Measurement by venous occlusion plethysmography of blood flow through surgically created arteriovenous fistulae in the human forearm

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Summary

1. Plethysmographs containing the hand plus forearm were used to measure blood flow in patients with a surgically created arteriovenous fistula in one forearm.
2. Apparent flow rate was stable over a limited range of collecting pressures; the absolute value of these pressures varied from patient to patient.
3. After arterial occlusion, blood flow increased by a similar amount on the normal side and on the side with the fistula.
4. Occlusion of fistular flow produced no significant change in heart rate.
5. Fistular flow, estimated as the difference between flow on the two sides, averaged 525 ml/min in seventeen patients.

Key words: blood flow rate, surgically created arteriovenous fistulae, venous occlusion plethysmography.

Introduction

The arteriovenous fistula, introduced by Brescia, Cimino, Appel & Hurwich (1966) to facilitate haemodialysis for chronic renal failure, has received wide acceptance. The amount of blood flowing through such a fistula would be expected to vary with fistular size and design and, in theory, might be large enough to cause cardiac embarrassment. It is therefore desirable to have a method of measuring fistular flow. The method should be as safe as possible and as convenient as possible. Venous occlusion plethysmography is a safe and relatively convenient procedure. This paper examines its validity for measuring fistular flow in patients with an artificial fistula for the treatment of chronic renal failure.

Methods

All the patients seen had a surgically created arteriovenous fistula in the forearm to facilitate haemodialysis for chronic renal failure. Cimino–Brescia fistulae were made by side-to-side anastomosis of the radial artery and a nearby vein; they had been found to function satisfactorily when used for haemodialysis. The purpose of the study was explained to the patients and they readily agreed to take part. They were studied while lying on a couch in a comfortably warm laboratory (temperature 21–24°C).

In an earlier study (Herron & Wallace, 1971), water-filled, temperature-controlled forearm plethysmographs (Greenfield, 1954; Greenfield, Whitney & Mowbray, 1963) were used. The method appears seriously to underestimate flow because it does not take account of increased hand blood flow due to the fistula (Jamison & Wallace, 1976). For this reason blood flow in hand plus forearm was measured on both sides with large plethysmographs which contained the hand and forearm to just below the elbow, a situation roughly similar to that obtaining with the early plethysmograph of Hewlett & Van Zwaluwenburg (1909) except that theirs was air-filled.
The plethysmographs were made in the local Department of Mechanical Engineering and were similar to the Greenfield (1954) plethysmograph, except that they were three times as long, were permanently closed at one end, and had two stirrers instead of one. Water temperature was 34°C. The plethysmographs were connected by air lines to Grass volumetric pressure transducers (PT5A) and a Devices M4 pen recorder.

Dynamic calibration of the equipment was carried out with a water-filled rubber balloon placed inside the rubber sleeve alongside the forearm in the plethysmograph. The balloon was connected through a rigid tube to a syringe whose plunger was moved rhythmically in and out by a motor. Sinusoidal volume changes were thus induced and recorded.

Resting blood flows were recorded in seventeen patients (twelve men and five women), a range of collecting pressures from 10 mmHg to approximately systolic pressure being used; several flows were recorded at each pressure. In five patients the effect of a 3 min arterial occlusion on hand plus forearm blood flow was studied. In eight patients the effect of occlusion of the fistula on resting heart rate was observed.

Results

Plethysmograms

Examples of the plethysmograms obtained are given in Figs. 1–3. Records on the fistular side showed a brief rapid rate of rise initially and the superimposed pulse waves were larger than on the normal side. Fig. 1 shows the records obtained when collecting pressure was varied from 10 to 100 mmHg in 10 mmHg steps. On the normal side, apparent flow varied between 40 and 60 ml/min with no systematic fluctuations over the collecting pressure range 20–70 mmHg. On the fistular side, apparent flow increased with the collecting pressure up to 30–40 mmHg, and then reached a short plateau and subsequently fell at collecting pressures of 60 mmHg and above. At higher collecting pressures, the record increasingly showed what appears to be an artifact associated with inflation of the collecting cuff.

The cuff artifact was further investigated in a different patient, as shown in Fig. 2. Here the artifact was recorded at collecting pressures of 40, 80 and 120 mmHg during occlusion of the circulation. On the normal side, the cuff artifact was negligible at pressures of 40 and 80 mmHg and even at 120 mmHg.

Fig. 1. Hand plus forearm plethysmograms recorded from the fistula side (upper trace) and the normal side (middle trace) at various collecting pressures (10–100 mmHg as shown at the top). The bottom trace shows the electrocardiogram. Flows estimated from the plethysmograms are given below each trace in ml/min.
was very small. The cuff artifact was clearly distinguishable from the plethysmogram recorded at a collecting pressure of 40 mmHg. On the fistular side, the cuff artifact was much larger, and increased with the collecting pressure. Here also, however, the plethysmogram at a collecting pressure of 40 mmHg was clearly distinguishable from the cuff artifact at that pressure. In particular, the spurious 'blood flow' obtained by measuring artifact slope at 40 mmHg was much less than the flow obtained from the plethysmogram at this collecting pressure. The slope of the cuff artifact increased in steepness and in duration with higher collecting pressure and might then cause a false estimate of blood flow as obtained from the plethysmogram.

Fig. 3 illustrates an example of such a case (patient no. 12, Table 1) where the patient's blood pressure was 195/130 mmHg and it was hence possible to record plethysmograms at high collecting pressures. In this patient apparent blood flow on the fistular side reached a plateau at around 600–750 ml/min over the collecting pressure range 50–130 mmHg. Above this collecting pressure, apparent flow increased as shown, to reach a maximum of around 1 l/min at 150 mmHg, before dropping sharply as collecting pressure was increased. A 'late peak' of this type was seen in only one out of seventeen patients and this patient's systolic and diastolic pressures were the highest seen.

The effect of collecting pressure on apparent blood flow was noted in all patients (Table 1) and three examples are given in Fig. 4. In each case a collecting pressure plateau was noted where a change in collecting pressure had little effect on apparent flow. The extent of the plateau was taken as including pressures where the observed fistular flow was within 20% of the maximum. Thus in Fig. 4, the plateau in patient no. 1 was taken as corresponding to collecting pressures 30–50 mmHg, in patient no. 2, to 40–70 mmHg and in patient no. 3, to 10–70 mmHg.

In the seventeen patients the mean span of the collecting pressure plateaux was 30–40 mmHg, ranging from 10 to 80 mmHg. The pressure at which the plateau was reached ranged from 10 to 60 mmHg; the pressure at which it ended ranged from 50 to 130 mmHg. No single collecting pressure was common to all plateaux, showing the need to determine the plateau for each individual patient.
### TABLE 1. Influence of collecting pressure on apparent blood flow rate (ml/min) through hand plus forearm on the fistular side

Blood pressure shown was measured by sphygmomanometer on the fistular side. Values shown in bold type include flows within 20% of the maximum. Results obtained in patient no. 12 at 140 mmHg and above are discussed in the text.

<table>
<thead>
<tr>
<th>Patient no. and sex</th>
<th>Arterial blood pressure (mmHg)</th>
<th>Apparent blood flow (ml/min) at following collecting pressures (mmHg)</th>
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<tr>
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<td>20</td>
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<tr>
<td>1 M 140/110</td>
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<tr>
<td>2 M 140/110</td>
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<td>3 M 140/110</td>
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<td>4 M 140/110</td>
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<tr>
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<td>17 M 140/110</td>
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</table>

**Fistular blood flow**

For each patient flow through the normal arm was subtracted from flow through the fistular arm; fistular flow was taken as the mean difference recorded over the collecting pressure plateau. The flows so obtained in seventeen patients ranged from 125 to 800 ml/min (mean 525 ml/min, SD 195 ml/min; Fig. 5).

Fig. 6 shows the effect of arterial occlusion for 3 min on subsequent blood flow in five patients. Blood flow on the two sides, fistular and normal, increased more or less in parallel, so that there was little change in estimated fistular flow. On the normal side, blood flow in the minute after occlusion averaged 287 ml, as compared with 115 ml in the minute before occlusion ($P<0.001$), an increase of 172 ml/min. Corresponding values on the fistular side were 716 and 551 ml/min (0.05 < $P$ < 0.10), an increase of 165 ml/min. Hence fistular blood flow showed no significant change, averaging 429 ml in the minute after occlusion as compared with 436 ml in the minute before occlusion (0.90 < $P$ < 1.00).
Measurement of flow in arteriovenous fistulae

**Fistular occlusion and heart rate**

After the resting pulse had been taken, a cuff was applied to the normal forearm and inflated to above systolic pressure; the pulse was again counted over 30 s. The same procedure was then repeated with the cuff over the fistula. The pulse was higher with the fistula occluded in three patients, lower in three and the same in two. The initial pulse averaged 88.6 beats/min. With the cuff on the normal forearm it was 88.4, and with fistular occlusion 86.9 beats/min (0.50 < P < 0.60).

**Dynamic calibration**

This showed that 20 ml oscillations at 0.42 Hz were recorded without appreciable loss. This volume change and mean rate of change (20 ml in 1.2 s or 1 litre/min) corresponded to that occurring in maximal fistular flow recordings.

**Discussion**

**Venous occlusion plethysmography**

It is widely accepted (Formel & Doyle, 1957; Conrad & Green, 1961; Greenfield *et al.*, 1963)

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**Fig. 5.** Estimated fistular flow in twelve male (○) and five female (●) patients, with mean value ± 2 SD shown at the right.

**Fig. 6.** Effect of arterial occlusion on mean hand plus forearm blood flow in five patients. Fistular flow (lower panel) has been estimated by subtracting flow on the normal side (lower curves, upper panel) from flow on the fistular side (upper curves, upper panel). Vertical lines indicate SEM values. After arterial occlusion for 3 min (at arrows) the flows on the normal side were significantly increased (P < 0.001); there was no significant change in fistular flow.
that venous occlusion plethysmography permits satisfactory estimation of blood flow in an extremity under normal haemodynamic conditions. It is necessary to consider whether this also applies under the abnormal conditions introduced by an arteriovenous fistula. The problem may be approached by examining the results of the present plethysmographic measurements and by comparing results with those obtained by other methods.

Conrad & Green (1961) laid down four assumptions which must hold if plethysmographic flow is to equal arterial inflow before occlusion. There should be, first, complete occlusion of veins; secondly, no initial reduction of arterial inflow, thirdly, no confusion from the occlusion artifact, and, fourthly, these factors should hold true for a time sufficient for measurement. Also, the air lines and recording system should be capable of transmitting and faithfully recording rapid rates of volume change. The ability of the present system to do so has been confirmed (see Dynamic calibration, above).

Occlusion of veins. Incomplete occlusion would lead to an underestimate of flow. In the absence of any hindrance to arterial inflow, the apparent flow would tend to increase with collecting pressure until occlusion is complete, when further increase in collecting pressure does not improve collection. Complete occlusion is achieved at low collecting pressures in normal forearms (Fig. 4). Apparent fistular blood flow tended to increase over a greater range of pressure, but still reached a plateau (Table 1). Of the seventeen patients whose results are given in Table 1, seven showed blood flows within 20% of the maximum by the time a collection pressure of 30 mmHg had been reached, fifteen by the time 50 mmHg had been reached, and the other two at 60 mmHg.

Reduction of arterial inflow. This normally leads to an underestimation of flow when collecting pressure exceeds diastolic pressure. The critical requirement is that reduction of arterial inflow shall not occur before the plateau indicating complete occlusion of veins. In most cases there was a plateau of considerable length (e.g. Fig. 4b,c). In all cases there were at least two maximal readings at a 10 mmHg interval within 20% of each other, but in a patient such as in Fig. 4(a), confidence that the plateau has been established is less than in most cases.

Occlusion artifact. In most cases, plethysmograms recorded on the fistular side showed a cuff artifact which was much larger than on the normal side and which increased with the collecting pressure (e.g. Figs. 1 and 2). The maximal effect of such an artifact would be over before the main steady rise of the plethysmogram was reached but a later slower rise due to the artifact could overestimate fistular flow, the effect increasing progressively with collecting pressure, probably accounting for the high flows recorded at 140-150 mmHg in patient no. 12 (Table 1). In this patient collection at high pressures was possible because of the high arterial pressure. The late spurious rise in apparent blood flow can be clearly distinguished as it occurs much later than the plateau between 50 and 130 mmHg.

Time available for measurement. The interval between inflation of the collecting cuff and levelling off of the forearm volume increase due to leak of blood under the cuff was in most cases very brief in view of the high rate of flow which rapidly filled the occluded veins. Greatest confidence can be placed in flow measurements where there is linear volume increase over at least the first three heart beats. This was so in some cases (e.g. Fig. 1) but in others (e.g. Figs. 2 and 3) only two heart beats were on the linear part of the plethysmogram. However, care was taken in such cases to obtain the slope of the plethysmogram by connecting two points on corresponding phases of the pulse wave.

The fact that the method was capable of detecting an increased flow on the fistular side similar to that on the normal side (Fig. 6) during the hyperaemia after arterial occlusion confirms the validity of the method. It also suggests that fistular flow is little affected by changes in tissue flow and hence basal resting conditions are not required during estimation of fistular flow.

Estimation of fistular flow

Fistular flow was estimated from the difference in flow through the two arms. This is valid only if tissue flow on the fistular side is little if at all affected by the presence of the fistula. Theoretically, diversion of blood through the fistula would tend to lower arterial pressure distally. This, together with the observed rise in venous pressure, would tend to lower perfusion pressure. Unless tissue resistance fell proportionately, tissue flow might fall. The presence of cool finger tips in some cases is consistent with this. However, the fact that, after arterial occlusion, blood flow on both sides rose by almost identical amounts suggests no serious interference with the
regulation of tissue flow. Thus the difference between flow on the two sides should provide a reasonable estimate of fistular flow; if anything, fistular flow might be slightly underestimated.

Other methods of estimating fistular flow

A very approximate indication of fistular flow is obtained by noting the effect on heart rate of occlusion of the fistula by a blood pressure cuff. Nickerson, Elkin & Warren (1951) studied patients with arteriovenous fistulae due to limb trauma. They estimated cardiac output by ballistocardiography and noted the effect of occluding fistular flow. This manoeuvre slowed heart rate on average by 16.0 beats/min in seven patients with femoral fistulae (mean flow 3.84 l/min calculated from their Table 1), by 10.1 beats/min in five patients with popliteal fistulae (3.21 l/min) and by 4.4 beats/min in eleven patients with tibial fistulae (1.46 l/min). The present finding of a non-significant slowing of 1-2 beats/min is consistent with a flow appreciably below 1.46 l/min. Brescia et al. (1966) reported that temporary obliteration of their fistula did not slow the heart rate; Lindstedt (1972) found a significant fall of 2.9 beats/min in the mean heart rate of ten patients during fistular occlusion.

Lindstedt (1972) compared cardiac output with fistula open and then closed in ten patients. The average difference obtained, 600 ml, was of the same order as the present results.

Forearm plethysmography

An earlier study using forearm plethysmography with an occluding wrist cuff (Herron & Wallace, 1971) gave a mean fistular flow of 123 ml/min. Hurwich (1969), using a similar technique, but without an occluding wrist cuff, obtained a mean fistular flow rate of around 200 ml/min. Bussell, Abbott & Lim (1971), using pneumatic forearm plethysmography, again without an occluding wrist cuff, found a mean difference between flow in the two forearms of 22.3 ml/100 ml of tissue. Assuming mean forearm volumes around 700 ml, this would give a fistular flow rate of around 150 ml/min. These results confirm the impression (Lindstedt, 1972; Jamison & Wallace, 1976) that forearm plethysmography, with or without an occluding wrist cuff, seriously underestimates fistular flow rates.

Conclusions

Hand plus forearm plethysmography offers a valid method for estimating blood flow in Cimino-Brescia arteriovenous fistulae in the human forearm provided that a range of collecting pressures is used, so that a measurement ‘plateau’ can be identified. The flow so recorded in the present series of patients was of the order of 500 ml/min.

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References


