THE BLOOD FLOW THROUGH THE HUMAN CALF
DURING RHYTHMIC EXERCISE

BY H. BARCROFT AND A. C. DORNHORST

From St Thomas's Hospital Medical School, London

(Received 22 November 1948)

It has generally been assumed that the blood flow through human muscle during rhythmic exercise cannot be determined with the plethysmograph (Abramson, 1944). We have, however, been able to make such determinations in special circumstances.

The new method has been used in experiments on the mechanical effect of rhythmic contraction on muscle blood flow. Kramer, Obal & Quensel (1939) showed that maximal rhythmic contractions obstructed the flow in dog's muscle. A. V. Hill (1948a, b) found that the tension in strongly contracted frog muscle was 100–300 mm. Hg. The work of Grant (1938) and others on sustained human contraction left little doubt that rhythmic contractions per se would restrict blood flow in human muscle.

METHODS

Principle for measuring blood flow in the exercising calf

This can best be explained with the aid of Text-fig. 1. The tracing shows a plethysmographic record of the calf volume; the excursions are due to the contractions and relaxations of the calf muscles. The blood flow during rhythmic exercise is obtained as follows:

Text-fig. 1, CP. A collecting pressure of about 90 mm. Hg is applied to the lower part of the thigh by inflation of a pneumatic cuff. Owing to compression of the veins the venous return is hindered and the calf swells. After the experiment a sloping line is drawn from which the rate of swelling is calculated. In Text-fig. 1 it was 11·0 c.c./100 c.c. calf/min. At first sight this would appear to be the rate of the blood flow during exercise. This is, however, not necessarily the case; the apparent flow may be too small, because, owing to the pumping action of the muscles, some venous blood may escape under the cuff back into the body (Barcroft & Dornhorst, 1949). Measurement of the amount that escapes in this way is the aim of the next procedure.
BLOOD FLOW THROUGH HUMAN CALF

Text-fig. 1, FO. Collecting pressure still applied—femoral artery occluded by digital pressure. The main supply of blood is now cut off and, as Text-fig. 1 shows, shrinkage of the calf takes place. This is usually fairly regular for some seconds at least, and is due to the blood being pumped out under the cuff. After the experiment a sloping line is drawn from which the rate of blood loss is calculated, in Text-fig. 1 it amounted to 3.2 c.c./100 c.c. calf/min. This method of estimating the rate of the pumped outflow may, however, not be quite accurate in all subjects. It will only be accurate if the entry of blood into the calf has been completely stopped by occluding the femoral artery. In some subjects this will indeed be the case, but in others there will still be a small inflow through collateral vessels. The rate of shrinkage of the calf will be a measure of the excess of the pumped outflow over and above the collateral inflow. The final procedure is aimed at estimating the collateral inflow, if any, so that it can be allowed for.

Text-fig. 1, R. Collecting pressure still applied, femoral artery still occluded—the subject stops the exercise and relaxes the calf muscles completely. The pumping action of the muscles having ceased the escape of venous blood is now effectively prevented by the collecting cuff. If there is no collateral inflow, the volume of the calf will remain constant, and the recorder will trace a horizontal line. If there is a collateral inflow there will be a gradual increase in calf volume and the line drawn by the recorder will slope upwards.

(i) Let us suppose that during Text-fig. 1, R, the recorder had traced a horizontal line, showing that there was no collateral inflow.

In that case the rate of shrinkage of the calf which followed femoral arterial occlusion, Text-fig. 1, FO would have been an accurate measure of the rate at which blood was being pumped out under the cuff.

PH. CIX.
To obtain the blood flow during exercise it would only have been necessary to add the apparent inflow, Text-fig. 1, CP, to the pumped outflow, Text-fig. 1, FO.

Blood flow during rhythmic exercise = Apparent inflow (Fig. 1, CP) + Pumped outflow (Fig. 1, FO)

= 11·0 + 3·2
= 14·2 c.c./100 c.c. calf/min.

(ii) In fact, after the subject ceased exercise, the record Text-fig. 1, R, slopes slightly upwards. This indicates that there was an inflow of blood from collateral vessels. Its rate was estimated as 2·0 c.c./100 c.c. calf/min.

In this case the rate of shrinkage of the calf which followed femoral arterial occlusion, Text-fig. 1, FO, represented the excess of the pumped outflow over the inflow from the collateral vessels. We shall call it the apparent pumped outflow.

To obtain the real pumped outflow the rate of the collateral inflow must be added to the apparent outflow. That is, the rate of the collateral inflow during exercise must be added. This is probably not the same as the rate of the collateral inflow when the subject was completely relaxed, which we know was 2 c.c., Text-fig. 1, R. It will be shown below that exercise hinders the blood flow through the calf so the collateral inflow during exercise is likely to be something less than the relaxation collateral inflow—in this case something between 2·0 and 0 c.c. For want of better knowledge we shall assume that exercise halves the rate of the collateral inflow. This is the best estimate that we can make, and a small error will not matter since the collateral inflow is usually small compared with the other values.

We can now calculate the blood flow during rhythmic exercise as follows:

\[
\text{Blood flow during rhythmic exercise} = \text{Apparent inflow (Fig. 1, CP)} + \text{Pumped outflow (Text-fig. 1, FO)}
\]

= 11·0 + 3·2 + 2·0/2
= 15·2 c.c./100 c.c. calf/min.

**Experimental**

The subjects were healthy men aged 20–30. The subject bared his right leg up to the groove and lay on a couch with his head raised. A calf plethysmograph was fitted (cf. Barcroft & Edholm, 1943, 1945). As the absolute level of flow was not important the plethysmograph was air-filled (Barcroft & Edholm, 1946). To take its weight off the leg it was suspended by a rope passing over a pulley to a counterpoise weight. The sock and shoe were put on, as also the ankle cuff for arresting the circulation in the foot, and the collecting cuff above the knee. The subject's position was adjusted; his feet on the pedal of the exercising machine, his shoulders supported by straps, and the plethysmograph clear of the couch.

The pressure point for digital compression of the femoral artery with one finger was then sought; it was at the point of most prominent pulsation about an inch below the groove. While the calf volume was being recorded a test compression was made. It was considered satisfactory if the pulse disappeared, proving that the artery was occluded, and the leg volume decreased. The
decrease of leg volume showed that the femoral vein was still patent, as no decrease occurred if the vein was deliberately compressed at the same time as the artery.

Resting flows were taken at 3 min. intervals for 10 min. Exercise then began. A weighted pedal was pressed down once a second to the sound of a metronome. As the pedal moved a pointer travelled over a scale, and as soon as the subject saw it reach a given mark he stopped pressing and relaxed completely. The pressure of the weight on the pedal brought the foot back to the resting position ready for the next contraction. Movement of the pelvis was prevented by making the subject do the same exercise simultaneously with the other foot on another similarly weighted pedal.

During the exercise, which lasted for 6 min., five records of the exercise flow were taken (Text-fig. 1) and also four records of the flow during brief interpolated periods of relaxation and four during brief interpolated periods of sustained contraction (Text-fig. 2). The ankle cuff was deflated for 5 sec. immediately after each estimation of the exercise flow. This prevented ischaemic pain in the foot while allowing 15 sec. between reinflation of the cuff and the next application of the collecting pressure.

After the subject had rested for ½ hr. the procedure was repeated with the thrust on the ball of the foot increased from 9 to 15 kg.

RESULTS

Text-fig. 3 shows the results obtained on six subjects doing the 9 kg. weight exercise. In every experiment the exercise flow was greater than the resting flow. The rate and amount of increase varied a good deal from subject to subject. The exercise flow was greater than the interpolated sustained contraction flow, and less than the interpolated relaxation flow. The immediate post-exercise flow is really analogous to an interpolated relaxation flow, and was greater than the exercise flow. Although the pattern differs the general findings are consistent. Text-fig. 4 shows the results for the exercises with the 15 kg. weight.
The separation of the exercise flows from the interpolated sustained contraction flows and from the interpolated relaxation flows is now very definite. Text-fig. 5 shows tracings from the experiments graphed in Text-fig. 4, nos. 3–5.

Text-fig. 3. Between the dotted vertical lines: exercise, raising 9 kg. weight once every second. Exercise flow: black dots; interpolated relaxation flows: crosses; interpolated sustained contraction flows: circles.

Text-fig. 6 shows the results of experiments to determine how much the procedures for measuring the exercise flow interfere with the normal reactions of the vessels supplying the active muscle. The top and bottom diagrams are from different subjects. Each diagram shows the blood flow through the calf recorded for 2 min. after each of four spells of exercise with 15 kg. weight,
Text-fig. 4. Between the dotted vertical lines: exercise raising 15 kg. weight once every second. Exercise flow: black dots; interpolated relaxation flows: crosses; interpolated sustained contraction flows: circles.
performed, with suitable intervals of rest, in the order in which they are charted. Each continuous line curve was recorded after 2½ min. continuous exercise, each broken line curve after a similar exercise during which three estimates of the exercise flow were made. It will be seen that the immediate post-exercise flow was somewhat greater when the exercise had been punctuated by these procedures, but that subsequent post-exercise flows are not increased.

Text-fig. 5. Tracings taken during exercise in the experiments shown in Text-fig. 4, nos. 3–5 showing typical patterns. Each tracing shows a record of the procedures for estimating a blood flow during rhythmic exercise, during interpolated sustained contraction and during interpolated relaxation. The figures under each record are calculated as explained in the text.

DISCUSSION

Grant (1938), Dolgin & Lehmann (1930), Barcroft & Millen (1939) and others have shown that strong sustained contraction of human muscle mechanically decreases the blood flow. It seemed that strong rhythmic contraction must do so too. The experiments just described confirm this. They show conclusively
that immediately the contraction stopped the blood stream, unhindered, quickened.

Text-fig. 6. Each curve represents the rate of blood flow through the calf during 2 min. immediately following a 2½ min. period of exercise. For further discussion see text.

Table 1 shows some approximate figures for the blood flow in the gastrocnemius soleus before, during, and after exercise.

<table>
<thead>
<tr>
<th>Weight on pedal (kg.)</th>
<th>9</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial resting flow</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>(c.c./100 c.c. muscle/min.)</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>Flow towards end of exercise (c.c./100 c.c. muscle/min.)</td>
<td>45</td>
<td>77</td>
</tr>
</tbody>
</table>

The figures were calculated from the averaged results of the calf flows shown in Text-figs. 3 and 4. The volume of the gastrocnemius soleus was taken as
740 c.c. (Reys, 1915); about three-quarters of it, say 550 c.c., was judged to have been in the plethysmograph. The total volume of calf enclosed averaged 1400 c.c., of which the gastrocnemius soleus, therefore, accounted for about \( \frac{550}{1400} \times 100 = 40\% \). The resting calf flow averaged 2 c.c., about half of which must have been going through the gastrocnemius, and the rest, namely 1 c.c., through the skin, bone and other muscles. The flow through the other tissues was taken as remaining substantially unaltered by the exercise. Accordingly the gastrocnemius muscle flows in the table were obtained by subtracting 1 c.c. from the averaged calf flows and multiplying the difference by \( \frac{100}{40} \), i.e. by 2½.

Table 1 emphasizes the following points:

(i) In the 9 kg. exercise the mean flow was 62% of the post-exercise flow. In the 15 kg. exercise it was 39%. The mechanical restriction of the flow with increasing load is most striking.

(ii) The mean flow in the two exercises was about the same. This is probably because mechanical hindrance was less in the 9 kg. exercise and although vasodilatation was less too, relatively more blood got through.

Finally, the following consideration is of some interest. Suppose that all the muscles in the body were working hard and had the same mean flow, 30 c.c., as that in the 15 kg. exercise. Total muscle blood flow would be about 81 1/min. (body wt. 70 kg.; 40% muscle, Bardeleben, 1912). Cardiac output would have been about 13 l. This is very low compared with the 20 l. which Hill (1948a, b) calculated to be the minimum for running at about 10 m.p.h. Difference in body temperature and arterial blood pressure may be factors in the discrepancy, and probably more important still, difference in the kind of movement. In running, relaxation may have lasted relatively longer than in pedalling. Further experiments would be interesting.

**SUMMARY**

1. A plethysmographic method is described for determining, approximately, in special circumstances, the blood flow through the human calf during rhythmic contraction of the gastrocnemius soleus.

2. Previous work showing that rhythmic contractions _per se_ must engender a mechanical resistance to the passage of blood through human muscle is confirmed.

3. During an exercise in which the subject pressed a weighted pedal once a second, the mechanical hindrance of the contractions reduced the flow to 40% of what it would otherwise have been.

The authors thank Prof. A. D. M. Greenfield for a suggestion that led to this investigation, Drs H. E. de Wardener and H. M. McClatchey for assistance, and Mr J. Dalrymple for technical assistance. They are also very much indebted to the students at St Thomas's Hospital Medical School who acted as subjects. The expenses were partly defrayed by the Medical Research Council.
REFERENCES


Hill, A. V. (1948b). Personal communication.


EXPLANATION OF PLATE

The plates show the plethysmograph; sling and counterpoise weight (A); collecting cuff on the lower part of the thigh; ankle cuff for arresting the circulation in the foot; heels resting on fixed supports; feet on pedals; horizontal bars at right angles to pedals: each is pivoted separately where pedal and bar join; weights on bars for adjusting work done; pointer actuated by movement of pedal and bar on right side (B); stops at head end of bar, one for taking weight off pedal during relaxation, the other to prevent movement of pointer beyond end of scale (A); metronome (B); straps supporting subject's shoulders (A); control board on end of kymograph table (A). The subject is looking at the pointer.