Venous cuff pressures from 30 mmHg to diastolic pressure are recommended to measure arterial inflow by plethysmography

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Venous cuff pressures from 30 mmHg to diastolic pressure are recommended to measure arterial inflow by plethysmography. J Appl Physiol 95: 342–347, 2003. First published April 4, 2003; 10.1152/japplphysiol.00022.2003.—Venous occlusion strain gauge plethysmography (VOP) is based on the assumption that the veins are occluded and arterial inflow is undisturbed by the venous cuff pressure. Literature is not clear concerning the pressure that should be used. The purpose of this study was to determine the optimal venous occlusion pressure at which the highest arterial inflow is achieved in the forearm, calf, and leg by using VOP. We hypothesized that, for each limb segment, an optimal (range of) venous cuff pressure can be determined. Arterial inflow in each limb segment was measured in nine healthy individuals by VOP by using pressures ranging from 10 mmHg up to diastolic blood pressure. Arterial inflows were similar at cuff pressures between 30 and 60 mmHg for the forearm, leg, and calf. Arterial inflow in the forearm was significantly lower at 10 mmHg compared with the other cuff pressures. In addition, arterial inflows at 20 mmHg tended to be lower in each limb segment than flow at higher cuff pressures. In conclusion, no single optimum venous cuff pressure, at which a highest arterial inflow is achieved, exists, but rather a range of optimum cuff pressures leading to a similar arterial inflow. Venous cuff pressures ranging from 30 mmHg up to diastolic blood pressure are recommended to measure arterial inflow by VOP.

arterial blood flow; forearm; upper leg; calf; perfusion pressure

VENOUS OCCLUSION PLETHYSMOGRAPHY is a well-established, noninvasive technique used to measure peripheral arterial blood flow (12, 27). The method is usually applied on the forearm and calf and, to a lesser extent, on the upper leg. In 1907, Hewlett and Zwaluwenburg (7) described, for the first time, a plethysmograph for cardiovascular measurements. In their paper on arterial flow, the authors stated that “the general accuracy of this method depends mainly on the answer to the question: Are the veins occluded and the arteries left open by the pressure cuff?” A study by Wilkins and Bradley in 1946 (26) showed that the apparent rate of arterial inflow in the arm is the same over a wide range of subdiastolic pressures in the venous occlusion cuff. However, these results were obtained with the volume-displacement technique with the limb surrounded by a water-filled chamber (water-filled plethysmograph), which is physically and technically quite different from strain gauge plethysmography. Nowadays, strain gauge plethysmography is widely used to measure arterial inflow while different venous cuff pressures are applied (1, 2, 5, 8, 11, 17, 19, 25), in the assumption that venous occlusion is achieved and arterial inflow is undisturbed. However, Hiatt et al. (8) showed, using echo Doppler ultrasound, that a venous cuff pressure as low as 20 mmHg at the arm and 40 mmHg at the leg reduced arterial diameter and blood flow in the brachial and femoral artery. They concluded that the higher the venous cuff pressure, the greater the reduction in diameter and arterial inflow. In addition, their results suggest that different venous cuff pressures are required to measure arterial inflow adequately in the arm vs. the leg. On the other hand, Pallarés et al. (15) stated that high subdiastolic pressures are needed to avoid underestimation of arterial inflow through blood “leak” at the venous side. Similarly, Lorentsen et al. (14) reported that venous cuff pressure just below or even at diastolic blood pressure resulted in the optimal (i.e., the highest) flow values. As far as we know, nobody measured arterial inflow in different limb segments, by strain gauge plethysmography, at different venous cuff pressures to determine (a range of) venous cuff pressure leading to the highest arterial inflow.

The purpose of this study, therefore, was to determine the optimal venous occlusion pressure at which the highest arterial inflow is achieved in the forearm, leg, and calf by using venous occlusion strain gauge plethysmography. Different venous cuff pressures, varying from 10 to 80 mmHg, will be applied, and the highest arterial inflow, measured by venous occlusion strain gauge plethysmography, is considered to represent the optimal venous cuff pressure. We hypothesized that, for each limb segment, forearm, upper leg, and calf; an optimal (range of) venous cuff pressure can be determined, and that this may differ for each limb segment.

METHODS

Subjects. Nine healthy volunteers, four men and five women, participated in this study. All were nonsmokers and were moderately physically active (general characteristics

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Table 1. General characteristics of the subjects
\(^{(n = 9)}\)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>28.9 ± 7.5</td>
<td>21–43</td>
</tr>
<tr>
<td>Height, cm</td>
<td>180.0 ± 9.0</td>
<td>172–198</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>74.3 ± 13.9</td>
<td>61–100</td>
</tr>
<tr>
<td>Diastolic blood pressure, mmHg</td>
<td>72.6 ± 7.6</td>
<td>60–83</td>
</tr>
<tr>
<td>Systolic blood pressure, mmHg</td>
<td>122.8 ± 13.7</td>
<td>110–155</td>
</tr>
<tr>
<td>MAP, mmHg</td>
<td>89.3 ± 5.1</td>
<td>80–96</td>
</tr>
<tr>
<td>Exercise, h/wk</td>
<td>3.4 ± 7.8</td>
<td>0–6</td>
</tr>
</tbody>
</table>

\(^{n = 9}\). MAP, mean arterial pressure.

are summarized in Table 1). The subjects’ medical history did not reveal any cardiovascular diseases. The study was approved by the Faculty Ethics Committee and confirms with the principles outlined in the Declaration of Helsinki. All subjects gave their written informed consent before the study.

All subjects refrained from caffeine and alcohol at least 4 h before the experiment. The subjects were studied in the supine position on a bed, in a quiet room, with a temperature kept between 24 and 26°C.

Measurements. During an acclimatization period of at least 15 min, the apparatus was connected. At the end of the acclimatization period, the blood pressure was measured manually at the brachial artery, according to the Riva-Rocci method. An automatic venous occlusion strain gauge plethysmograph (E-4 Hokanson, Hokanson, Bellevue, WA) (8) was used to measure relative volume changes (from which arterial inflow was calculated) of the forearm, calf, and leg after applying a venous occlusion to the upper arm or leg. Venous occlusion cuffs connected to an adjustable air pressure source (E-20 Hokanson Rapid Cuff Inflator and AG-101 Cuff Inflator Pressure Source, Hokanson) were attached around the upper arm (13-cm width) and upper thigh (12-cm width). Strain gauges were attached around the thickest part of the forearm, around the lower thigh at 10 cm above the top of the patella, and around the thickest part of the calf (15). Arterial occlusion cuffs were attached around the ankle and the wrist (both 9-cm width) to exclude the circulation of the hand and foot (13). Throughout the experiment, the measured arm, leg, and calf were supported ~10 cm above heart level, to empty the venous system and facilitate venous outflow between the venous occlusions.

Protocol. Each measurement consisted of two stages: first the measurements at the arm, followed by the measurements at the leg. Each stage consisted of seven different venous cuff pressures, ranging from 10 to 70 mmHg for the arm and 20 to 80 mmHg for the leg. In two individuals, the 70-mmHg venous cuff pressure at the arm was not performed because this pressure was above their diastolic blood pressure. For the same reason, the 80-mmHg venous cuff pressure measurement at the leg was not performed in five individuals. At each cuff pressure, 10 consecutive venous occlusions of 10 s each were made, with a 10-s interval in between each occlusion in which the cuff was instantly deflated. Before the measurements, an arterial occlusion of >200 mmHg was applied at the wrist or ankle. After three consecutive cuff pressures, the arterial occlusion was released. To prevent invalid measurements as a result of reactive hyperemia, a 5-min break was taken before measurements were continued (3, 16, 24).

The arterial inflow measurements at the calf could not be analyzed (bad quality of the slopes, long delays), because our experimental design was not appropriate, as appeared afterwards. The reason for this problem was the placement of the venous cuff at the upper thigh instead of at the lower part of the thigh, as usually is done (1, 6, 8, 11, 15, 25). An additional experiment was started in which we measured six healthy volunteers. The measurements and protocol described earlier were applied, with the difference that the venous cuff was attached just above the knee on the lower part of the thigh instead of around the upper thigh.

Data analyses. Arterial inflow (in ml·min\(^{-1}\)·100 ml tissue\(^{-1}\)) was calculated (using Matlab 6.1) as the slope of the volume change over a 6-s interval. Registrations with artifacts, due to movements, were excluded. An initial steep rise, previously observed and attributed to a cuff inflation artifact (4), was skipped. Averaged values were calculated from the slopes of the 10 consecutive venous occlusions for each cuff pressure in each subject, representing arterial inflow.

Statistical analyses. All values are shown as means ± SE, unless otherwise indicated. A repeated-measurement ANOVA was used to determine whether there was a venous cuff pressure effect on the arterial inflow for each limb segment. Paired student t-tests were applied between each venous cuff pressure for each limb segment to determine whether there were differences in arterial inflow between the venous cuff pressures. A P value of <0.05 was considered to indicate significance.

RESULTS

In the forearm, arterial inflow was similar for venous cuff pressures of 30–60 mmHg, but a significantly lower apparent arterial inflow was observed at a venous cuff pressure of 10 mmHg compared with all higher pressures. Moreover, at a venous cuff pressure of 20 mmHg, there was a tendency for apparent arterial inflow to be reduced. Within the group, a wide variety of arterial inflow in the forearm was seen, but all of the individuals seemed to follow the same pattern, i.e., showing no venous cuff pressure effect between 30 and 60 mmHg (Table 2, Fig. 1).

In the leg, arterial inflow was similar for venous cuff pressures of 30–70 mmHg, but a venous cuff pressure of 20 mmHg showed a tendency for apparent arterial inflow to be reduced. Within the group, a wide variety of arterial inflow in the leg was seen, but all individuals seemed to follow the same pattern, i.e., showing no

Table 2. Arterial inflow of the forearm, leg, and calf at different venous cuff pressures

<table>
<thead>
<tr>
<th>Venous Cuff Pressure, mmHg</th>
<th>Forearm (n = 9)</th>
<th>Upper leg (n = 9)</th>
<th>Calf (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.6 ± 0.2*</td>
<td>3.4 ± 0.3</td>
<td>2.4 ± 0.3</td>
</tr>
<tr>
<td>20</td>
<td>3.0 ± 0.5</td>
<td>4.0 ± 0.5</td>
<td>2.7 ± 0.5</td>
</tr>
<tr>
<td>30</td>
<td>3.4 ± 0.6</td>
<td>4.0 ± 0.6</td>
<td>2.6 ± 0.5</td>
</tr>
<tr>
<td>40</td>
<td>3.6 ± 0.7</td>
<td>3.9 ± 0.6</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>50</td>
<td>3.6 ± 0.7</td>
<td>3.9 ± 0.5</td>
<td>2.5 ± 0.6</td>
</tr>
<tr>
<td>60</td>
<td>4.3 ± 0.7†</td>
<td>3.9 ± 0.5</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>70</td>
<td>4.3 ± 0.7‡</td>
<td>4.0 ± 0.5</td>
<td>2.5 ± 0.6</td>
</tr>
<tr>
<td>80</td>
<td>3.7 ± 0.5†</td>
<td>3.7 ± 0.5</td>
<td>2.5 ± 0.6</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of subjects. *Significantly different from forearm inflows at the other venous cuff pressures, P < 0.05. †These are the results from the additional calf experiment; ‡n = 7; §n = 4.
venous cuff pressure effect between 30 and 70 mmHg (Table 2, Fig. 2).

The results from the additional measurement at the calf show that arterial inflow was similar for venous cuff pressures of 30–70 mmHg, but that a venous cuff pressure of 20 mmHg showed a tendency for apparent arterial inflow to be reduced. Within the group, a variety of arterial inflows in the calf was seen, but all individuals seemed to follow the same pattern, i.e., showing no venous cuff pressure effect between 30 and 70 mmHg (Table 2, Fig. 3).

DISCUSSION

The main finding of this study is that no single optimum venous cuff pressure, at which the highest arterial inflow is achieved in forearm, calf, or leg by using venous occlusion plethysmography, exists, but rather that a range of venous cuff pressures all show a similar arterial inflow rate. A venous cuff pressure of <30 mmHg should not be used in venous occlusion plethysmography, because these pressures seem to result in lower apparent arterial inflows. Ranges of venous cuff pressures from 30 mmHg up to diastolic blood pressure are recommended for forearm, calf, as well as upper leg venous occlusion plethysmography.

Arterial inflow values measured by venous occlusion plethysmography, as found in the present study, are in agreement with previously published blood flow values in the forearm (8, 11, 19), the upper leg (15), and the calf (5, 11, 15).

Apparent arterial inflow in the forearm was significantly lower at a venous cuff pressure of 10 mmHg compared with the other venous cuff pressures (Fig. 1). In addition, apparent arterial inflows at 20 mmHg tended to be lower in the arm, the upper leg, and the calf than flow at higher cuff pressures (Table 2). This suggests that a venous cuff pressure of 10 or 20 mmHg fails to occlude the veins entirely. Incomplete vein occlusion will lead to venous “leakage” and a concomitant attenuated limb volume increase. Consequently, arterial inflow will be underestimated. Venous cuff pressures from 30 mmHg up to diastolic blood pressure (70–80 mmHg) showed no differences in arterial inflow for the forearm, leg, or calf measurements. This suggests that the veins are completely occluded at these pressures and that these occlusion pressures have no

Fig. 1. Forearm arterial inflow at different venous cuff pressures for the whole group (A; n = 9) and for each individual (B). Note the dissimilarity of the arterial inflow scale of A and B. Values are means ± SE. †Significantly different from the other venous cuff pressures, P < 0.05. ‡Group value for n = 7.

Fig. 2. Leg arterial inflow at different venous cuff pressures for the whole group (A; n = 9) and for each individual (B). Note the dissimilarity of the arterial inflow scale of A and B. Values are means ± SE. †Group value for n = 4.
effect on the arterial system. The latter may be related to the short duration (10 s) of the pressure, or, alternatively, these occlusion pressures may exert a uniform effect on the arterial vascular system (see below). The finding of the present study, that a range of optimum cuff pressures to measure arterial inflow by plethysmography exists, seems to be in agreement with findings by Wilkins and Bradley (26), but in contrast to those of Hiatt et al. (8), suggesting a cuff pressure effect. The study by Wilkins and Bradley (26) demonstrated that the pressure in the distal artery is unaffected when the cuff is inflated to any subdiastolic pressure and, moreover, that the rate of arterial inflow in the arm is the same over a wide range of subdiastolic cuff pressures. Hiatt et al. (8) demonstrated a profound cuff pressure effect, even at subdiastolic cuff pressures, on arterial diameter and flow, such that the extent of the diameter reduction increased (up to 40%) with increasing cuff pressure up to 50 mmHg. Hiatt et al. reported a decrease in red blood cell velocity; however, others (14) have reported a concomitant increase in red blood cell velocity, counteracting the diameter reduction. Red blood cell velocity in Hiatt’s study was measured proximal to the venous occlusion cuff in the superficial femoral artery under an assumed Doppler angle of 15°, whereas the diameter changes of the superficial femoral artery were measured underneath the occlusion cuff. One may argue that, in an area of “stenosis,” velocity and diameter should be measured at the same location to provide information on blood flow changes.

Lorentsen et al. (14), who showed higher calf arterial inflows at cuff pressures of 80 and 90 mmHg compared with 50, 60, and 70 mmHg in healthy subjects, suggested that those higher pressures should be used because these pressures exerted the highest arterial inflows. However, Wilkins and Bradley (26) suggested that supradiastolic cuff pressures impede retrograde flow that normally occurs during diastole. First of all, this leads to an overestimation of the arterial inflow per heartbeat. Second, the reduction in regurgitant arterial flow by a supradiastolic venous cuff pressure will lead to an increase in arterial pressure distal to the cuff and may be associated with an increase in forward blood flow distally until venous pressure rises high enough to impede the flow.

The present study clearly shows that apparent arterial inflow appears independent of the venous occlusion pressure over a wide range. This, however, does not exclude the possibility that arterial inflow measured by venous occlusion strain gauge plethysmography is impeded by the cuff pressure and may be lower than arterial inflow measured by echo Doppler, as has been suggested by several researchers (8, 15, 23). Hiatt et al. (8) reported a profound reduction in arterial flow velocity and diameter, measured by Doppler ultrasound, in the brachial as well as the femoral artery, due to the venous occlusion cuff pressure. The mechanism of this possible blood flow reduction has not been resolved. A reduction in arterial diameter after cuff inflation has been suggested to cause a blood flow decrease (8); however, others (14) have reported a concomitant increase in red blood cell velocity, counteracting the diameter reduction. Tschakovsky et al. (23) found no change in blood flow at the first beat of the venous occlusion period and suggested that diameter changes, therefore, are not likely to explain the observed decrease in flow during venous cuff pressure. Alternatively, venous occlusion by cuff inflation will lead to venous distension and increase in local venous pressure up to approximately the cuff pressure, thereby decreasing the pressure gradient for blood perfusion and, consequently, reducing arterial inflow (23, 26). Because the time of the subdiastolic venous occlusions is short (10 s), the rate of pressure rise in the venous system will be uniform, independent of the applied venous cuff pressure, as has been described by Wilkins and Bradley (26). Therefore, the decrease in perfusion pressure gradient will be similar for all pressure levels and may explain the results found in the present study: that, over a range of subdiastolic cuff pressures (30–80 mmHg), arterial inflows are uniform.

The original calf blood flow measurement in this study, as mentioned in METHODS, could not be analyzed due to an inappropriate experimental design. In our
initial experimental design, the purpose was to measure upper leg and calf arterial inflow simultaneously. To achieve this, a venous cuff was attached high around the upper thigh, and strain gauges were attached around the lower part of the thigh and around the calf. However, the calf volume curves turned out to be of bad quality and showed a delay in reaction. The cuff indicates that the placement of the cuff is critical and should be as close to the strain gauges as possible without causing too much of a cuff artifact. Greenfield and colleagues (6) in 1963, using a water-filled plethysmograph, suggested, when curves were noninterpretable, that “the cuff and plethysmograph must be brought closer together.” In most studies on calf inflow (1, 8, 11, 15, 25), the venous cuff is attached around the lower part of the thigh, just above the knee, which we did in our additional experiment. The values obtained in this additional experiment were in agreement with those in other studies (1, 8, 11, 15, 25).

In the present study, we observed an interindividual variety in arterial inflow for each limb segment, resulting in high standard errors. This interindividual variability can be explained by the heterogeneous composition of the experimental group. The experimental group consisted of men as well as women. Literature indicates that gender influences arterial diameter and arterial inflow; women are characterized by lower arterial diameters and lower blood flows (18, 20, 22). In addition, the level of physical activity differed among subjects, with a range of 0–6 h of exercise per week. It is well known that the level of physical activity contributes to an interindividual variety in blood flow to the limb (10, 11, 21).

**Limitations.** When a study of a method is performed, one hopes for the broadest possible application. In that respect, the present study deals with resting flows in the arm, leg, and calf of healthy, normothermic, normotensive adults. The results of the present study may not be applicable during active or reactive hyperemia, during orthostatic challenges, or under pathological conditions. Although the present study provides valuable information for a large number of studies using strain gauge plethysmography, additional research is needed to elucidate some of the above-mentioned issues.

**Conclusion.** No single optimal venous cuff pressure, at which the highest arterial inflow is achieved, exists for the forearm, leg, or calf by using venous occlusion strain gauge plethysmography. Venous cuff pressures ranging from 30 mmHg up to diastolic blood pressure (70–80 mmHg) lead to uniform arterial inflows and are recommended for arterial inflow measurements by plethysmography. The recommended venous cuff pressure values do not differ between limb segments.

**REFERENCES**


