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THE EFFECT OF PNEUMATIC TOURNIQUETS ON SKELETAL MUSCLE PHYSIOLOGY

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The effect of 3- and 5-hour pneumatic tourniquets on skeletal muscle physiology was investigated. Maximum isometric tension development, contraction and half relaxation times were measured in the muscles lying immediately under and distal to the tourniquet. On release of the tourniquet no consistent difference between control and experimental muscles was observed with respect to contraction and half relaxation times; however, there was a marked reduction in maximum isometric tension development. On the sixth day after release of a 5-hour tourniquet, isometric tension was reduced to 2–20 per cent of the control value in the distal muscle and to 40–60 per cent of the control value in the compressed muscle. Six days after a 3-hour tourniquet the compressed muscle tension was reduced to approximately 80 per cent of the control value whilst in the distal muscle, tension development varied from normal to 64 per cent of the control value. Thus it is shown that the effect on muscle contraction after a 3-hour tourniquet is not immediately reversed by the restoration of the blood supply. A reduction in muscle strength follows which may take a week or more to recover.

Key words: ischaemia; isometric tension; muscle physiology; pneumatic tourniquet

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Physiological and biochemical changes are known to occur in muscle and nerve shortly after the application of a tourniquet. The venous blood supply from ischaemic limbs in man shows a significant fall in Po_2 and pH after 30 minutes whilst the Pco_2 is raised (Wilgis 1971). Other studies in man have demonstrated a reduction of muscle phosphocreatine and a rise in lactate levels after 30 minutes; however, the amount of ATP shows no marked change after 90 minutes (Haljämae & Enger 1975). Paul (1961) found a block in neuromuscular transmission after 13 minutes in a rat muscle nerve preparation subject to anoxia, whilst the muscle fibres of the preparation remained sensitive to direct electrical stimulation for 40 minutes. On release of 3-hour pneumatic tourniquets from baboons a block in nerve conduction has been observed which, in the case of some animals, did not show significant signs of recovery until 6 to 8 weeks had elapsed (Fowler et al. 1972). However, there was little change in the conduction capacity of the nerve distal to the tourniquet.

The effect of pneumatic tourniquets on muscle and nerve is important in orthopaedic practice. Our research interests have centred on establishing the safety margins for their use. By selecting a primate as our experimental animal, it is hoped to obtain results which closely parallel the human situation.

Recently the effect of pneumatic tourniquets on the ultrastructure of the rhesus monkey skeletal muscle has been investigated (Patterson & Klenerman 1979). These studies indicated that 3 hours is close to the limit that a tourniquet may be applied to a limb without causing severe structural damage. In addition, it was found that the compressed muscle lying under the tour-

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niquet was more severely affected than the distal muscle. These investigations have now been extended to examine the physiology of muscle from limbs that have been subjected to 3- and 5-hour pneumatic tourniquets.

MATERIALS AND METHODS

Adult cynomolgus monkeys weighing 2.5 to 4 kg were used. After a preliminary injection of ketamine hydrochloride (10 mg/kg) anaesthesia was induced by nitous oxide, halothane and oxygen. The animal was intubated and an intravenous drip (0.18 per cent saline, 4.2 per cent dextrose) was set up for the duration of the anaesthesia. Anaesthesia was maintained with 33 per cent oxygen in nitrous oxide and 0.6–0.7 per cent halothane. Ventilation was controlled using a Harvard rodent ventilator. The right internal carotid artery was cannulated and connected to a Bell and Howell pressure transducer for continuous monitoring of the blood pressure on a devices M19 light channel recorder. Shortly after the induction of anaesthesia physiological measurements were made on the muscle to be subsequently compressed by the tourniquet, the quadriceps, and on a muscle lying distal to the tourniquet application site, the gastrocnemius/soleus complex. On completion of the measurements a Kidde tourniquet cuff of infant size was applied to the mid-thigh of the right lower limb for periods of 3 or 5 hours at a pressure of 300 mmHg. Immediately the tourniquet was released the physiological measurements were repeated. Other experiments were performed in which animals were anaesthetised and tourniquets subsequently applied to the right lower limb for periods of 3 or 5 hours. On removal of the tourniquet the animals were allowed to recover from the anaesthesia and returned to their cage. After 1, 6 or 7 days the animals were anaesthetised again and physiological measurements carried out to assess the delayed effects of the application of a tourniquet. In the majority of cases two animals were used for each set of experimental conditions. The opposite limb served as a control in all experiments.

Measurement of physiological properties

The animals were positioned on a specially made stand with knees flexed to 90° and the calves parallel to the surface of the stand (see Figure 1). Kirchner wires passed through the upper and lower ends of each tibia were used to securely anchor the limbs to the stand. The quadriceps tendon was attached by a wire passed through the patella to a force transducer and the gastrocnemius/soleus complex was similarly secured by a wire passing through a segment of bone including the insertion of the tendo Achilles which had been excised from the calcaneum. The gastrocnemius complex and

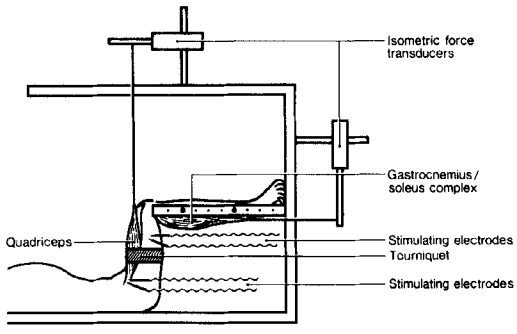

Figure 1. Apparatus employed to measure isometric tension development in the hind limb of the monkey.

quadriceps muscles were stimulated through the sciatic and femoral nerves respectively using a DC square wave stimulator to supply 0.5 millisecond pulses at 80 volts. The sciatic nerve was stimulated in the lower third of the thigh distal to the level of the tourniquet cuff and the femoral nerve just below the inguinal ligament at a site above the level of the tourniquet cuff. The voltage employed was twice that required to give the maximal isometric response. Muscles were stimulated at frequencies of 5, 8, 10, 15, 20, 30, 40, 50 and 60 pulses per second and the tension development recorded. In addition the muscles were given single stimuli at 1 second intervals for 30–40 seconds. From these isolated isometric twitches, contraction and half relaxation times (time for decay from maximum to 50 per cent of maximum twitch tension) were determined.

RESULTS

Monkeys returned to their cage after being subjected to 3 or 5 hour tourniquets showed no tendency to develop foot drop or impaired knee extension; however, the tourniquets did result in a marked swelling of the whole limb.

Physiological measurements

Maximum isometric tension was attained at a stimulus frequency of 40 per second or less in all experiments. The maximum tension development immediately after release of 3 and 5 hour tourniquets is shown in Figures 2 and 3. The results are expressed as a percentage of the pretourniquet value. Control limbs subject to the same measurement procedure showed no change in maximum tension development over the experi-

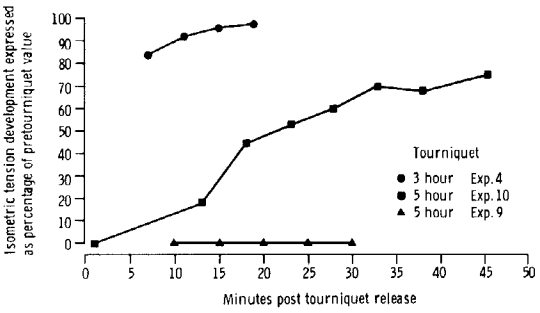

Figure 2. Maximum isometric tension in the gastrocnemius/soleus complex immediately after release of 3- and 5-hour tourniquets.

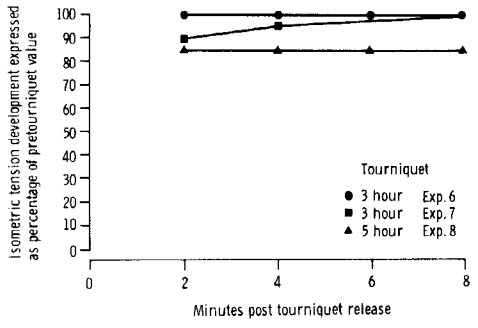

Figure 3. Maximum isometric tension development in the quadriceps immediately after release of 3- and 5-hour tourniquets.

mental period. Figures 2 and 3 illustrate a marked deterioration in isometric tension development when tourniquet periods were extended from 3 to 5 hours. Tension development returned to 95 per cent of the initial value, 15 minutes after release of a 3-hour tourniquet, in both the quadriceps and gastrocnemius/soleus muscles. After one 5-hour tourniquet experiment (experiment 9) it was not possible to obtain a contractile response from the gastrocnemius/soleus whilst in another experiment (experiment 10) a gradual increase in maximum isometric tension was observed, 75 per cent of the pretourniquet value being attained 48 minutes after release. The effect of 5-hour tourniquets on tension development measured immediately after tourniquet release appeared to be more severe in the gastrocnemius/soleus than in the quadriceps muscle.

Tension development measured on days 1, 6 or 7 after tourniquet release is shown in Table 1. These results are expressed as a percentage of the tension attained by the control limb. One day after release of a 5-hour tourniquet there was a marked reduction in tension development in both the quadriceps and the gastrocnemius/soleus muscles. Six days after a 3-hour tourniquet, only one muscle attained a maximum isometric tension which was similar to that of the control muscle.

The effects of 5-hour tourniquets were more severe than those lasting for 3 hours. Tension development was drastically reduced in the gastrocnemius/soleus muscles and, even at 6 or 7 days after release, there was little indication of recovery. With the exception of the rather anomalous value obtained in experiment 18, there was a significant reduction in the quadriceps tension development but this was generally less severe than in the gastrocnemius/soleus.

Table 1. Isometric tension development after tourniquet release. Results expressed as a percentage of control muscle tension.

	gastrocnemius/soleus	quadriceps
3-h tourniquet 1 day post release exp. 12	77	67
3-h tourniquet 1 day post release exp. 13	54	57
3-h tourniquet 6 days post release exp. 14	64	84
3-h tourniquet 6 days post release exp. 17	112	80
5-h tourniquet 1 day post release exp. 11	22	76
5-h tourniquet 1 day post release exp. 18	0	128
5-h tourniquet 7 days post release exp. 15	19	38
5-h tourniquet 6 days post release exp. 16	2	61

Electron microscopy was performed after a 5-hour tourniquet, the sample being taken 6 days after release. Both the gastrocnemius and quadriceps muscle fibres showed erosion of the Z disc similar to that described previously (Patterson & Klenerman 1979).

Measurement of contraction and half relaxation times revealed no consistent differences between control and experimental muscles. The frequency of stimuli required to produce complete tetanus (inability of the muscle to isolate repetitive stimuli) was similar in control and experimental muscles.

DISCUSSION

The present experiments on cynomolgus monkeys indicate that a 3-hour tourniquet causes a marked reduction in the ability of muscle to develop isometric tension. This reduction was only obvious 24 hours after release of the tourniquet in both the quadriceps and gastrocnemius/soleus muscles. An almost normal response was obtained within a few minutes of release of the tourniquet. Strock (1969) has demonstrated that on release of a tourniquet blood flow does not immediately return to all areas that had been ischaemic. In addition there is swelling of the limb and an increase in the interstitial muscle pressure (Miller et al. 1979). These factors may contribute to the deterioration in muscle performance observed 24 hours after tourniquet release. The deterioration in muscle strength was not fully reversed by the sixth day.

There was no consistent difference between experimental and control muscles with respect to the time course of contraction or the stimulation frequency at which tetanus is reached. This suggests that fibres which do contract are physiologically normal and that the reduction in maximum isometric tension reflects fewer fibres being brought into action in accordance with the all-or-nothing law.

After a 5-hour tourniquet tension development was more severely depressed, both in the immediate post-ischaemic phase and 6 or 7 days afterwards. The reduction in isometric tension was more marked in the gastrocnemius/soleus than in the compressed quadriceps muscle. The results show that a more marked deterioration in muscle contractile performance occurred when the tourniquet period was extended from 3 to 5 hours.

The reduction in isometric tension in all experiments was greater in the gastrocnemius/soleus than in the compressed quadriceps muscle. This is contrary to what would be expected from the previous ultrastructural findings in the rhesus monkey (Patterson & Klenerman 1979) but may possibly be accounted for by the morphology of the quadriceps muscle. The fibres of the quadriceps do not all run the whole length of the muscle as the rectus femoris is bipennate. The tourniquet was positioned in the middle third of the thigh and thus there was muscle proximal, distal and beneath the tourniquet which probably produced a mixed effect on the contractile power. Muscle samples from under and distal to the tourniquet were examined 6 days after a 5-hour tourniquet. Both muscles showed fibres with extensive erosion of their Z discs which would consequently render tension development impossible. Similar ultrastructural changes were observed after a 5 hour tourniquet in the rhesus monkey experiments but not so late as day 7 in the recovery phase. Thus although qualitatively similar events may occur in the cynomolgus monkey the time scale may be somewhat different.

It is difficult to be certain of the nature of the changes produced in muscle as a result of the ischaemia. They may reflect exhaustion of muscle ATP levels, alteration in the resting membrane potential of the muscles fibres, impairment of the excitation-contraction coupling system, a neuro-muscular block or an inability to generate action potentials in all the nerve fibres supplying the muscle. ATP levels are maintained in muscle by the breakdown of phosphocreatine. Studies by Haljäme & Enger (1975) have shown that phosphocreatine levels are decreased by 60 per cent after 90 minutes of ischaemia while ATP levels are unaltered. Thus it is conceivable that after 3 hours there may be insufficient phosphocreatine to maintain normal ATP levels. Little information is available on the effect of ischaemia on the excitation contraction coupling system of muscle but there is evidence that changes in the innerva-

tion system do occur during ischaemia (Creese et al. 1958, Paul 1961, Dahlbäck 1970). More recently (Weingarden et al. 1979) EMG abnormalities have been detected in the muscles of patients who had pneumatic tourniquets applied to their limbs during surgery.

Fowler et al. (1972) have applied tourniquets at a pressure of 1,000 mmHg to the limbs of baboons for periods of 1 to 3 hours. This resulted in a nerve conduction block at the tourniquet application site; however, there was no marked effect on the conduction of impulses in the nerve distal to the site of the tourniquet. Thus the impaired muscle response observed in our experiments employing a tourniquet pressure of 300 mmHg is unlikely to be attributable to pressure on the nerve since the nerve supplying the most severely affected muscle, the gastrocnemius/soleus complex, was stimulated below the tourniquet site.

From the viewpoint of the clinician these experiments have shown that although a limb apparently returns to normal as it flushes pink with release of a tourniquet, changes may occur which take some time to disappear. With regard to muscle, a 3 hour tourniquet produces effects on contraction which last about a week. This should be remembered after a long operation when patients are apparently slow in regaining muscle control around a joint such as the knee. These findings in relation to the muscle physiology taken in conjunction with the effects noted on electron microscopy (Patterson & Klenerman 1979) and on the acid-base level in the limb (Klenerman et al. 1980) reinforce the conclusion that 3 hours of ischaemia is near the upper limit of safety for the application of a tourniquet for elective procedures.

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