designed for compartment-pressure monitoring was used to measure the soft-tissue pressures under the tourniquets. A stereotactic technique was used to give accurate knowledge of the position of the tip of the catheter in the soft tissues.

Starting from one edge of the tourniquet, the slit catheter was placed along each of the five paths with the aid of a twenty-centimeter, number-14 needle. The other three edges in the same plane were also used as entry points to generate the slit-catheter paths that were required to obtain pressure readings at all of the points on the matrix.

A continuous pressure-position curve along each path was obtained by withdrawing the slit catheter at a speed of 0.5 centimeter per minute while simultaneously infusing fluid at a rate of 0.093 milliliter per minute with a Harvard infusion pump, to prevent spurious lowering of pressure due to catheter transit (Fig. 1, *B*). The rate of infusion was determined empirically to give a flat pressure-position curve in muscle for a transit speed of 0.5 centimeter per minute or less and to have less than a 5 per cent rise in pressure if the transit was stopped for five minutes. The pressure measurements in the plane under the tourniquet, shown in Figure 1, *A*, were repeated in the three longitudinal planes oriented at 60 degrees to each other (Fig. 1, *C*). The pressures at all of the points on the matrix, shown in Figure 1, *A*, for each plane were obtained from the pressure-position tracings in each plane.

From the matrix of pressures, longitudinal pressure curves along the zero, one-quarter, one-half, three-quarters, and one-diameter lines in each plane were constructed. Then isobaric lines joining the isobaric points on these longitudinal pressure curves were constructed.

Results

A typical pressure-position tracing for path 4 (Fig. 1, *A*) under the Esmarch bandage is shown in Figure 2. There was no indication on any of the tracings that the pressure in any compartment was increased or decreased by the surrounding fascial planes, or that the bone had any effect on surrounding soft-tissue pressures. An identical pressure distribution was found in all three planes and was symmetrical about the central longitudinal axis (axisymmetrical). The pressure was highest midway along the width of the tourniquet and was lowest at the edges of the tourniquet.

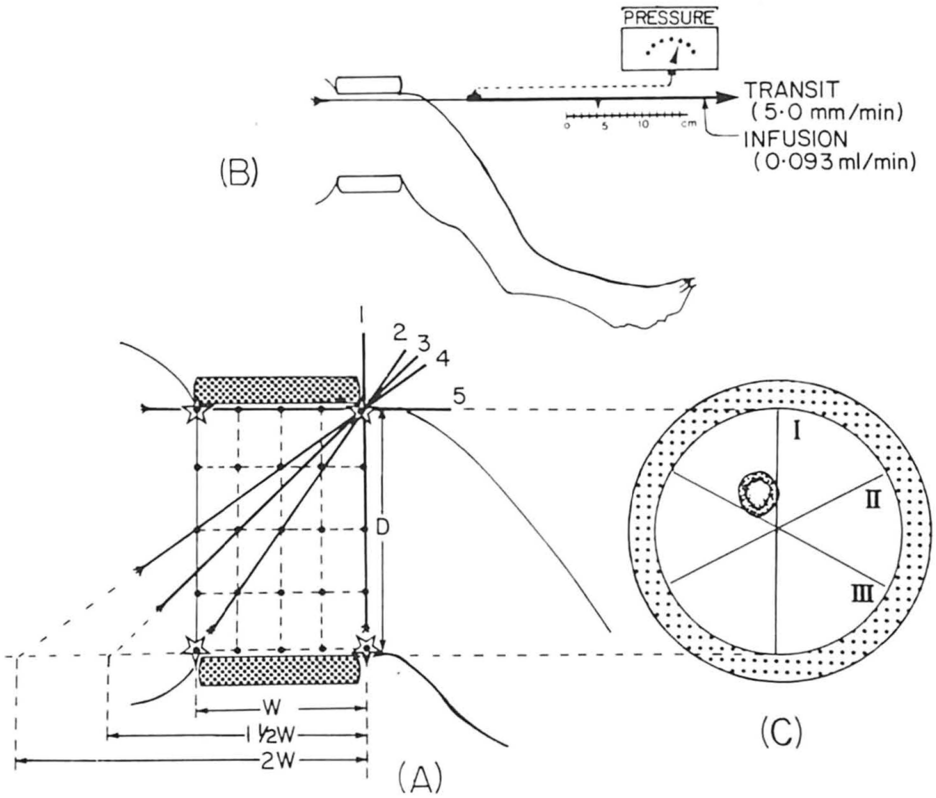

FIG. 1

Experimental method. *A:* Sagittal section of the canine thigh with the tourniquet in place. The location of point values used to construct the isobaric plots are indicated by black circles. Slit-catheter paths 1 through 5 were used at each entry point in that longitudinal plane. The four entry points are indicated by stars. *B:* The slit catheter, the transducer-monitor, the infusion rate of 0.093 milliliter per minute, and the measured catheter-transit rate of five millimeters per minute. *C:* A cross section of the thigh under the tourniquet. The three longitudinal planes — I, II, and III — are oriented at 60 degrees to each other. The pressure measurements described in *A* are taken in all three planes.

Pneumatic Tourniquet: Tissue-Pressure Distribution

The tissue-pressure distribution under the pneumatic tourniquet that was inflated to a pressure of 200 millimeters of mercury is shown in Figure 3. The pressure at the leading edge of the cylindrical cuff on the conical thigh was slightly higher than at the distal edge. The pressure at the proximal edge was 12 per cent of the cuff-inflation pressure, compared with 9 per cent of the cuff-inflation pressure at the distal edge.

The peak pressure was found in the subcutaneous tissue just proximal to the mid-position along the tourniquet width. This pressure was 97 per cent of the inflation pressure. The pressure readings were progressively lower in the tissues that were closer to the edges of the tourniquet, with a drop

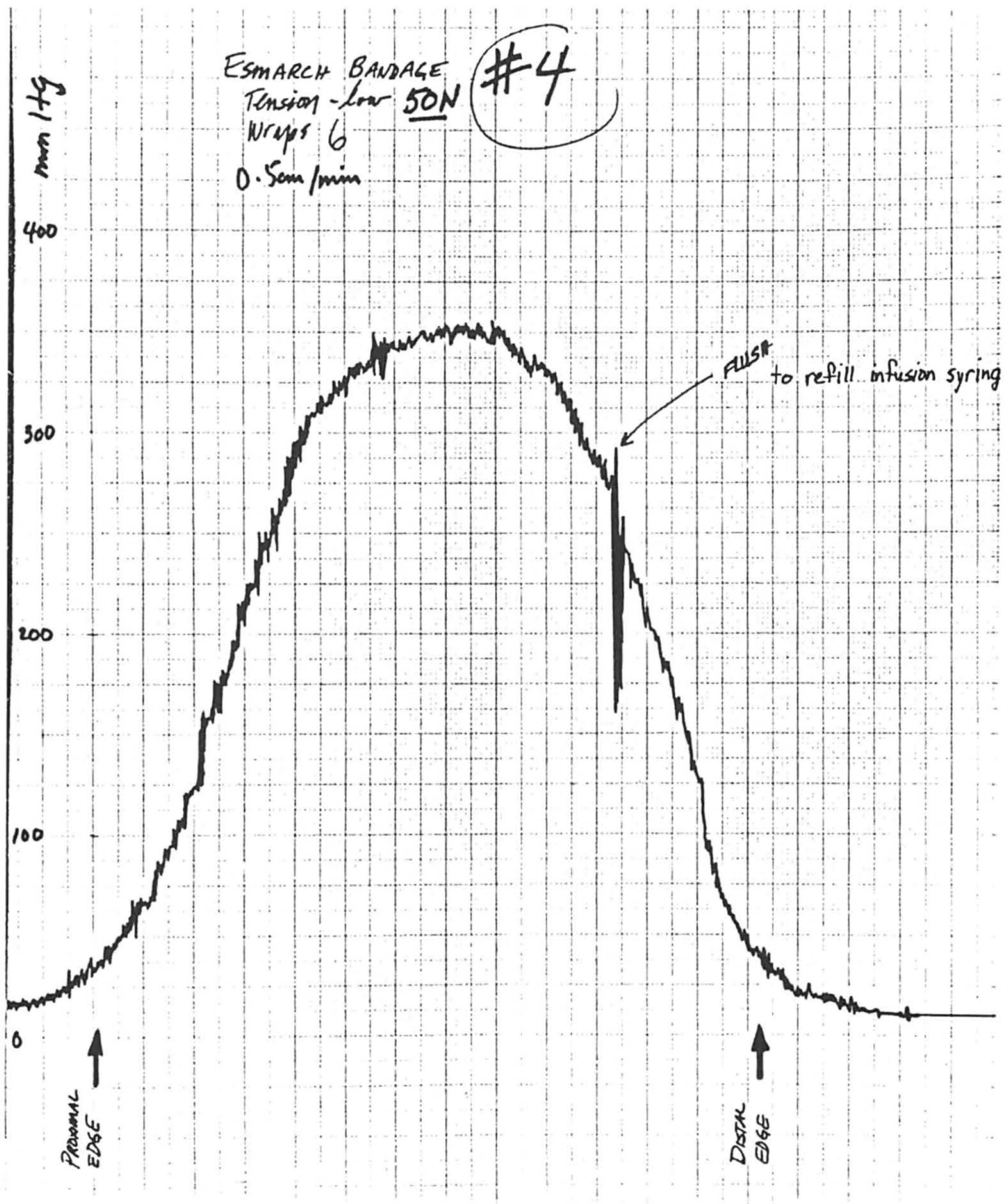

FIG. 2

Pressure-position tracing; path 4, Esmarch bandage.

in pressure from the middle to the periphery of about 90 per cent. The pressure readings were lower in the deeper tissues as well, but to a much lesser degree; the drop in pressure from the surface to the center was about 2 per cent, with a maximum central pressure of 95 per cent of the cuff-inflation pressure.

Esmarch Bandage: Tissue-Pressure Distribution

The tissue-pressure distribution under the Esmarch bandage applied at a tension of approximately fifty newtons for six wraps of the bandage is shown in Figure 4. Although the approximate tension of application of the Esmarch bandage is known, the pressure applied by the Esmarch bandage is not known. Therefore, we discuss the deep pressures as a percentage of the peak subcutaneous pressure, which is probably somewhat less than but presumably close to the applied pressure. At the proximal edge of the tourniquet the pressure was 11 per cent of the peak subcutaneous pressure and at the distal edge the pressure was 13 per cent of the peak subcutaneous pressure. Midway along the width of the tourniquet, the pressure in the deep tissues did not decrease but rather increased to 109 per cent of the maximum subcutaneous pressure at the center of the limb. The pressure gradient over the proximal and distal quarters of the width of the Esmarch bandage applied at fifty newtons of tension was more than 250 millimeters of mercury, compared with less than 140 millimeters of mercury for the pneumatic tourniquet.

Esmarch Bandage: Subcutaneous Pressure

The peak subcutaneous pressures under the Esmarch bandage applied at the three different tensions, for six wraps each, are shown in Figure 6. This pressure increased with increased tension. A pressure greater than 1000 millimeters of mercury was measured under six wraps at the maximum-tension application.

The peak subcutaneous pressures under the Esmarch bandage applied at approximately 125 newtons of tension

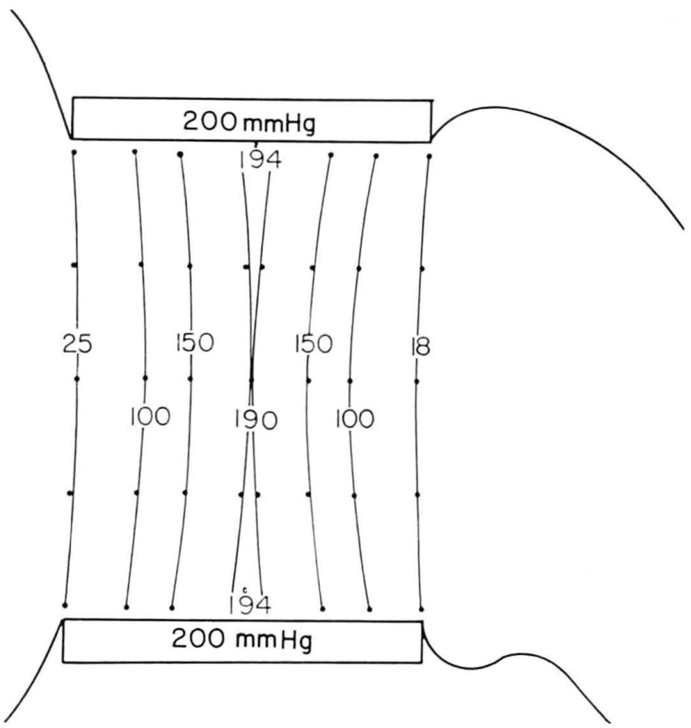

FIG. 3

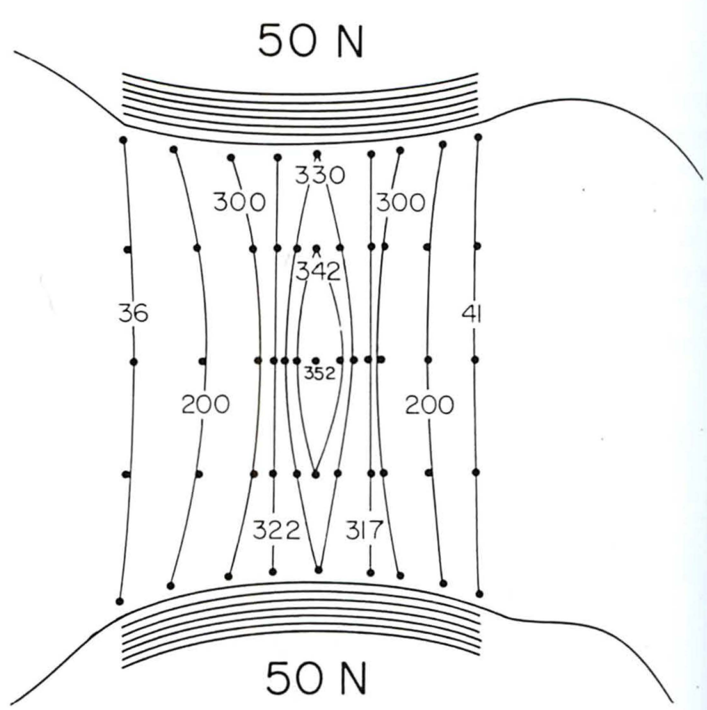

FIG. 4

Fig. 3: Tissue-pressure distribution under the pneumatic tourniquet at an inflation pressure of 200 millimeters of mercury. This is an isobaric plot of results obtained using the method outlined in Fig. 1. The highest pressure was 97 per cent of the cuff pressure located subcutaneously at the center of the cuff. The pressure decreases with depth and toward the edges of the cuff.

Fig. 4: Tissue-pressure distribution under the Esmarch-bandage tourniquet applied for six wraps at a tension of fifty newtons. This is an isobaric plot of results obtained using the method outlined in Fig. 1. The highest pressure is 109 per cent of the peak subcutaneous pressure, at the center of the limb and the center of the bandage. The pressure decreases at regions closer to the edges of the bandage.

for different numbers of wraps around the thigh are shown in Figure 7. This pressure increased with the number of wraps. A pressure in excess of 1000 millimeters of mercury was measured under seven wraps.

Discussion

The results of our investigation confirm previous reports that the inflation pressure of a pneumatic cuff may not represent the actual pressure in the soft tissues under the cuff[1,5,15,17,18]. Shaw and Murray showed a decrease in pressure with soft-tissue depth, midway along the width of a cylindrical pneumatic tourniquet. We also observed this. The results of our study also confirm that there is a large change in pressure across the width of the tourniquet. As soft-tissue injury is related to the pressure to which these tissues are subjected, we propose that the important factor with respect to tissue injury is not the inflation pressure *per se*, but the resultant pressure that is actually applied to the limb and the area over which the pressure is applied. Deep-tissue pressures theoretically are dependent on the width of the pressure pattern that is applied to the limb. Using the theoretical arguments of Griffiths and Heywood to calculate

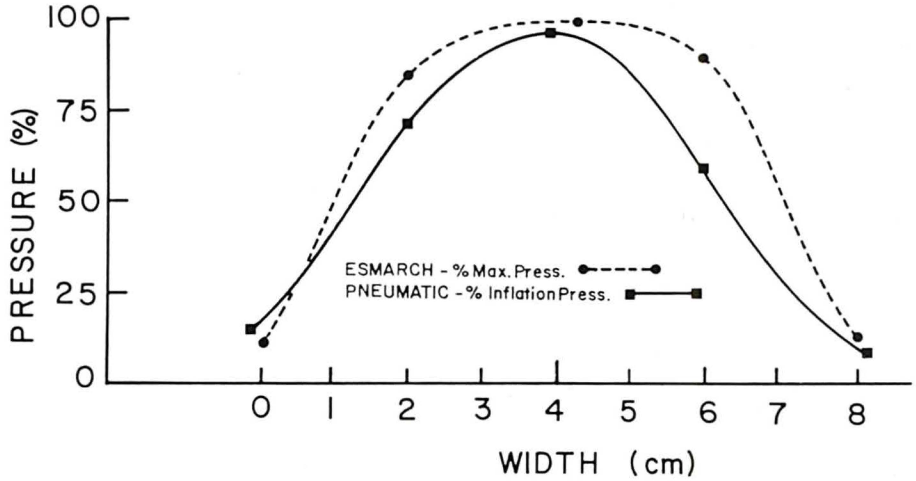

FIG. 5

Subcutaneous tissue pressure versus position under the tourniquet. The change of pressure with change of position is greater under the edges of the Esmarch-bandage tourniquet.

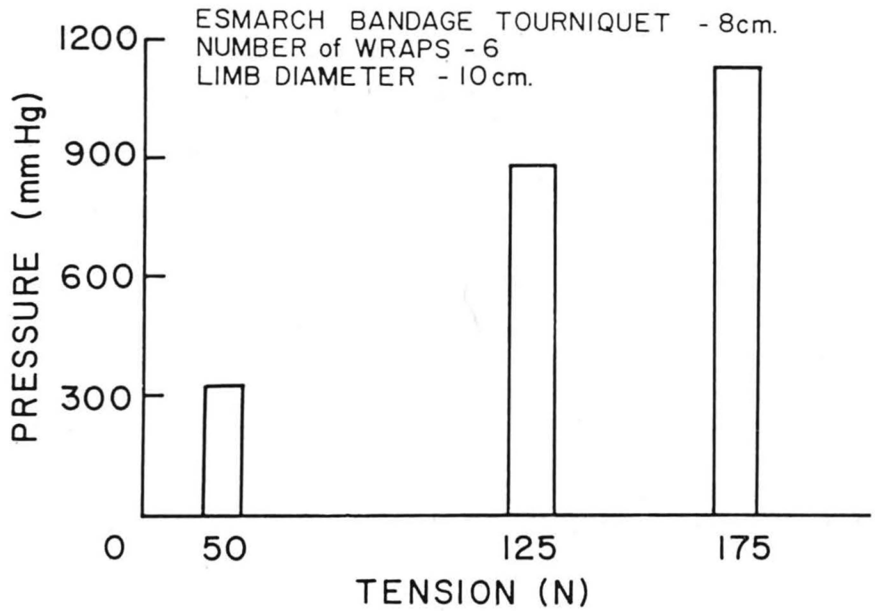

FIG. 6

Subcutaneous pressure versus tension of the Esmarch-bandage tourniquet. The pressure increases with the tension of application of the bandage, to a value of 1130 millimeters of mercury for a tension of 175 newtons and six wraps.

the pressure concentration under an infinitely wide pressure band, the pressure at the center of a limb could approach a value 50 per cent higher than the applied pressure. Pressure concentration at the center of the limb was seen under the Esmarch-bandage tourniquet but not under the pneumatic tourniquet.

A tourniquet exerts pressure on a band around the limb. This band of pressure is not uniform. The zone where the pressure is 95 per cent of the maximum pressure or more may be an index for judging the performance of the tourniquet. The 95 per cent maximum-pressure band found under the Esmarch bandage applied at fifty newtons of tension for six wraps was wider than that found under the pneumatic tourniquet that was applied at 200 millimeters of mercury. This may explain the pressure concentration that occurred under the Esmarch bandage and not under the pneumatic tourniquet, as this concentration occurred between the 95 per cent isobars.

The 95 per cent isobars under the pneumatic tourniquet meet at the center of the limb, suggesting that the band of pressure applied to the limb must be greater than a critical width in relation to the diameter of the limb, if it is to result

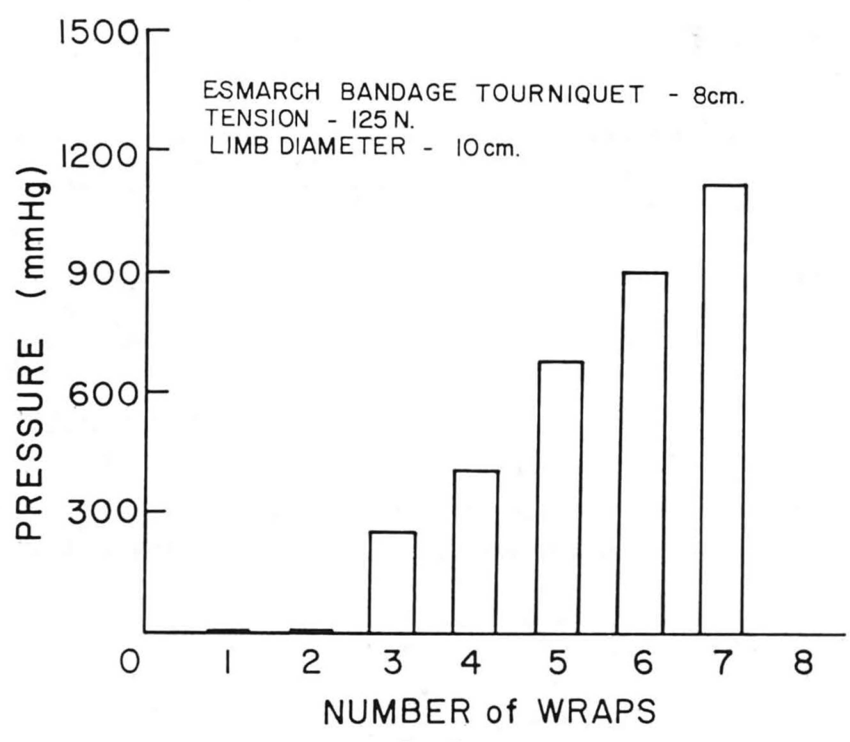

FIG. 7

Subcutaneous pressure versus number of wraps of the Esmarch-bandage tourniquet. The pressure increases with each wrap, to a value of 1120 millimeters of mercury for a tension of fifty newtons and seven wraps.

in pressure concentration at the center of the limb.

We do not know the reason for the wider 95 per cent maximum-pressure band under the Esmarch bandage than under the pneumatic tourniquet; however, it may be due to structural differences or to the higher pressure.

The great variations between deep-tissue pressures and cuff inflation pressure make any reliable method to determine the minimum effective pressure of inflation appealing. Reid et al. described a possible method using Doppler measurements of blood flow distal to the tourniquet in order to determine the inflation pressure.

The cone theory[15] of pressure concentration under the tight proximal edge of a cylindrical tourniquet on a conical thigh was not supported by the results in this study. The tissues easily accommodated the mismatch in shape between the tourniquet and the limbs used in this study. The pressure-position tracings that we obtained had no abrupt changes or steps in pressure. This suggests that fascial planes have no shielding or concentrating effects on the pressure distribution and supports the findings by other authors that exsanguinated soft tissues behave as a homogeneous solid[1,5].

The use of an Esmarch-bandage tourniquet has been associated with a higher incidence of nerve injury than the use of a pneumatic tourniquet[1,5,9]. High pressure and shear stresses from twisting during application have been suggested as the underlying mechanisms[1,5]. Our study has shown that extremely high pressures can be produced in the subcutaneous tissues under the Esmarch bandage and that pressure concentration in the deep tissues can occur under the bandage.

There can be great variation in pressure with tension of application and with the number of times that the bandage is wrapped around the limb. Our experience has been that the Esmarch bandage is rarely, if ever, applied by a surgeon at a tension as low as fifty newtons, and that it is rarely, if ever, applied for only three wraps. If the guidelines for a relatively safe pressure of application are accepted (systolic blood pressure, thirty to 100 millimeters of mercury[6,8]; or Doppler occlusion pressure, fifty to seventy-five millimeters of mercury[13]), then an eight-centimeter Esmarch-bandage tourniquet on a ten-centimeter-diameter limb can be expected to exert pressure above the safe limit, often by a great amount. The high pressures found in this study can explain the higher incidence of nerve injury associated with the use of the Esmarch-bandage tourniquet[11].

Conclusions

Tissue pressures under a tourniquet vary widely from the applied pressures. Tissue planes and incongruities between the shape of the limb and that of the tourniquet do not cause pressure concentrations. Pressure concentration can occur in the center of a limb under a tourniquet. The safe range of pressure is easily exceeded by an Esmarch-bandage tourniquet.

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