Pooling in Chronic Orthostatic Intolerance
Arterial Vasoconstrictive but not Venous Compliance Defects

Julian M. Stewart, MD, PhD

Background—Orthostatic intolerance is characterized by postural tachycardia syndrome (POTS) with exaggerated tachycardia, orthostatic symptoms, and “pooling” (which comprises acrocyanosis and dependent edema when upright). My colleagues and I tested the hypothesis that pooling results from increased venous compliance in POTS patients.

Methods and Results—Fifteen patients aged 13 to 19 years were compared with 11 healthy, age-matched controls. The POTS group was divided into patients with high venous pressure (\(P_v > 20\) mm Hg) and normal \(P_v\), on the basis of resting supine \(P_v\), obtained in previous work. Subjects were studied using strain gauge plethysmography to measure blood flow, \(P_v\), and the venous compliance volume-pressure relation while supine and during incremental head-up tilt testing at \(-10^\circ, 0^\circ, 20^\circ,\) and \(35^\circ\). Volume-pressure relations of controls and POTS patients with normal \(P_v\) and high \(P_v\) were not different and were unchanged by orthostasis. Supine leg peripheral resistance was greater than control resistance in patients with high \(P_v\) (54.9 versus 30.6 mm Hg·mL\(^{-1}\)·min\(^{-1}\)) and 100 mL·min\(^{-1}\) and less than control resistance in patients with normal \(P_v\) (17.2 mm Hg·mL\(^{-1}\)·min\(^{-1}\)) and 100 mL·min\(^{-1}\). On upright tilt, resistance decreased in high \(P_v\) to approximate resistance in normal \(P_v\). Resistance in controls increased throughout tilt. Leg \(P_v\) increased in patients with normal \(P_v\) and in controls but remained unchanged in the high \(P_v\) group.

Conclusions—The findings suggest that pooling in POTS is due to blunted arterial vasoconstriction, which produces passive redistribution of blood within peripheral venous capacitance beds. Venous compliance in POTS is similar to that in control subjects. (Circulation. 2002;105:2274-2281.)

Key Words: vasoconstriction ■ veins ■ regional blood flow ■ vascular capacitance

The postural tachycardia syndrome (POTS) in adolescents is characterized by tachycardia and frequent orthostatic symptoms during upright tilt.\(^1\) Prior work has demonstrated acrocyanosis and visible swelling in patients, which has been attributed to venous pooling in the lower extremities.\(^2\) Potential mechanisms for such pooling include increased arterial inflow enhancing venous filling, defective venous mechanical function increasing venous capacity, altered capillary permeability, or impaired venous and lymphatic emptying.\(^3,4\) Any of these can cause increased collection of blood and extravascular fluid in dependent extremities. Previous work suggested vasoconstrictor deficits in lower limbs distinguished by venous hypertension were the cause.\(^5\) Venous capacitance abnormalities were not ruled out. In the present work, I hypothesized that increased venous capacitance existed in POTS. To test this hypothesis, I used strain gauge plethysmography to generate volume-pressure capacitance vessel relations in POTS and healthy control subjects and used incremental tilt to generate multiple volume-pressure relations for each subject to test whether the relations change with orthostasis.
heart disease. Patients and controls were also free of all obvious systemic illnesses and were not taking any medications. There were no trained competitive athletes in the study.

Eleven healthy control subjects aged 13 to 19 years (mean age, 15.8±1.1 years; 8 girls and 3 boys) were studied. Subjects were recruited from adolescents referred for innocent heart murmur. The Committee for the Protection of Human Subjects of New York Medical College approved all protocols.

Laboratory Evaluation

The ECG and blood pressure (BP) were monitored continuously with an arterial tonometer (Pilot, Collin Instruments) that was placed on the right radial artery and recalibrated every 5 minutes by oscillography. Leg BP was also obtained by a BP cuff placed around a calf. A respiratory impedance plethysmograph (Respirtrac 200, NIMS Inc) was used. Respiratory, ECG, pressure, and strain gauge information (see below) were interfaced to a personal computer through an A/D converter (DataQ, Inc) at a sampling rate of 250 Hz.

Peripheral Vascular Evaluation

I used mercury in silastic strain gauge plethysmography to measure the resting P, forearm blood flow and calf blood flow and the forearm and calf capacitance/compliance (volume-pressure) relation. Because compliance is pressure dependent, I chose to obtain the entire capacitance vessel volume-pressure relation. Strain gauge plethysmography measures volume changes in normalized units of mL/100 mL of tissue. The overall total increase in normalized volume is designated the maximum venous capacitance in accord with the definitions of Rothe.6 Measurements were obtained in a steady-state condition at various angles of tilt during the study. Plethysmographic methods were adapted from the work of Gamble et al.7 While supine, occlusion cuffs were placed around the upper and lower limbs 10 cm above a strain gauge attached to a Whitney-type strain gauge plethysmograph (Hokanson, Inc). After 30 minutes of rest, data collection began.

Measurement of Blood Flow

Occlusion cuffs were inflated suddenly to a pressure just below systolic BP to prevent venous egress. Inflating a smaller secondary cuff to above systolic BP briefly prevented wrist and ankle flow. Arterial inflow in triplicate in units of mL · 100 mL tissue⁻¹ min⁻¹ was estimated as the rate of change of limb cross-sectional area.

Measurement of P

After returning pressure to baseline, occlusion pressure was then gradually increased until limb volume change was just detected. This represents resting Ps.7

Calculation of Arterial Resistance

I used the mean arterial pressure (MAP), which was calculated as [0.33×(systolic BP)]+[0.67×(diastolic BP)], and P, to calculate the peripheral arterial resistance in units of mm Hg · mL⁻¹ · 100 mL tissue⁻¹ · min⁻¹ using (MAP–P)/total flow.

The Volume-Pressure Relation: Decreasing Volume Portion

With cuffs deflated and the subject supine, I progressively elevated the limb, measured the elevation at the level of the strain gauge, and recorded the simultaneous decrease in limb volume with each elevation. This is shown in Figure 1. Heart rate and BP remained unchanged, suggesting that autonomic status was not perturbed. P, at the strain gauge was estimated from the hydraulic formula P=P0+pgh/ρ or, equivalently, P=P0+ρgΔh/ρ, where P indicates pressure, the constant 0.776 is the pressure conversion factor from centimeters of blood to mm Hg, and Δh is the height of the strain gauge. The method was used to generate the decreasing volume portion of the volume-pressure relation in order to find zero filling.

The Volume-Pressure Relation: Increasing Volume Portion

After returning to baseline I used 10 mm Hg pressure steps to a maximum of 60 mm Hg to produce progressive limb enlargement. Pressure steps started at the first multiple of 10 exceeding P, By fixing pressure with the congestion cuff the increasing volume portion of the volume-pressure relation was obtained.

Separating Filtration From Vascular Filling

At lower occlusion pressures, as shown in Figure 1, the limb size reached a plateau. With higher pressures, an initial curvilinear change representing venous filling occurred, and thereafter the limb continued to increase linearly in size due to microvascular filtration. This is shown in the lower right of Figure 1. Using least-squares analysis,10 venous filling was separated from filtration by “curve stripping” the latter linear portion, leaving only the plateau-reaching curvilinear portion representing capacitance vessel filling. Pressure remained constant for at least 4 minutes to accomplish this.

Computation of the Volume-Pressure Relation

Once the volume response was partitioned into contributions from filling of capacitance vessels and from filtration, the volume-pressure relation was constructed as shown in Figure 2. Percent volume was measured, and volume is therefore expressed in normalized units of mL of volume change/100 mL of tissue. The identical procedure was performed in the forearm and the calf.

Incremental Tilt-Table Testing

An electrically driven tilt table (Cardiosystems 600) with a footboard was used. I collected data for blood flow, P, and the volume-pressure relation during a quasi-steady state at angles considerably lower than the tilts of 60° to 80° that are usually used for orthostatic stress testing; accurate data cannot be obtained during large tilts because of dramatic flow changes and patient movements. In pilot studies, I verified that accurate volume-pressure data could be obtained at positive tilt angles up to 30° to 45°. No subjects had overt orthostatic intolerance or fainting over a 15-minute time period at these angles.

After supine vascular measurements were complete, the subjects underwent incremental tilt at ±10°, 20°, and 35°. The angle −10° was used to unload the baroreceptors. The angle 20° was chosen because it achieved orthostatic stress comparable to −20 mm Hg lower body negative pressure (LBNP), at which low pressure baroreceptors are unloaded. The angle 35° was chosen because it achieved orthostatic stress comparable to −30 mm Hg LBNP, at which low and high pressure baroreceptors are unloaded. During these tilts, arm occlusion cuffs were rapidly inflated to 50 mm Hg to measure blood flow. Leg occlusion cuffs were inflated to a pressure just below diastolic pressure, as verified by BP measured on the contralateral calf. Upright tilt increases calf arterial BP due to hydrostatic forces. A timer was used to measure forearm and calf flow every 30 seconds. Subjects were then tilted to −10° for 10 minutes while measuring flow. In practice, flow and limb size reached a new steady state within ~2 minutes. Steady state was defined by no further change in limb flow and a linear change in limb size at positive angles signifying complete capacitance vessel filling. With the timer off, I repeated measurements of forearm and calf P, I reapplied sequential 10 mm Hg pressure steps to compute the volume-pressure relation. The P, at the strain gauge transducer was assumed to differ from the pressure at the cuff because of the hydrostatic column of blood between the cuff and the gauge. I corrected for the height of this column of blood at given angle of tilt by adding 0.776×D×sin(angle), where D is the distance between the edge of the cuff bladder and the strain gauge.

After measurements at −10° were complete, timed measurements of forearm and calf flow were restarted, the subjects were tilted to 20°, and steady-state flows, P, and volume-pressure measurements were repeated. Subjects were tilted a final time to 35°, and measurements were repeated. The increasing volume portion of the volume-pressure curve starting from the measured value of P, at each angle was thereby generated.
Heart Rate and BP Variability

Heart rate variability analysis and computed low frequency baroreflex gain were used as ancillary indices of autonomic state. After a minimum 15-minute waiting period, at least 500 beats were acquired during baseline supine conditions and during incremental tilts. I used custom software to collect RR intervals and systolic, diastolic, and mean BPs as sequences of discrete point events for each heart beat. RR interval and BP beat sequences were analyzed for ectopy, which was corrected by cubic spline interpolation. Tachyarrhythmias or couplets were never observed. Beat epochs were linear-detrended and approximate wide-sense stationarity was verified by calculating autocorrelations of RR intervals in consecutive 200-beat subsets and comparing them with 500 beat records. For current purposes, only frequency domain indices are reported. An autoregressive model was used to calculate the RR interval spectrum, BP power spectrum, and cross spectrum. Beat sequences were transformed into equivalent impulse trains in which pulses were arranged at the mean RR interval with impulse heights equal to the RR intervals or BP as appropriate. Autoregression was performed and digital power spectra were calculated using the extended Yule-Walker equations; the final order of the model was chosen to minimize Akaike’s final prediction error. This yields the interval spectrum, which is converted to the spectrum of counts by dividing by the mean RR interval. The spectral power within a given band was computed by taking the power in the actual frequency band. For the current analysis, I focused on low frequency (0.04 to 0.15 Hz) and high frequency (0.15 to 0.40 Hz) power bands. The total power was also calculated, which included contributions from ultra low frequency (0.004 to 0.01 Hz) and very low frequency (0.01 to 0.04 Hz). The normalized cross-

Figure 1. A representative supine leg plethysmographic tracing is shown. After measurement of $P_v$, the leg was elevated to generate the decreasing volume portion of the volume-pressure compliance relation, as shown in lower left. Thereafter, the increasing volume portion of the relation was computed by using 10-mm Hg pressure increments beginning at 20 mm Hg. At higher pressures, the change in volume was separated into contributions from venous filling and from microvascular filtration, as shown in lower right. Flow, $P_v$, and volume-pressure measurements were repeated at tilt angles of $-10^\circ$, $20^\circ$, and $35^\circ$.

Figure 2. A representative compliance relation is shown. The volume scale has a line at 0 volume change corresponding to $P_v$. The increasing and decreasing volume portions of the capacitance vessel volume-pressure relation have been labeled.
spectrum between RR and systolic BP was used to calculate the magnitude of the transfer function between systolic BP and RR interval as an index of baroreceptor gain when coherence exceeded 0.5.12

### Data Analysis of the Volume-Pressure Relation

To construct a volume-pressure relation for all subjects, I normalized each subject curve by that subject’s maximum change in percent volume during volume-pressure generation in the supine position, ie, by the maximum capacitance. For example, if the overall increase in capacitance were 6 mL/100 mL, I divided all volume change measurements made at all angles in that subject by 6 to obtain a normalized volume change. Each individual volume-pressure relation generated a normalized curve and an overall capacitance parameter. Then, the supine volume-pressure curve was generated for a given subject. The emptied limb volume obtained by limb lifting while supine was used as the zero of venous volume at all angles of tilt. This enabled the placement of P<sub>v</sub> measured at a particular angle of tilt for a given subject at a volume measured from an absolute zero for that given patient. Thereafter, normalized percent increases in volume in that subject and angle during sequential occlusions were added to this initial point at P<sub>v</sub>. This procedure was repeated for each angle and for every subject. Any consistent increase or decrease in capacity with upright tilt would be detected as an increase or decrease in the ordinate of the curve with respect to the normalized supine volume pressure curve. Capacitance was calculated for each patient and with each angle of tilt.

### Statistics

Data were compared by 2-way ANOVA for repeated measures. Paired data were used whenever possible. When significant interactions were demonstrated and when deemed appropriate, the ratio of F values was converted to a t distribution using Scheffé’s test, and probabilities were determined. A Bonferroni correction was used to correct for small samples. Except for compliance curves, results are reported as mean ± SEM. Statistically significant differences are reported for P<0.05. Volume-pressure data are presented in their entirety (every data point). For heuristic purposes, data for individual subject groups at different angles of tilt were fit to a logistic (V=AP/(B+P)), where A and B are curve fitting parameters, V is venous volume, and P is venous pressure, using a non-linear least-squares method.15,16

### Results

#### MAP and Heart Rate as a Function of Tilt

Data appear in Table 1. Mean arterial arm pressures did not change with tilt. Mean arterial leg pressures increased by an amount approximately equal to MAP<sub>leg</sub>=PV<sub>sys</sub>+[0.776×Δh×sin(angle of tilt)], where Δh is the distance from the estimated location of the right atrium and the leg BP cuff. Thus, the hydrostatic column of blood accounted for an increased leg arterial pressure when upright. Heart rate increased significantly in all subjects during orthostasis but increased significantly more in POTS patients.

#### Peripheral Resistance and P<sub>v</sub>, as a Function of Tilt

Arterial resistance and P<sub>v</sub> are shown as a function of tilt angle in Figure 3. Arm and leg resistance increased monotonically with tilt angle in control subjects. There was no significant difference in forearm peripheral resistance among control or POTS groups. Supine calf resistance was decreased in normal P, POTS patients and increased in high P, POTS patients. Calf resistance remained lower than control levels in normal P, POTS patients and decreased with orthostasis in high P, POTS patients. At 35°, calf resistance was significantly lower than control levels in both POTS subgroups. Forearm P<sub>v</sub> was unaffected by tilt; however, calf P<sub>v</sub> increased in control subjects and normal P<sub>v</sub> patients in proportion to the hydrostatic column of venous blood, which is expressed as approximately PV<sub>sys</sub>=[PV<sub>sys</sub>+[0.776×Δh×sin(angle of tilt)]]. Thus, MAP−P<sub>v</sub> did not change for these groups. However, P<sub>v</sub> increased more slowly for the high P<sub>v</sub> subgroup, such that P<sub>v</sub> at 35° was not different from control subjects in this group.

#### Heart Rate and BP Variability

Figure 4 shows results. Indices of heart rate variability and baroreflex gain are decreased in POTS patients. High frequency power was similar in control subjects and in normal P<sub>v</sub>, POTS patients. Baroreflex gain fell by 35°, indicating activation of the sympathetic nervous system.

#### The Volume-Pressure Relation

Figure 5 shows the volume-pressure relation for the arm and leg for control subjects compared with normal P<sub>v</sub> and high P<sub>v</sub>, POTS patients. Every data point is presented. The increasing volume portion of the arm compliance relation is obtained at regular 10 mm Hg pressure steps starting at 20 mm Hg. The leg compliance relation and decreasing volume of the arm compliance relation are not obtained at regular pressure steps because the pressure at the strain gauges equaled the sum of imposed pressure steps and the hydrostatic pressure of the column of venous blood between occlusion cuff and strain gauge.

Continuous curves represent separate curvilinear fits to supine data for control and POTS subjects. There was no significant difference in any fit to arm or leg data at any angle of tilt. Capacitance data appears in Table 2. There is no difference in supine or upright capacitance.

### Discussion

Venous return to the heart during orthostasis can be compromised by abnormally increased venous capacity. Conditions

<table>
<thead>
<tr>
<th>TABLE 1. Changes in Mean Arterial Pressure and Heart Rate</th>
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<tr>
<td>Control</td>
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<tr>
<td>Forearm mean arterial blood pressure, mm Hg</td>
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<tr>
<td>0°</td>
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<tr>
<td>−10°</td>
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<td>+20°</td>
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<td>+35°</td>
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<td>Calf mean arterial blood pressure, mm Hg</td>
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<td>Heart rate, bpm</td>
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* P<0.05 compared with 0°; † P<0.05 compared with control. All results are mean±SEM.
such as varicose veins may have some degree of orthostatic intolerance as a component of their illness. Pooling, which is thought to relate to venous congestion, also occurs in patients with POTS, but its origins are unclear. Increased venous capacitance has been thought to play a role in pooling. These data indicate that POTS is characterized by defective vasoconstriction that produces resting venous hypertension and venous congestion, but it is not associated with abnormalities in the volume-pressure relations or overall venous capacitance while supine or during orthostasis. Thus, for the angles of upright tilt used, venous capacitance is not different from control and does not change with orthostasis. Therefore, venous capacitance may not play an important role in the venous pooling of POTS.

With respect to orthostasis, the data are most consistent with a peripheral venous model in which arterial vasoconstriction reduces $P_v$ and allows for passive elastic recoil.

Steady-State Arterial Vasoconstriction Is Abnormal in POTS

These data also show that arterial vasoconstriction, the expected normal response to orthostasis, does not occur normally in POTS. Normal $P_v$ patients have little change in peripheral arterial resistance during low angle upright tilt. High $P_v$ POTS patients have a decrease in resistance while upright at 35°. I have previously attributed high $P_v$ in high $P_v$ POTS to a defective venoarterial reflex and a related increased flow to the lower extremities due to the effects of gravity and the failure of venoarterial reflex–mediated vasoconstriction when upright. Current data still suggest abnormal vasoregulation. However, I demonstrated increased supine resting resistance during venous hypertension, which suggests that vasoconstriction does occur during venous hypertension. A dilator response to increased $P_v$ may account for the decrease in resistance in high $P_v$ patients during 35° upright tilt. Failure of vasoconstriction is consistent with defective norepinephrine secretion, which was demonstrated at rest and during stress by Jacob et al in similar patients.

When Does Venoconstriction Usually Occur?

The results do not address the general question of whether normal venoconstriction occurs in POTS. Venoconstriction occurs in connection with thermoregulation and stress. As shown by Shoukas and Bohlen and Robinson, veins can change the volume of blood that they contain at the same pressure, and such active vertical shifts in the volume-pressure curve downward toward the pressure axis constitute a change in capacitance. However, such a change did not occur with orthostasis and is not important for pooling in POTS.

There is certainly support for the innervation of peripheral veins by adrenergic sympathetic nerves and for venoconstric-
tion in response to stimuli such as physical and mental stress, exercise, and biochemicals, including adrenergic agents. Venoconstriction to adrenergic stimulation is regional; thus, there is excellent evidence dating to Donegan’s work on human splanchnic and cutaneous venoconstriction in response to sympathetic stimulation, but there is less evidence for the response of other venous beds. Cutaneous nerves mainly subserve thermal reflexes and not the arterial baroreflex, and even the splanchnic response depends on passive redistribution. The idea of a uniform generalized sympathetic/autonomic response to maintain homeostasis has not been demonstrated in practice. Although frequently assumed, it is often true that apparent active venoconstriction results from changes of venous filling or emptying.

Limitations
Select POTS patients have low blood volume and decreased venous capacity under resting conditions. In individual cases such venous changes may be important. Individual differences can be lost when group averages are obtained. However, I have never observed a POTS patient with increased capacity. Therefore, it seems unlikely that increased venous compliance plays an important role in POTS. It is curious in this regard that the range of normal capacity in the control group is very wide (3.8 to 7.5 mL/100 mL in the forearm and 2.5 to 5.3 mL/100 mL tissue in the calf), which could imply structural remodeling even under normal conditions.

Results may not apply across other vascular beds. In particular, I do not know whether splanchnic compliance is abnormal in POTS. However, data indicate that splanchnic arterial inflow is abnormal in POTS, which could potentially alter gastrointestinal venous pooling without a change in venous properties. Also, the lower extremities and buttocks are the major pooling reservoirs during orthostasis. Relatively low angle tilts were used, and therefore differences in volume-pressure relations could emerge at higher angles. However, arterial vasoconstriction was activated in the controls at the angles of tilt employed, indicating at least a much lower threshold for arterial vasoconstriction compared with venoconstriction.

Steady states were studied, and the study design required prolonged compliance measurements. Thus, potentially useful information could have been missed. It was evident from the data that when arterial vasoconstriction occurred, it occurred rapidly. A similar time course for venoconstriction might be reasonable. It is possible, for example, to have used a more rapid measurement technique, such as that of Halliwill et al. However, a transient response would be expected to exert little influence on the response to prolonged orthostatic stress.

Orthostatic-prone subjects might demonstrate a different pattern of change in unstressed volume; therefore, I have shown that for given change in pressure, the changes in stressed volumes are similar. Thus, the conclusions that there is no change in capacitance with orthostasis still hold.

Figure 4. Heart rate variability and the amplitude (gain) of the BP to RR interval transfer function are shown as a function of the angle of tilt. Low frequency power (LFP; 0.04 to 0.15 Hz) and high frequency power (HFP; 0.15 to 0.4 Hz) are shown on left, whereas total power (TP; 0.004 to 0.4 Hz) is shown in the top right. The gain at low frequency (LF Gain) is shown in the bottom right. Indices of heart rate variability are decreased (#P<0.05 compared to controls) in POTS patients along with baroreflex gain, although low frequency power was relatively independent of orthostasis. High frequency power was similar in control subjects and in normal Pv, POTS patients. Low frequency gain decreased significantly (*P<0.05 compared with baseline) by 35° tilt.
Age limitations to generalizability may exist. However, I think these conclusions do apply across a maturational age range. Adolescents may not perfectly represent findings in mature adults. However, cardiovascular structure and function is essentially mature by puberty and, therefore, results can be regarded as at least qualitatively similar to older age groups. The gender distribution is characteristic for POTS, with females comprising ~80% of all patients that I have seen.

TABLE 2. Changes in Calf Volume and Venous Capacity

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<tr>
<th></th>
<th>Control</th>
<th>Normal P&lt;sub&gt;v&lt;/sub&gt;</th>
<th>High P&lt;sub&gt;v&lt;/sub&gt;</th>
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<td>Calf volume change, mL/100 mL</td>
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<td>0°</td>
<td>3.8±0.4</td>
<td>4.0±0.3</td>
<td>4.5±0.5</td>
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<tr>
<td>−10°</td>
<td>0.22±0.16</td>
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<td>0.021±0.14</td>
<td>0.05±0.13</td>
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<td>+35°</td>
<td>0.16±0.17</td>
<td>0.18±0.10</td>
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<td>Forearm capacitance and change, mL/100 mL</td>
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<td>5.1±0.5</td>
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Values are expressed as mean±SEM.

*P<0.05 compared with 0°; †P<0.05 compared with control.

Figure 5. All volume-pressure data points from all subjects at all angles of tilt are shown. Arm data are shown at top, whereas leg data are shown at bottom. Left panels compare control subjects with normal P<sub>v</sub>, POTS patients. Right panels compare control subjects with high P<sub>v</sub>, POTS patients. The lines represent curvilinear fits to control and POTS group on the basis of supine data alone. There is no difference among compliance relations derived at any angle for any patient. C indicates control; Ni, normal; and Hi, high.

Importance

Orthostatic tolerance depends on a rapid response that restricts blood entering dependent venous pools and remobilizes pooled blood. The results of the present study suggest that the arterial system but not the venous system (of the limbs) has such a response in healthy adolescents and that the lack of an appropriate arterial system response accounts for findings in POTS.

Acknowledgments

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References


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