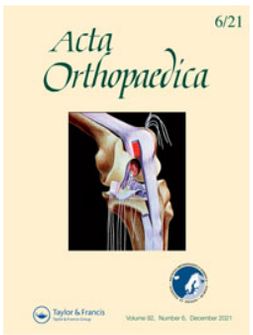

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HYPERAEMIA AND SWELLING OF A LIMB UPON RELEASE OF A TOURNIQUET

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Using monkeys, a quantitive study was carried out to measure the effect of a tourniquet on the lower limb on peak flow, the amount of acute swelling and the time for it to recover. The disappearance of acute swelling is related to the duration of the period of ischaemia. No significant change in peak flow was demonstrated as the duration of the tourniquet was increased.

Key words: lower limb; monkey; peak flow; swelling; tourniquet

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It is important for the surgeon who operates in a bloodless field to be aware of the effects of the ischaemia that has been produced. Although complications from the use of a tourniquet are rare, one of the most obvious effects is the occurrence of swelling due to the accumulation of fluid in the previous anoxic tissues. This swelling is the commonest cause of morbidity following operations in a bloodless field. Some of the fluid is a result of bleeding following surgical trauma. The purpose of this study was to measure the effect of varying periods of ischaemia produced by a tourniquet on the blood flow to a limb and also to record the amount of swelling which was produced. Postoperative swelling interferes with limb function and it is hoped that these measurements will provide a basis for a rational plan to reduce swelling to a minimum.

Santavirta et al. (1978) applied a tourniquet for up to 3 hours to the hind leg of the rabbit and found that reactive hyperaemia always occurred after release of the tourniquet. Using the ^{133}Xe washout technique, they showed no significant increase of peak blood flow with the length of time of tourniquet application; indeed their results suggest a slight decrease. The time taken to return to the normal baseline flow was longer after 2- and 3-hour periods of ischaemia than after 1 hour, but no statistical tests were applied.

In their experiments, different animals were used for 1-, 2- and 3- hour tourniquets, so it seems likely that the differences may be more clearly seen if all three measurements are made on the same animal. The object of this work is to influence the treatment of human patients, so the monkey, with its anatomy nearer to that of the human, appeared to us as a better choice of animal.

The ^{133}Xe technique is subject to errors due to the trauma of injection and uptake of ^{133}Xe by fat near the site of injection (Tonnesen & Sejersen 1970). However, it has the advantage that there is negligible recirculation allowing several repeat measurements over a relatively short period of time (Lassen 1971).

MATERIAL AND METHODS

Ten cynomolgus monkeys were used for this series of measurements and three measurements were made on each animal with a period of at least 1 week between measurements. The animal was anaesthetised using nitrous oxide, halothane and oxygen. An infant size Kidde tourniquet cuff was applied to the proximal part

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of the leg and a mercury in silastic plethysmograph was placed around the distal part of the leg at about the level of the proximal gastrocnemius muscle. In order to reduce temperature changes in the mercury, the silastic tube containing the mercury was threaded through a series of plastic blocks that kept the tube 4 mm from the skin.

The plethysmograph was calibrated using a vernier gauge and its stability was checked by placing it around a plastic cylinder and recording the measured circumference for 16 hours. This check showed that the plethysmograph drifted for the first 10 minutes, presumably owing to temperature changes in the components of the bridge circuit.

When the plethysmograph had reached a steady level on the animal's leg, the tourniquet was inflated to 300 mmHg and maintained at that pressure for 1, 2 or 3 hours. Whilst the tourniquet was inflated, sodium iodide scintillation detectors with crystals 50 mm diameter and 3 mm thick were placed over the distal part of the leg with a tourniquet and over the same area of the other leg as a control. Details of the detectors and collimators have been published elsewhere (Crawley & Veall 1975), and Hine (1967) has shown that a 3 mm thick sodium iodide crystal will absorb 95 per cent of 80 KeV photons.

The outputs of the detectors were taken via single channel analysers set to select the 80 KeV peak of ^{133}Xe to ratemeters with time constants of 0.3 seconds driving chart recorders. The detector over the leg with a tourniquet was also connected to a multiscaler with a dwell time of 0.8 second.

About 1 MBq (40 μCi) of ^{133}Xe in 0.1 ml isotonic saline was injected into the gastrocnemius muscle of each leg and the count rates were recorded for at least 15 minutes. When the tourniquet was released the control leg was given a second injection within 2 mm of the site of the first injection and the multiscaler was used as well as the chart recorder to record count rates from the experimental leg. Recording was continued until both legs gave similar washout curves upon simultaneous injection. The legs were re-injected within 2 mm of the original site whenever the count rate fell to about 10 per cent of the peak.

Blood pressure, rectal temperature and the temperature of the plethysmograph were monitored throughout the experiment. Usually two animals were measured on 1 day, using different times for the two tourniquets in order to avoid the need for urgent attention to both animals at once. When only one animal was available, plethysmographs were applied to both legs in order to check that the control leg did not change its diameter upon releasing the tourniquet.

Muscle blood flow was calculated from the slope of a smoothed curve of the logarithm of the count rate against time (Figure 1) using a Commodore PET computer which also gave a blood flow based upon a least squares fit over any selected portion of the curve. A blood tissue partition coefficient for ^{133}Xe of 0.7 was

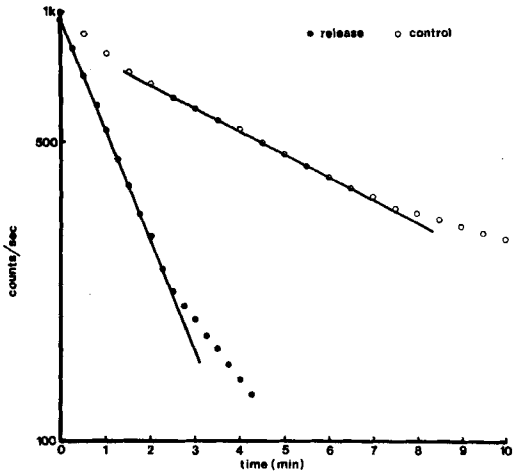

Figure 1. Washout of ^{133}Xe upon release of a tourniquet and simultaneous injection of a bolus into the control leg. Both curves have a long straight portion used to calculate flow and a slow final portion due to the presence of fat. The bolus injection gives rise to an initial fast flow due to trauma.

assumed (Lassen 1971). The PET computer was also used to correct measurements of leg diameter for changes in the temperature of the plethysmograph. The temperature coefficient of the plethysmograph was found by placing it around a cylinder with a low temperature coefficient of expansion and measuring the apparent change in diameter with temperature.

Because absolute measurements of flow are subject to errors, the results were expressed as the ratio of flows between the experimental and control legs as well as peak flows.

The ratio of flows decayed from a peak soon after release of the tourniquet to unity approximately as a single exponential, so the time to recover from the hyperaemia was expressed as a half period. The maximum percentage change in the circumference of the leg below the site of the tourniquet was used as a measure of swelling, which increased rapidly in the first 10 minutes after release of the tourniquet and then fell linearly to the initial value. The time to return to the initial value was taken as the time of swelling. With relatively small numbers of results it was not possible to show a normal distribution of errors; thus, results were compared using Wilcoxon's Signed Rank Test.

As a check on the reproducibility of the ^{133}Xe washout technique, a human leg (JCWC) was injected at the same site on each of three mornings (Tuesday, Wednesday and Thursday) immediately upon arriving at work. Resting flow, and flow under exercise on a treadmill were measured on each occasion (Crawley et al. 1977).

Table 1. Comparison of 1-hour, 2-hour and 3-hour tourniquet on a series of 10 monkeys

Measurement		1 h	difference 2–1	2 h	difference 3–2	3 h	difference 3–1
Peak flow (ml/100 g/min)	Mean	27.9	7.5	35.4	–3.6	31.8	3.9
Wilcoxon's Signed	S.D.	15.5	18	16.4	23	19.2	16
Ranks Test	*P*		N.S.		N.S.		N.S.
Peak ratio	Mean	7.4	0.17	7.6	0.15	7.7	0.32
Wilcoxon's Signed	S.D.	5.6	6	4.5	6	7.2	6
Ranks Test	*P*		N.S.		N.S.		N.S.
Half period of hyperaemia (min)	Mean	5.6	6.2	12	14	26	20
Wilcoxon's Signed	S.P.	2.2	9.2	10	22	18	18
Ranks Test	*P*		N.S.		N.S.		<0.01
Swelling (% of circumference)	Mean	1.2	0.59	1.8	0.91	2.7	1.5
Wilcoxon's Signed	S.D.	0.93	1.4	1	2.5	1.8	2
Ranks Test	*P*		N.S.		N.S.		N.S.
Time for swelling to recover (min)	Mean	6.1	36.7	42.8	111	154	148
Wilcoxon's Signed	S.D.	3	45	46	114	93	93
Ranks Test	*P*		<0.01		<0.05		<0.001
Blood pressure	Mean	89	7	96	–3.5	92.7	3.5
Wilcoxon's Signed	S.D.	14	17	14	34	22	2.5
Ranks Test	*P*		N.S.		N.S.		N.S.

RESULTS

A series of repeat measurements on the control legs of each animal was conducted as part of each experiment and combining all the measurements gives a coefficient variation of 29 per cent. Table 1 is a summary of all 30 measurements; for some animals there were large differences in blood pressure between the three experiments. For this reason the ratio of the flows was used rather than the difference when calculating the half period of the recovery, although no significant correlation between control leg and blood pressure was found on the few occasions when the blood pressure changed during an experiment.

Table 2. Measurements on a human leg on three successive days immediately upon arrival at work

		Blood Flow ml/100 g/min Rest	Exercise (4 km/h)
TUESDAY	before exercise	1.0	16.9
	after exercise	0.5	
WEDNESDAY	before exercise	0.7	16.8
	after exercise	1.4	
THURSDAY	before exercise	1.2	16.7
	after exercise	0.8	

The results of repeat experiments on a human gastrocnemius muscle are shown in Table 2. Whilst the coefficient of variation was only one per cent for the muscle flow under exercise, it was 36 per cent for the muscle at rest.

DISCUSSION

No significant change in peak flow with the duration of the tourniquet was observed, confirming the results of Santavirta et al. (1978). A correlation between peak flow and duration of ischaemia was observed by Nielsen & Sejersen (1972) in

experiments in man involving periods of ischaemia up to 30 minutes. These authors also showed that the rate of increase decreased with duration of the tourniquet. This may be because there is an upper limit to the capacity of the blood vessels which is reached by the hyperaemia following a 1-hour tourniquet. If there is a "perfusion debt" to be recovered (Klenerman et al. 1980), the only way to clear waste products is to prolong the hyperaemia, and this is what seems to happen. There is a considerable cooling of the limb which in turn would reduce the metabolic rate, so a smaller increase between 2 and 3 hours is not unexpected. The experiments could only be conducted on 1 day per week so there was a period of one to several weeks between measurements on the same animal. That the animals were not necessarily in the same physiological state on the three occasions is suggested by variations in blood pressure between the three measurements. This may be the reason for the smaller variation in the means of the peak ratios compared with the means of the peak flows.

The high coefficient of variation for repeat measurements on resting muscle in both monkey and man may be due to changes in the state of the muscle as well as errors in the measurement. Lassen & Holstein (1974) found a coefficient of variation of 25 per cent for a series of measurements of blood flow in human calf muscle and Tonnesen & Sejersen (1967) showed that in the gastrocnemius muscle of the cat, minute to minute variations in flow, measured by drop counting, could give rise to a coefficient of variation of 56 per cent.

The surprisingly close agreement between the three measurements of human muscle under exercise may be due to the more precise physiological condition of the muscle as well as the improved accuracy of the method due to the higher slope of the curve of the logarithm of counts against time.

The increase in diameter of the leg depends upon the position of the plethysmograph. The heat insulating plastic blocks were 8 cm wide, so a reasonable length of leg was measured. There is a small but not significant increase in the amplitude of the swelling (Table 1) whilst there is a highly significant increase in the duration of swelling between 1- and 3-hour tourniquets.

Trauma to the animal was minimal, a period of anaesthesia and a few intramuscular injections of ^{133}Xe in saline. It was possible to use each animal for three of these experiments and in most cases to allow them to survive for other work.

It appears that whilst the maximum hyperaemia flow and the maximum swelling are not directly related to the duration of the tourniquet, because there is individual variation, the time for acute swelling to recover after the use of a tourniquet depends upon the length of the period of ischaemia. The swelling which results from a tourniquet for 1 hour is rapidly overcome but the effects are much more obvious after 2 and 3 hours. When attempting to obtain haemostasis after release of a tourniquet prior to closure of the wound the surgeon should remember that for a 1 hour tourniquet the hyperaemia falls to one half in about 5 minutes but it takes about 12 and 25 minutes, respectively, for this to occur after 2 and 3 hours of tourniquet time.

CONCLUSIONS

1. The time for acute swelling to regress after the application of a tourniquet is related to the duration of the period of ischaemia.
2. No significant change in peak flow with the duration of the tourniquet was observed.

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