Venous Occlusion Pressure Plethysmography in the Human Upper Limb


ABSTRACT
Two techniques of venous occlusion pressure plethysmography were examined experimentally in the human upper limb. The first was the classical method, in which external pressure is applied to the limb solely by way of the plethysmograph. In the second, the entire upper limb including the plethysmograph and venous occlusion cuff was enclosed in a box within which the air pressure could be raised. For each method the predictability of perfusion pressure was estimated by measuring local tissue pressure, venous pressure and arterial pressure. Artifacts in the recording of blood flow were also sought. In the first method there was a nonuniform increase in tissue pressure, venous pressure and probably arterial pressure. The changes were uniform and predictable in the second. Flow cessation pressure was 19 to 36 mm Hg in the warm hand and 13 to 30 mm Hg in the forearm using the first method. It was less than 10 mm Hg with the other method. It is suggested that the second technique offers a method for reexamining pressure-flow relations in the human upper limb under more precisely controlled conditions than hitherto.

ADDITIONAL KEY WORDS
blood pressure forearm arteries
blood flow forearm muscles veins

The principle of positive pressure venous occlusion plethysmography depends on the thesis that whether the pressure within the arteries supplying a vascular bed is lowered, or whether the pressure in the tissues surrounding the vascular bed is raised, a similar reduction in perfusion pressure can be effected. This principle has been used to study pressure-flow relations in the human upper limb by Burton and Yamada (1), by Ashton (2), and by ourselves (3). These workers raised the pressure within a conventional venous occlusion plethysmograph, and measured blood flow at depressed perfusion pressures.

It is clear that the use of this method relies on a number of suppositions. One is that a rise of pressure within the plethysmograph induces predictable and uniform changes in arterial, venous, and tissue pressure in the enclosed limb segment; another is that the measurement of blood flow is unaltered in accuracy by this maneuver.

We believed there was a prima facie case for suspecting these assumptions, and have therefore tested some of them directly. As a result we have devised a modified technique of venous occlusion pressure plethysmography which has allowed us to reexamine pressure-flow relations in the hand and forearm under more precisely controlled conditions.

Methods
Our approach to the problem was first to examine the proposition that a rise in pressure surrounding the upper limb would reduce perfusion pressure in a predictable fashion, then to consider the accuracy with which venous occlusion plethysmography could be used to measure blood flow under these conditions.

Blood flow was measured by venous occlusion plethysmography in the hand, and in a segment of the forearm. For the most part, air plethysmographs were used, because of their small bulk and ease of application, following the technique described by Graf and Westersten (4, 5) and used previously in this laboratory (3, 6). These took one of two forms: a slightly conical, well-fitting, double-walled rubber plethysmograph enclosing a 10-cm segment of forearm; or a double-walled...
rubber glove enclosing the hand distal to the radiocarpal joint. The volumes of the forearm segments studied ranged from 428 to 540 ml (mean, 490), and of the hands from 400 to 450 ml (mean, 427). Volume change in the tissue enclosed by the plethysmograph was recorded as an air pressure change, by a low-pressure strain gauge and pen recorder. The maximum pressure rise during an inflow trace was 1.0 mm Hg. Calibration was done by the injection of known volumes of air, and was linear over the range 3 to 6 mm Hg.

On some occasions a conventional water plethysmograph was used, which enclosed a 16-cm segment of forearm. The design was similar to that of Greenfield (7). The volumes of the forearm segments ranged from 712 to 790 ml (mean, 751).

Forearm plethysmographs were located about 1 cm distal to the flexion crease at the elbow. A 5-cm wide venous occlusion cuff was placed immediately above the elbow, and an arterial occlusion cuff immediately distal to the plethysmograph. In the case of the hand, a 5-cm wide venous occlusion cuff was placed on the wrist. Intermittent venous occlusion was produced automatically by way of gas solenoids which were actuated by a timing circuit. The inflation pressure of the venous occlusion cuffs was recorded by a strain gauge.

Two alternative methods of applying positive pressure to the limb segment under study were tested (Fig. 1). The first resembled the conventional method of pressure plethysmography, in that the pressure in the center of the plethysmograph itself was set at a predetermined level between 5 mm Hg (control) and 120 mm Hg. This was done by air injection in the case of the air plethysmograph, and by a water leveling device in the case of the water plethysmograph (1). The plethysmographs were recalibrated at each pressure used. The venous occlusion cuff pressure was kept constant at 5 mm Hg below diastolic pressure, unless the plethysmograph pressure exceeded this level; an inflation pressure 5 mm Hg above that in the plethysmograph was then used.

In the modified method, the whole upper limb to the level of the anterior axillary fold was enclosed in a box and a rubber sleeve was glued to the skin of the upper arm to render the system airtight. The air pressure within the box could be accurately set at any level up to 120 mm Hg, and was recorded by a strain gauge. A differential regulating valve maintained the pressure in the air plethysmographs 5.0 ± 0.5 mm Hg higher than that in the box. By this means the calibration factor was maintained constant.

When arterial pressure was measured directly, a 0.5-mm o.d. catheter was inserted into the brachial artery at the elbow, with its tip lying in the radial artery at the middle of the forearm. When venous pressure was measured, catheters were inserted into the median basilic vein and directed selectively into either a deep or superficial vein, also to mid-forearm level. Palpation and the response of venous pressure to muscle contraction were used to check their location.

If tissue pressure was to be measured, similar catheters were inserted obliquely with their tips lying in the subcutaneous tissue, or in the muscle substance of the wrist extensors, at mid-forearm. Further details of this technique can be found elsewhere (8). The initial location of the catheter tip was estimated from the angle of insertion of
the catheter and its known length. In each subject two methods were used to vary its position relative to the upper margin of an overlying plethysmograph. Either the plethysmograph was shifted along the limb by measured distances, or the catheter was intermittently withdrawn by measured amounts. The results were substantially identical. The strain gauges were calibrated to ensure equality of reading to within 2.0 mm Hg over the range 0 to 150 mm Hg. They were placed at the same horizontal level as the catheter tip; a small hydrostatic correction was made during withdrawal.

The subjects were normal volunteers among ourselves and our colleagues. They lay comfortably on a couch, lightly clad, with both arms elevated. The middle of the forearms lay about 5 cm, and the hands about 10 cm, above the mid-axillary line. Room temperature was maintained at 22 to 24°C unless otherwise stated. Hand and forearm skin temperature were monitored by surface thermists.

**Results**

**CHANGE IN PERFUSION PRESSURE WITH CHANGE IN EXTERNAL PRESSURE**

**Tissue pressure**

In the 2 subjects tested, subcutaneous pressure averaged 6.6 mm Hg (sd 1.3) and intramuscular pressure 11.2 mm Hg (sd 1.5), under resting conditions and with repeated measurements.

When the whole upper limb was enclosed in the box, increments of external atmospheric pressure induced equal increments of tissue pressure at all depths within narrow limits. Over a range of external pressure of 0 to 100 mm Hg, the pressure difference between either muscle or subcutaneous tissue and the atmosphere remained within 2.5 mm Hg of the control difference in 35 of 42 readings, the discrepant results being randomly distributed over the range of applied pressure.

When external pressure was exerted by the plethysmograph itself, this same relationship held true for subcutaneous pressure, with a sharp decrement close to the upper margin of the plethysmograph (Fig. 2). However, the intramuscular pressure reached the predicted level only toward the middle of the plethysmograph; as the catheter tip lay progressively nearer its upper margin, so the intramuscular pressure fell in relation to the plethysmograph pressure (Fig. 2).

**Venous pressure**

Three subjects were tested. Superficial venous pressure averaged 4.4 mm Hg (sd 1.4) and deep venous pressure 5.3 mm Hg (sd 2.1) at normal atmospheric pressure and with repeated measurements.

With the whole upper limb in the box, increments of external pressure induced equal increments of both superficial and deep venous pressure within narrow limits. Over a range of external pressure of 0 to 100 mm Hg, the pressure difference between either vein and the atmosphere remained within 2.5 mm Hg of the control level in 46 of 47 readings.

A similar relation obtained for superficial venous pressure when external pressure was applied solely by a plethysmograph, with a
sharp decrement to normal at the upper margin of the plethysmograph (Fig. 3). However, deep venous pressure reached the predicted level only when the point of measurement was more than 2 to 4 cm inside the plethysmograph; there was a gradual decrement in pressure from this point proximally.

Arterial pressure

The response of mid-radial arterial pressure to increase in box pressure was studied in 2 subjects (Fig. 4). A suprasystolic cuff was applied at the wrist. Both subjects were normotensive, with average radial arterial pressures of 100/64 and 110/66 mm Hg.

Internal systolic pressure remained constant at all levels of box pressure short of suprasystolic. Internal diastolic pressure behaved similarly, until it was approached by the box pressure. It then averaged 6.2 mm Hg (± 2.0) above the box pressure. This resulted in a rise of mean arterial pressure, which at the same time became relatively closer to the diastolic level. When the box pressure was less than diastolic pressure, the true mean pressure lay 5.0 mm Hg (± 2.4) above that predicted by the empirical formula \(2 \times \text{diastolic} + \text{systolic} \div 3\). At higher levels, it lay 5.6 mm Hg (± 2.4) above that predicted by the formula \(2 \times \text{box pressure} + \text{systolic} \div 3\).

The effect on mid-radial arterial pressure of inflation of the venous occlusion cuff was also measured in 1 subject. When the inflation pressure was less than diastolic, no effect on systolic, diastolic or mean pressure was apparent. At 4.9 mm Hg above the box pressure, radial systolic pressure was unchanged, diastolic rose by 2.1 mm Hg, and mean by 0.8 mm Hg. At 9.0 mm Hg above the box pressure, radial diastolic pressure rose by 5.0 mm Hg, and mean by 3.1 mm Hg.

MEASUREMENT OF BLOOD FLOW WITH CHANGE IN EXTERNAL PRESSURE

Arterial inflow curves

When external pressure was applied by way of the plethysmograph alone, it was noted that
as the pressure was increased, there was a progressive delay in the onset of a rise in the trace following inflation of the venous occlusion cuff. Indeed there always came a point, when the estimated perfusion pressure was still 13 to 36 mm Hg, where no inflow was apparent after 24 sec even though pulsations persisted. In the 1 subject in whom this was specifically studied, it was noted that the inflow trace only began to rise when venous pressure between the venous occlusion cuff and the plethysmograph approached the plethysmograph pressure.

When pressure was applied to the whole upper limb by way of the box, the venous occlusion cuff pressure was set at 5 mm Hg below diastolic arterial pressure until the latter was approached by the box pressure. Thereafter an inflation pressure 5 mm Hg above the box pressure was used. Increase in the inflation pressure by a further 5 mm Hg did not affect the slope of the inflow traces. The latter always took off within 2 sec of inflation of the cuff.

In general, arterial inflow could be recorded while pulsations persisted, and vice versa (Figs. 5 and 6). As the box pressure was raised, the normal minute-to-minute variations in arterial inflow became less evident in the forearm but persisted in the hand. Arterial inflow could be measured with confidence...
down to a level of 0.2 ml/100 ml of tissue per min, though an inflow period of 16 to 18 sec was often necessary to allow for phasic respiratory variations. That such low levels of arterial inflow were not artifact could be demonstrated by inflating an arterial tourniquet high on the upper arm, which resulted in a horizontal trace.

Pressure-flow curves for three normal hands by the box technique (left, closed symbols), and by local air pressure plethysmography (right, open symbols). Values of perfusion pressure and flow normalized for comparison.

Pressure-flow curves for two normal forearms by the box technique (left, closed symbols) and by local water pressure plethysmography (right, open symbols). Values of perfusion pressure and flow normalized for comparison.
Pressure-flow curves were determined by each method for the hand and for the forearm. Arterial pressure was measured by contralateral brachial sphygmomanometry, and a hydrostatic correction was made for the vertical distance between the brachial artery and the center of the plethysmograph. Mean pressure was calculated by the empirical formulas already derived in Results. Internal venous pressure was taken as being 5 mm Hg above the level of external pressure applied by the box or plethysmograph (see Results). Perfusion pressure was taken to be the mean arteriovenous pressure difference. Ten inflow traces were recorded at each level of perfusion pressure, over a period of 3 to 4 min. The mean slope of the last 5 was used in constructing pressure-flow curves.

Three hands were examined under warm environmental conditions (room temperature 29 to 30°C). The average resting flow was 12.8 ml/100 ml per min (10.1 to 16.7) during local air pressure plethysmography, and 13.8 ml/100 ml per min (11.7 to 17.3) when external pressure was applied using the box. The corresponding average perfusion pressures were 67 mm Hg (58 to 75) and 58 mm Hg (48 to 66). Skin temperatures remained constant to within ±0.5°C, and the mean resting hand flow did not vary by more than ±15% at normal atmospheric pressure during the measurements in an individual subject.

Using local pressure, flow became apparently zero at perfusion pressures of 19, 33 and 36 mm Hg. When the box technique was used the pressure-flow curve intercepted the axes near the zero point (Fig. 7); in each subject flow could be confidently recorded at less than 10 mm Hg perfusion pressure.

Two forearms were similarly examined, this time comparing local water pressure plethysmography with the box technique. Resting forearm flow by the former method was 4.4 and 3.5 ml/100 ml per min, and by the latter 4.2 and 4.1 ml/100 ml per min.

With local water pressure plethysmography and an inflow period of 12 sec, blood flow became apparently zero at a perfusion pressure of 13 and 30 mm Hg in the respective forearms. With the box technique, flow was recordable until the perfusion pressure was less than 10 mm Hg (Fig. 8).

Discussion

It is clear that there are at least two major sources of error in the technique of local pressure plethysmography in which external pressure is applied to the limb solely by the plethysmograph.

The application of positive pressure to the forearm by a water plethysmograph results in a nonuniform rise in tissue pressure in the enclosed limb segment (Fig. 2), similar to that which Thomson and Doupe (9) found beneath a sphygmomanometer cuff. While the validity of measurement of absolute tissue pressure by needle or catheter techniques has been doubted (10) and Guyton (11) has reported subatmospheric pressures using a new method, our concern was chiefly with short-term changes in pressure and with their geometric distribution. The method is unlikely to be seriously in error in these respects.

The average resting level of superficial venous pressure in the forearm (4.4 mm Hg) was close to that found in the subcutaneous tissue (6.6 mm Hg). Ryder et al. (12) have shown previously that in the human upper limb the pressure within superficial veins is marginally greater than that in the surrounding tissue while venous flow persists. That we apparently found the converse is explicable by the fact that our measurements of tissue pressure and venous pressure were undertaken on different days. The discrepancy between resting deep venous pressure (5.3 mm Hg) and intramuscular pressure (11.2 mm Hg) is no doubt because the deep veins catheterized are inter- rather than intramuscular. These minor anomalies do not affect the general thesis that within a local pressure plethysmograph the geometric distribution of pressure in veins reflects that in the surrounding tissues (Figs. 2 and 3).

The effect of external pressure on internal radial artery pressure was also tested (Fig. 4). It is clear that diastolic pressure is deter-
mined by the surrounding tissue pressure when this latter approaches or exceeds the original diastolic level. It follows therefore that the change in perfusion pressure caused by raising the plethysmograph pressure varies quite widely through the length and breadth of the limb segment. For example, in a subject with an arterial pressure of 100/70 mm Hg (mean 80), and at a plethysmograph pressure of 50 mm Hg, the mean arteriovenous pressure difference may range from 30 to 80 mm Hg at different points in the tissue contained by the plethysmograph.

With local pressure plethysmography there is also a potentially serious source of error in the blood flow measurements themselves. When a positive pressure of, say, 50 mm Hg is applied by the plethysmograph alone, venous pressure decreases steeply to 5 mm Hg at or just within the upper margin of the plethysmograph, creating a classic venous waterfall effect. It is clear that the veins between the venous occlusion cuff and the plethysmograph must be filled before any pressure rise (or volume increase) occurs in the veins within the plethysmograph. At low rates of blood flow it is easy to interpret the absence of volume change in the plethysmograph during this latent period as representing zero blood flow. Holling and Verel (13) noticed a similar phenomenon when they studied blood flow in the upper limb as the latter was progressively elevated.

By enclosing the entire upper limb in a pressure-box, many of these sources of error are removed. Increments of external pressure cause equal increments of both tissue and venous pressure, and these changes occur uniformly, at any rate in the forearm. The mean arterial pressure is equally predictable, so the perfusion pressure can be determined with a reasonable degree of accuracy. No significant venous waterfall exists at the upper end of the plethysmograph.

Perhaps the chief potential source of error with this modified pressure plethysmographic technique is that a venous occlusion cuff pressure which is 5 mm Hg above internal diastolic arterial pressure must be used. However, we have shown this to have a minimal effect on mean arterial pressure distally, and we could not find evidence that venous occlusion was incomplete. It seems that the risk of a significant error in blood flow measurements exists only if perfusion pressure approaches closely to zero, when flow may be underestimated.

The pressure-flow curves which we obtained for the forearm by the method of local pressure plethysmography differ from those reported by Burton and Yamada (1) and by Ashton (2) only in that ours were more consistently convex to the pressure axis. They found that forearm blood flow ceased at a perfusion pressure of 10 to 74 mm Hg in normal subjects. Using an identical technique, we found under warm conditions a positive perfusion pressure intercept of 13 to 30 mm Hg (Fig. 8). With an air pressure plethysmograph we obtained curves for the warm hand which resembled those for the forearm and which had a positive perfusion pressure intercept of 19 to 36 mm Hg (Fig. 7).

When external pressure was applied to the whole arm by its inclusion in the box, the pressure-flow curves were greatly different. Those for the hand had a parabolic form, convex to the pressure axis, and intercepting the latter close to zero (Fig. 7). They resembled those reported by Green et al. (14) in an isolated perfused skin vascular bed. Those for the warm forearm had a more complex shape, as is to be expected from a mixture of skin and muscle vascular beds, but also passed very close to the zero point, and in no case did flow apparently cease at a perfusion pressure greater than 9 mm Hg. In this latter respect our results resemble those of Jones and Berne (15) and of Folkow (16) who examined isolated muscle vascular beds in animals.

The method described here has the advantage that skin and muscle vascular beds can be examined without interference with blood constituents, and with the ability to vary perfusion pressure from normal levels to zero. Innervation is intact, and in the hand (though to a lesser extent in muscle) the
tonic influence of the sympathetic can be varied at will. In a subsequent paper we shall present the results of a more detailed examination of the vascular beds of the hand and forearm.

Acknowledgment

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References

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