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THE EFFECTS OF POSITION AND SKIN TEMPERATURE ON THE CAPILLARY PRESSURES IN THE FINGERS AND TOES

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SUMMARY

1. Direct measurements of the capillary pressure (P_c) were made in capillaries at the base of the nails of the fingers and toes of two subjects (the authors of this paper).

2. With the hand or foot at heart level, P_c varied over the range of 7–70 cm H_2O with mean values of 43 cm H_2O in both the fingers and the toes. P_c was higher in the arterial limb (mean 49 cm H_2O) than in the venous limb (mean 34 cm H_2O) of the capillary loops. The plasma colloid osmotic pressures for the two subjects were 33 and 34 cm H_2O.

3. For capillaries at heart level there was a strong positive correlation between P_c and skin temperature when the latter was varied over the range 23–36 °C.

4. When the hand or foot was lowered, P_c increased less than the local arterial (P_a) and venous pressures (P_v). Furthermore the variation in P_c was reduced. In fourteen measurements of P_c made on capillaries in the toes of standing subjects, P_c was no more than 10 cm H_2O greater than P_v. It is argued that the increase in the ratio $(P_a - P_c)/(P_c - P_v)$ with hydrostatic load represents an increase in the ratio of pre- to post-capillary resistance.

5. When P_v was increased by inflating a sphygmomanometer cuff around the upper arm, $(P_a - P_c)/(P_c - P_v)$ increased in the hand held at heart level. These changes were similar to those seen with changes in position.

6. The implications of the results are discussed with respect to fluid balance between the blood and tissues. It is argued that since P_c in the warm hand was never less than the plasma colloid osmotic pressure, fluid is not reabsorbed from the tissues into the capillaries of the warm skin of the hand even at heart level. Compensatory changes in the circulation appear to minimise the filtration of fluid into the feet of the standing subject but the mechanism of these changes remains obscure.

INTRODUCTION

Capillary pressure is the most variable of the several forces governing fluid movement across the capillary wall. Its value, which is intermediate between the local arterial and venous pressures, is considered to be determined by these pressures and by the ratio of the pre- to post-capillary resistances to blood flow (Pappenheimer & Soto-Rivera, 1948). Thus capillary pressure should be affected by adjustments of

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arteriolar and venular tone and by postural changes which alter the local arterial and venous pressures.

There have been relatively few direct measurements of capillary pressure in man. In his classical study, Landis (1930) measured the pressure in capillaries at the base of the finger nails. When the finger was at the level of the heart, the mean capillary pressure approximated to the colloid osmotic pressure of the plasma proteins. When the hand was lowered, the increment of capillary pressure was 'almost identical with the theoretical hydrostatic increment of pressure due to the column of blood in the veins'.

The measurements reported in this paper are an extension of some of Landis's observations. Since postural changes affect vascular pressures in the feet more than in the hands we have measured capillary pressures in the nail folds of the toes as well as the fingers. With hand or foot at heart level we have observed a wide range of values for capillary pressure and we have been able to correlate this variation with skin temperature. By contrast during quiet standing, the capillary pressures measured in the toes vary little and are always close to the venous pressure.

A preliminary communication has been published previously (Levick & Michel, 1976).

METHODS

The subjects were the two authors.

Measurement of capillary pressure (P_c)

The techniques used were similar to those of Landis (1930). A finger or toe was steadied in a bed of plasticine beneath a Wild M5 dissecting microscope, so that the capillary loops in the skin at the base of the nail (the nailfold) could be viewed by reflected light. The dry superficial epidermis was gently and painlessly removed with a sharp scalpel and the tissue covered with a drop of glycerine. A chosen vessel was then cannulated with a micropipette (tip diameter 5–10 μm) filled with sterile heparin solution (5000 units ml.$^{-1}$) lightly coloured with the dye, Patent Blue V. The micropipette was connected to an adjustable water manometer and mounted in a simple micromanipulator system (Landis, 1927; Michel, Baldwin & Levick, 1969). The dye was added to the heparin to improve the visibility of the pipette during the cannulation procedure.

As soon as the micropipette entered the capillary, blood flowed rapidly into the barrel of the pipette. The height of the water column in the manometer then was raised rapidly to expel all but a few red cells from the pipette and to prevent the rapid clotting reaction from blocking the lumen of the pipette. Capillary pressure, P_c, was determined by adjusting the height of the water column until there was no net movement of blood into or out of the pipette, the few remaining red cells simply oscillating with each heart beat. Measurements were reproducible to 1–2 cm H_2O. Although minute unavoidable movement by the subject often limited the period of observation to a few minutes, in some cases measurements were continued for as long as 20 min. Whenever a micropipette broke *in situ*, its debris was extracted. Neither subject suffered any complication.

Measurement of arterial (P_a) *and venous pressures* (P_v).

Popliteal arterial pressure was measured at heart level and at 70 cm below the heart using a thigh cuff and a sphygmomanometer. Sphygmomanometric measurements of arterial pressure were made on the arm of both subjects in every experiment. Mean arterial pressure was calculated as diastolic pressure + 1/3 (pulse pressure).

For measurements of venous pressure, the dorsal veins of the hands and feet were cannulated with 23-G 'Butterfly' cannulae connected to an SE 488 pressure transducer the output of which was read on an ultra-violet recorder.

Measurement of plasma colloid osmotic pressure

This was measured on samples of venous blood taken from the venous cannulae or by venepuncture using a modified Hansen osmometer (Hansen, 1961). The osmometer was fitted with an Amicon Type UM 05 membrane and serial measurements on the same sample agreed within $\mp$ 0·5 cm H_2O (Prather, Gaar & Guyton, 1968).

Skin temperature

In all later experiments of the series, the temperature of the skin of the nailfold was measured by a thermistor laid on the surface after each capillary cannulation. Most experiments were carried out with the subject lightly clad and subjectively comfortable in a room of temperature 21–22 °C. In some experiments nail fold temperature was increased by wrapping an electric blanket around the forearm or by preliminary immersion of the hand or foot in warm water; in others the nail fold was cooled by fanning cold air over the arm and preliminary immersion in cold water (approx. 10 °C).

Capillary surface area

As an index of the number of patent capillaries perfused by blood, the vessels in a defined area of the nailbed were counted first with the extremity at heart level and then again after the finger or toe was lowered.

Changes in position of hand and foot relative to the heart

The vertical distance of capillaries below the heart was varied by having the subjects adopt postures which ranged from lying supine, through sitting on chairs of various heights, to standing on the microscope bench. The level of the heart (right atrium) was taken to be 7 cm below the manubrio-sternal angle in the erect subject (sitting and standing) and at the mid-axillary line when the subject was supine. A straight edge with a spirit level was used to refer the position of the capillary or the heart to a vertical scale.

Several capillaries were cannulated at each position, since it was not possible to change position while recording pressure in the same capillary.

RESULTS

1. *Capillary pressures at heart level*

At heart level P_c varied very considerably, the range of values being 7–70 cm H_2O. This wide variation was similar in both subjects and similar in the hands and in the feet. The mean value of P_c in the hands was 43·0 cm H_2O and in the feet it was 43·3 cm H_2O. When a capillary remained cannulated for several minutes no consistent change of P_c was seen: occasionally it increased 1–5 cm H_2O and occasionally it decreased to a similar extent. On two occasions when the subject performed the Valsalva manoeuvre, P_c was raised by 14 and 16 cm H_2O, while placing the opposite hand in cold water reduced P_c by 2 cm H_2O. In most cases, capillary pressure was pulsatile and the pulse pressure was estimated on several occasions to be approximately 5 cm H_2O.

Two factors contributing to the great variation of P_c were (i) systematic differences in P_c between the arterial and venous limbs of the capillary loops, and (ii) a relationship between P_c and skin temperature.

The differences in P_c between the arterial and venous ends of the capillary loops are summarized in Table 1.

The observed mean P_c in the arterial limb of 49 cm H_2O is comparable with, though greater than the mean value of 43·5 cm H_2O reported by Landis. Our mean value of 34 cm H_2O for P_c in the venous limb is more than double Landis's figure of

16·5 cm H_2O. Our figures are similar to those recently reported by Mahler, Muheim & Intaglietta (1976) who used a servonul feed-back micropressure system to measure P_c in the finger nailfolds of healthy subjects: their mean values ranged from 34 to 53.4 cm H_2O.

TABLE 1. Mean values of P_c at heart level (cm H_2O)

	Hand	Foot	Arterial limb	Venous limb
P_c	43·3	43·0	49·2	33·9
S.E. of mean	∓ 2·0	∓ 4·3	∓ 3·0	∓ 3·2
n	40	10	13	13

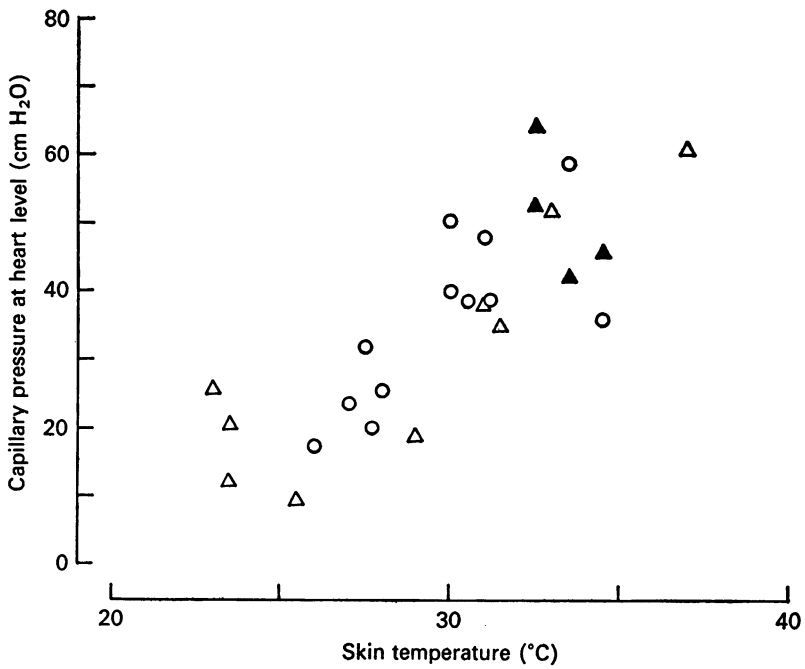

Fig. 1. The relation between capillary pressure at heart level and skin temperature. The different symbols indicate the subject and site of the capillary: △, J.R.L. finger; ○, C.C.M. finger; ▲, J.R.L. toe. The correlation coefficient between the variables is +0·805 ($P < 0·001$).

That P_c varies with skin temperature was demonstrated by measuring P_c when skin temperature was varied with local warming and cooling. The strong positive correlation is shown in Fig. 1 which summarizes all the data from these experiments.

Plasma colloid osmotic pressure was determined for the two subjects on three separate occasions. The blood was taken from veins held at heart level and the values of colloid osmotic pressure were reproducible to within 1 cm H_2O for each of the two subjects. The mean values were 34 cm H_2O (J.R.L.) and 33 cm H_2O (C.C.M.). Thus the plasma colloid osmotic pressure did not exceed P_c even at the venous end of most capillaries.

2. *Capillary pressures at different levels below the heart*

Fig. 2 shows values of P_c at and below heart level measured in 112 separate cannulations of capillaries in the fingers and toes of both subjects. P_c varied over a wide range at heart level (*vide supra*). As the extremity was lowered P_c increased

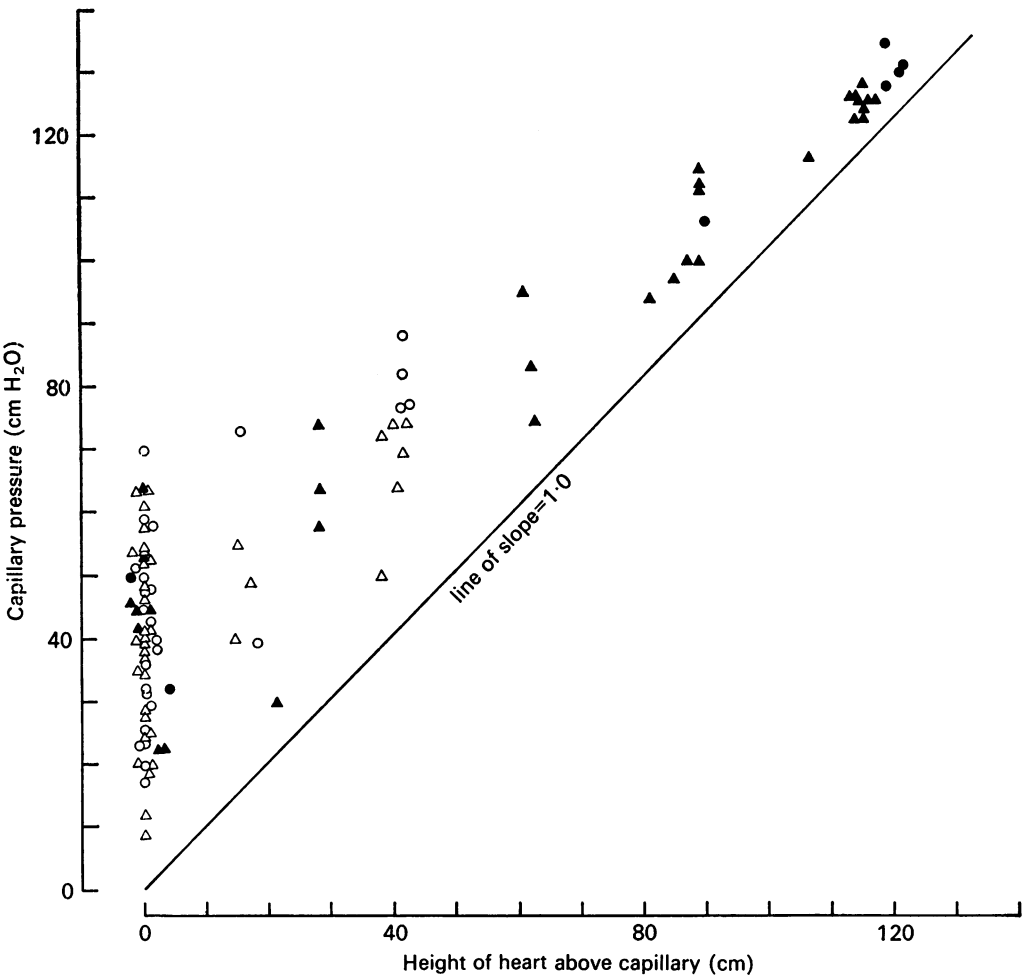

Fig. 2. The relation between capillary pressure and the height of the heart above the capillary. Each point represents a single measurement on one capillary: different symbols indicate the subject and site of the capillary: △, J.R.L. finger; ○, C.C.M. finger; ▲, J.R.L. toe; ●, C.C.M. toe. The continuous line has been constructed to pass through the origin and have a slope of unity.

but its variation at any one level appeared to be reduced. The decrease in the variability of P_c was most clearly seen in the feet of the standing subject (115 cm below the heart) where the values of P_c all lay within a range of 6 cm H_2O. This lack of variation of P_c in the feet of the standing subject was accompanied by attenuation of its pulsations and was observed in spite of the skin temperature varying between 29 and 35 °C.

The changes with position of the arterial, venous and mean capillary pressures in the feet are shown in Fig. 3. The arterial and venous pressures changed linearly with the height of the column of blood between the heart and the site of measurement. By contrast increments of mean P_c with vertical position were considerably less than the increased hydrostatic load. As the foot was lowered mean P_c approached the venous pressure more and more closely so that when the subjects were standing P_c in the toe was never more than 10 cm H_2O greater than the venous pressure.

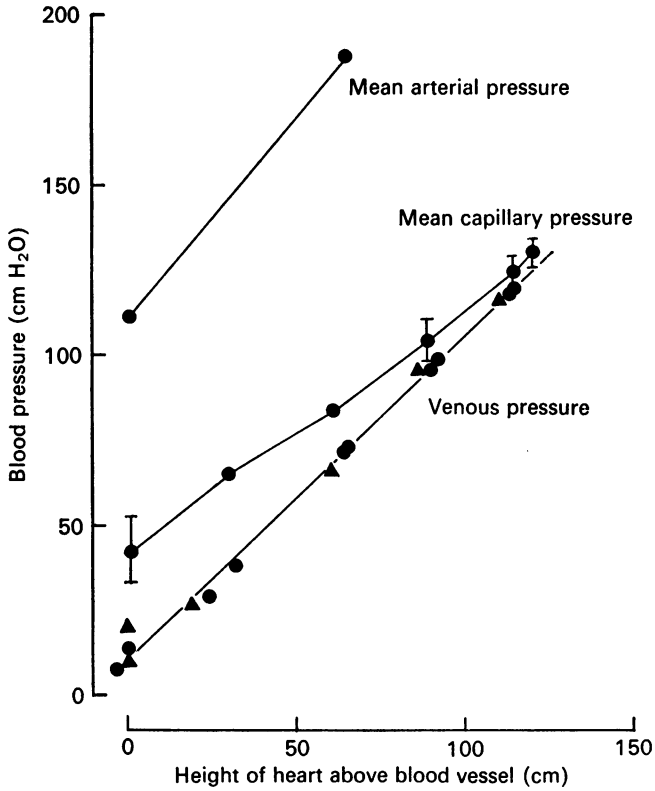

Fig. 3. The relation between local blood pressure in the feet and the height of the heart above the foot. Mean values for capillary pressure (P_c) of both subjects have been plotted. Vertical bars which indicate 95% confidence limits of these means are omitted at 30 cm and at 60 cm which are averages of only three values. The variation of local arterial pressure is based on measurements of popliteal arterial pressure. Variations of venous pressure represent direct measurements on both subjects: different symbols indicate subject as in Fig. 2. The regression coefficient of P_c against height (+0·715) is significantly less than the regression coefficient of P_v against height (+0·941): $P < 0·001$.

A similar but less striking picture emerged from the measurements of P_c on the fingers (Fig. 4). As the hand was lowered, the mean P_c increased less than the local venous pressure.

It is convenient to express the changes in P_c relative to the mean arterial pressure (P_a) and the venous pressure (P_v) in terms of the ratio of the pressure drop between artery and capillary to the pressure drop between capillary and vein, $(P_a - P_c)/$

$(P_c - P_v)$. If the circulation in the finger were a simple series arrangement of artery–capillary–vein, this ratio of pressures would be equal to the ratio of pre-capillary to post-capillary resistance. Although the interpretation of $(P_a - P_c)/(P_c - P_v)$ may be more complicated for the microcirculation of skin, the increase in its value which occurs in the extremities as they are lowered, indicates that these changes of position are accompanied by changes in the distribution of resistance in the local circulation.

As a limb is lowered, both P_a and P_v increase. In the next section we describe changes in P_c when changes occur in P_v alone.

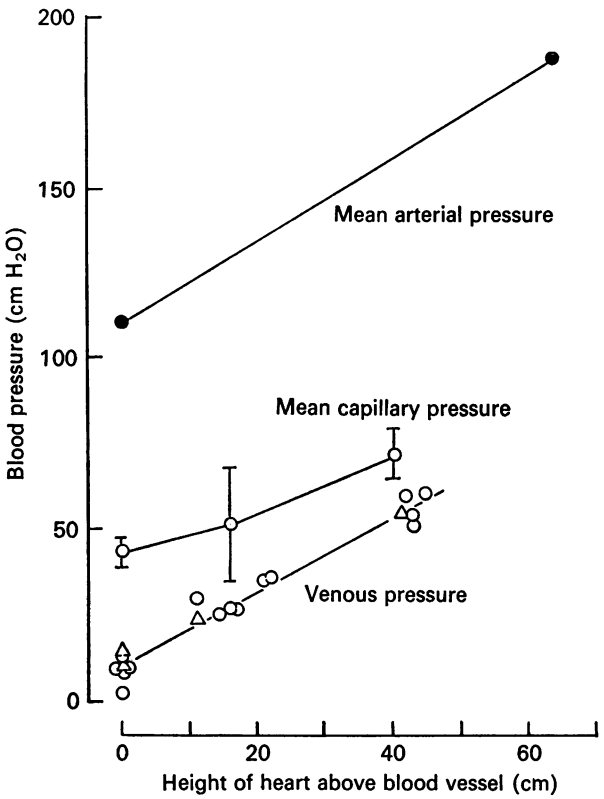

Fig. 4. The relation between local blood pressure in the hand and the vertical distance of the hand below the heart. Values for capillary pressures are mean values and the vertical bars are 95 % confidence limits. The regression coefficient of P_c against height (+0·737) is significantly less than the regression coefficient of P_v against height (+1·087): $P < 0{\cdot}001$.

3. *Effects of changes of venous pressure on capillary pressure*

The experiments were all carried out on the capillaries of the hand.

A capillary in the nailbed was cannulated and P_c measured. With the micropipette still in position, a sphygmomanometer cuff was inflated around the upper arm to raise the venous pressure, which was recorded directly in the veins at the back of the hand. P_c was measured until it became steady again.

There was a high failure rate in these experiments for the micropipette was often

broken by small movements induced by the swelling of the hand, which occurred as the venous pressure was raised.

The results of the successful experiments are shown in Fig. 5. Since the cuff pressure was never raised above the diastolic pressure it was assumed that P_a was constant. Once cuff pressure exceeded normal venous pressure, it corresponded closely to P_v. Cuff inflation increased P_c less than P_v and the ratio $(P_a - P_c)/(P_c - P_v)$ increased with P_v. In Fig. 6 the changes in $(P_a - P_v)/(P_c - P_v)$ with increased P_v are compared with the changes of the ratio observed with changes in position of the hand and foot. Over the range of P_v investigated the changes of $(P_a - P_c)/(P_c - P_v)$ are similar during cuff inflation and with posture.

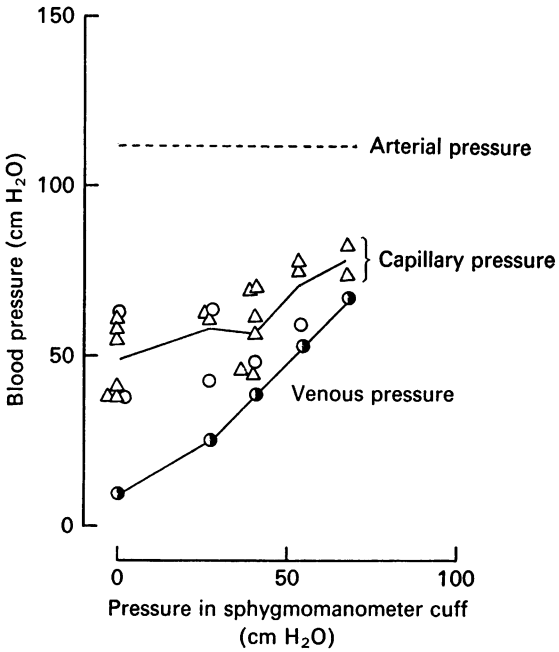

Fig. 5. The arterial, capillary and venous pressures in the hand during inflation of a sphygmomanometer cuff around the upper arm. Arterial and venous pressures are mean values of both subjects. Open symbols represent pressures determined in eight capillaries. In each vessel P_c was measured before the cuff was inflated (shown as values of P_c at zero cuff pressure). The cuff was then inflated and the micropipette held in position until a new steady value of P_c could be determined. The line drawn through the open symbols represents the trend of mean P_c.

On all but one occasion, P_c approached a new value without overshooting or undershooting as P_v was raised and lowered. On one occasion, an increase in P_v led P_c to rise to an initial value which was higher than that maintained from 2 to 10 min later.

4. *Changes in the number of open capillaries with posture*

The number of open capillaries in a defined area of the nail bed were counted in the fingers and toes of both subjects, first with the digits at heart level and then with the hand approximately 50 cm and the foot 115 cm below the heart.

Observations were made at 1, 5 and 9 min after the extremity had been lowered. On all occasions the capillaries which were patent at heart level remained patent after the limb was lowered and no new capillaries were seen to open.

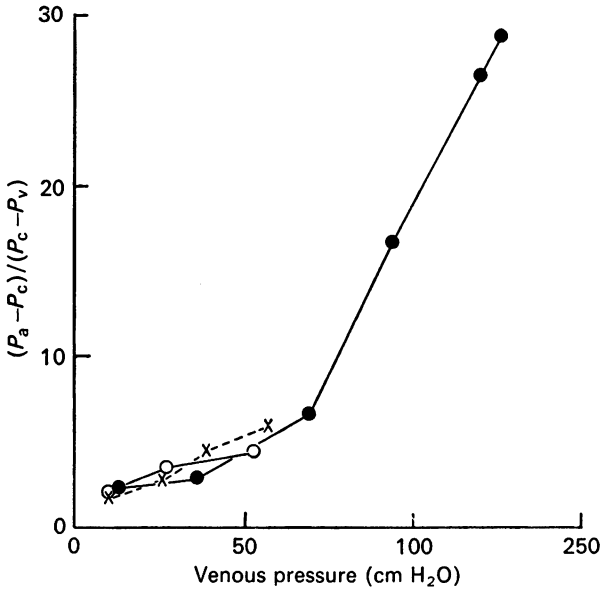

Fig. 6. The relation between $(P_a-P_c)/(P_c-P_v)$ and venous pressure (P_v) with postural changes and venous congestion. Postural changes in finger, ○--○; postural changes in toe, ●--●; changes in finger in response to venous congestion produced by inflating a cuff around the upper arm ×---×.

DISCUSSION

Two findings clearly emerge from our measurements. These are (i) at heart level P_c varies over a wide range most of which is above the colloid osmotic pressure of the plasma and (ii) as the hands and feet are lowered P_c increases less than P_v.

Variations of P_c at heart level

To some extent the very wide variation of P_c in capillaries at heart level may be accounted for in terms of the differences between the arterial and the venous ends of the capillary loop and in terms of variations in skin blood flow with changes in temperature.

The differences in pressure between the arterial and venous limbs of the capillary loops (15 cm H_2O) were smaller than those reported by Landis (27 cm H_2O), while the absolute pressures were higher. A possible explanation of the differences between Landis's figures and ours, and also those reported by Mahler *et al.* (1976), may be that subjects in modern laboratories are warmer than they were half a century ago.

Our finding of a positive correlation between P_c and skin temperature is to be expected. Eichna & Bordley (1942) noted that P_c in the finger nailfold decreased when skin temperature fell below 27 °C and Landis (1930) observed a rise in P_c when skin temperature was raised to 45 °V and a fall in P_c when skin temperature fell to 10 °C. Our observations that capillary pulsations were more obvious in the warm skin

indicate that some relaxation of arteriolar tone had occurred, and provide support for the view that changes in skin blood flow with skin temperature are largely the result of changes in arteriolar or pre-capillary resistance. An alternative interpretation would be that warming the skin results in the opening of arteriovenous anastomoses.

Variations in capillary pressure with position

Our observations on the changes of P_c with vertical position are an extension of the classical work of Carrier & Rehberg (1923) and Landis (1930) who described increments of P_c proportional to the hydrostatic load as the hand was lowered. Our work adds two refinements to this picture. As the hand or foot is lowered below the heart (i) variation of P_c at any one level is reduced and (ii) the mean value of P_c approaches the local venous pressures, i.e. the ratio $(P_a - P_c)/(P_c - P_v)$ increases.

These observations suggest that in the dependent extremity there is a tighter control of P_c. Previously we have mentioned that if capillaries are the only links between the pre-capillary and post-capillary resistances, changes in the ratio $(P_a - P_c)/(P_c - P_v)$ may be interpreted as changes in the ratio of pre-capillary to post-capillary resistances (r_a/r_v). Such an interpretation needs to be justified in the vascular bed of the nailfold where there are richly innervated arteriovenous anastomoses (Grant & Bland, 1931). A simple analysis of a vascular bed with shunt and capillary vessels in parallel, suggests that if P_a and P_v are held constant, an increase in shunt resistance would lower P_c providing that a significant fraction of the total resistance lay between the terminations of the shunts and the larger veins. Our observations that in the feet of the erect subject P_c may be only a few cm H_2O above P_v militates against this hypothesis and suggests that the changes in $(P_a - P_c)/(P_c - P_v)$ may be cautiously interpreted in terms of changes of r_a/r_v. This interpretation is in accord with the generally-held view that arteriovenous anastomoses are controlled principally by the hypothalamic temperature 'centres' (Fölkow & Neil, 1971).

Although it would be reasonable to expect that an increase in P_v might reduce r_v (and thus increase r_a/r_v) by passive distensions of the veins and venules, we do not think this mechanism could account for our findings. The compliance curves of veins indicate that they show nearly maximum distension at relatively low pressures, their diameters and hence their resistances changing little as transmural pressures are further increased. On this basis, one might expect larger decreases of r_v (and thus larger increases of r_a/r_v) to occur at low transmural pressures. This prediction does not match our finding that, in the feet, $(P_a - P_c)/(P_c - P_v)$ increased most with transmural pressure when P_v exceeded 50 cm H_2O.

It seems most reasonable therefore to interpret the changes in $(P_a - P_c)/(P_c - P_v)$ in terms of an increase in r_a. Our observation that pressure pulsations in the capillaries were attenuated in the dependent hand and foot is independent evidence supporting this view.

Possible mechanisms adjusting the circulation through the skin with postural change

Although we have no direct evidence for the mechanisms involved it would seem likely that the vascular adjustments which we have observed with changes in position are the result of local mechanisms rather than central baroreceptor reflexes.

Our arguments against the involvement of baroreceptor reflexes are (i) similar changes in $(P_a - P_c)/(P_c - P_v)$ were observed in the hand and foot with changes in position even though the degree of stimulation of the baroreceptors was quite different when the positions of the hands and feet were changed, and (ii) changes in P_v at constant P_a produced changes in $(P_a - P_c)/(P_c - P_v)$ quantitatively similar to those accompanying changes in P_v with vertical position. Furthermore although baroreceptor reflexes have been shown to affect blood flow through the skin (e.g. Crossley, Greenfield, Plassarus & Stephens, 1966) the effects are slight (Roddie & Shepherd, 1957) and transient in response to postural changes (Beaconsfield & Ginsberg, 1955).

Two local mechanisms which may be responsible for the adjustments of vascular resistance we have observed are the myogenic response of vascular smooth muscle (Bayliss, 1902) or a local (axon) reflex (Henriksen, 1976*a*, *b*).

The myogenic mechanism has been favoured by many workers but of considerable relevance to our investigation are the studies of Mellander, Oberg & Odelram (1964) who, from measurements of capillary filtration capacity in the human foot and the isolated cat calf preparation, suggested a myogenic mechanism closed precapillary sphincters as the region was lowered below the heart. To account for our observations the myogenic mechanism would have to operate on the arterioles: and for changes in P_v to stimulate the changes in resistance accompanying changes in posture, the most sensitive elements of arteriolar smooth muscle would have to be closed to the capillaries (cf. Johnson, 1964; McCloskey & Torrance, 1971).

The alternative of a local reflex mechanism has recently received powerful support from Henriksen (1976*a*, *b*). When the limbs are lowered blood flow through the skin and subcutaneous tissues of the hands and feet is reduced and similar reductions result when P_v is increased. The effects of P_v on blood flow are transmitted locally (Henriksen, 1976*b*) and are present immediately after sympathectomy but diminish and disappear four days later (Henriksen, 1976*b*). Although the nature of such a local reflex remains obscure, it seems likely that Henriksen's observations are related to the variations of vascular resistance we have observed.

Vascular adjustments and fluid balance in the hands and feet

Our findings have several interesting implications with respect to fluid balance between the blood and the tissues of the extremities.

The colloid osmotic pressures of the plasma measured in venous samples of blood taken from the two subjects at heart level were 33 and 34 cm H_2O respectively. Thus they were below the mean values of P_c even at the venous ends of the capillary loops. Under these conditions there would be little scope for reabsorption of interstitial fluid into the blood and filtration of fluid must occur throughout the whole length of the capillaries. By contrast Landis's figures for P_c neatly straddle the colloid osmotic pressure of the plasma and suggest that filtration of fluid from the arterial end of capillaries is balanced by reabsorption of fluid back into the plasma at the venous end. It is around Landis's figures for the arteriovenous gradient of P_c that the well known diagram of the Ludwig–Starling filtration–reabsorption hypothesis is based. Our data suggest that this diagram may have to be revised to indicate an outward flow along the entire capillary. Since oedema was never apparent

in the hands and feet of our subjects we must assume that the volume of fluid filtered is very low i.e. the filtration coefficient of the capillaries is very low.

If P_c in the foot increased on standing by an amount equal to the increased hydrostatic load, it would rise from a mean value of 43 cm H_2O to one of 161 cm H_2O. The measured P_c on standing was close to 125 cm H_2O, thus the actual increase in P_c was 82 cm H_2O, i.e. only two thirds of the unregulated value.

We can combine our estimate of P_c with the estimates of capillary filtration coefficient (CFC) made by Mellander *et al.* (1963) to calculate the rate of swelling of the foot during quiet standing. In the supine subject Mellander *et al.* estimated the CFC of 100 g of soft tissue to be $5{\cdot}9 \times 10^{-3}$ ml. min^{-1} cm H_2O^{-1}. Taking our values of P_c at heart level (43 cm H_2O), of plasma colloid osmotic pressure (33 cm H_2O) and neglecting interstitial pressures, for a soft tissue mass of the foot of 480 g (60 % of the total mass) the rate of net fluid filtration into the foot is 17 ml. h^{-1}.

If, on standing, there were no regulation of CFC and if P_c increased directly with hydrostatic load, the rate of fluid filtration in the erect position would be 221 ml. h^{-1}. With the actual increment of P_c of 82 cm H_2O and with CFC reduced to $1{\cdot}1 \times 10^{-3}$ ml. min^{-1} cm H_2O^{-1} 100 g^{-1} (Mellander *et al.* 1963) the fluid filtration should increase only to 29·4 ml. hr^{-1}, a figure which is similar to the swelling rates observed experimentally (Waterfield, 1931; Mellander *et al.* 1964).

This relatively small value for the filtration of fluid into the foot during quiet standing depends critically upon the low value of CFC. Mellander *et al.* proposed that CFC in the foot is reduced in the erect position by the closure of five sixths of the capillary bed by precapillary sphincters. Although we do not dispute the CFC measurements in the erect subject, we find it difficult to understand how the contraction of precapillary sphincters alone could close off a large fraction of the capillary bed when high venous pressures might be expected to fill the capillaries retrogradely. Furthermore, while admitting that the capillary bed of the nailfold is not necessarily typical of capillary beds in the rest of the foot we draw attention to our failure to observe differences in the number of perfused capillaries here in the supine and erect positions. Thus the mechanism whereby CFC in the feet is reduced on standing appears to be unclear and would seem to be a problem for further investigation.

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