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THE EFFECT OF SMALL DEGREES OF VENOUS DISTENSION ON THE APPARENT RATE OF BLOOD INFLOW TO THE FOREARM

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Gaskell & Burton (1953) have recently published observations on the effect of posture on the apparent rate of blood inflow to the toes. They found a much lower apparent inflow rate to the toe of a leg depressed as little as 15° below the horizontal level than was seen simultaneously in the toe of the control horizontal or slightly raised leg. The lowered rate was ascribed to a veni-vasomotor reflex, distension of the veins causing a constriction of the arteries. They did not prove the reflex nature of the phenomenon by observations on completely denervated limbs, and the observations of Patterson & Shepherd (1954) on what may be a similar phenomenon throw doubt on its reflex nature. Whatever the mechanism, however, the observations, as pointed out by Gaskell & Burton, throw serious doubt on the validity of the classical method of measuring the rate of blood flow by venous occlusion plethysmography. It is suggested that the very act of collecting blood in the vessels of a part by distending the veins reduces the arterial calibre and the rate of arterial inflow. Gaskell & Burton confined their observations to the toe and the finger, and even if their interpretation of these observations is accepted it does not follow that the method is invalid in other situations, although it must be suspected. Suspicion is extended to the forearm by the recent evidence from this laboratory that considerable distension of the vessels brought about by venous congestion (Patterson & Shepherd, 1954) or exposure of the arm to subatmospheric pressure (Greenfield & Patterson, 1954) is followed by vasoconstriction. These observations were made by venous occlusion plethysmography, but the conclusions are based on differences in apparent flow rates in the control and experimental arms, and do not depend on the absolute reliability of the method. A great deal of work on the peripheral circulation in man has, since the first observations of Hewlett & Zwaluwenburg (1909), depended on measurements of the rate of blood flow by venous occlusion plethysmography. It is important, therefore, to re-examine the validity of the method.

METHODS

Observations were made on four healthy young men, recumbent on a 4 in. thick latex foam mattress with the head and shoulders slightly raised, in a room at 20–22° C. The blood flow was measured simultaneously in both forearms. The forearms were enclosed in plethysmographs (Greenfield, 1954) containing stirred water at 35° C. The forearms were slightly below, and the water levels in the plethysmographs were slightly above, the level of the sternal angle. The wrist cuffs, 6 cm wide, encircled the arm, and were inflated to above 200 mm Hg 1 min before flow observations started. The collecting cuffs, 12 cm wide, were arranged with the lower border just above the fold of the elbow. Both collecting cuffs were inflated to 70 mm Hg for 12 sec every 15 sec throughout a sequence of observations. Between collections, the cuff on the left arm was always returned to atmospheric pressure, but that on the right was returned to atmospheric pressure during the 'rest periods' and to some chosen pressure, usually 10–30 mm Hg above atmospheric, during the 'distension periods'. A sequence of observations consisted of about seven rest and seven distension periods, and each wrist cuff was kept inflated throughout. All distension periods lasted 1 min, during which four records of flow were obtained. The rest periods were continued until at least four apparently steady consecutive flows (as judged by inspection) had been recorded in each forearm. In some experiments the flow in the right arm was apparently raised or lowered immediately after a distension period; in these the subsequent rest period had sometimes to be prolonged to two or more minutes in order to secure the four apparently normal flows which would constitute the base-line for the next distension period.

RESULTS

A typical series of plethysmographic recordings is shown in Fig. 1. In this example, the means of four observations (in ml./100 ml./min) before the distension period were, on the left (*Cb*), 5·1, and on the right (*Eb*), 4·7, and during

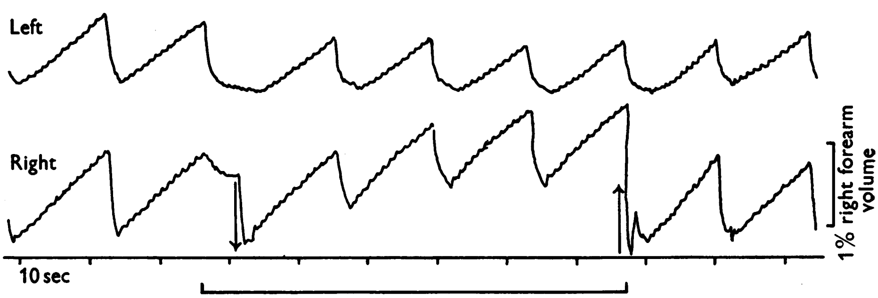

Fig. 1. Observations on G.C.P. Over the period indicated the pressure in the collecting cuff on the right arm was returned to 20 mm Hg between collections. The arrows indicate the direction and extent of shifts of the lower recorder equivalent to 0·83 % of the forearm volume.

the distension period were, on the left (*Co*), 4·8, and on the right (*Eo*), 5·1. The blood flow on the right during the distension period, expressed as a percentage of the flow that would have been expected had there been no local disturbance of the circulation, and had all general disturbance acted symmetrically (Greenfield & Patterson, 1954), is

$$\frac{Eo}{Eb} \times \frac{Cb}{Co} \times 100 = \frac{5 \cdot 1}{4 \cdot 7} \times \frac{5 \cdot 1}{4 \cdot 8} \times 100$$

$$= 115\%.$$

In this example, measurement of the record (allowing for the imposed shift of 0·83 %) shows that at the commencement of the four flows during the distension period, the volume of the right arm was increased respectively by 1·0, 1·3, 1·4 and 1·5 % (mean 1·3 %) of its normal resting volume. In this example, therefore, the inflow was 115 % of the expected rate, and the distension amounted to 1·3 % of the resting volume of the limb. The results of seventy-two such observations on four subjects are shown in Fig. 2. For comparison

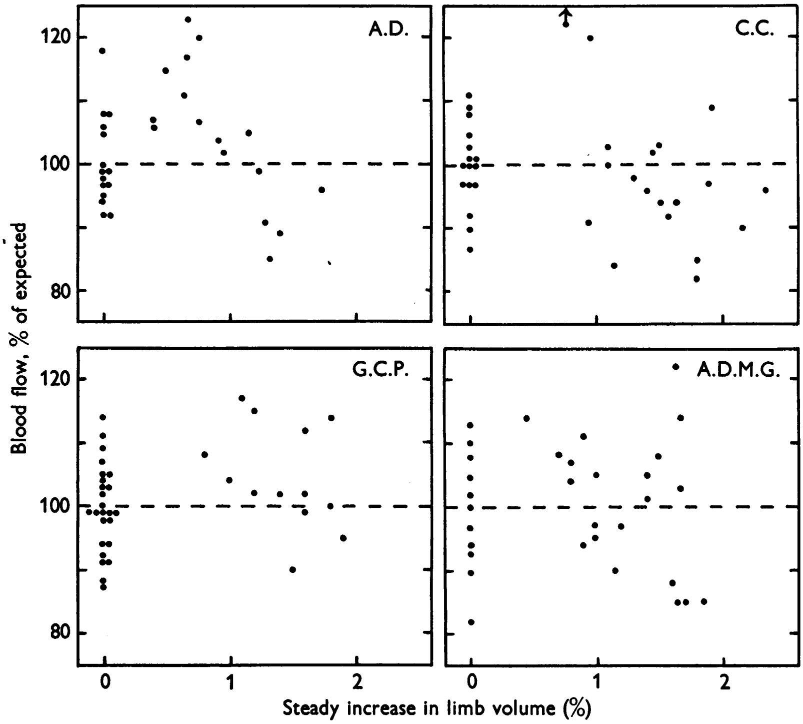

Fig. 2. Each point on this diagram represents the results of an experiment of the type illustrated in Fig. 1.

are shown sixty-eight control observations, calculated in exactly the same way, but in which the pressure in the collecting cuff on the right arm was returned to atmospheric during the distension as well as the rest periods. These results are analysed in Table 1. The difference between the mean of the control series and the mean of the pooled observations during distension is not significant. On the other hand, when the pooled observations during distension are examined there is found to be a highly significant correlation ($0{\cdot}001 > P$) between blood flow and distension. On examining the level of apparent flow at various levels of distension, this is found to differ significantly ($0{\cdot}05 > P$) from 100 % at distension between 0·51 and 1 % of limb volume, the mean being 107·9 %. At the other levels of distension (1·01–1·5 and 1·51–2·0 %) the mean is not significantly different from 100 %. It will be seen that even over the 0·51–1·00 % range, the mean, although significantly different from 100 %, is raised only by about one part in thirteen. The striking feature of the observations is the very small or negligible effect of small degrees of distension on the apparent inflow rate to the forearm.

TABLE 1. Blood flow expressed as a percentage of the flows which would be expected if distension caused no local disturbance of the circulation

Distension, %	0 (controls)	0·51–1	1·01–1·5	1·5–2	0·1–2·5 (pooled)
No. of observations	68	21	21	21	72
Mean blood flow, %	100·0	107·9	99·3	98·6	101·1
S.E. of mean	0·87	2·48	1·87	2·6	1·36
P for difference from 100 %	$1{\cdot}0 > P > 0{\cdot}9$	$0{\cdot}01 > P > 0{\cdot}001$	$0{\cdot}8 > P > 0{\cdot}7$	$0{\cdot}6 > P > 0{\cdot}5$	$0{\cdot}5 > P > 0{\cdot}4$

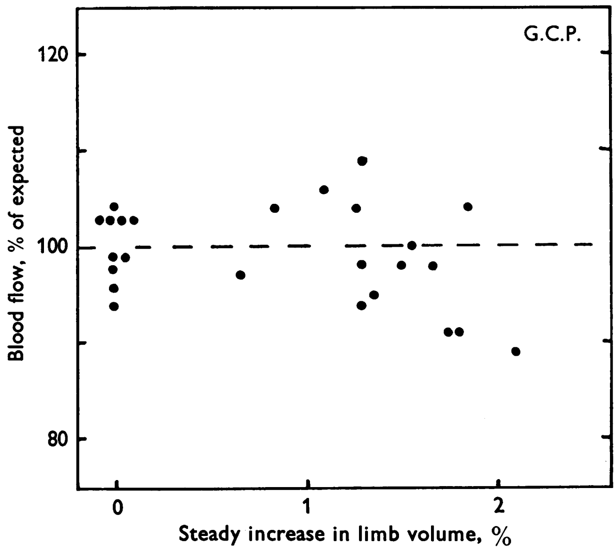

Fig. 3. Observations on G.C.P., the blood flow to the forearm being raised throughout to 10–20 ml./100 ml./min by a combination of local and general heating.

In all the observations so far described, the level of resting flow was in the range 2–6 ml./100 ml. of forearm/min. It is possible that distension operates differently at high levels of flow. An experiment was therefore conducted in which the subject was wrapped in blankets, both feet were immersed in stirred water at 43° C and both forearm plethysmographs were maintained at this temperature. In this experiment the flow in both forearms at the start was about 10, and at the end about 20 ml./100 ml./min. The flows on the two sides rose gradually throughout. The results, plotted in the same way as the other observations, are shown in Fig. 3. The ten control observations without distension have a mean of 100·2, S.E. ± 3·32, and the fifteen observations with distension have a mean of 98·5, S.E. ± 1·05. Neither mean is significantly different from 100 (the values of P are respectively $0{\cdot}9 > P > 0{\cdot}8$ and $0{\cdot}4 > P > 0{\cdot}3$).

DISCUSSION

These observations show that a degree of venous back pressure sufficient to cause a steady increase of up to 2 % in the volume of the forearm is not associated with any significant alteration in the apparent rate of blood inflow as determined by the classical method of venous occlusion plethysmography. Since the volume increase of the forearm during a blood flow estimation is usually less than 1 %, and need never be more than this, there is no evidence that during the ordinary application of the method venous distension causes vasoconstriction. These experiments offer no evidence for the existence of a veni-vasomotor reflex in the forearm. Other experiments (Patterson & Shepherd, 1954) have shown that the resistance vessels of the forearm may constrict after a period of more severe venous congestion, and the work of Greenfield & Patterson (1954) makes it extremely likely that this response is due to a raised transmural pressure in the arterial and not in the venous side of the circulation.

Before considering these findings in relation to those of other workers, it is convenient to consider what happens during a blood flow estimation by venous occlusion plethysmography. Fig. 4 shows a record of the volume changes in the forearm during inflation of a collecting cuff on the upper arm to 70 mm Hg for 130 sec; a wrist cuff was inflated to 200 mm Hg throughout. The mean pressures, as measured by a damped condenser manometer, in the brachial artery and in the antecubital vein at the level of the elbow are also shown. The 'apparent inflow' has been computed from the record of volume changes. The 'actual inflow' and 'actual outflow' are conjectural; they have not been measured. The events may be divided into three phases; these merge into each other, and the positions of the dividing lines in Fig. 4 are arbitrary. Our interpretation of the events during these phases is as follows:

Phase 1. The veins and other capacity vessels are relatively empty at the start. During this initial period of distension the pressure within them rises only slightly, and the arteriovenous pressure difference is only slightly reduced. The venous outflow is completely arrested. The apparent rate of inflow is identical with the actual rate of inflow, and this is the same as the resting inflow.

Phase 2. Accumulation of blood in the veins and other capacity vessels leads to a progressive rise of pressure within them, but the pressure is as yet insufficient to cause venous blood to leak past the collecting cuff. The arteriovenous pressure difference is reduced but the resistance vessels may be passively dilated or may be actively dilated or constricted. The apparent rate of inflow is identical with the actual rate of inflow, but both may differ from the resting rate of inflow.

Phase 3. Accumulation of blood in the veins and other capacity vessels has raised the pressure in them sufficiently for blood to leak back under the collecting cuff. The arteriovenous pressure difference is much reduced. The intra-

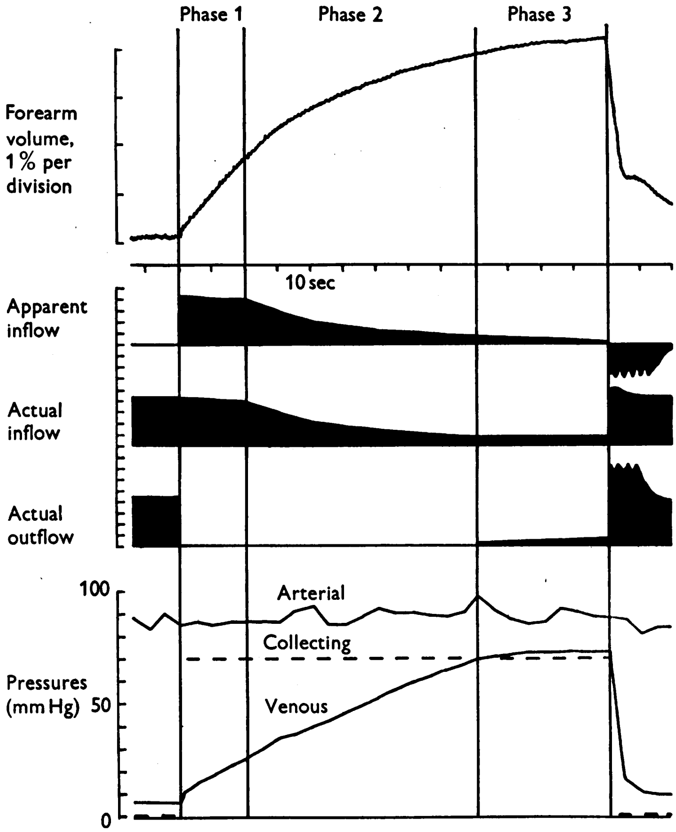

Fig. 4. Events during venous occlusion plethysmography. For explanation, see text. Actual inflow = actual outflow + apparent inflow. Each division on vertical scale for inflow and outflow represents 1 ml./100 ml. of forearm per min. Total duration of collection, 130 sec.

vascular pressures remain steady in all vessels throughout this phase, but the capacity vessels continue for some time to distend under the influence of the steady pressure. There is, therefore, an apparent rate of inflow, but this is less than the actual rate of inflow, which is in turn less than the resting rate of inflow.

It is clear from this that only in phase 1 can the apparent rate of inflow possibly be taken as a valid measure of the resting rate of inflow before the venous occluding cuff is inflated. If the circulation is disturbed, even this measure must be inaccurate. Only in situations, such as the forearm or the calf, where the inflow curve is straight for a considerable distance, is it possible to deduce with reasonable certainty that the circulation is not disturbed during the first phase of inflow. A straight curve implies either an instantaneous disturbance when the collecting cuff is inflated (which is unlikely) or no disturbance until the curve deviates from a straight line.

The inflow curve is, however, often fairly straight in phase 3 as well as in phase 1 (Fig. 4), and it is quite unsafe to conclude that because the curve is straight, the apparent rate of inflow represents either the actual rate of inflow or the resting rate of inflow.

It is necessary to reconcile our present findings with the observations made on the toes by Gaskell & Burton (1953) with the venous occlusion plethysmographic method. In the first place, the vessels in the toes and forearm may behave differently. Secondly, Gaskell & Burton interpreted the apparently lower rate of blood inflow to the toe of the dependent as compared with the toe of the horizontal leg as a real decrease in blood flow brought about by a hypothetical veni-vasomotor reflex. Other interpretations are possible. In the dependent toe the veins are already distended before the collecting cuff is inflated; conditions in the limb are already as shown late in phase 2 in Fig. 4. The pressure in the veins may therefore rise above the surrounding tissue pressure in the region of the collecting cuff very soon after the cuff is inflated. In other words, the collecting cuff may fail to occlude the veins completely, and the actual blood flow must then exceed the apparent flow by the amount of the venous leakage. Similar consideration may explain the apparently reduced blood flow in the finger observed by Yamada & Burton (1954) during exposure of the finger to subatmospheric pressure. Calorimetric observations made by one of us (A.D.M.G.), in association with Drs Shepherd and Whelan (Whelan, 1951) in this department, support this interpretation of the observations. The heat release from the distal 2·8 cm of the index finger to water at 29–30° C was measured by the method of Greenfield & Shepherd (1950). The right arm was dependent throughout. The left arm was dependent for the initial and final periods of 10 min, but for a middle period of 10 min it was raised so that the finger in the calorimeter was 15 cm above the sternal angle. This was approximately the posture in which Gaskell & Burton recorded the largest apparent inflow rate. The results on three subjects are shown in Table 2. There is no

TABLE 2. Heat loss from left index finger as a percentage of heat loss from right index finger

The average rate of heat loss from the right index finger in each 10 min period throughout these observations lay between 201 and 430 cal/100 ml./min.

	Period 1 R Dependent L Dependent	Period 2 R Dependent L Raised	Period 3 R Dependent L Dependent
J.T.S.	111	91	85
R.F.W.	106	110	107
A.D.M.G.	105	91	85

evidence that the rate of release of heat from the fingers of the slightly raised and fully dependent arms was appreciably different. Unless, therefore, the conditions for heat exchange are grossly different in the raised and dependent positions, there is no evidence for a reduced rate of flow in the dependent finger. It appears that the plethysmographic records from dependent digits are misleading; Greenfield & Shepherd (1950) reported similarly misleading curves obtained on fingers during cold vasodilatation.

Another interpretation of Gaskell & Burton's observations is possible. It may be that although the steady level of blood flow in the toes of a dependent leg is no less than in the toe of a horizontal or slightly raised leg, the actual flow as well as the apparent flow is reduced by vasoconstriction when the venous occlusion cuff is inflated. If so, the response may arise not from the veins but from the arterioles. If the veins are already distended, any interference with venous outflow must quickly lead to a raised pressure in all the vessels, including the arterioles, back to the arteries. This may be the explanation of the fall in toe volume below the base-line level after release of the occluding cuff. This fall does not, of course, mean that the resistance vessels are constricted, although this would be one possible cause of such a fall.

The apparently negative flows sometimes seen when the collecting cuff is inflated are difficult to explain. As there is no evidence in Gaskell & Burton's records of an initial increase in digital volume, it is difficult to believe that this is a reflex effect initiated by distension of the veins.

SUMMARY

1. The apparent rate of inflow to the forearm, measured by the classical method of venous occlusion plethysmography, is almost unaltered in the presence of a venous back-pressure sufficient to increase the resting forearm volume by amounts up to 2%.

2. There is no evidence that a veno-vasomotor reflex, or other similar mechanism, invalidates the measurements made under normal conditions by this method.

3. A reinterpretation is suggested of evidence which has been held to support the existence of a veno-vasomotor reflex in the toes and fingers.

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