Acta orthop. scand. *48*, 291–295, 1977

LIMB BLOOD FLOW IN THE PRESENCE OF A TOURNIQUET

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There is little accurate data on the blood flow to a limb distal to the site of application of a tourniquet. This has been studied in Rhesus monkeys with 50 μ diameter microspheres labelled with ^{51}Cr and by the washout of ^{22}Na injected into the tissues. One limb was exsanguinated and the circulation occluded with a pneumatic tourniquet and the opposite limb used as a control. The results show that blood flow to the occluded limb is less than 1 per cent of the flow to the control limb. It is unlikely that this relieves the ischaemia in any way as has been suggested.

Key words: blood flow; ischaemia; limb; tourniquet

Accepted 19.i.77

It has been suggested that despite the application of a tourniquet to the proximal portion of the upper or lower limb, as is the practice in orthopaedic operations, blood may flow into the limb by way of the medullary canal. This may result after 30 minutes in an ooze into what was previously a dry field (Furlow 1971). Measurements of this blood flow have been made both experimentally in rabbits and at operation and the amount of blood by-passing the tourniquet has been recorded as varying from 1–26 per cent of the total flow to the unoperated limb (Spira et al. 1965). This circulation has been described as a factor in relieving the ischaemia produced by the tourniquet and to be of help in prolonging the period it is safe to keep it in place.

In order to clarify the situation, an investigation has been carried out on Rhesus monkeys. These animals were chosen because of their anatomical similarity to the human subject. The questions posed were: How much blood reaches the distal end of a limb with a tourniquet occluding the arterial inflow, and under these conditions, what is the extent of venous return?

MATERIAL AND METHODS

In the first series of animals, radioactive microspheres, about 50 μ in diameter, were used to study blood distribution, because they are almost completely extracted from the blood as it passes through the capillary bed (Wagner et al. 1969). The second series of animals was studied using ^{22}Na, plus the local clearance of a diffusable tracer, injected into tissue. At low flow rates, the washout rate provides an index of the blood perfusion (Kety 1949). ^{22}Na was also used to estimate the venous return from the limb.

Rhesus monkeys were anaesthetised using nitrous oxide, halothane and oxygen. The limb under investigation was exsanguinated with an Esmarch's bandage and the circulation was then occluded with the infant size cuff of a Kidde tourniquet, pumped up to a pressure of 300 mm of mercury, applied to the proximal portion of either upper or lower limb. Measurements of intra-arterial blood pressure in the aorta in Rhesus monkeys have shown a range similar to

man 175–110/95–65 mm of mercury with an average of 134_176 (Werdegar et al. 1964) and 136–117/84–71 mm of mercury (Forsyth & Baireuter 1967).

In the first series of animals, a catheter was passed into the left ventricle under radiological control and 10^6–10^7 particles (Tracer Sephadex 50 Pharmacia, Uppsala, Sweden) labelled with ^{51}Cr (Radio Chemical Centre, Amersham) in 0.3–1.0 ml were injected over a period of 20–40 seconds. The catheter was flushed with 5 ml of isotonic saline and a bolus of 5 ml of radiopaque contrast medium was used to check that the catheter was still in place and therefore that material from the catheter was well mixed before entering the aorta.

The activity in the syringe was measured before and after injecting the particles and the activity in the catheter was measured after it had been withdrawn. The external measuring system consisting of two 7.5 diameter × 5 cm thick sodium iodide scintillation detectors with 5 cm thick lead collimators was used to measure the activity in the extremities of the monkey as well as the injected dose. The effects of background from the trunk of the monkey was reduced by fixing a lead screen between it and the detectors, passing the limb through a 5 cm wide slot in the screen. After each measurement, a background reading was taken with the limb moved to a position just outside the lead screen. In each experiment the fraction of cardiac output to the region of the limb with the tourniquet was compared with a similar region on the opposite limb as a control. Measurements were made on six animals, i.e. five hands, five forearms, three feet and three lower legs.

Two animals were sacrified after the particles had been injected. In these experiments an arm and a leg were occluded with tourniquets and the catheter was passed via the carotid artery. When external measurements were complete, the animal was dissected. The hands, feet, lower leg muscles, forearm muscles, tibiae, lungs, liver, spleen and kidneys were placed in sealed plastic pots and then measured in a bulk sample counter (Cronquist et al. 1975). This consisted of two 12.5 cm diameter × 5 cm thick sodium iodide detectors completely surrounded by lead 5 cm thick. The activity of the syringe before and after injection, and the activity of the catheter were also measured in this detector system. In one animal, the upper and lower halves of the humerus and femur were counted separately. Samples of muscle (about 5 g) were placed in stoppered bottles with formalin; balanced weights of the shaft of the tibiae were placed in similar bottles and the samples counted using a gamma ray counter incorporating a well-type sodium iodide crystal (LKB-Wallac). The control samples were counted until 10,000 counts had been accumulated and the samples from the limbs which had been occluded by tourniquets were counted for 1,000 seconds.

The sodium washout and venous return from a limb with an occluding tourniquet was studied in two animals. Approximately 1.5 μCi of ^{22}Na was injected into the muscle of the leg distal to the tourniquet. One of the 7.5 cm diameter sodium iodide detectors was placed over the site of injection and the activity was monitored using a ratemeter and chart recorder as well as a scaler and timer. Blood samples were taken from the inferior vena cava at regular intervals for 1 hour. The detector was then transferred to a similar region of the control limb and approximately 1.5 μCi of ^{22}Na was injected into the corresponding muscle. The activity was monitored until it fell to about half of its initial value, whilst blood samples were taken at frequent intervals.

The detector was returned to the limb with a tourniquet, the tourniquet released, and the activity monitored whilst blood samples were taken. This experiment was repeated on one further animal to investigate the possible return of blood by way of the medullary circulation. In both limbs the ^{22}Na was injected into the medullary cavity of the distal end of the femur through a small hole drilled through the articular surface of the distal surface of the femur.

RESULTS

The average of 17 external measurements of control feet, hands, lower legs and forearms was 1.7 per cent of the injected dose with a standard deviation of 1.2 per cent. The activities of the corresponding regions of the limbs with tourniquets were expressed as a percentage of the control regions and gave a mean of 3.1 per cent with a scatter from 0.3 to 15 per cent.

The radioactivity of parts of limbs that were removed for counting in the bulk sample counter are summarised in Table 1. The results of measurements made in the well-type counter are shown in Table 2, where only the percentage of an equivalent weight from the control side could be calculated.

In Table 3, the activities of the major organs are used to calculate the per-

Table 1. Dissected animals. Microspheres. Activity of parts of the limb with tourniquet as a percentage of the count rate from the corresponding part of the control limb.

Animal no.	1	2
Time from injection to death	5 min	1 h 30 min
Hand	0.05	0.24
Arm muscle	0.4	1.16
Foot	0.01	0.69
Leg muscle	0.3	0.55
Tibia	0.01	0.76
Radius		0.76
Mean	0.15	0.69
Standard deviation		0.3
Upper humerus		87
Lower humerus		8
Upper femur		92
Lower femur		18

centage of cardiac output reaching the individual organs. The figures are compared with those obtained by Hoffbrand & Forsythe (1969) and Forsythe et al. (1968).

Table 2. Dissected animals. Microspheres. Samples counted in well-type counter. Count rate of samples from limb with tourniquet as a percentage of control.

Animal no.	1	2
Arm muscle	0.5	0.96
Leg muscle	0.1	0.26

The external measurements of ^{22}Na are in Table 4. The values of the half periods during the period of occlusion suggest a

Table 3. Dissected animals. Microspheres. Major organs of the body.

Animal no.	1		2		Earlier results Forsyth et al. (1968) ($n = 13$) Hoffbrand & Forsyth (1969) ($n = 42$)					
	% body weight	% dose	% body weight	% dose	% body weight	S.D.	% dose	S.D.	% dose	S.D.
Liver	4.2	6.1	3.1	8.6	4.4	0.8	4.6	3.8	4.8	3.2
Spleen	0.8	2.6	0.6	6.3	0.2	0.1	1.9	1.2	2.5	1.4
Kidneys	1.2	21.0	1.1	6.2	0.7	0.1	12.3	3.1	15.7	3.7
Lungs	3.1	6.1	2.9	4.3	1.1	0.7	0.5	0.6	0.9	0.9

Note. Forsyth et al. (1968) and Hoffbrand & Forsyth (1969) measured unanaesthetised monkeys that were sitting in a restraining chair. The animals that we studied were anaesthetised and supine and this may account for the difference in lung uptake.

Table 4. Washout of ^{22}Na.

Animal no.	3	4	5
Site	Leg muscle	Leg muscle	Femur
Tourniquet (T½)	50 h	Zero slope	25 h
Control (T½)	23 min	11 min	2.4 h
Control T½ as % tourniquet T½	0.8	0	9.5
After release (T½) (1)		2.8 min	6.3 min
After release (T½) (2)		14.1 min	3.9 h
Control T½ as % tourniquet T½		78	62

The half periods (T½) were calculated from a least squares fit of log counts/second against time. 'Tourniquet' means an injection into a limb with a tourniquet, 'control' an injection into the corresponding region of the control limb and 'after release (1)' and 'after release (2)' are the slopes immediately after release and when the limb had recovered from hyperaemia.

muscle blood flow of less than 1 per cent of the control. No measurements were possible after release of the tourniquet on animal No. 1. because it went into a state of shock.

Table 5. Blood samples taken during washout of ^{22}Na.

Animal no.	3	4	5
Tourniquet			
counts/1000s	391	378	390
standard deviation	32	16	13
no. of samples	4	5	7
background	366	372	333
Control			
peak × 1000	25.4	21.5	5.9
at (min)	10	2	0.5
plateau × 1000	5.6	5.8	3.5
at (min)	25	31	27
Release			
peak × 1000		24.1	12.5
at (min)		2	2
plateau × 1000		7.8	4.3
at (min)		21	28

Table 5 gives the measurements on blood samples. There was no detectable return of isotope from intramuscular injection to the leg of the animal but there was a significant return, less than 0.1 per cent of the control, from the distal end of the femur. The slow flow that carried away the isotope must therefore have been into the lower part of the limb. When isotope was injected into the control limb, a peak of activity was detected in blood samples and this was followed by a slowly decreasing level. This 'plateau' level can be compared with 2 standard deviations of the background count in setting an upper limit to the venous return.

DISCUSSION

Measurements of the radioactivity of isolated segments of the sacrificed animals suggest that all *in vivo* radioactivity measurements gave results which were too high. This was probably due to the difficulty in screening the occluded limbs from the activity in the rest of the body. When 10^6 particles were injected very few reached the limbs with the tourniquet. For example, in the isolated foot of animal No. 1 the number of particles was of the order of 10, whilst in the samples of muscle, there were less than 5. For this reason long counting times at low background do not substantially improve the accuracy of measurement.

Buckberg et al. (1971) showed that statistical errors due to the random distribution of particles are an important source of error when the number of particles present is less than 500. In order to produce this number in the limbs to which tourniquets had been applied, in a further experiment, approximately 10^7 particles were injected into the left ventricle. The results of this experiment confirm that the blood flow to the limb with a tourniquet is small and does not exceed 1 per cent of that of the control limb.

The experiments with ^{22}Na confirm that there is negligible venous outflow past the tourniquet and that the perfusion of muscle distal to the tourniquet is very small. The measurements on this muscle consisted of digital counts of approximately 40,000, so that the standard deviation due to statistical fluctuations was 0.5 per cent. The series of counts remained with ± 2 standard deviations on both animals for 1 hour. A least squares fit to the set of digital counts gave a slope corresponding to a half period of 50 hours on animal No. 6. and zero slope on animal No. 4. This makes the upper limit of the blood perfusion about 0.7 per cent of the unoccluded value.

The blood samples confirmed that no blood was detected leaving the limb with a tourniquet; in this case the minimum detectable activity from the limb with a

tourniquet was 2 standard deviations (10 per cent) of the background. The upper limit of venous return from the limb with a tourniquet was therefore about 0.2 per cent of that from the control limb.

When isotope was injected into the distal end of the femur, the venous return was still less than 1 per cent of that from the control limb.

The amount of blood flow detected here is not likely to be significant for the relief of ischaemia and the limb is virtually isolated from the circulation. The result obtained does not totally differ from those of Spira et al. (1965) because of the difference in technique. These workers injected ^{51}Cr labelled red blood cells and compared tourniquet and control limbs after 3 hours. If less than 0.5 per cent of cardiac output reached the limb with a tourniquet, there could be a build-up of activity to the levels they reported particularly if venous outflow was completely stopped.

In our experiments, the uptake of microspheres was measured from one passage so that the input to the limb with a tourniquet consisted of a bolus rather than a continuous supply. Under these conditions the number of microspheres detected is directly related to the blood flow to the limb.

Conclusions

1. The amount of blood reaching the limb distal to a tourniquet is less than 1 per cent of the blood flow to the control limb.
2. The venous return is less than 0.2 per cent of that of the control limb.
3. The limb with a tourniquet is virtually isolated from the circulation so the amount of blood reaching the tissues is not likely to be significant for the relief of ischaemia.

ACKNOWLEDGEMENTS

We are most grateful to Dr. R. Wootton for preparing the labelled microspheres and for advice on their use and to Dr. R. Wilkins and Dr. L. Kreel who catheterised the animals for microsphere studies. Mr. D. Hinge provided technical assistance on the isotope measurements.

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