Comparison of Blood Flow Measured by Plethysmograph and Flowmeter During Steady State Forearm Exercise

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SUMMARY
Forearm blood flow was determined at rest and during steady state grip exercise by the venous occlusion technique with a single strand mercury-in-rubber strain gauge plethysmograph and was compared with blood flow simultaneously determined by an electromagnetic flowmeter around the brachial artery before, during, and after intermittent isotonic grip exercise in eight subjects. The comparison of plethysmographic flow (y axis) with simultaneously measured flowmeter flow (x axis) yielded a correlation coefficient of 0.797, a slope of 1.15 and a y intercept of 9.62. When flow was normalized per 100 cc of forearm, the correlation coefficient was 0.823, the slope 1.21, and the y intercept 0.871. The overestimation of the flowmeter blood flow by the plethysmograph could be explained by flow through skin vessels which bypassed the flowmeter. When averaged plethysmographic flow was compared to total planimetered flowmeter flow during exercise, there was a 1.7 times overestimation by the former technique, which was constant over the range of exercise employed.

Additional Indexing Words:
Venous occlusion plethysmography Electromagnetic flowmeter Forearm blood flow

The original consideration and description of the two strand mercury-in-rubber strain gauge plethysmograph by Whitney1,2 led to the development of a simplified means of measuring limb blood flow. Later the single strand strain gauge plethysmograph was introduced as an instrument that was simpler in design, and therefore, more easily constructed and employed in the measurement of peripheral blood flow.3,4,5 Both types of strain gauge plethysmographs have been applied to a wide variety of research and clinical problems. The validation of the strain gauge methods of measuring peripheral blood flows appears to be theoretically sound2 and compares well with the volume plethysmograph.4,6,7 Indeed, strain gauge plethysmography has been used as a standard by which other specialized methods of measuring blood flow have been compared. Any discrepancy between plethysmographically determined blood flow and flow measured by such methods as 133Xenon and radioactive albumin6,8 has been taken as evidence that the latter methods measure nutritional flow and the plethysmograph measures total limb flow. Although the absolute accuracy of the strain gauge plethysmograph has yet to be determined by a nonplethysmographic technique, this need has been recognized.9 Therefore, it was the purpose of this study to compare the measurement of a wide range of peripheral blood flows by electromagnetic flowmeter with measurements made by the mercury-in-rubber strain gauge used with venous occlusion plethysmography.

Materials and Methods
Eight subjects ranging from 40 to 63 years of age undergoing diagnostic left heart catheterization via brachial arteriotomy were evaluated after obtaining informed consent. Two patients had aortic stenosis, one, mitral insufficiency, three, coronary artery disease, and one, hypertensive heart disease. One subject was found

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to be disease free. All subjects were premedicated with 100 mg of pentobarbital given parenterally two hours before the blood flow study.

Following exposure of the brachial artery, a Biotronex model BC610 sine wave flow transducer of the appropriate size was placed around the vessel to fit snugly but not to interfere with the lumen of the vessel. At the completion of the study, a brachial angiogram was performed by introducing a 5 Fr catheter through a brachial arteriotomy at a point where the flowmeter had been attached, and the tip was positioned at the brachial-axillary artery junction so as to visualize the distribution and bifurcation of the brachial artery as well as any significant collateral circulation around the flowmeter site. It was determined that in all eight subjects the placement of the flow transducer was proximal to the brachial arterial bifurcation. Zero flow was obtained by slowly occluding the artery just distal to the transducer. Since it was impossible to calibrate the flowmeter in situ, the flow transducers were calibrated by passing dog blood of an appropriate hematocrit at multiple controlled flow rates through an isolated section of a canine femoral artery after completion of all studies. All calibrations were carried out in triplicate with less than 5% variation. The relationship between electromagnetically measured flow and actual flow through the vessel was linear in all instances.

On the ipsilateral forearm a single strand mercury-in-rubber strain gauge plethysmograph of the type described by Holling, Boland, and Russ was placed at midforearm for the determination of flow by the venous occlusion technique as previously described, using a venous collecting pressure of 30 mm Hg. A three inch wrist cuff was inflated to greater than 250 mm Hg at least one minute prior to any flow determinations to exclude the hand from the circulation. The plethysmograph was balanced at a tension of 10 g and calibrated by progressively stretching it known increments of length.

To obtain a wide range of flows the plethysmographic and electromagnetic flowmeter (EMF) measurements of flow were compared simultaneously on the same forearm prior, during, and after three levels of exercise. The exercise consisted of isotonically gripping a rubber hand bulb to 25, 50, or 100 mm Hg for 5 sec followed by a 10 sec relaxation period (fig. 1). This was repeated four times per minute for a 3% min exercise period. The measurements of blood flows were taken during the last 5 sec of each relaxation period. The portion of electromagnetic flowmeter tracing that was taken for comparison with plethysmographic flow was that which was averaged over the initial to midportion of the plethysmographic tracing. All plethysmographic slopes were drawn and all flowmeter averaging lines were drawn before numerical calculations were performed. In all subjects the forearm was considered to be a truncated cone and its volume determined according to the formula

\[ V = \frac{\pi h}{3} (r_1^2 + r_2^2 + r_1 r_2) \]

where \( h \) is the height of the cone and \( r_1 \) and \( r_2 \) the two end radii calculated from the circumferences measured at the flowmeter site and proximal border of the wrist cuff. Knowing the volume of the arm allowed interconversion of flowmeter and plethysmographic blood flows to both ml/min and ml/min • 100 ml tissue.

Results

During rhythmic grip exercise, characteristic changes occurred in the blood flow to the forearm (fig. 1). During the 5 sec of isotonic grip the blood flow, measured by the flowmeter, fell as the vessels traversing the fascial plane were partially occluded. With relaxation there was a rapid hyperemia which became less as the metabolic debt was repaid toward the end of the 10 sec relaxation. Likewise, profound changes occurred in the plethysmographic recording of forearm circumference (fig. 1). When the subject gripped the rubber bulb, there was an upward distortion of the plethysmographic tracing related to the rapid geometrical changes of the forearm muscle under the strain gauge. This was followed by a slower drop which was likely secondary to venous emptying, followed by a plateau that was maintained during grip, presumably indicating that arterial filling was equal.
to venous emptying. After the grip was completed, the plethysmographic tracing fell precipitously, frequently to below base line levels, associated with configurational changes and the decreased venous blood volume. Five seconds after relaxation the venous occlusion cuff was inflated and the blood flow was recorded as a function of the rate of increase in circumference.

Throughout the course of exercise the plethysmographic blood flow slope closely followed the flowmeter blood flow measured during the first half of the plethysmographic venous occlusion cycle and was proportional to the severity of exercise (fig. 2). An average of 35 correlations of blood flow were made on each subject, six at rest, 19 during exercise and ten during the postexercise period. In the individual patient there was a close correlation between blood flow measured by plethysmograph and by flowmeter (fig. 2).

The paired forearm blood flows for all subjects were compared on an absolute basis in ml/min (fig. 3) as well as after normalization in terms of ml/min·100 ml tissue (fig. 4). Plethysmographic blood flows range from 7 to 268 ml/min (1 to 32 ml/min·100 ml tissue). Electromagnetic blood flows range from 7 to 169 ml/min (0.8 to 20 ml/min·100 ml). These values are similar to those reported elsewhere. Regression lines to fit these data have slopes of 1.15 and 1.21 and y-intercepts of 9.62 and 0.87 for absolute flow and normalized flow respectively. There is a nonsignificantly higher correlation for normalized data (r = 0.823) than for absolute flows (r = 0.797). In individual subjects higher correlations were found (fig. 5). The plethysmograph appears to overestimate the flowmeter blood flow at all levels of flow.

The normalized total flow was averaged under the flowmeter tracing by planimetry during the entire exercise period and related to the average plethysmographic blood flow during each level of exercise. Plethysmographic blood flow was significantly higher at each of the three levels of exercise, 25, 50, and 100 (Plethysmograph: 8.5 ± 1.3 SEM; 10.5 ± 1.6; 15.8 ± 2.9 ml/min·100 cc. Flowmeter:

![Figure 2](attachment:image1.png)

**Figure 2**

Average plethysmograph and flowmeter forearm blood flows measured at rest, during steady state exercise at 25, 50 and 100 mm Hg and during recovery. Exercise procedure described in the text.

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![Figure 3](attachment:image2.png)

**Figure 3**

Comparison of multiple paired plethysmographic and flowmeter measurements of total forearm blood flow in eight subjects.
4.9 ± 0.7, \( P < 0.05 \); 6.6 ± 0.4, \( P < 0.05 \); 8.7 ± 0.8, \( P < 0.05 \).

Brachial angiograms demonstrated that the flowmeter was situated above the bifurcation of the brachial artery and only minor skin collaterals were found to bypass the flowmeter and supply the tissues under the plethysmograph.

Discussion

The measurement of forearm blood flow by a noninvasive technique during steady state dynamic exercise is very difficult. Reliable invasive techniques have been used and exercise has been temporarily interrupted to measure postexercise flow with a plethysmograph. In the present study a slow rhythmic gripping exercise was employed in order to evaluate the magnitude of the discrepancy between blood flow measured by plethysmography during the intermittent relaxation phases, and that measured simultaneously by flow transducer. There was quite good correlation between both techniques (figs. 3, 4); however, plethysmographic blood flow was significantly higher. This does not imply that one method is better than the other. Wetterer has reviewed and confirmed the accuracy of the electromagnetic flowmeter both theoretically and practically. Likewise, the plethysmographic technique appears to be based on sound theoretical grounds.

How might the differences in blood flow be explained? The absence of significant muscle collateral vessels was demonstrated; however, there were a few skin collaterals shown radiographically. Thus, it seems likely that the difference between techniques is explained by the fact that the plethysmograph also measures skin flow, whereas the brachial flow transducer measures predominantly muscle flow. Since the duration of exercise performed by all patients was short and the levels of exercise were no more than a mild systemic stress, it is unlikely that there would be any more than a slight increase in skin blood flow since there would be minimal need to dissipate heat. If skin blood flow were not seen at all by the flowmeter and remained at resting levels throughout the exercise period, one would expect that the percent overestimation of blood flow by the flowmeter technique might decline as muscle blood flow increased; the correlation between the two techniques would still be expected to be good, although the regression equation might demonstrate a significant \( y \) intercept.

On the other hand, it is possible that some blood flow to the bone of the forearm may not be detected by the flowmeter. Bone blood flow similarly would not be recorded by the plethysmograph if...
the venous drainage did not pass under the strain gauge. Although approximately 20% of the forearm tissue is composed of bone and tendon,16 these tissues are relatively poorly vascularized17 and thus could only account for about 10% of the resting forearm blood flow and a much smaller amount of the exercising flow. Also, on angiography, vessels to the elbow originating distal to the flowmeter site were sparse.

One problem inherent in a comparison of methods of measuring blood flow over the range employed in this study is the necessity to use dynamic exercise to increase flow, since an unsteady state is present during the post contraction hyperemia. Whereas the flowmeter recording of blood flow varies moderately, the plethysmographic tracing defines a rather constant rate of venous filling (fig. 1). This implies that during the period of active hyperemia the plethysmograph is recording an average of the summated flow events. Therefore, the portion of the flowmeter tracing corresponding to the pulsations seen on the more accurate initial portion of the plethysmographic recording (excluding any cuff artifacts) was averaged for comparison by the two techniques. It is fortunate that the plethysmograph appears to register an integrated average of dynamic circulatory transients during the terminal portion of the relaxation phase of this type of rhythmic exercise. If the plethysmograph faithfully followed all the instantaneous flow events, it would not develop the smooth slope which we observed during venous collection, and it could not be used to estimate total metabolic blood flow.

It seems clear that the single strand mercury-in-rubber strain gauge plethysmograph is reliably measuring the rate of collection of blood in the veins beneath it during temporary venous occlusion. However, what relationship does this measurement have to total metabolic flow to the exercising muscle? During muscular contraction, flow is inhibited and during relaxation a hyperemia is seen on the flowmeter tracings (fig. 1). The plethysmograph, measuring only the hyperemia phase, would be expected to significantly overestimate flow. In fact, when total flowmeter blood flow averaged by planimeter was evaluated, it was found to be only 58% of the plethysmographic flow. An important result was the constancy of the relationship that held for mild as well as the more strenuous levels of exercise. These data would suggest that the plethysmograph can be used to reliably record a discrete range of metabolic flows during this type of steady state intermittent exercise, and that the recordings bear a constant relationship to the actual forearm muscle blood flow as measured by a flowmeter. These observations, therefore, help to establish plethysmography as a useful technique for studies of forearm metabolism during exercise.

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