Venous emptying mediates a transient vasodilation in the human forearm

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Tschakovsky, M. E., and R. L. Hughson. Venous emptying mediates a transient vasodilation in the human forearm. Am J Physiol Heart Circ Physiol 279: H1007–H1014, 2000.—We tested the hypothesis that venous emptying serves as a stimulus for vasodilation in the human forearm. We compared the forearm blood flow (FBF; pulsed Doppler mean blood velocity and echo Doppler brachial artery diameter) response to temporary elevation of a resting forearm from below to above heart level when venous volume was allowed to drain versus when venous drainage was prevented by inflation of an upper arm cuff to ~30 mmHg. Arm elevation resulted in a rapid reduction in venous volume and pressure. Cuff inflation just before elevation effectively prevented these changes. FBF was briefly reduced by ~16% following arm elevation. A transient (86%) increase in blood flow began by ~5 s of arm elevation and peaked by 8 s, indicating a vasodilation. This response was completely abolished by preventing venous emptying. Arterial inflow below heart level was markedly elevated by 343% following brief (4 s) forearm elevation. This hyperemia was minor when venous emptying during forearm elevation had been prevented. We conclude that venous emptying serves as a stimulus for a transient (within 10 s) vasodilation in vivo. This vasodilation can substantially elevate arterial inflow.

INCREASES IN LOCAL BLOOD FLOW are believed to be determined by increases in vascular conductance (VC) and by the pressure gradient from arteries to veins across the vascular bed (14, 21). Venous emptying, as might occur with limb elevation above the heart level or following muscle contraction, is thought to increase local blood flow via an increase in the local pressure change (∆P) (14, 23). This mechanical effect forms the basis for the muscle pump hypothesis, which predicts that muscle blood flow can be elevated by the mechanical venous emptying of muscle contractions (14). However, this hypothesis does not consider a potential vasodilatory effect of venous emptying.

It has been demonstrated that venous filling, as occurs when a limb is moved into the dependent position, mediates a reflex vasoconstriction in both subcutaneous (5, 30) and muscle tissue (4, 6, 7). This appears to be mediated by a local sympathetic axon reflex known as the venoarteriolar reflex. Conversely, reductions in venous distension might therefore result in a withdrawal of this reflex vasoconstriction and a subsequent elevation in blood flow. Consistent with this are the observations of Nielsen (17) who demonstrated an increase in blood flow to resting anterior compartment muscles in the lower leg during heel-raising exercise in which posterior compartment venous volume and pressure were reduced. More recently, Leyk et al. (16) observed a larger increase in resting leg blood flow during slow tilt from upright to supine when leg venous volume was allowed to empty versus when an upper leg cuff inflated to 60 mmHg maintained venous congestion.

The existence of a vasodilatory response to reductions in venous volume might be important in maintaining or increasing blood flow under conditions where venous volume is decreased such as limb elevation or relaxation after muscle contraction (29). Therefore, we tested the hypothesis that a reduction in forearm venous volume results in a vasodilation that can elevate forearm blood flow (FBF). Our approach was to compare the FBF response during acute (4 s) and prolonged (2 min) arm elevation from below to above heart level when venous volume was allowed to drain versus when venous drainage was prevented. Doppler ultrasound allowed us to measure FBF beat by beat as the arm was moved between above- and below- heart positions. Such information is not attainable with conventional in vivo methods commonly used to measure limb blood flow such as strain-gauge plethysmography or 133Xe clearance (6, 7, 17). Our results indicate that venous emptying with forearm elevation serves as the stimulus for a substantial transient vasodilation.

METHODS

Subjects. Nine healthy female subjects participated in this study (age: 22.8 ± 1.2 yr, height: 167.4 ± 2.3 cm, weight: 59.4 ± 1.2 kg) (means ± SE) and gave written consent on a form approved by the Office of Human Research of the University after receiving full written and verbal details of the experimental protocol and any potential risks involved. No standardization concerning the timing of the measurements relative to the menstrual cycle or the use of oral contraceptives was performed.

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**Experimental apparatus.** To achieve changes in resting forearm position relative to heart level, subjects sat upright in a chair with their right arm supported in an arm rest. The arm rest supported the right forearm at the wrist and from just distal of the elbow to approximately halfway up the length of the upper arm. The chair could be raised and lowered via a pulley system, in effect raising and lowering the heart relative to the arm because the arm rest remained at the same height and rotated about a fixed axis. Raising and lowering of the subject resulted in an average midforearm level of 18.9 ± 2.0 cm below heart level (arm below) and 25.0 ± 0.5 cm above heart level (arm above). This represents a hydrostatic column of ~32 mmHg.

**Measurements.** Heart rate (HR, central manubrium, 5th lead placement of electrocardiograph electrodes) and arterial pressure (photoplethysmograph finger blood pressure cuff, Ohmeda 2300, Finapres, Lakewood, CO) were measured beat by beat. Arterial pressure was measured at heart level during the experimental manipulations in arm position. FBF was obtained beat by beat as the product of brachial artery mean blood velocity (MBV) and arterial cross-sectional area and calculated by the following: FBF (ml \cdot min^{-1}) = MBV (cm/s) \times 60 s/min \times \pi(bra\vphantom{l}chial artery diameter (cm)/2)^2/[ forearm volume (ml) \times 0.01].

Brachial artery blood velocity was measured with a 4-MHz pulsed Doppler ultrasound probe (model 500V, Multigon Industries, Mt. Vernon, NY), which was fixed to the skin over the brachial artery at the level of the antecubital fossa of the right elbow. With this placement and arm position, probe insonation angle relative to the skin is 45° and the brachial artery is approximately parallel with the skin (28). Velocity measurements were performed on three separate trials for each of the experimental conditions. Arterial cross-sectional area was measured by a separate, linear 7.5-MHz echo Doppler ultrasound probe operating in B mode (Toshiba model SSH-140A, Tochigi-Ken, Japan). This was done during an acute forearm elevation and a prolonged forearm elevation trial before the trials in which blood flow velocity was measured, because it was not possible to obtain simultaneous velocity and artery diameter measurements. Imaged data were saved on videotape for subsequent analysis. There was no difference in diameter between the two arm positions or over time; therefore the diameter values used to calculate brachial artery blood flow were the average of 10 separate measures of diameter over the duration of each of the acute and prolonged arm elevation protocols. Diameter measurements at these times consisted of the average of three separate caliper measures of a frozen screen image of the brachial artery during diastole. Radegran (20) reported virtually no (1–2%) difference between systolic and diastolic diameters in the femoral artery. Our observations in the brachial artery also suggest minimal differences. All measurements were performed by the same operator.

To express FBF (in ml \cdot 100 ml^{-1} \cdot min^{-1}), forearm volume was measured in each subject before the experiment in the dependent position via water displacement. Forearm volume averaged 714 ± 29 ml (means ± SE). During the experimental manipulations, changes in forearm volume were inferred from forearm circumference measurements via a mercury in Silastic rubber strain gauge (Hokanson EC-4 plethysmograph, D. E. Hokanson) around the right forearm at the point of largest circumference. This method is commonly used to estimate changes in limb volume (9, 13) and assumes that circumference changes at the strain-gauge site are proportional to total forearm volume changes (i.e., 1% change in circumference represents a 1% change in forearm volume). With the arm in the below-heart baseline position, the gauge was reset to 0. Percentage changes in arm volume with altered limb position could then be followed and expressed relative to baseline (as ml/100 ml). Calibration of the strain gauge was performed with an internally generated voltage equivalent to a 1% change in strain-gauge length.

In five of nine subjects, venous pressure measurements were made via a 20-gauge, 3.8-cm catheter inserted in a retrograde direction to venous flow in an antecubital vein to confirm the effects of arm elevation and upper arm cuff inflation on forearm venous pressure. The catheter was connected to a pressure transducer (Gould P23 Db series, Gould, Oxnard, CA) affixed to the arm rest at the level of the catheter tip. Brachial artery MBV, arterial pressure, HR, forearm volume, and venous pressure were all collected at 100 Hz on the same dedicated computer.

**Experimental protocol.** Subjects were seated in the chair, and the arm rest position was adjusted to correspond with the range of chair elevation. The chair was then lifted so that the forearm was below heart level. Subjects began with the forearm position below the heart level for all experimental conditions. Figure 1 profiles the two protocols for changing forearm position. Forearm elevation above heart level was maintained for 4 s (acute) and 2 min (prolonged). Transitions between arm positions were completed smoothly over a 2-s period.

Within each of these two protocols, two experimental conditions were tested. The first condition was venous emptying. In this condition, venous drainage was allowed during arm elevation. The second condition was venous cuff. In this condition venous drainage was prevented during arm elevation. This was achieved by the rapid (<0.5 s) inflation of a venous occlusion cuff around the upper arm to ~30 mmHg immediately before the forearm moving into the above-heart position and a similarly rapid deflation immediately after the forearm was again in the below-heart level position. The order of experiments was randomized.

Before the initiation of experimental trials, the hand and arm were cooled to minimize skin blood flow. This was achieved with a fan blowing on the hand and forearm. The purpose of this was twofold. First, we wanted to investigate the muscle circulatory response. Second, this minimized temporal oscillations in FBF due to the rhythmic opening and closing of skin arteriovenous anastomoses (1) and thereby
improved the sensitivity of our measurements to temporal alterations in FBF induced by arm elevation and lowering. Once the temporal oscillations in FBF were minimized, the fan was no longer required and these oscillations did not return during the experiment.

**Statistical analysis.** Effects of condition and time were evaluated with two-way repeated measures ANOVA. Where an interaction was detected, specific hypothesis testing comparing responses within a condition across changes in arm position was performed using one-way repeated measures ANOVA. Further multiple comparisons were performed using a Student-Newman Keuls post hoc test when ANOVA indicated significant differences existed across time within a condition. Comparisons between conditions at specific times during the arm elevation and lowering were performed with one-way repeated measures ANOVA. The level of significance for ANOVA was set at $P < 0.05$. All data are presented as means ± SE.

**RESULTS**

There were no changes in either HR or mean arterial pressure with time in any of the experimental conditions. Therefore changes in FBF could be interpreted with respect to changes in vascular tone or changes in the hydrostatic component of the local pressure gradient as the forearm was moved relative to heart level.

**Prolonged (2 min) forearm elevation.** Figure 2 provides both the means ± SE and individual 1-s interpolated FBF during prolonged arm elevation with venous emptying allowed (Fig. 2A) and venous emptying prevented (Fig. 2B). Data are not shown for the transitions because of motion artifacts during changes in arm position. FBF was reduced by ~16% only for the first second of arm elevation (main effect, $P < 0.001$). Specific reductions in FBF (in ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$) during the first second of arm elevation for each experimental condition versus baseline were as follows: prolonged arm elevation venous emptying 2.0 ± 0.2 vs. 2.1 ± 0.1; prolonged arm elevation venous cuff 1.9 ± 0.2 vs. 2.2 ± 0.2; acute arm elevation venous emptying 1.8 ± 0.2 vs. 2.3 ± 0.1; acute arm elevation venous cuff 2.0 ± 0.3 vs. 2.2 ± 0.2 (see Fig. 5 for acute arm elevation data).

Within 5-s of forearm elevation, FBF had increased compared with baseline when venous emptying was allowed, peaking by 8 s (3.9 ± 0.4 vs. 2.1 ± 0.1 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$, $P = 0.0004$; Fig. 2A). Thereafter, FBF fell over the next few seconds but stabilized at a level that was still significantly elevated versus baseline (40–50 s average: 2.6 ± 0.2 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$ vs. baseline: 2.1 ± 0.1 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$, $P = 0.008$). In contrast, maintenance of venous volume on forearm elevation with the venous cuff abolished the transient hyperemia within 10 s (Fig. 2B). The individual baseline of the below-heart position and peak transient hyperemia responses of the above-heart position shown in Fig. 3 demonstrate the consistency of the peak transient increase in flow within 8 s of arm elevation when venous emptying was allowed (Fig. 3A) compared with when it was prevented (Fig. 3B). However, FBF did increase slightly but significantly over time such that it soon matched the FBF observed after the transient hyperemia in the venous emptying condition (40–50 s average venous cuff: 2.6 ± 0.2 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$) (Fig. 2B). Thereafter, flow continued to increase slightly in the venous emptying condition (significantly elevated 110–120 s average: 3.1 ± 0.2 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$ vs. 30–40 s average: 2.6 ± 0.2 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$, $P < 0.05$) (Fig. 2A) but did not change in the venous cuff condition (Fig. 2B). When the forearm was lowered to the below-heart position after the prolonged period of elevation, a similar transient hyperemia was observed in both conditions (venous emptying: 5.3 ± 0.5 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$ and venous cuff: 4.8 ± 0.5 ml \cdot 100 ml$^{-1}$ \cdot min$^{-1}$) (Fig. 2, A and B).
With venous emptying, the forearm volume decreased markedly on arm elevation and recovered slowly on return to the below-heart position of the arm (Fig. 4A). During arm elevation with the venous cuff inflated, we observed a small, rapid increase in forearm volume in most subjects as measured at the strain-gauge site (Fig. 4A). Thereafter, a further slight increase in forearm volume occurred over the 2-min elevation period. In three subjects, a slight initial decrease occurred followed by maintenance of arm volume over the duration of cuff inflation. The initial, rapid phase of the apparent increase in forearm volume can be explained as an artifact of forearm volume redistribution in the hand-up position, because the magnitude of the immediate decrease in forearm volume as measured at this site was similar upon arm lowering. The slight, continued increase in arm volume over 2 min of arm elevation and the slight continued decrease upon arm lowering also match, suggesting that this volume change was likely extravascular and represented capillary fluid leak. These interpretations are supported by the observation that, with arm elevation and lowering, the venous pressure change at the site of the catheter was characterized only by a rapid increase and decrease in pressure and no delayed slow component. These data indicate that the venous cuff was successful in preventing normal venous drainage during prolonged arm elevation. During acute arm

Fig. 3. Baseline blood flow in below-heart position and the peak forearm blood flow within 8 s of forearm elevation during the above-heart position are contrasted between when venous emptying was allowed (A) and when venous emptying was prevented (B). Large symbols indicate mean responses ± SE. Smaller symbols indicate individual subject values connected by a solid line between two arm positions.

Fig. 4. Forearm volume (A) and venous pressure (B) response to prolonged forearm elevation. Data are presented as means ± SE and as individual values as in Fig. 2. Venous emptying allowed during arm elevation (○); n = 9 except for venous pressure, where n = 5 with venous emptying allowed and n = 3 with venous emptying prevented.
Venous emptying induces vasodilation

**Discussion**

This study sought to determine in vivo whether rapid reductions in venous volume can elevate arterial inflow by serving as the stimulus for a vasodilation. The important novel finding was that venous emptying with passive arm elevation does serve as the stimulus for a substantial transient vasodilation. This vasodilation results in a transient elevation in resting FBF above-heart level, initiated ~5 s after the arm is elevated. The approximate fivefold increase in FBF observed when the arm is lowered during this transient vasodilation is substantially greater than when arm lowering occurs after this transient phase of vasodilation has passed.

**Methodological considerations.** Quantitative measures of FBF with Doppler ultrasound require measurement of both brachial artery blood velocity and arterial cross-sectional area. Cross-sectional area is calculated as \( \pi (\text{diameter}/2)^2 \). In this study, diameter measurements were performed using a separate echo Doppler and therefore had to be performed on different trials than velocity measurements. This raises the question of repeatability of measurements from trial to trial. We have previously shown that diameter measurements between separate trials of exercise are highly reproducible, with a coefficient of variation of 2–4% (25). Additionally, we are able to detect changes of 0.1 mm in diameter with Doppler in our laboratory (24). In a number of cases in the current study, the diameter measures were repeated on separate trials, and no differences were observed. We observed no change in brachial artery diameter across the duration of the experiment. That is, even when there was an increase in blood flow from ~2 to ~10 ml/min, no dilation of the conduit artery occurred. This is consistent with results during moderate intensity forearm (24) and leg (20) exercise. Flow-induced dilation of the brachial artery has been observed following release of occlusion cuffs (26). Perhaps the relatively short duration of the hyperemia in the current study can account for the differences between experiments.

The mean blood velocity response for each subject was determined as the average of the response to three separate trials in each of the conditions. The mean blood velocity response demonstrated good repeatabil-
ity. This approach of multiple trials helps to account for trial-to-trial variability and, considering the fact that the mean blood velocity response demonstrated good repeatability, we are confident that calculations of flow based on separate trial measurements of diameter and velocity as performed in this study provided valid estimates of FBF.

Venous emptying mediates a transient vasodilation. In a recent investigation, Leyk et al. (16) observed an increase in leg blood flow during a gradual (40 s) transition from head-up to head-down tilt that was blunted by maintaining venous congestion with leg cuffs inflated to 60 mmHg. This gradual tilt approach was necessary to avoid rate-sensitive baroreflex responses to tilt. However, due to the gradual nature of the venous emptying in their study, they were unable to identify potential differences between the acute versus prolonged response to venous emptying. In our study, rapid elevation of the arm from below- to above-heart level, along with rapid lowering after 4 s versus 2 min of arm elevation allowed us to investigate the acute versus prolonged forearm vascular response to venous emptying.

Elevation of a resting forearm above-heart level results in venous drainage and a reduction in local arterial and venous pressure. Previous reports investigating the effect of limb position relative to heart level on blood flow have relied on techniques such as strain-gauge plethysmography (10) and $^{133}$Xe clearance (18). However, these techniques do not provide adequate time resolution to assess the transient responses of the vasculature. Additionally, strain-gauge plethysmography cannot be used to measure limb blood flow of the below-heart level. Some investigators have suggested that blood flow is reduced with limb elevation of the above-heart level (10), whereas others observed no change (18). With the beat-by-beat capability of Doppler ultrasound, we have demonstrated that, in the resting forearm, elevation from below to above-heart level results in an initial, brief (1 s) reduction in FBF followed by a transient increase beginning at ~5 s and peaking by ~8 s (Fig. 2A). This response was consistent across all subjects. There was no change in arterial pressure at this time. Additionally, most of the venous pressure change was complete by this time such that the observed transient flow increase could not be explained by changes in arterial-venous pressure gradient. Therefore, this transient hyperemia represented a vasodilation.

It might be argued that this transient vasodilation was a myogenic response to the reduction in local arterial transmural pressure (2, 11, 12) with arm elevation. However, the data from trials where venous emptying was prevented argue strongly against this interpretation. Local forearm arterial transmural pressure with arm elevation and lowering depends on the arterial hydrostatic column and therefore was reduced to the same degree with arm elevation whether venous emptying was allowed or prevented with upper arm cuff inflation to ~30 mmHg. Therefore, if a myogenic response was responsible for the transient vasodilation, it should have occurred independent of whether the veins were allowed to empty or not. Yet, we observed that when venous emptying was prevented, no transient elevation in blood flow above-heart level occurred (Fig. 2B). In addition, prevention of venous
emptying markedly attenuated the hyperemia observed when the arm was lowered after 4 s of elevation (Fig. 5A; Fig. 6, A vs. B). The instantaneous arterial inflow velocity profile for one subject in Fig. 6 clearly illustrates the substantial difference in the magnitude and characteristics of arterial inflow upon arm lowering when venous emptying was allowed versus prevented. A considerable diastolic inflow with arm lowering was characteristic in all subjects when venous emptying was allowed, whereas only a minimal change in the flow velocity waveform occurred with arm lowering when venous emptying was prevented. Collectively, these data support the hypothesis that venous emptying acted as the stimulus for this vasodilation.

Interpretation of the hyperemia upon arm lowering must take into account the potential contribution of an elevated \( \Delta P \) with versus without venous emptying (29). Below-heart forearm, arterial pressure estimated from the addition of the heart-to-midforearm hydrostatic column and heart-level arterial pressure was estimated at \( \sim 118 \) mmHg. Venous pressure measured at the elbow was \( \sim 25 \) mmHg. Even after complete venous drainage with arm elevation, this gradient could have increased at most by \( \sim 27\% \). If no vasodilation occurred, this might explain a 27% increase in arterial inflow. The fact that arterial inflow increased by 343% means that an increase in \( \Delta P \) could at most account for only a minor portion of this hyperemia, indicating that the vasodilation that occurred was substantial.

We observed that FBF above heart level, after the transient elevation and subsequent return to near baseline levels, gradually increased over the 2 min of arm elevation. Because arterial pressure was not changing, these flow changes represented a vasodilation. This gradual increase was blunted at 2 min of arm elevation when venous emptying was prevented. These observations are similar to those of Leyk et al. (15, 16), who observed a blunted vasodilation in the legs during gradual transition from head-up to head-down tilt when leg venous congestion was maintained by inflation of a leg cuff to 60 mmHg (16). These investigators interpreted their data to indicate that venous emptying contributed to the leg arterial dilation observed with head-down tilt. However, in our study, we also assessed the forearm vasodilation due to prolonged arm elevation by rapidly lowering the arm and restoring the original below-heart arterial pressure head. We observed a hyperemia upon lowering the forearm that was not significantly different whether venous drainage was allowed or prevented, indicating that the slow, progressive vasodilation over 2 min of arm elevation was not necessarily related to reductions in venous volume. Rather, because elevation of the forearm above-heart level reduced arterial perfusion pressure in the forearm in both venous emptying and venous cuff conditions, it is possible that this maintained vasodilation was mediated by a myogenic mechanism (2, 11, 12). Furthermore, the fact that venous emptying resulted in a substantial vasodilation within 5 s of arm elevation, but did not appear to determine the vasodilation after 2 min, indicates the importance of considering the vasodilatory stimulus and response across the duration of arm elevation. The magnitude of the hyperemia following 4 s vs. 2 min of arm elevation when venous drainage was allowed reinforces the physiological significance of the transient vasodilation induced by venous emptying.

**Venoarteriolar reflex.** At present, the only known mechanism linking changes in venous pressure to alterations in vascular conductance is the local venoarteriolar sympathetic axon reflex. Rygaard et al. (22) demonstrated the presence of nerve fiber collaterals from the sympathetic arteriolar plexus to adjacent venules in dog muscle and suggested that this represents the anatomical substrate for the local venoarteriolar sympathetic axon reflex. Whereas some research has suggested that a threshold of venous pressure of 25 mmHg is required to trigger the reflex (5), it is not exactly clear what the stimulus is or how it is transduced into alterations in arterial sympathetic nerve activation. To date, the action of this reflex on arterial vascular tone has predominantly been examined in terms of the vasoconstriction induced when a limb is moved into the dependent position (5–7, 30). Evidence confirming that vasoconstriction is due to a local axon reflex stems from observations that it is not diminished with central sympathetic blockade via epidural anesthesia (8), but it is affected by peripheral \( \alpha \)-adrenergic receptor blockade or local anesthetic (7, 17). There is some evidence to suggest that reduction of venous pressure might conversely result in vasodilation (16, 17). Nielsen (17, 18) demonstrated that when subjects performed heel raisings in the upright position, resting lower leg muscles of the anterior compartment experienced an increase in blood flow. This effect was abolished with proximal cuff inflation to 40 mmHg, which was designed to maintain venous congestion during muscle contractions. More importantly, the increase in blood flow was absent in areas infiltrated with lidocaine, supporting their hypothesis that a decrease in neurogenically mediated vasoconstrictor activity was the mechanism for the vasodilation.

In this study, we hypothesized that rapid venous emptying with passive arm elevation would act as the stimulus for a vasodilation, based on the potential for withdrawal of venoarteriolar reflex vasoconstriction with reductions in venous volume and pressure. Our results are in agreement with this hypothesis. However, it must be stated that, whereas our data clearly point to venous emptying as a stimulus for vasodilation, we can only speculate that it is mediated by withdrawal of venoarteriolar reflex constriction.

**Potential implications for exercise hyperemia.** At the onset of exercise, muscle contractions empty venous volume, reducing venous pressure provided that venous valves are competent (17, 19, 27). It has been suggested that this mechanical effect of contractions elevates muscle blood flow at exercise onset by increasing the local arterial to venous pressure gradient (3, 14). In support of this, we have observed an immediate increase in FBF following a brief (1 s) mechanical venous emptying via inflation of a forearm cuff and...
maintained flow elevation with rhythmic mechanical venous emptying below but not above the heart (29). However, a vasodilatory effect of venous emptying within the exercising muscle has not been considered. Evidence from this study indicates that rapid venous emptying can result in a substantial, transient vasodilatory effect. Given that contractions reduce venous volume and pressure intermittently, it is possible that venous emptying during exercise might serve as the stimulus for part of the vasodilation responsible for the exercise hyperemia. This hypothesis remains to be tested.

In summary, the use of Doppler ultrasound in this study has allowed us to characterize the time course of vasodilation induced by rapid venous emptying on a beat-by-beat basis. These data are the first to characterize a delayed, transient overshoot in this vasodilation initiated by venous emptying under resting conditions. This vasodilation begins ~5 s after arm elevation and peaks by 8 s. The stimulus for this vasodilation appears to be the emptying of venous volume, because the prevention of venous emptying abolishes the vasodilatory response. We speculate that the most likely mechanism linking the observed arterial vasodilation to rapid emptying of venous volume is the withdrawal of venoarteriolar reflex-mediated vasoconstriction. This transient vasodilation has a substantial impact on the magnitude of the hyperemia observed on returning the forearm to below heart level.

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