PERINEURAL PRESSURES UNDER THE PNEUMATIC TOURNIQUET IN THE UPPER EXTREMITY

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The literature indicates that tourniquet-induced neurological injuries are relatively common and frequently occur at a subclinical level. In order to evaluate the pressure transmitted to the major peripheral nerves of the arm by an externally applied pneumatic tourniquet, a fully implantable biomedical pressure transducer was placed adjacent the radial, median and ulnar nerves in six cadaver upper extremities of average dimensions. This sensor allowed accurate, reproducible measurements of perineural pressures without requiring significant disruption of the normal anatomical structures of the test limb for its installation. At levels of tourniquet cuff inflation which are commonly used in clinical practice, there was little or no decrease in the pressure detected in the perineural regions over that applied to the surface of the limb. In addition, there was a steep gradient of perineural pressure between locations beneath the edge of the cuff and those under its midpoint. This was most marked at the highest levels of tourniquet inflation. At presently accepted levels of inflation, pneumatic tourniquet cuffs transmit high pressures to the peripheral nerves without any significant attenuation by the intervening soft tissues. The distribution of these forces is one which may subject the underlying nerves to deleterious shear forces, especially at higher levels of inflation.

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Although the use of the pneumatic tourniquet has become a routine element of extremity surgery, the literature indicates that tourniquet-induced injury to soft tissues is relatively common and frequently occurs at a subclinical level (Bolton and MacFarlane, 1978; McGraw and McEwen, 1987; Middleton and Varian, 1973; Shaw and Murray, 1982; Yates et al., 1981). The pathogenesis of nerve injuries related to the use of a pneumatic tourniquet remains unclear but it is generally agreed that the incidence and severity of electrophysiological abnormalities is related to both excessive and prolonged pressure applied to nerves beneath the cuff (Bentley and Schlapp, 1943; Fowler et al., 1972; Parkes, 1973).

Published recommendations for the safe use of pneumatic tourniquet systems have often been based on clinical observations (Hurst et al., 1981; Klenerman, 1980; Moore et al., 1987; Mullick, 1978; Parkes, 1973; Rudge, 1974; van Roekel and Thurston, 1985). Several authors have attempted to produce more objective quidelines based on the evaluation of soft tissue pressure distributions at standard levels of tourniquet cuff inflation (Griffiths and Heywood, 1973; Hargens et al., 1987; McLaren and Rorabeck, 1985; Shaw and Murray, 1982) but these studies have used experimental models which may not accurately replicate the clinical situation. The goal of this study was to estimate the magnitude and distribution of pressures applied to the major peripheral nerves of the arm by an externally applied pneumatic tourniquet cuff inflated to pressures commonly utilized in clinical practice.

Method

A new biomedical tissue pressure transducer was designed for this study and comprised a longitudinally arrayed series of five electrical switches encased within an inflatable, ribbon-shaped, plastic enclosure (McEwen, 1989) (Fig. 1). The five sensing units are equally spaced along the enclosure so that, when implanted into a cadaveric limb, the proximal and distal switches are directly beneath the proximal and distal edges of an externally applied, standard-width pneumatic tourniquet cuff. Activation of each individual switch occurs in the following way: inflation of the sensor with a small volume of compressed gas separates each of the five electrical contact points. The pressure inside the sensor is continuously monitored while an external compression force is applied. When the external pressure exceeds that inside the sensor, the switch is activated by contact between the two surfaces of the compressed sensor and the pressure inside the device is recorded. In this way, the pressure distribution at five separate points along the longitudinal axis of the sensor can be determined. An automated data acquisition system using a customized software program was designed to calibrate the pressure sensor, intitiate the valves, control the rate of inflation and deflation of the pressure sensor, monitor the status of the sensor contacts and convert transducer output voltage into pressure data (Breault, 1988).

Six fresh, unembalmed upper extremities were tested. The limbs were intact and were not removed from the cadaver while the data were being collected. The limb circumference was determined by calculating the average of the circumference of the extremity at the proximal and distal edges of the tourniquet cuff.

Implantation of the tissue pressure transducer was carried out by making a 10 cm. incision over the anterolateral aspect of the arm. The plane between the brachialis and biceps muscles was gently developed and the flat sensor placed immediately adjacent to the median

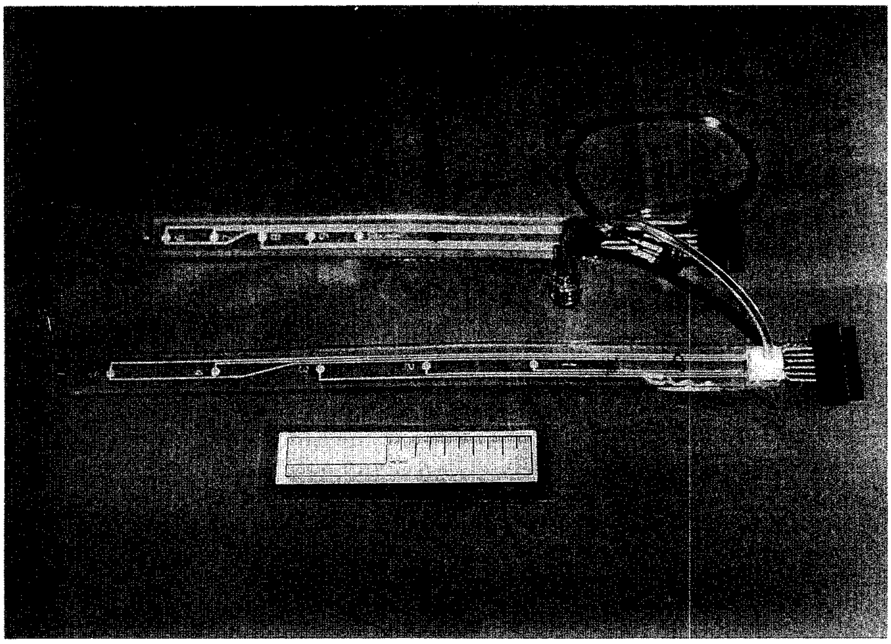

Fig. 1 The pressure transducer is ribbon-shaped facilitating its implantation. The five sensing contacts are equally spaced along the longitudinal axis of the device. The upper unit was used for perineural and limb surface pressure measurements under standard width 8.5 cm. upper limb tourniquet cuffs. The lower unit was used for measurements under lower extremity cuffs.

and ulnar nerves. A second transducer was placed next to the radial nerve in its location in the spiral groove on the posterior aspect of the humeral diaphysis (Fig. 2). In both locations, insertion of the sensor was accomplished with minimal disruption of the normal anatomical structures and the wounds were meticulously closed in order to preserve intact the normal soft tissue envelope of the limb. An additional sensor was also placed on the surface of the limb, beneath the tourniquet cuff. This allowed an accurate estimate of the pressure actually applied to the surface of the extremity by the inflated cuff.

A contoured Aspen pneumatic tourniquet cuff with a width of 8.5 cm. (Aspen Labs, Greenwood Village, Colorado) was used. The snugness of cuff application was qualitatively controlled by always wrapping the cuff onto the limb so that one finger could be admitted under the proximal edge of the cuff, but sufficiently tight so that three fingers could not be readily admitted (Breault, 1988). Cuff inflation was carried out using the Aspen ATS 500 tourniquet system (Aspen Labs, Greenwood Village, Colorado). All testing was completed within 24 hours of death.

In all six limbs, observations of perineural pressure distribution were made with the cuff inflated to 200 mmHg. In one specimen the cuff was also inflated to 100 mmHg. and 300 mmHg.

Results

The cadavers were all of normal body habitus. There were no obese specimens. The limb circumference ranged between 21.6 and 28.2 cm. with a mean of 24.7 cm. Collation of the pressure data obtained at each of the five sensing cells of the tissue pressure transducer allowed an estimate of the pressure distribution along the longitudinal axis of each nerve beneath the tourniquet cuff. For both the radial and median/ulnar nerve locations this corresponded to a parabolic curve with the peak pressures located under the midpoint of the cuff and the smallest pressures detected at the proximal and distal edges of the cuff. The pressure distribution at the limb surface was very similar. At a cuff inflation pressure of 200 mmHg., the pressure distribution in the two perineural locations corresponded very closely to that at the limb surface indicating no significant attenuation of pressure transmission in the subcutaneous tissues (Fig. 3).

In the limb in which perineural pressures were monitored at cuff inflations of 100 mmHg., 200 mmHg. and 300 mmHg., a similar type of parabolic pressure distribution was observed. At each inflation pressure, the peak perineural pressures detected under the midpoint of the tourniquet cuff were the same as those detected at the limb surface and were approximately equal to the cuff inflation pressure. Under the edges of the cuff, the

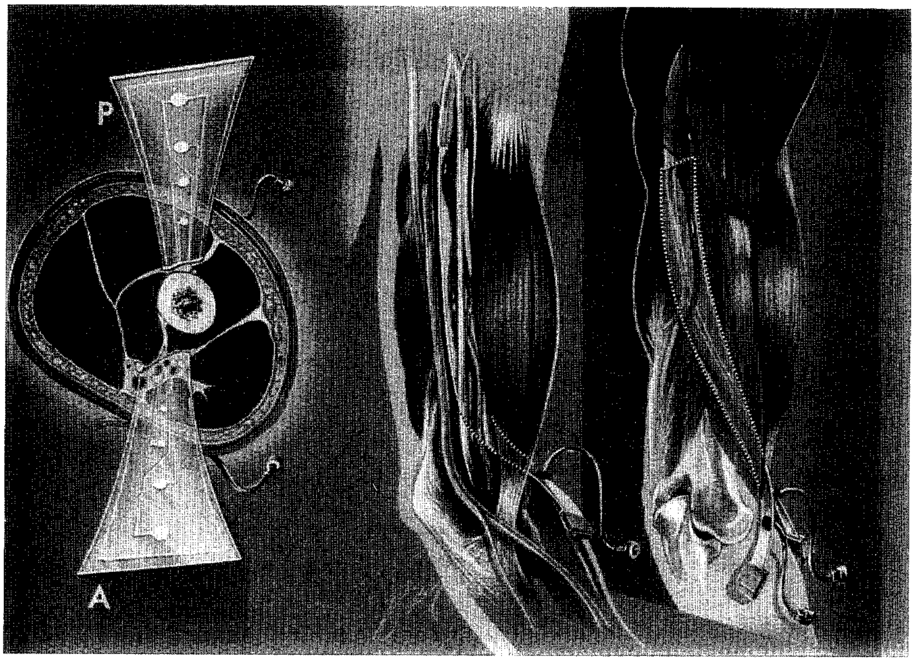

Fig. 2 Transducers were placed immediately adjacent the median and ulnar nerves on the medial aspect of the anterior compartment of the arm (centre) and the radial nerve in the spiral groove (right).

pressures at the limb surface and the perineural locations were only slightly increased. This resulted in a much steeper gradient of pressure between the areas under the edges and midpoint of the cuff at the higher levels of inflation (Fig. 4).

Discussion

Previous studies which have described soft tissue pressure distribution under a pneumatic tourniquet cuff have utilized a variety of experimental models and measurement techniques. Shaw and Murray (1982) reported the results of observations on previously frozen hip disarticulation specimens. A tubular pressure probe inserted through the proximal portion of the limb, was placed at various locations in the thigh under a standard 8.5 cm. pneumatic tourniquet cuff. They noted that the soft tissue pressure tended to decrease as the probe was placed more deeply in the limb from a subcutaneous position to a location nearer the bone. In the smaller specimens the attenuation of pressure through the limb was only about 20 mmHg. However, in obese specimens there was a much greater loss of pressure in the subcutaneous layer. They concluded that the pressure centrally in the limb is consistently lower than the tourniquet pressure by an amount proportional to the circumference of the limb. The results of their study suggest that, for limbs of average size, the soft tissue pressure was close to that applied to the surface of the limb by the tourniquet cuff. Their use of a previously frozen specimen may have influenced the soft tissue elasticity even after thawing and the effect of this variable is not known. In addition, the use of a free limb introduces the possibility that any loss of soft tissue pressure through the open end of the amputated extremity may have resulted in spuriously low pressures.

A similar study by Hargens et al. (1987) reported soft tissue pressures in fresh disarticulation specimens of upper and lower extremities under an 8.0 cm. pneumatic tourniquet. Pressure measurements were made with a slit catheter in subcutaneous, subfascial, mid-muscular and periosseous locations. Their results confirmed the earlier findings of Shaw and Murray using a different technique for measuring pressure. They also noted that the peak pressures were located under the midpoint of the cuff. Similar findings have been noted in studies using animal models (McLaren and Rorabeck, 1985).

The results of our study confirm these earlier findings and provide more specific information regarding the transmission of externally applied forces to the perineural areas under a pneumatic tourniquet cuff. In limbs of normal dimensions, the forces applied to the perineural areas is approximately the same as that applied to the limb surface by the inflation of a pneumatic tourniquet cuff. Under the midpoint of the cuff the pressures are the highest and approximately equivalent to the level to

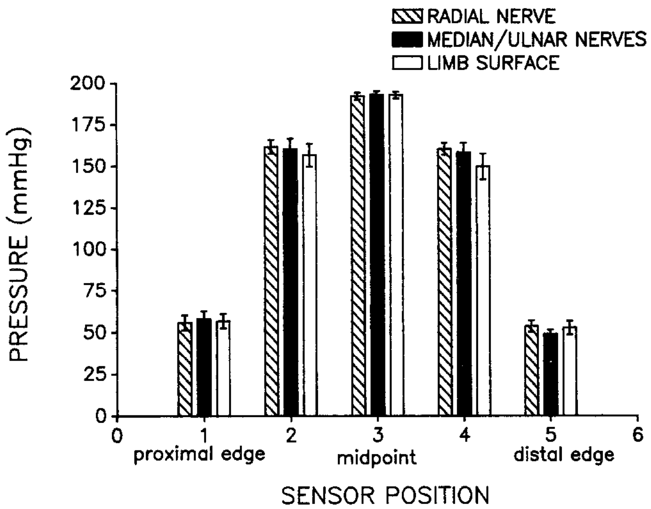

Fig. 3 Perineural and limb surface pressures under a pneumatic tourniquet cuff inflated to 200 mmHg. The pressure distribution in the perineural region of the radial and median/ulnar nerves, as well as on the limb surface, corresponded to a parabolic curve with the highest pressures detected under the midpoint of the cuff and the lowest pressures under the proximal and distal edges.

which the cuff is inflated. In addition, there is a pressure gradient between perineural areas under the edges and midpoint of the pneumatic cuff. At higher levels of inflation this gradient is markedly increased and may create significantly shearing forces on the nerves. Ochoa et al. (1972) have shown in a primate model that

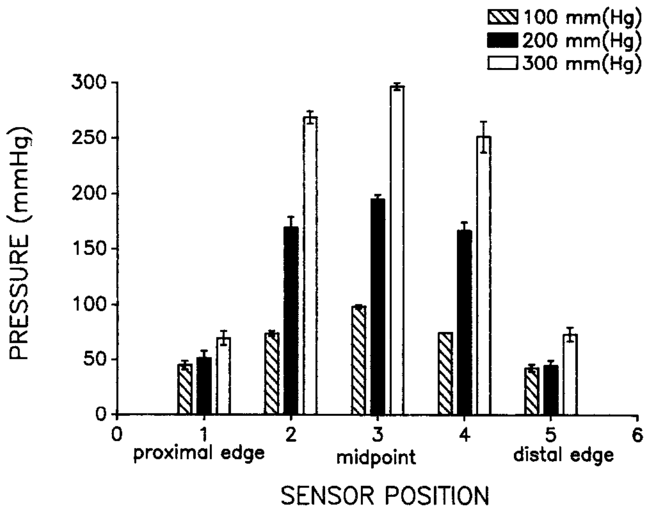

Fig. 4 Average perineural pressure at the radial and median/ulnar nerves under a pneumatic tourniquet cuff inflated to 100 mmHg., 200 mmHg. and 300 mmHg. At higher levels of inflation, the gradient in pressure between the perineural areas under the edges and midpoint of the tourniquet cuff becomes progressively greater.

compression of peripheral nerves by a thin tourniquet causes proximal and distal displacement of the nerve away from the point of peak pressure under the midpoint of the tourniquet cuff and toward the areas of smaller pressure at the cuff edges. Subluxation of the myelin sheath at the nodes of Ranvier was observed and related to the direction and magnitude of externally applied pressure.

There is little published data in the literature relating externally applied tourniquet pressures to those forces around neurovascular structures inside obese limbs. Our data was derived only from cadavers of a normal body habitus and any conclusions based on these results can only be applied to limbs which are normal in size. Our previous studies (Breault, 1988; Graham et al., in press) have shown that the relationship between the width of the tourniquet cuff and the circumference of the limb is an important consideration in determining the minimum effective inflation pressure ensuring a cessation of arterial flow distal to the cuff. For larger limbs it may be safer and equally effective to use a wider, well contoured tourniquet cuff inflated to slightly supersystolic pressures than to use a standard cuff inflated to a much higher level.

On the basis of observations, we conclude:

1. Pressures applied to a normally sized arm by an externally applied tourniquet cuff are transmitted to underlying peripheral nerves with no significant attenuation in the intervening soft tissues.
2. The highest pressures are manifested under the midpoint of the cuff and the lowest pressures are under the cuff edges.
3. At higher levels of inflation the pressure gradient between areas under the edges and midpoint of the cuff may result in the creation of deleterious shear forces applied to the nerves.

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