Occlusion of Arterial Flow in the Extremities at Subsystolic Pressures Through the Use of Wide Tourniquet Cuffs

BRENT GRAHAM, M.D., F.R.C.S.C., MARTINE J. BREAULT, M.A.SC.,
JAMES A. MCEWEN, PH.D., P.ENG.CCE, AND ROBERT W. MCGRAW, M.D., F.R.C.S.C.

Tourniquet-induced peripheral neuropathy is at least partially attributable to excessive forces applied to the nerves beneath cuffs inflated to high pressures. Lowering the inflation pressure to the minimum necessary to obtain an effective arrest of blood flow distal to the tourniquet cuff should increase the safety of these systems. Tourniquet cuffs with widths varying from 4.5 cm to 80 cm were applied to the upper and lower extremities of 34 healthy, normotensive volunteers. Occlusion pressure for the arterial system under study was estimated by determining that level of cuff inflation at which the distal pulse became detectable by ultrasonic flowmetry. The occlusion pressure was inversely proportional to the ratio of tourniquet cuff width to limb circumference and was in the subsystolic range at a cuff width to limb circumference ratio above 0.5. Wide tourniquet cuffs can achieve an effective arrest of the regional arterial circulation at subsystolic pressures of inflation. Wide cuffs may reduce the risk of tourniquet-induced injury to underlying soft tissues by lowering the inflation pressure required to secure a bloodless field.

Although the precise pathogenesis of tourniquet-induced neuropathy remains controversial, it is generally agreed that the incidence and severity of electrophysiologic abnormalities is related to excessive and prolonged pressure applied to neurologic structures beneath the tourniquet cuff.[1,4,5,19,21] A previous study demonstrated, in limbs of normal dimensions, that tourniquet inflation pressures are transmitted to the major peripheral nerves of the limbs with little or no attenuation.[6] Furthermore, the distribution of perineural pressures under a tourniquet cuff is described by a parabolic curve, with peak levels at the midpoint of the cuff and much lower pressures at the proximal and distal edges.[6] The difference between soft-tissue pressures at the midpoint and edges of the cuff increases at higher levels of cuff inflation.[6] This distribution of pressure may lead to the development of shear forces that can cause structural damage to underlying nerves.[18] These findings indicate a need for improved cuff designs, which are effective at lower inflation pressures and allow a better distribution of forces to underlying soft tissues.

Previous investigations have shown that sphygmomanometer estimates of arterial blood pressure in the upper extremity vary with the ratio of blood pressure cuff width to limb circumference.[25,26] These findings predict that wide tourniquet cuffs, applied to adult limbs of normal size, will arrest arterial blood flow at levels of inflation that are much lower than those required by standard tourni-

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From the Departments of Orthopaedic Surgery and Biomedical Engineering, University of British Columbia, Vancouver, British Columbia, Canada.

Reprint requests to Dr. Brent Graham, Department of Orthopaedic Surgery, 3rd Fl., 910 W. 10th Ave., Vancouver, B.C. Canada V5Z 4E3.

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quet cuffs. The objective of this study was to test this hypothesis by determining the occlusion pressure for arterial blood flow in the upper and lower extremities under tourniquets of varying width.

MATERIALS AND METHODS

Tourniquet and blood pressure cuffs with widths of 4.5, 5.5, 7.5, 8.5, 10, 15.5, and 18 cm (Aspen Labs, Englewood, Colorado) were applied to the upper and lower extremities of 34 healthy, normotensive volunteers who had no evidence or history of vascular disease. In addition, an air splint that could be applied to the entire upper or lower limb through a width of 65–80 cm also was used to apply pressure over the maximal area available proximal to the hand or foot. Snugness of cuff application was qualitatively controlled by wrapping the cuff onto the limb, sufficiently tightly so that one finger could be admitted readily under the cuff from the proximal edge, but so that three fingers could not be readily admitted.[3] Measurements of limb circumference were made at the proximal and distal edges of the tourniquet cuff. Systolic and diastolic blood pressures were measured using a standard blood pressure cuff and an automatic, noninvasive arterial blood pressure monitor (Dinamap, Critikon, Tampa, Florida) before and after testing, as well as at three- to five-minute intervals during cuff inflation. Arterial flow distal to the tourniquet was monitored with an ultrasonic Doppler flowmeter (Parks model 801-A, Aloha, Oregon) at the radial artery in the wrist and the dorsalis pedis artery on the dorsum of the foot. The tourniquet cuff was inflated to a level approximately 100 mm Hg above the observed systolic blood pressure using an Aspen ATS 1000 pneumatic tourniquet system (Aspen Labs). The cuff then was deflated at a rate of about 1 mm Hg per second. The level of inflation at which flow in the distal limb was detected by the Doppler flowmeter was recorded as the estimated occlusion pressure for the arterial system beneath the tourniquet. Several determinations were made for each testing situation so that an average estimate for occlusion pressure could be established.

RESULTS

An inverse relationship was noted, in both the upper and lower extremity, between occlusion pressure and tourniquet width. The data obtained from testing in the arm and leg were combined by plotting occlusion pressure against the ratio of cuff width to limb circumference (Fig. 1). At a ratio of less than 0.1:1, occlusion pressure was in excess of 400 mm Hg. Conversely, cuff width to limb circumference ratios above 0.5:1 were associated with occlusion pressures in the subsystolic range. Occlusion pressure approached the diastolic blood pressure at a cuff width to limb circumference ratio of about 1:1.

Computer-assisted curve fitting allowed a mathematical description of the data to be obtained, incorporating terms for systolic and diastolic blood pressure, cuff width, and limb circumference:

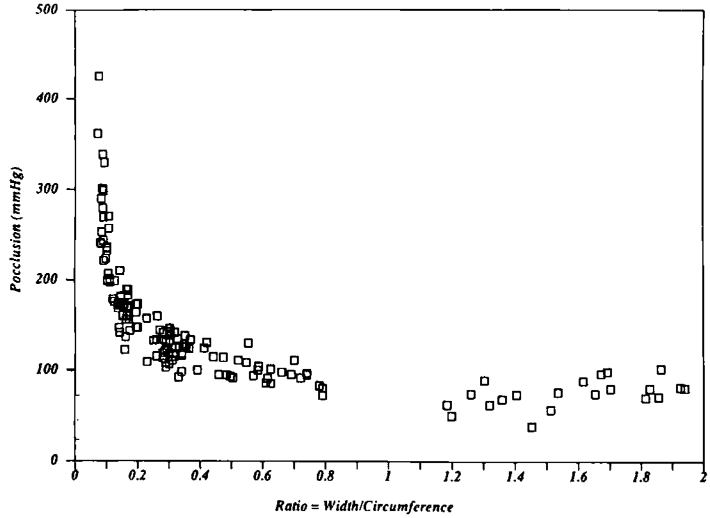

FIG. 1. Occlusion pressure ($P_{occlusion}$) versus the ratio of tourniquet cuff width to limb circumference. At ratios of less than 0.1:1, the occlusion pressure is more than 400 mm Hg. However, at ratios above 0.3, the occlusion pressure is in the subsystolic range ($P_{occlusion}$ = occlusion pressure; width/circumference = ratio of tourniquet cuff width to limb circumference).

$$P_{occc}$$

$$= \frac{(P_{sys} - P_{dia})(\text{limb circumference})}{3(\text{cuff width})} + P_{dia}$$

where

P_{occ} = occlusion pressure

P_{sys} = systolic blood pressure

P_{dia} = diastolic blood pressure

This relationship predicts that the occlusion pressure (P_{occ}) will be subsystolic for a normotensive patient when the cuff width to limb circumference ratio is greater than 0.3:1.

DISCUSSION

The obvious advantage of establishing a bloodless field for surgical procedures on the extremities has made utilization of the pneumatic tourniquet a standard practice in surgery of the extremities. The occurrence of tourniquet-related morbidity is commonly reported, however, and subclinical injuries to soft tissues probably occur frequently.[2,13,15,21,24] Structural[18] and metabolic[20] abnormalities associated with standard tourniquet cuffs have stimulated attempts to determine the maximum inflation pressure that can be safely maintained for the duration of a surgical procedure.[1,7-10,14,16,17,19,20,23,26] Current recommendations generally assume that, to be effective, cuff inflation pressure can be no lower than the patient's systolic blood pressure. Although it is well known that measurements of blood pressure are affected by the ratio of blood pressure cuff width to limb circumference, the role of this variable in defining the minimum tourniquet cuff inflation pressure necessary to secure a regional circulatory arrest has not been extensively investigated.

Shaw and Murray[23] studied soft tissue pressure-distributions under a pneumatic tourniquet cuff of standard width in disarticulated anatomic specimen limbs of different sizes. They concluded that in larger extremities, cuff inflation to higher than usual levels was necessary to achieve a pressure in the center of the limb sufficient to exceed the systolic blood pressure of the patient. McLaren and Rorabeck[14] suggested that the use of a wide tourniquet might result in a pressure concentration within the limb. This was based on observations of soft-tissue pressure distributions within canine hindlimbs to which pneumatic tourniquets or Esmarch bandages had been applied.

Moore *et al.*[16] studied wide tourniquet cuffs applied to the upper extremity in healthy normotensive volunteers and demonstrated that Doppler occlusion pressures were lowest in association with a tourniquet cuff having a width of 15.5 cm. The highest pressures were observed with a cuff 4.5 cm in width, and intermediate findings were associated with a cuff 8 cm wide. Their analysis of this data indicated that occlusion pressure was strongly related to tourniquet cuff width. They noted a less significant relationship between occlusion pressure and limb circumference and did not find any significant effect of the variable of systolic blood pressure on occlusion pressure.

A similar study was done under clinical conditions by van Roekel and Thurston.[27] A tourniquet cuff of unspecified width was applied to upper and lower limbs of patients treated with elective surgical procedures. Cuff pressure was maintained at a high level throughout the case but, before the wound closure, a slow deflation was carried out and the pressure at which capillary bleeding began was recorded. They noted a direct relationship between the pressure at which capillary bleeding occurred and the limb circumference. These data were used to derive equations relating predicted effective inflation pressure to limb circumference and systolic blood pressure. This relationship was used to predict an occlusion pressure that successfully achieved a bloodless surgical field in a subsequent series of 15 patients. An examination of their data indicates that, at the smallest limb circumferences in the arm and the leg, the pressure at which capillary bleeding occurred was less than the systolic blood pressure.

The data obtained in the current study largely confirms these earlier findings using a similar experimental protocol. An important factor that was not considered in the previous reports is the snugness of cuff application. Pilot studies from the authors' laboratory have indicated that the maximum pressure actually transferred to the limb by a loosely applied inflatable cuff may be as little as 50% of the pressure in the cuff bladder.[3]

Combining the variables of cuff width and limb circumference and controlling snugness of cuff application allowed observations of Doppler occlusion pressure in the upper and lower extremity to be evaluated together. The results show that there is a constant inverse relationship between occlusion pressure and the ratio of cuff width to limb circumference. The occlusion pressure enters the subsystolic range when the ratio of cuff width to limb circumference is greater than 0.3 and approaches the diastolic pressure when the cuff width/limb circumference ratio equals 1.0.

The manner in which arterial flow is impeded by a wide tourniquet inflated to subsystolic pressure is not known. The analysis of blood flow within a collapsible tube is complex, owing to the non-Newtonian characteristics of blood, its variable viscosity under conditions of changing shear rates, and the autoregulation of biologic systems.[22] The authors concur with Moore *et al.*,[16] however, that accumulation of frictional resistance along a segment of a blood vessel that is partially collapsed under a low-pressure pneumatic tourniquet may completely eliminate flow without actual occlusion of the vessel lumen.[3]

For clinical situations in which the use of a very wide tourniquet cuff is practical, the minimum effective pressure that will allow achievement of a bloodless surgical field will be in the subsystolic range. The authors' previous studies on soft-tissue pressure distribution under pneumatic tourniquets have shown that, at lower inflation pressures, forces transmitted to the perineural area of the major peripheral nerves of the upper and lower extremities are smaller.[3,6] Furthermore, the magnitude of pressure gradients in the soft tissues are smaller at lower inflation pressures, thus reducing the risk of significant shearing forces at the edges of the tourniquet cuff. The use of wider pneumatic tourniquet cuffs inflated to low pressure offers the potential for effective hemostasis under conditions that may provide greater safety than conventional systems currently in use.

As an extension of these studies and to facilitate routine and safe clinical usage of wider cuffs, the authors are developing a set of calibrated tourniquet cuffs in a variety of widths.[11] The calibration markings on the outer edge of the cuff will indicate to the clinician the minimum effective occlusion pressure when that type of cuff is snugly applied to a normal limb having an arbitrary circumference, and will do so within a 99% confidence limit. The longer-term objective is to incorporate calibrated wide cuffs into a complete adaptive tourniquet system that will vary inflation pressure in relation to ongoing changes in the patient's intraoperative blood pressure,[12] thus permitting the ideal tourniquet pressure to be approached more closely.

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