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Venous response to orthostatic stress

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Venous response to orthostatic stress. Am J Physiol Heart Circ Physiol 295: H1587–H1593, 2008. First published August 15, 2008; doi:10.1152/ajpheart.00571.2008.—Head-up tilt (HUT) induces a reduction in preload, which is thought to be restored through sympathetic venoconstriction, reducing unstressed volume (Vu) and venous compliance (VeC). In this study, we assessed venous inflow and outflow responses and their reproducibility and determined the relation with autonomic function during HUT. Eight healthy non-pregnant women were subjected to 20° head-down tilt to 60° HUT at 20° intervals. At each rotational step, we randomly assessed forearm pressure-volume (P-V) curves (venous occlusion plethysmography) during inflow (VeCIN) and outflow (VeRCOUT). VeCIN was defined as the ratio of the slope of the volume-time curve and pressure-time curve, with direct intravenous pressure measurement. VeRCOUT was determined using the derivative of a quadratic regression model using cuff pressure. We defined Vu as the y-intercept of the P-V curve. We calculated, for both methods, the coefficients of reproducibility (CR) and variation (CV). Vascular sympathetic activity was determined by spectral analysis. VeCIN decreased at each rotational step compared with the supine position (P < 0.05), whereas VeRCOUT increased. CR of VeCIN was higher in the supine position than VeRCOUT but lower during HUT; CV varied between 19% and 25% (VeCIN) and between 12% and 21% (VeRCOUT). HUT decreased Vu. The change in VeCIN and VeRCOUT correlated with the change in vascular sympathetic activity (r = −0.36, P < 0.01, and r = 0.48, P < 0.01). This is the first study in which a reproducible reduction in VeCIN and Vu, and a rise in VeRCOUT during HUT are documented. The alterations in venous characteristics relate to changes in vascular sympathetic activity.

head-up tilt; venous compliance; venous emptying rate; venous capacity; autonomic system

The venous system plays an important role in hemodynamic control. About two-thirds of the total blood volume is captured by the venous system (9). An alteration in its capacity has profound effects on venous return and cardiac output. As the heart cannot store blood, venous return and cardiac output must be equal at any time. With increasing blood supply to the heart, the (stretched) ventricles increase their force of contraction (Starling’s law), leading to a (transient) larger stroke volume and, therefore, cardiac output (9, 27, 31, 43).

Women with prepregnant low plasma volume are prone to develop vascular complications in pregnancy (2). Those women are unable to augment stroke volume during physical activity (3), and an extra volume load cannot be accommodated in their venous compartment (1), leading to a state of relative venous overfill. These observations suggest reduced venous dimensions and, therefore, a reduced venous storage capacity.

Orthostatic stress testing is a valuable tool to measure the adjustments, and the buffering capacity, of the venous compartment. Positive head-up tilt (HUT) induces an initial decrease in venous return, thereby reducing cardiac preload. The decrease in venous return will normally be counterbalanced by sympathetic stimulation. The venous system is highly sensitive to sympathetic activation (6, 15, 31). Sympathetic venuconstriction, reducing venous unstressed volume (Vu), but also decreasing venous compliance, will raise venous pressure and thus right atrial pressure, filling, and cardiac output (6, 31, 43). Determination of these presumed venous responses during HUT requires fast methods, but these have not been established.

The aims of this study were to assess 1) responses of the venous system to orthostatic stress and 2) their reproducibility. We repeatedly assessed forearm pressure-volume changes during venous inflow, which represents the elastic property of the venous wall [venous compliance (VeC)], and during venous outflow, as a measure of the venous emptying rate (VER). In addition, the relation between venous adjustments at the graded tilt test and autonomic function was calculated.

METHODS

Subjects

Eight healthy nonpregnant women participated in the study after being fully informed of the risks associated with the procedures and signing informed consent. All participants were recruited by advertisement. None of them took any medication. This study was approved by the Institutional Review Board (CMO no. 2006/111).

All participants were studied on day 5 ± 2 of the follicular phase to prevent hormonal influence. Participants were requested not to smoke or drink alcohol after 8 PM on the day before the measurements. Participants were tested in four sessions on 2 successive days. Sessions were 1.5 h after a light breakfast and 1.5 h after a light lunch.

Experimental Protocol

Subjects were positioned on a comfortable mattress on a tilt table. The forearm was positioned at the heart level to ensure adequate venous emptying during the deflation period. In addition, the arm was stabilized to minimize muscular activity. Environmental conditions were kept constant. Room temperature was kept at 26°C, and distractions due to light and sound were minimalized (11).

Participants remained supine for 10 min; thereafter, orthostatic stress was imposed by passively changing the body posture from 20° head-down tilt (−20°) to 60° HUT (+60°), each time with increasing steps of 20° at 8-min intervals.

Measurements

At each rotational step, venous adjustments and autonomic function were assessed at steady state. Hemodynamic changes occur immediate
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Model: Pressure was assumed to be equal to cuff pressure. Data obtained at a...might induce more extravasation in pregnant women, affecting Star...randomization determined in which order the VeCIN and VEROUT measurements would be applied at each rotational step.

Inflow. Cuff pressure was gradually increased from 0 to 40 mmHg in 60 s. Changes in forearm volume and intravenous pressure were recorded. VeCIN was defined as the ratio of the slope of volume-time curve and slope of the pressure-time curve as follows:

\[ \text{VeCIN} = \frac{\Delta \text{volume}/\Delta \text{time}}{\Delta \text{pressure}/\Delta \text{time}} \]

Only the data of the linear part of this relationship were used, until the increase rate of intravenous pressure and forearm volume diminished.

Outflow. The method used was a modification of the method described by Halliwill et al. (10). Cuff pressure was immediately set at 40 mmHg (instead of 60 mmHg). We chose this modification because using a cuff pressure of 60 mmHg would be inappropriate for the obstetric field. Capillary leakage is increased in pregnancy. This might induce more extravasation in pregnant women, affecting Star...forces by increasing tissue pressure. The effect is intensified when...to the antecubital crease. Changes in limb volume were expressed in milliliters per deciliter of limb tissue. A venous collecting cuff was placed 5 cm proximal to the antecubital crease. The pressure cuff was connected to a rapid cuff...system, at a sampling rate of 100 Hz, and stored for further analysis (MIDAC, Biomedical Engineering Department, Radboud University Nijmegen Medical Centre, Nijmegen, The Netherlands). Pressure-volume curves were assessed in two different sessions of venous inflow (VeCIN) or venous outflow (VEROUT). Before the tilt test, randomization determined in which order the VeCIN and VEROUT measurements would be applied at each rotational step.

\[ \text{VEROUT} = p_1 + (2 \times p_2 \times \text{cuff pressure}) \]

where \( \beta_0, \beta_1, \) and \( \beta_2 \) are regression parameters. VEROUT was defined as the derivate of the pressure-volume curve as follows:

\[ \text{VEROUT} = \beta_1 + (2 \times \beta_2 \times \text{cuff pressure}) \]

To be able to compare values within and between sessions, an (arbitrary) cuff pressure of 20 mmHg was used (10). For both methods, we considered pressure-volume regression lines with an explained variation \( (r^2) > 0.9 \) to be representative of original data. Only those were included for further analysis.

Ve is defined as the volume when transmural pressure is equal to 0 mmHg (6, 9). We determined Ve during each rotational step for both methods. During VeCIN, the volume-pressure curve was generated using a linear model of both the volume-time curve and pressure-time curve. The intercept of this constructed pressure-volume curve was used to determine Ve. For the VEROUT method, the averaged volume-pressure curve was generated using the quadratic regression model. In this model, regression parameter \( \beta_0 \) was defined to represent Ve (10).

Autonomic function. Fluctuations in heart rate and arterial blood pressure (ABP) were measured continuously using a finger ABP-monitoring device attached to the third digit of the right hand at a sampling rate of 100 Hz (Finometer, Finapres) to determine sympathetic activity, parasympathetic activity, and baroreflex sensitivity (BRS). We derived relative brachial pressure from the finger arterial pressure by the application of waveform filtering and level correction.

We quantified autonomic activity and BRS by the spectral analysis technique (18). Recordings were subdivided into data segments of 100 s, overlapping for 50%, and resampled at 5.12 Hz. Each segment was then analyzed with a fast Fourier transformation that searched for rhythmic fluctuations in systolic blood pressure (SBP) and pulse interval (PI) with a frequency range between 0 and 2.56 Hz. The amplitude of each fluctuation determined the power at each frequency. Subsequently, SBP and PI powers were expressed as a function of the frequency. Vascular sympathetic activity was defined as the natural logarithm of the power of the low-frequency (LF) component of the variations in SBP, and the ratio of absolute LF and high-frequency powers of the PI was assumed to represent the cardiac autonomic balance between the sympathetic and vagal system. BRS, which provides information about the changes in heart rate (output) in response to fluctuations in SBP (input), was defined as the (LF) transfer gain from SBP to PI (expressed in ms/mmHg).

Statistics

Data are presented as median (interquartile ranges) unless otherwise stated. Differences between venous responses during inflow and outflow, heart rate, vascular sympathetic activity, cardiac autonomic balance, and BRS during HUT were analyzed by the Wilcoxon signed-ranks test for paired values. The pooled coefficient of variation (CV) and coefficient of reproducibility (CR) were calculated per method. CV was determined by the pooled ratio of each individual SD and median value of Ve or VER, respectively. CR at each rotational step was determined using the following formula:

\[ \text{CR} = 2 \sqrt{2 \times \frac{\sum (r_i - 1)^2 \text{SD}_i^2}{\sum (r_i - 1)}} \]

in which \( r_i \) is the number of measurements in each participant (generally 4 measurements in the present study) and SDi is each individual SD (4).

Nonparametric Spearman’s rho analysis was used to test correlations between variables.

Results

We included eight women with a median age of 25 (21–26) yr and a median body mass index of 23 (19–24) kg/m². SBP was 114 (110–123) mmHg, and diastolic blood pressure was 60 (58–66) mmHg. None of the measurements during both VeCIN and VEROUT were excluded due to low \( r^2 \) of the pressure-volume regression line.

During the orthostatic stress test, heart rate and vascular sympathetic activity increased and BRS decreased (Fig. 1). In the supine position, VeCIN was 0.066 (0.043–0.089) ml/dl⁻¹·mmHg⁻¹ and VEROUT was 0.052 (0.040–0.059) ml/dl⁻¹·mmHg⁻¹ (\( P < 0.01 \)). As shown in Fig. 2, VeCIN decreased by −35%, −45%, and −53% at 20, 40, and 60° HUT, respectively (all \( P < 0.05 \)). In contrast, during VEROUT, the effect was reversed. VEROUT was +23%, +30%, and +60% higher compared with the supine position (all \( P <
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Fig. 1. Heart rate [HR; in beats/min (bpm); left], vascular sympathetic activity (LnLFsys; middle), and baroreflex sensitivity (BRS; right) in response to head-up tilt (HUT). Values are presented as means ± SE. #P < 0.05 compared with the supine position.

At −20° head-down tilt, VEROUT was 43% lower compared with the supine position, but VeCIN remained unchanged.

We calculated the CR and CV of both methods to assess reproducibility (Table 1). In the supine position, the CR of VeCIN was higher compared with VEROUT (0.068 vs. 0.050 ml·dl⁻¹·mmHg⁻¹) but lower during the tilt test at 20, 40, and 60° HUT. The CV of the VeCIN method varied between 19% and 25%, and the CV of the VEROUT method varied between 12% and 21%.

As sympathetic venoconstriction reduces Vu to compensate for the decline in venous return, we determined the change in Vu both during VeCIN and VEROUT. Figures 3 and 4 show the constructed averaged volume-pressure curves during VeCIN (using a linear model) and VEROUT (using a quadratic regression model), respectively. Using the pressure-volume curve during VeCIN, a decrease in the y-intercept during HUT was observed. In the supine position, Vu was 0.01 (−0.3 to 0.6) ml/dl. It decreased to −0.5 (−0.2 to −0.9) ml/dl at +60° HUT (P = 0.045).

VER was determined using a quadratic regression model. The three parameters β0, β1, and β2 decreased with tilt (all P < 0.01). The HUT-induced decreases in β0, β1, and β2 resulted in a downward shift of the pressure-volume curve and an upward shift of the VER-pressure curve, which are shown in Fig. 4. Parameter β0 was assumed as a representative of Vu. It decreased from 1.1 (0.8−1.3) ml/dl at the supine position to −1.9 (−2.8 to −1.3) ml/dl at +60° HUT (P < 0.01).

Correlation analysis showed that the change in VeCIN assessed during inflow and VEROUT related to the change in vascular sympathetic activity measured at the different tilt angles (r = −0.36, P < 0.01, and r = 0.48, P < 0.01; Fig. 5).

DISCUSSION

The aim of the present study was to measure venous responses during stepwise-inflicted orthostatic stress. We assessed pressure-volume curves during inflow and outflow of the forearm veins at different tilt angles. Theoretically, HUT induces an initial decrease in venous return, which is compensated by a decrease in venous capacitance through a decrease in Vu and VeC (6, 31, 43). To our knowledge, this is the first study in which these venous alterations, and their reproducibility, during HUT are documented.

We observed a reproducible decrease in VeC and Vu during HUT and an increase in VER. Both observations relate, at least partly, to changes in vascular sympathetic activity. Veins are highly sensitive to sympathetic stimulation (6, 31). Karim et al. (15) reported 50% of the maximum response (at 20 Hz) of the capacitance vessels at only 1-Hz sympathetic stimulation, in contrast to 10% of the maximum response of the resistance vessels. Sympathetic stimulation realizes an increase in stressed volume and a decrease in VeC (6). Many studies have observed a downward shift of the pressure-volume curve, which implicates a decrease in Vu, but unaflecting the slope of the curve (and thus a similar VeC) during sympathetic stimulation (6, 9, 10, 31). We observed both a decrease in Vu during inflow and outflow and a decrease in the slope of the pressure-volume curve during venous inflow. In contrast to exclusively applying sympathetic stimulation by α-adrenergic agonists, cold pressure, isometric handgrip, or mental arithmetic stress, as used in most studies (5, 10, 21, 33, 35, 36), during HUT, both an increase in vascular sympathetic activity and baroreflex activation and a decrease in parasympathetic activity occurs. Studies on the venous response at lower body negative pressure (LBNP) and carotid sinus baroreflex activation have suggested sympathetic stimulation of the veins via...
both cardiopulmonary low-pressure and high-pressure receptors (35, 37, 41, 42, 50). We speculate that the cooperative activation of these two types of receptors during HUT might contribute to the decrease in \( V_u \) and venous compliance, to counterbalance the reduction in cardiac preload during HUT. Monahan et al. (21) performed venous outflow measurements at the calf and observed, in contrast to our findings, no change in the response to LBNP in women. Nonetheless, both venous capacitance and \( V_u \), as indicated by the \( y \)-intercept of the pressure-volume curve, decreased, suggesting activation of the venous contractile system. Compared with our study, there are some methodological differences. First, in the Monahan et al. study, measurements were performed at the right calf while LBNP was applied to the left leg and pelvic region. During this procedure, women more than men tend to pool more blood in the pelvic region (47), so this procedure may have affected calf venous outflow. Second, the researchers used a cuff pressure of 60 mmHg for 8 min, which might be supradiastolic in women, because it has been reported that the changes in muscle sympathetic nerve activity (22). In addition, concomitant features in this group of patients, such as assumed venous atrophy, reductions in muscle mass, and the effects of inactivity and compensatory mechanisms to ascertain cardiac hemodynamics, complications to discern the role of the sympathetic nervous system in venous function (7, 13, 23, 46). Alternatively, venous sympathetic activity can be impaired by \( \alpha \)-adrenoceptor antagonists and ganglionic blockers (23), which might be used in future research to study the contribution of the sympathetic system to venous function during HUT.

We determined autonomic function with the use of spectral analysis, which is a noninvasive, well-validated technique and frequently used during HUT (18, 28–30). Although this method has limitations (25, 39), in this study, we used the changes in sympathetic activity to correlate with venous responses. It has been reported that the changes in blood pressure variability results correspond well with the changes in muscle sympathetic nerve activity (22). In addition, it has good reproducibility both in the resting supine position and at higher tilt angles (12, 16, 26) and, therefore, might be valid to present.

For the inflow method, we used the first part of the pressure-volume curve, in which a linear relationship between intravenous pressure and forearm volume is present, resulting in one value for \( V_{ei} \). The pressure-volume relationship in the vein is dependent on tissue pressure and, therefore, on the used cuff pressure (10, 14, 17, 32). Using the first (linear) part of the pressure-volume relationship can adequately represent \( V_{ei} \), especially when using intrave-
We acknowledge that pressure measurements, and makes comparisons be­
tween the different situations possible (32).
VeC is generally measured in the calf. In the present study, we choose to perform measurements at the forearm to prevent
influencing factors during HUT. First, activation of the calf muscles is a natural response to gravitational forces. Passive
tilting, using a tilt table with a footstep, as used in this study, can minimize muscle activation compared with the response to
standing. Although calf muscle activation only minimally affects volume expansion (44), plethysmographic measures
would be less reproducible. Second, loss of (intravascular) plasma volume occurs during HUT due to increased fluid
filtration through capillary walls, which is also influenced by the duration of the orthostatic stimulus (20, 40, 48). This effect
might be more pronounced in the lower part than upper part of the body during HUT. In addition, stress relaxation might play
a role. Stress relaxation refers to the characteristic of the vessel wall of progressive delayed stretching in response to an in­
crease in volume, returning pressure back to normal. This phenomenon occurs in minutes to hours (9). Measuring VeC at
the forearm, which is placed at heart level in a stable position, will minimize muscle contraction, prevent capillary filtration,
and diminish the contribution of stress relaxation. However, active distribution of venous volume, by reducing VeC in the
nonsplanchnic part of the venous system, accounts for only 25% of the total blood transfer (34) and the legs taking a larger
part than the arms. In the present study, we intended to qualify
this response, but one must realize that the splanchnic veins are
thought to play the most important role in restoring venous
return as these vessels contain the most venous blood (6).
VeC, measured during inflow of the vein, can be assessed in 1
min. This short duration makes this method appropriate for mea­
urements in which brief maneuvers are allocated, as in orthostatic
stress testing. Additionally, due to its slowly increasing and finally
low cuff pressure (8), it is a reliable method to measure VeC in
those with low blood pressure, as in this study.
In conclusion, HUT reproducibly decreases VeC and Vu and
increases VER and sympathetic activity. The extent of changes
in sympathetic activity relate to the magnitude of venous
adjustments made during HUT.

Fig. 5. Correlation between VeCiN (r = −0.36, P < 0.01; left) and VEROUT (r = 0.48, P < 0.01; right), respectively, and the percent change in LnLFsys.
REFERENCES


