Local Compression Patterns Beneath Pneumatic Tourniquets Applied to Arms and Thighs of Human Cadavera

Alan R. Hargens, A. Gavin McClure, Michael J. Skyhar, Richard L. Lieber, David H. Gershuni, and Wayne H. Akeson

Division of Orthopaedics and Rehabilitation (V-151), Veterans Administration Medical Center and University of California, San Diego, La Jolla, California, U.S.A.

Summary: Distributions of tissue fluid pressure were examined beneath a standard pneumatic tourniquet in six upper extremities and six lower extremities of fresh human cadavera, disarticulated at the shoulder and hip, respectively. A standard 8-cm-wide tourniquet cuff was applied at mid-humerus or mid-femur position. Tissue fluid pressures were measured by 100-cm-long slit catheters inserted parallel to the bone at four tissue depths: (a) subcutaneous, (b) subfascial, (c) mid-muscle, and (d) adjacent to bone. All arms and thighs were studied at the following cuff pressures: 100, 150, 200, 250, 300, 400, and 500 mm Hg. Tissue fluid pressure was always maximal in subcutaneous tissue at mid-cuff. Transmission of cuff pressures to deeper tissues was significantly less ($p < 0.01$) in the thighs with a girth of 40–52 cm than in the arms with a girth of 22–33 cm. At the four tissue depths studied, tissue fluid pressures fell steeply in a longitudinal direction near the cuff edge to levels near zero at points 1–2 cm outside each cuff edge. Our results suggest that wider cuffs are required on thighs than on arms to provide a bloodless field during limb surgery and to minimize underlying tissue injury associated with high cuff pressures. Our recommendation for wider tourniquet cuffs than those presently used during orthopaedic surgery is contrary to recent prevailing knowledge. **Key Words:** Pneumatic tourniquet—Limb surgery—Tissue fluid pressure.

Tourniquet occlusion of blood flow is used routinely for surgery on the upper and lower limbs to provide a bloodless operating field. The common acceptance of the tourniquet as a surgical appliance, however, should not suggest that its use is benign. Complications are more common than may be appreciated, and some of the morbidity of tourniquet use is often unrecognized (17). Reported complications include: muscle damage observed histologically (12,23,36,38), functionally (8,24), and biochemically (2,16,19,32,33); and vascular problems such as deep vein thrombosis (26), arterial thrombosis (9), false aneurysm (37), fractured vessel walls (15), and postischemic edema (16,25,39). Neurologic problems also attributed to tourniquet application include damage to ulnar (1), sciatic (28,34), femoral (34,40), and other nerves (1,25,34,40).

The length of time during which it is safe to apply a tourniquet on a limb is an important variable in surgical practice (13,14,33). Similarly, the surgeon should know the minimum pressure necessary to

occlude blood flow in a limb in order not to cause complications due to excessive compression. These minimum pressures for hemostasis are not well defined, however. For a standard 8-cm-wide tourniquet, commonly recommended cuff pressures for the arm and leg range between 250 and 300 mm Hg and 300–400 mm Hg, respectively. Most previous studies of tourniquet injury have focused on the effects of ischemia in tissues *distal* to the applied cuff. However, recent studies of tissue pressures (18,35), muscles (11,23), nerves (4,7,22,27,29–31), and blood vessels (9) directly beneath the tourniquet cuff suggest that these underlying tissues are more seriously jeopardized. Although tissue pressure decreases with depth beneath pneumatic cuffs applied to cadaveric thighs (35) and canine hindlimbs (18), no study has quantitated longitudinal distributions of tissue pressure in human arms and thighs to correlate local compression levels with patterns of potential tissue injury. Therefore, the objective of this study is to examine local distributions of tissue fluid pressure beneath a standard surgical cuff applied to limbs at varying tourniquet pressures with a view to improving tourniquet design.

METHODS

Distributions of tissue fluid pressure (TFP) were measured beneath a standard 8-cm pneumatic tourniquet (W. Kidde & Co., Bloomfield, NJ, U.S.A.) in six arms and six legs of fresh human cadavera, disarticulated at the shoulder and hip, respectively, immediately prior to experimentation. Muscle compartments were left intact during amputation, and TFP studies were performed in specimens at temperatures between 12 and 20°C. The tourniquet cuff was applied at mid-humerus or mid-femur position. TFPs were measured by 100-cm-long slit catheters (Howmedica, Inc., Rutherford, NJ, U.S.A.) inserted parallel to the bone at four tissue depths: (a) subcutaneous, (b) just beneath the most superficial fascial layer (subfascial), (c) halfway between skin and bone (mid-muscle), and (d) adjacent to bone (Fig. 1).

Each catheter was inserted via 50-cm-long, 1-mm ID, steel tubes through the disarticulated end of the limb and exited through an incision just proximal to the elbow or knee. Radiographic studies of some specimens documented that the tubes were parallel to the bone. After the steel tubes were completely

retracted, the cuff was inflated to a designated pressure and each catheter was withdrawn in 1-cm increments to measure TFP at positions from 5 cm proximal to the proximal cuff edge to 5 cm distal to the distal cuff edge. TFP was measured by low-volume displacement pressure transducers (model HP 1280, Hewlett Packard, San Diego, CA, U.S.A.) and continuously monitored by a four-channel strip-chart recorder (HP 7754A). All arms and thighs were studied at the following cuff pressures: 100, 150, 200, 250, 300, 400, and 500 mm Hg as calibrated by a mercury manometer. For sequential studies of TFPs at different cuff pressures, the steel tubes were reproducibly reinserted by landmarks located at the distal entry points and proximal incision for the four tissue depths under study. The cuff was deflated during catheter reinsertions. A 1-min equilibration time was taken for each longitudinal position before TFP was recorded. Each limb was studied for a period of 2–3 h. Limb circumference was measured at mid-humerus or mid-femur for each limb. TFPs were averaged for all six limbs at each longitudinal position and depth for each cuff pressure, plotted using an LSI-11/23 + computer, and analyzed statistically by one-way analysis of variance (6). Separately, isobaric plots of TFP were generated from meaned data for each longitudinal and radial position beneath the cuff. Statistical significance was set at the 95% confidence level.

RESULTS

In 12 fresh cadaveric limbs with standard 8-cm cuffs applied at seven different pressure levels between 100 and 500 mm Hg, TFP was always maximal in subcutaneous tissue at mid-cuff. Because cuff pressures of 200–300 mm Hg are commonly employed during surgery of the upper extremity, our results (mean TFP for each tissue depth) for arms (circumference of 22–33 cm at mid-humerus) are graphically presented for 200 mm Hg (Fig. 2) and 300 mm Hg (Fig. 3). A cuff compression of 200 mm Hg produced a gradient of TFP with tissue depth from a mean ($\pm$ SEM) of 195 $\pm$ 7 mm Hg in subcutaneous tissue to 114 $\pm$ 6 mm Hg in the center of the biceps brachii (Fig. 2). TFP was maximal within 1 cm of mid-cuff (4 cm from proximal edge of cuff) at all tissue depths and cuff pressures. At the four tissue depths studied, TFPs usually fell steeply in longitudinal directions near each cuff
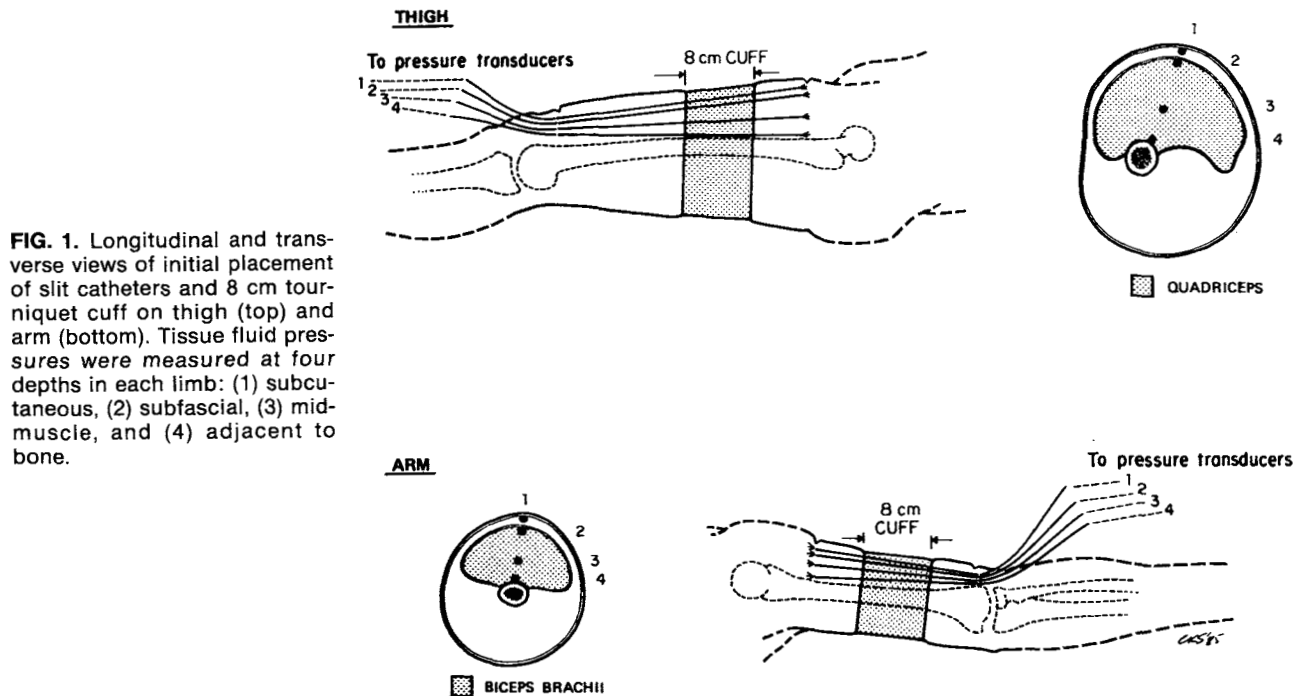
THIGH

FIG. 1. Longitudinal and transverse views of initial placement of slit catheters and 8 cm tourniquet cuff on thigh (top) and arm (bottom). Tissue fluid pressures were measured at four depths in each limb: (1) subcutaneous, (2) subfascial, (3) midmuscle, and (4) adjacent to bone.

ARM

edge to levels near zero at a point 1–2 cm outside each cuff edge. Only mid-muscle TFP proximal to the proximal cuff edge at a cuff pressure of 200 mm Hg in the arms deviated from this pattern; pressure at this depth was 19–24 mm Hg, perhaps due to the muscle's containment within a relatively tight compartment. Distributions of TFP in arms at all pressures exhibited the same depth relationships in that compression of deeper tissues was always less than

that in superficial tissues. Henceforth, "compression" is defined as elevation of TFP.

Compression patterns at a clinically relevant cuff pressure of 300 mm Hg (intermediate between those commonly used for arms and thighs) indicated that transmission of cuff pressure to deeper tissues was significantly less ($p < 0.02$) in the thighs with a girth of 40–52 cm than in the arms with a girth of 22–33 cm (Fig. 3). Again, mid-cuff TFPs were significantly higher ($p < 0.05$) in subcutaneous tissue (293 ± 13 mm Hg in arms, 278 ± 13 mm Hg in thighs) than in muscle near bone (257 ± 16 mm Hg in arms, 191 ± 12 mm Hg in thighs). At 300 mm Hg, therefore, the 8-cm cuff was much less effective in transmitting compression to deeper tissues when it was applied to the larger thighs as compared with smaller arms. For example, mid-cuff TFPs at the four tissue depths were 7–60 mm Hg below cuff pressure (300 mm Hg) for the arms but 22–100 below cuff pressure for the thighs. Again, TFPs formed rather sharp maxima at mid-cuff position and fell to near zero within 1–2 cm of each cuff edge.

Inflation of the standard cuff to 400 mm Hg on six thighs (Fig. 4) produced TFP patterns similar to those observed at lower cuff pressures. Mid-cuff TFPs in thigh subcutaneous tissue were 45 mm Hg below cuff pressure (400 mm Hg), whereas mid-cuff
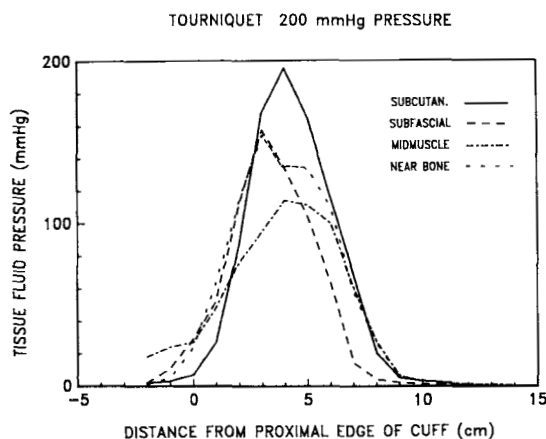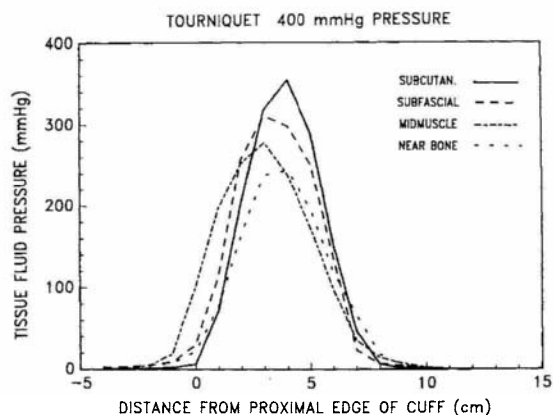

FIG. 2. Distribution of tissue fluid pressure at four depths beneath pneumatic tourniquet with cuff pressure of 200 mm Hg applied on arms. Values represent means for six arms.
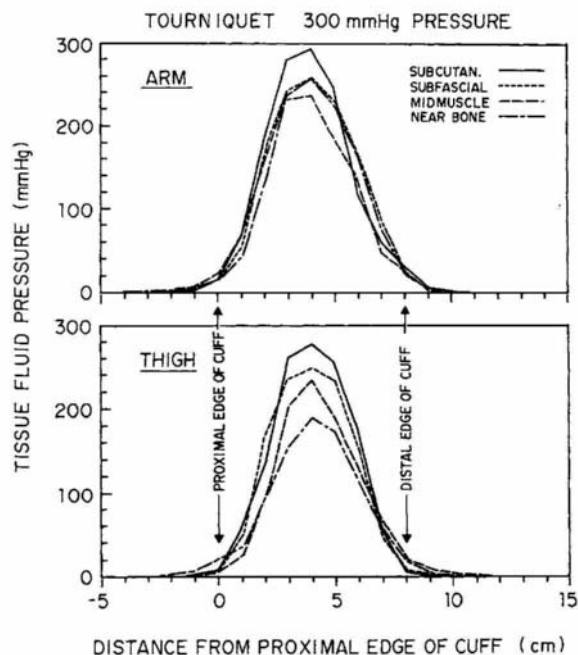
FIG. 3. Distribution of tissue fluid pressure at four depths beneath pneumatic tourniquet with cuff pressure of 300 mm Hg applied on arms (top) and thighs (bottom). Values represent means for six limbs on each graph.

TFPs in tissues near the femur were 155 mm Hg below cuff pressure, indicating lower effectiveness of cuff compression to deeper tissues.

Regional TFPs at higher and lower cuff pressures followed the same patterns as those depicted for 200 mm Hg (Fig. 2), 300 mm Hg (Fig. 3), and 400 mm Hg (Fig. 4), but TFP differences between tissue levels were not significant. At all four depths studied, TFP fell steeply in longitudinal directi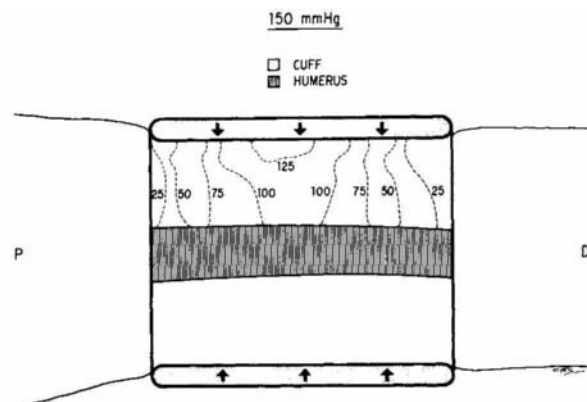ons near the edges of the cuff. Transmission of cuff pressure to deeper tissues was less in limbs of larger girth, and TFP fell to near zero at a point 1–2 cm outside the cuff edge. Isobaric patterns of TFP for a cuff pressure of 150 mm Hg applied to the arms (Fig. 5) and 300 mm Hg applied to the thighs (Fig. 6) demonstrated narrow cones of subcuff TFP directly beneath mid-cuff, with TFP decreasing rapidly with depth and distance from mid-cuff regions.

DISCUSSION

Our study investigated both radial and longitudinal patterns of TFP beneath a standard 8-cm tourniquet cuff applied to arms and thighs of fresh human cadavera. A major finding was that these cuffs are rather inefficient in compressing deep tissues near bone wherein some of the major arteries lie. This phenomenon explains why higher cuff pressures are routinely used on thighs as compared with arms to provide bloodless fields during orthopaedic surgery. Although they examined only radial distribution of total tissue pressure beneath thighs, Shaw and Murray (35) developed a nomogram relating tissue pressure beneath a standard 8-cm cuff to thigh circumference. Their study indicated that cuff pressure must be set at nearly 400 mm Hg on a thigh with a girth 59 cm and at ~250 mm Hg on a thigh with a girth of 34 cm to maintain a tissue pressure of 200 mm Hg in deep tissues near bone. They recommend a tissue pressure of 70–100 mm Hg above blood pressure to maintain a bloodless field under most clinical conditions.

Our present study, however, indicates that the standard 8-cm tourniquet cuff provides a rather narrow wedge of diminishing tissue compression di-

FIG. 4. Distribution of tissue fluid pressure at four depths beneath pneumatic tourniquet with cuff pressure of 400 mm Hg applied on thighs. Values represent means for six thighs.

FIG. 5. Isobaric (equal pressure) patterns of tissue compression beneath 8-cm tourniquet cuff applied to arms at a pressure of 150 mm Hg. All isobars are expressed in mm Hg. P, proximal; D, distal.

rectly beneath mid-cuff regions only (see wedge-shaped isobars in Figs. 5 and 6). Furthermore, another study by our laboratory indicates that wider tourniquet cuffs provide more effective, wider plateaus of tissue compression at all tissue depths (3) as compared with the standard cuff used in this investigation. For example, tissues near the femur receive only 64% of a 300-mm Hg cuff pressure when a standard 8-cm cuff is used (Fig. 3), whereas similar regions receive >95% of a 300-mm Hg cuff pressure when a 18-cm-wide cuff is used (3). In addition, studies of Doppler pulses distal to an arm tourniquet in 10 normal volunteers demonstrated that blood flow was eliminated at significantly lower cuff pressures when wide tourniquets were used as compared with results obtained with standard tourniquets as well as narrow tourniquets (20).

Comparing Esmarch-bandage tourniquets with standard 8-cm tourniquets, McLaren and Rorabeck indicated that "a wider tourniquet relative to limb diameter will generally lead to greater pressure concentration in the deep tissues" (18). Therefore, they concluded that these situations increase the risk of nerve injury. Readers of their article may assume that a wide cuff requires the same internal pressure as a narrow cuff to occlude blood flow to distal tissues. Results in our present study indicate, however, that the standard tourniquet ineffectively transmits compressive forces to deep tissues. Subsequent studies confirm that wider cuffs provide better transmission of tissue compression (3) and lower the cuff pressure necessary for hemostasis (20).

It is not known why wide tourniquet cuffs eliminate blood flow at lower pressures than narrow

FIG. 6. Isobaric patterns of tissue compression beneath 8-cm tourniquet cuff applied to thighs at a pressure of 300 mm Hg. All isobars are expressed in mm Hg. P, proximal; D, distal.

cuffs. It is possible that wide cuffs create hemostasis without total collapse of the artery as a result of frictional resistance accumulation along the length of compression. On the other hand, very narrow cuffs require very high internal pressures (much greater than systolic blood pressure) to collapse deep arteries and occlude arterial flow. Therefore, depending on the extent of the surgical field required, we recommend using as wide a tourniquet cuff as possible in order to minimize the cuff pressure necessary for maintaining a bloodless field (20).

Although TFP gradients under cuffs exist from subcutaneous tissue (high TFP) to bone (low TFP) in cadaveric limbs, such gradients occur in an opposite direction when similarly inflated tourniquets are applied to isotropic Swedish sausages without bones (5). Therefore, our data suggest that tissue anisotropy prevents full transmission of an externally applied cuff pressure to tissues and blood vessels near bone. The material properties of cadaveric tissues probably change with time after death and tissue temperature; therefore, such changes may alter pressure patterns that we measured beneath the tourniquet cuff. The steep longitudinal gradients of TFP detected in this study suggest that tissue displacement away from mid-cuff is maximized in tissue regions beneath the cuff edges where tourniquet lesions primarily occur. Recent radiological studies of metal pellet movements beneath tourniquets (B. L. Rydevik, personal communication, 1986) and modeling studies (4) agree with this suggestion. In addition, although the limbs in our present study were fresh, cadaveric specimens, they were relatively small in girth due to the patients' advanced ages. Therefore, TFP gradients and tissue deformation under standard cuffs applied to younger patients may be even greater.

Injury to nerves is greatest beneath the tourniquet edges (4,21), and such lesions probably result from accumulation of shear stresses and greater tissue deformation at the edges of applied tourniquet cuffs (10). Because higher cuff pressure increases the pressure gradient and, presumably, tissue displacement at the cuff edge, the lowest cuff pressure that maintains hemostasis should be used. Although wide cuffs compress a greater mass of underlying tissue, risks of nerve lesions are probably reduced because lower cuff pressures may be used to provide a bloodless field. Overall, our results provide a quantitative framework for future studies of tissue pressure/tissue displacement/
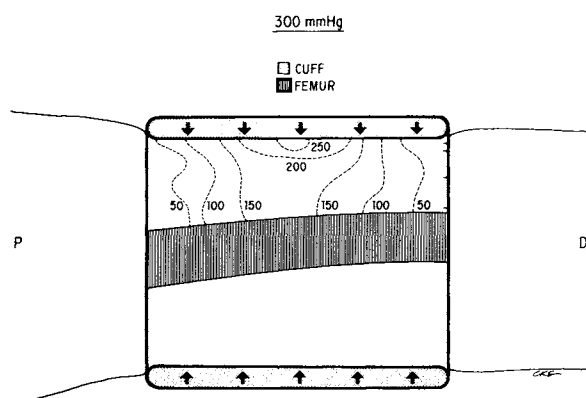
tissue necrosis patterns beneath cuffs applied to limbs for varying periods of time. Such knowledge is necessary for creating the best design and making best use of pneumatic tourniquets in orthopaedic surgery.

REFERENCES

1. Bolton CF, McFarlane RM: Human pneumatic tourniquet paralysis. *Neurology* 28:787–793, 1978
2. Chiu D, Wang HW, Blumenthal MR: Creatine phosphokinase release as a measure of tourniquet effect on skeletal muscle. *Arch Surg* 111:71–74, 1976
3. Crenshaw AG, Hargens AR, Gershuni DH, Rydevik B: Wide tourniquet cuffs: More effective deep tissue compression and loss of arterial pulse at lower inflation pressure. *J Bone Joint Surg* (submitted for publication)
4. Dahlin LB, Rydevik B, Lundborg G: Pathophysiology of nerve entrapments and nerve compression injuries. In: *Tissue Nutrition and Viability*, ed by AR Hargens, New York, Springer-Verlag, 1986, pp 135–160
5. Dahlin LB, Rydevik B, Lundborg G, Hargens AR, Skalak R: Distribution of tissue fluid pressure beneath a pneumatic tourniquet. *Trans 30th Ann ORS* 9:362, 1984
6. Dixon WJ: *Biomedical Data Processing Statistical Software.* Berkeley, CA, University of California Press, 1983, pp 347–358
7. Fowler TJ, Danta G, Gilliatt RW: Recovery of nerve conduction after a pneumatic tourniquet: Observations on the hind-limb of the baboon. *J Neurol Neurosurg Psychiatry* 35:638–647, 1972
8. Gardner VO, Caiozzo VJ, Long ST, Stoffel J, McMaster WC, Prietto CA: Contractile properties of slow and fast muscle following tourniquet ischemia. *Am J Sports Med* 12:417–423, 1984
9. Gianestras NJ, Cranley JJ, Lentz M: Occlusion of the tibial artery after a foot operation under tourniquet: A case report. *J Bone Joint Surg* 59A:682–683, 1977
10. Griffiths JC, Heywood OB: Bio-mechanical aspects of the tourniquet. *Hand* 5:113–118, 1973
11. Hargens AR, Gershuni DH, Gould RN, Gelberman RH, Zweifach SS, Mubarak SJ, Akeson WH: Tissue necrosis associated with tourniquet ischemia. *Recent Adv Microcirculatory Res, Bibl Anat* 20:599–601, 1981
12. Heppenstall RB, Balderston R, Goodwin C: Pathophysiologic effects distal to a tourniquet in the dog. *J Trauma* 19:234–238, 1979
13. Klenerman L: Tourniquet time—How long? *Hand* 12:231–234, 1980
14. Klenerman L, Biswas M, Hulands GH, Rhodes AM: Systemic and local effects of the application of a tourniquet. *J Bone Joint Surg* 62B:385–388, 1980
15. Klenerman L, Lewis JD: Incompressible vessels. *Lancet* 7963:811–812, 1976
16. Larsson J, Bergstrom J: Electrolyte changes in muscle tissue and plasma in tourniquet ischemia. *Acta Chir Scand* 144:67–73, 1978
17. Love BT: The tourniquet. *Aust NZ J Surg* 48:66–70, 1978
18. McLaren AC, Rorabeck CH: The pressure distribution under tourniquets. *J Bone Joint Surg* 67A:433–438, 1985
19. Modig J, Kolstad K, Wigren A: Systemic reactions to tourniquet ischaemia. *Acta Anaesth Scand* 22:609–614, 1978
20. Moore MR, Hargens AR: Wide tourniquets eliminate blood flow at low inflation pressures. *J Hand Surg* (submitted for publication)
21. Ochoa J, Danta G, Fowler TJ, Gilliatt RW: Nature of the nerve lesion caused by a pneumatic tourniquet. *Nature* 233:265–266, 1971
22. Ochoa J, Fowler TJ, Gilliatt RW: Anatomical changes in peripheral nerves compressed by a pneumatic tourniquet. *J Anat* 113:433–455, 1972
23. Patterson S, Klenerman L: The effect of pneumatic tourniquets on the ultrastructure of skeletal muscle. *J Bone Joint Surg* 61B:178–183, 1979
24. Patterson S, Klenerman L, Biswas M, Rhodes A: The effect of pneumatic tourniquets on skeletal muscle physiology. *Acta Orthop Scand* 52:171–175, 1981
25. Prevoznik SJ: Injury from use of pneumatic tourniquets. *Anesthesiology* 32:177, 1970
26. Risberg B: Fibrinolysis and tourniquets. *Lancet* 8033:360–361, 1977
27. Rorabeck CH: Tourniquet-induced nerve ischemia: An experimental investigation. *J Trauma* 20:280–286, 1980
28. Rorabeck CH, Kennedy JC: Tourniquet-induced nerve ischemia complicating knee ligament surgery. *Am J Sports Med* 8:98–102, 1980
29. Rudge P: Tourniquet paralysis with prolonged conduction block: An electro-physiological study. *J Bone Joint Surg* 56B:716–720, 1974
30. Rydevik B, Lundborg G: Permeability of intraneural microvessels and perineurium following acute, graded experimental nerve compression. *Scand J Plast Reconstr Surg* 11:179–187, 1977
31. Rydevik B, Lundborg G, Bagge U: Effects of graded compression on intraneural blood flow: an *in vivo* study of the rabbit tibial nerve. *J Hand Surg* 6:3–12, 1981
32. Santavirta S, Kauste A, Rindell K: Tourniquet ischemia: Clinical and biochemical observations. *Ann Chir Gynaec* 67:210–213, 1978
33. Sapega AA, Heppenstall RB, Chance B, Park YS, Sokolow D: Optimizing tourniquet application and release times in extremity surgery. *J Bone Joint Surg* 67A:303–314, 1985
34. Saunders KC, Louis DL, Weingarden SI, Waylonis GW: Effect of tourniquet time on postoperative quadriceps function. *Clin Orthop* 143:194–199, 1979
35. Shaw JA, Murray DG: The relationship between tourniquet pressure and underlying soft-tissue pressure in the thigh. *J Bone Joint Surg* 64A:1148–1152, 1982
36. Solonen K, Hjelt L: Morphological changes in striated muscle during ischaemia. *Acta Orthop Scand* 39:13–19, 1968
37. Thio RT: False aneurysm of the ulnar artery after surgery employing a tourniquet. *Am J Surg* 123:604–605, 1972
38. Tountas CP, Bergman RA: Tourniquet ischemia: Ultrastructural and histochemical observations of ischemic human muscle and of monkey muscle and nerve. *J Hand Surg* 2:31–37, 1977
39. Ward CM: Oedema of the hand after fasciectomy with or without tourniquet. *Hand* 8:179–185, 1978
40. Weingarden SW, Louis DL, Waylonis GW: Electromyographic changes in postmeniscectomy patients. *JAMA* 241:1248–1250, 1979