

# Effects of a 6-mo endurance-training program on venous compliance and maximal lower body negative pressure in older men and women

Juliane P. Hernandez and Warren D. Franke

*J Appl Physiol* 99:1070-1077, 2005. First published 14 April 2005;

doi: 10.1152/jappphysiol.01169.2004

## You might find this additional info useful...

---

This article cites 35 articles, 13 of which you can access for free at:  
<http://jap.physiology.org/content/99/3/1070.full#ref-list-1>

This article has been cited by 3 other HighWire-hosted articles:  
<http://jap.physiology.org/content/99/3/1070#cited-by>

Updated information and services including high resolution figures, can be found at:  
<http://jap.physiology.org/content/99/3/1070.full>

Additional material and information about *Journal of Applied Physiology* can be found at:  
<http://www.the-aps.org/publications/jappl>

---

This information is current as of August 7, 2013.

*Journal of Applied Physiology* publishes original papers that deal with diverse area of research in applied physiology, especially those papers emphasizing adaptive and integrative mechanisms. It is published 12 times a year (monthly) by the American Physiological Society, 9650 Rockville Pike, Bethesda MD 20814-3991. Copyright © 2005 the American Physiological Society. ISSN: 8750-7587, ESSN: 1522-1601. Visit our website at <http://www.the-aps.org/>.

## Effects of a 6-mo endurance-training program on venous compliance and maximal lower body negative pressure in older men and women

Juliane P. Hernandez<sup>2</sup> and Warren D. Franke<sup>1</sup>

<sup>1</sup>Department of Health and Human Performance, Iowa State University, Ames, Iowa;  
and <sup>2</sup>Department of Physical Education, Southern Illinois University, Carbondale, Illinois

Submitted 18 October 2004; accepted in final form 14 April 2005

**Hernandez, Juliane P., and Warren D. Franke.** Effects of a 6-mo endurance-training program on venous compliance and maximal lower body negative pressure in older men and women. *J Appl Physiol* 99: 1070–1077, 2005. First published April 14, 2005; doi:10.1152/jappphysiol.01169.2004.—Aging and chronic exercise training influence leg venous compliance. Venous compliance affects responses to an orthostatic stress. The extent to which exercise training in a previously sedentary older population will affect venous compliance and tolerance to the simulated orthostatic stress of maximal lower body negative pressure (LBNP) is unknown. The purpose of this investigation is to determine the influence of a 6-mo endurance-training program on calf venous compliance and responses and tolerance to maximal LBNP in older men and women. Twenty participants (exercise group:  $n = 10$ , 5 men, 5 women; control group:  $n = 10$ , 6 men, 4 women; all  $>60$  yr) underwent graded LBNP to presyncope or 4 min at  $-100$  mmHg before and after a 6-mo endurance-training program. Utilizing venous occlusion plethysmography, calf venous compliance was determined in both groups using the first derivative of the pressure-volume relation during cuff pressure reduction before training, at 3 mo, and at the end of the training program. The exercise group improved their fitness with the 6-mo endurance-training program, whereas the control group did not change ( $14 \pm 3$  vs.  $<1 \pm 2\%$ ;  $P < 0.05$ ). LBNP tolerance did not differ between groups or across trials ( $P = 0.47$ ). Venous compliance was not different between groups or trials, either initially or after 3 mo of endurance training, but tended to be greater in the exercise group after 6 mo of training ( $P = 0.08$ ). These data suggest that a 6-mo endurance-training program may improve venous compliance without affecting tolerance to maximal LBNP in older participants.

orthostatic tolerance; peripheral circulation; baroreceptor sensitivity

DESPITE EXTENSIVE investigation, the effects of either cardiovascular fitness or age on orthostatic tolerance remain uncertain. In younger people, some cross-sectional investigations have shown that endurance-trained participants have lower tolerance to head-up tilt or lower body negative pressure (LBNP) (6, 27), whereas others have found no fitness-related differences in tolerance (10, 16). Longitudinal investigations have shown that exercise training has improved (5, 13), had no effect on orthostatic tolerance (4, 33), or diminished tolerance to head-up tilt (26) and LBNP (28, 36).

Much less attention has been given to the effects of exercise training on orthostatic tolerance in older adults. Aging has been associated with a higher incidence of orthostatic hypotension (21, 30), which might increase the risk of falls in this population. A greater predisposition to orthostatic hypotension as a result of endurance training in an older population would be

undesirable. On the other hand, if endurance training improved blood pressure regulation, then it would further support the inclusion of this type of exercise training in current recommendations for fall prevention (18). In this regard, Fortney et al. (8) found that highly trained ( $52.4 \pm 1.7$  ml·kg<sup>-1</sup>·min<sup>-1</sup>) older participants had smaller decreases in cardiac volumes and mean arterial pressure (MAP) and smaller increases in heart rate (HR) in response to submaximal LBNP compared with a control group ( $31.0 \pm 2.9$  ml·kg<sup>-1</sup>·min<sup>-1</sup>). Tolerance per se was not assessed. In contrast, longitudinal studies of older individuals found cardiovascular responses to prolonged head-up tilt to be unchanged in the trained compared with the untrained participants (2, 12). However, Carroll and colleagues (2) specifically excluded participants who became presyncopal from their analysis, whereas only 10% of the individuals that Gabbett and colleagues (12) tested became presyncopal. Using a cross-sectional design and a protocol designed to evoke presyncope, we found that fit and unfit older individuals did not differ in their tolerance to maximal LBNP (16).

Cross-sectional studies suffer from the inability to differentiate between individuals who had low tolerance before training and those who became less tolerant as a consequence of training (6). Thus our cross-sectional study, while the first to assess the effects of chronic exercise training on orthostatic tolerance in older adults, was limited in its generalizability. To the best of our knowledge, no investigation to date has specifically assessed differences in tolerance to a maximal orthostatic challenge before and after an endurance-training program in older men and women. Furthermore, differences in the responses to submaximal LBNP stress between young and older fit and unfit groups suggested that, whereas the groups tolerated maximal LBNP equally well, they did so utilizing different mechanisms (16). The time course of the adaptations to exercise training, associated with these different mechanisms, may differ as well.

Calf venous compliance may be a critical factor in determining the cardiovascular stress associated with changes in orthostasis. Preventing fluid shifts into the legs markedly reduces reflex responses to an orthostatic stressor (15). Calf venous compliance may be lower in older adults (17, 19, 23), which some have suggested may help protect older participants during orthostatic stress (19, 38). Calf venous compliance is higher in endurance-trained young and older individuals (5, 10, 17, 22, 23). Tsutsui and colleagues (38) suggested that lower leg compliance was associated with higher orthostatic tolerance in old compared with the young participants. However,

Address for reprint requests and other correspondence: J. P. Hernandez, Dept. of Physical Education, Southern Illinois Univ., 109 Davies Hall, mail code 4310, Carbondale, IL 62901–4310 (e-mail: juliane@siu.edu).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

the generalizability of this observation is limited: since compliance was assessed during the LBNP protocol rather than during rest, 65% of the participants tolerated the orthostatic challenge, and fitness was not considered (38). Recent cross-sectional data suggest that endurance training may improve venous compliance without affecting tolerance to maximal LBNP (17). However, as with studies of the effects of exercise training on orthostatic tolerance, the extent to which preexisting differences in compliance affected these findings is unknown. Furthermore, the time course and mechanisms responsible for alterations in venous compliance are not completely understood. Determining the adaptation in venous compliance over 6 mo of endurance exercise training may provide insight into the mechanisms responsible for these changes.

In summary, it remains unclear whether chronic endurance training affects tolerance to an orthostatic challenge in older men and women in general and, more specifically, whether changes in venous compliance with endurance training may affect this tolerance. Therefore, the purposes of this investigation were to determine the effects of a 6-mo endurance-training program on calf venous compliance and the responses and tolerance to the orthostatic stressor of maximal LBNP in older men and women. We hypothesized that tolerance to maximal LBNP would decrease following the endurance-training protocol and that increased calf venous compliance would be associated with this reduced tolerance.

## METHODS

**Participants.** Twenty-eight older men and women volunteered to participate in this investigation. These volunteers were screened with a review of their medical and exercise history, with written clearance to participate by their personal physicians, and, finally, with a maximal graded exercise test using the modified Bruce protocol. Eight volunteers were excluded from the study due to  $\beta$ -blockade use ( $n = 4$ ), various arrhythmias ( $n = 3$ ), or significant cardiovascular disease discovered during the graded exercise test ( $n = 1$ ). The 20 selected were free of overt cardiovascular disease and orthopedic limitations to exercise testing or training. They were randomly assigned to either an exercise or control group (exercise group:  $n = 10$ , 5 men, 5 women; control group:  $n = 10$ , 6 men, 4 women). Peak  $\dot{V}O_{2\text{peak}}$  estimates were obtained for all of the participants using the time to

termination of the stress test as the criterion (9). All of the women were postmenopausal, and none was on hormone replacement therapy during testing or intervention. Participant characteristics are summarized in Table 1.

**General experimental design.** Participants reported to the laboratory on four separate occasions following receipt of physician approval for participation. The first meeting was to assess anthropometric status and conduct the graded exercise test. The second visit served to orient the participants to the testing apparatus and protocol. The third visit was for the initial LBNP tolerance test. The final visit was to obtain the initial calf venous compliance data. The LBNP and calf venous compliance tests were performed after 3 mo and at the end of the 6-mo endurance-training program. Participants were tested at the same time of day pre- and posttraining. Before data collection, all participants were verbally informed of the risks and benefits of this study and provided written, informed consent. The Institutional Review Board of Iowa State University approved this investigation. The following testing procedures were similar to those reported previously from our laboratory (16, 17).

**LBNP testing.** Each participant reported to the laboratory no sooner than 48 h after the graded exercise test and, following instrumentation, was placed in a supine position inside the LBNP testing chamber. Once inside, they straddled a padded bicycle seat with their feet clear of the base of the chamber and sealed at the level of the iliac crest. Following 12-min rest at ambient barometric pressure, negative pressure was induced using a commercially available vacuum and quantified with a pressure transducer (PS309, Validyne, Northridge, CA). Graded LBNP was invoked with 10-mmHg increases in negative pressure every 4 min. The LBNP test was terminated when the participant completed 4 min at  $-100$  mmHg, at the onset of presyncope symptoms, or by participant request. Signs of impending presyncope included dizziness, nausea, profuse sweating, or a rapid change in blood pressure defined as either a decrease in systolic blood pressure by 25 mmHg or a decrease in diastolic blood pressure by 15 mmHg within 1 min. All participants refrained from any exercise, alcohol, tobacco, or caffeine ingestion for 12 h and food intake for 3 h before their LBNP test.

**Assessment of cardiovascular responses.** Forearm blood flow (FBF) was measured by using mercury-in-Silastic strain gauge plethysmography (D.E. Hokanson, Bellevue, WA) (14) with the strain gauge placed around the proximal portion of the left forearm about one-third the distance from the olecranon to the ulnar styloid. A wrist cuff was used to occlude circulation to the hand during FBF measurements; FBF was assessed every 20 s. Blood pressure was measured

Table 1. Participant characteristics and resting cardiovascular variables

	Exercise		Control	
	Pre	Post	Pre	Post
Age, yr	73.6 $\pm$ 4.7*		68.1 $\pm$ 3.1	
Height, cm	167.3 $\pm$ 9.2		165.2 $\pm$ 11.1	
$\dot{V}O_{2\text{peak}}$ , ml $\cdot$ kg $^{-1}\cdot$ min $^{-1}$	31.4 $\pm$ 1.8		32.6 $\pm$ 3.2	
BMI, kg/m $^2$	27.7 $\pm$ 1.1	27.5 $\pm$ 1.8	25.4 $\pm$ 1.2	25.5 $\pm$ 1.8
Mass, kg	79.1 $\pm$ 14.7	78.2 $\pm$ 13.7	68.9 $\pm$ 11.5	69.0 $\pm$ 11.9
Body fat, %	34.3 $\pm$ 6.2	30.2 $\pm$ 5.6	28.4 $\pm$ 10.0	28.9 $\pm$ 8.9
6-min Walk, yards	614 $\pm$ 80	699 $\pm$ 80 $\dagger$	571 $\pm$ 101	572 $\pm$ 101
HR, beats/min	67 $\pm$ 5	64 $\pm$ 5	60 $\pm$ 3	61 $\pm$ 3
SV, ml/beat	85 $\pm$ 8	93 $\pm$ 8	89 $\pm$ 11	86 $\pm$ 7
MAP, mmHg	92 $\pm$ 3	89 $\pm$ 3	87 $\pm$ 4	85 $\pm$ 6
FVC, units	0.041 $\pm$ 0.005	0.049 $\pm$ 0.003	0.035 $\pm$ 0.015	0.045 $\pm$ 0.015
TPC, units	0.063 $\pm$ 0.004	0.067 $\pm$ 0.005	0.065 $\pm$ 0.007	0.064 $\pm$ 0.006
Calf volume, ml	3,265 $\pm$ 254	3,186 $\pm$ 210	3,196 $\pm$ 247	3,235 $\pm$ 266
LTI, mmHg/min	261 $\pm$ 32	287 $\pm$ 15	321 $\pm$ 16	323 $\pm$ 16

Values are mean  $\pm$  SE. Pre, preintervention; Post, postintervention;  $\dot{V}O_{2\text{peak}}$ , peak  $\dot{V}O_2$  uptake; BMI, body mass index; HR, heart rate; SV, stroke volume; MAP, mean arterial pressure; FVC, forearm vascular conductance; TPC, total peripheral conductance; LTI, lower body negative pressure tolerance index. \* $P < 0.05$  vs. Control.  $\dagger P < 0.05$  vs. Preintervention.

every minute via a Dinamap (Johnson & Johnson Medical, Tampa, FL). HR was assessed continuously using five-lead electrocardiography. Stroke volume (SV) was determined every minute using impedance cardiography (Minnesota Impedance Cardiograph model 304B, Surcom, Minneapolis, MN) (31) and ensemble R-wave averaging on 55 s of data acquired in each 60-s period. The analog HR and FBF signals were input into an online personal computer system using commercially available software (BIOPAC, Santa Barbara, CA). The HR and impedance cardiograph signals were analyzed by using commercially available software (Microtronics Corp, Chapel Hill, NC) to determine SV and calculate cardiac output ( $\dot{Q}$ ).

**Venous compliance.** The test used was a modified version of that reported elsewhere (14, 23). Briefly, participants were placed in the supine position with the right leg elevated above heart level and supported at the ankle and thigh. Using the formula  $\pi r^2 * L$ , where  $L$  is length, calf volume was calculated from four girth measures obtained equidistantly between the medial malleolus and the tibial plateau and one calf segment length. Changes in limb volume relative to baseline were measured noninvasively using strain gauge plethysmography at the maximal calf circumference. A venous-collecting cuff was placed ~5 cm proximal to the knee on the right leg and inflated to 60 mmHg for 8 min and then reduced at a rate of 5 mmHg/5 s (over 1 min) to 0 mmHg.

**Endurance-training protocol.** The 6-mo aerobic training program consisted of the participants exercising 3 days/wk, 20–45 min per session, at 40–85% of HR reserve. The peak HR achieved during the stress test was considered the maximum HR. Resting HR was assessed weekly, and the target HR was adjusted biweekly. The duration and intensity of training were initially at the low end of these ranges due to the low initial fitness levels of the participants. It was increased accordingly such that, during the last 3 mo of the protocol, all participants were exercising at 65–85% of their HR reserve for 40 min each session. Participants primarily trained their legs using treadmills and upright and recumbent cycle ergometers. The control group was instructed not to change their daily activity level. They were contacted every 2 wk to confirm their relative inactivity.

Within 2 wk of the participant's initial LBNP and calf venous compliance tests, all participants underwent the Senior Fitness Test Battery (29), which included a 6-min walk test for cardiovascular endurance. For the present study, this test was used as the measure of changes in cardiovascular fitness. This test was chosen to complement the results of the graded exercise test. In older unfit individuals, the limiting factor in a stress test is typically local leg fatigue or poor muscular endurance. Performance in the 6-min walk is another indicator of this local muscular endurance and more functionally practical.

**Analysis.** LBNP tolerance was quantified as the LBNP tolerance index (LTI). This index was calculated as the sum of the products of duration spent at each negative pressure and the change in pressure from the previous stage (20). The LTI is a linear function for the conditions used in the present study.  $\dot{Q}$  was calculated every minute as the product of SV and the concurrent HR. MAP was determined every minute from the Dinamap. Forearm vascular conductance was calculated as FBF/MAP and total peripheral conductance (TPC) as  $\dot{Q}$ /MAP.

The anthropometric, estimated  $\dot{V}O_{2\text{ peak}}$  and LTI data were compared by using two-way repeated-measures ANOVA (group  $\times$  trial). Mean cardiovascular responses for minutes 2–4 of each stage of LBNP common to all participants, the last completed stage of each participant, and each of the last 2 min of LBNP were compared by using three-way (group  $\times$  trial  $\times$  LBNP level) repeated-measures ANOVA for each variable. Post hoc comparisons were made by using the Tukey test. Statistical significance was set at 0.05, with data reported as means  $\pm$  SE.

Determination of venous compliance entailed generating pressure-volume curves from the pressure-volume relationship as pressure was decreased at the rate of 5 mmHg/5 s from 60 to 10 mmHg. Pressure-volume curves were compared by means of the quadratic regression model [ $\Delta$ limb volume =  $\beta_0 + \beta_1 * (\text{cuff pressure}) + \beta_2 * (\text{cuff$

pressure) $^2$ ] for each individual, where  $\Delta$  is change. Regression models were calculated using the general linear model procedure in SPSS and included between-participant classifications for age and training status. The pressure-volume relation is not linear; therefore, a single number is not sufficient to characterize the slope of the pressure-volume curve. Thus the group-averaged regression parameters  $\beta_1$  and  $\beta_2$ , determined by the pressure-volume curves for each participant in the relevant groups, were used together as an estimate of compliance, such that compliance =  $\beta_1 + 2 * \beta_2 * (\text{cuff pressure})$  or the derivative of the pressure-volume curve (14, 23). The coefficient of variation of this method has been reported to be 4.9% (23).

## RESULTS

Table 1 summarizes the anthropometric characteristics and resting cardiovascular variables of all participants in the study. The exercise group was older than the control group ( $P < 0.05$ ), but there were no other significant differences in the preintervention data. While there were no differences between the groups in  $\dot{V}O_{2\text{ peak}}$  or 6-min walk performance preintervention, the exercise group performed significantly better on the 6-min walk test postintervention, whereas the control group did not change ( $14 \pm 3$  vs.  $<0.1 \pm 2\%$ ;  $P < 0.05$ ). None of the participants was a smoker, and none reported performing regular moderate or vigorous physical activity within the last year. None was overtly hypertensive, although four in the exercise group and three in the control group were prehypertensive. One participant in each of the exercise and control groups was moderately overweight (body mass index  $> 30$  kg/m $^2$ ). Average attendance at exercise sessions for all participants was 96%. Resting SV tended to be higher postintervention in the exercise group ( $P = 0.07$ ), but there were no significant differences between groups or trials in the resting cardiovascular variables. Following the 6 mo of training, tolerance as expressed by LTI was not different either between groups or across trials (Table 1).

**Cardiovascular responses to submaximal LBNP.** Hemodynamic responses to LBNP are illustrated in Figs. 1–3. Two participants became presyncopal (one woman and one man from the exercise group, initial trial) before  $-40$  mmHg of LBNP and were excluded from the submaximal analyses. There were no significant main effect differences between the groups or trials. However, some LBNP  $\times$  trial interactions were found.

In all the trials except the control group preintervention trial, HR rose above rest at the last completed stage of LBNP (Fig. 1) ( $P < 0.05$ ); in this group, HR rose above rest 1 min before the end of the test (e-1) (Fig. 1) ( $P < 0.05$ ). SV fell below rest at  $-30$  mmHg in the exercise group preintervention, at  $-40$  mmHg in the exercise group postintervention trial, and in the last stage for the control group pre- and postintervention ( $P < 0.05$ ) (Fig. 1).  $\dot{Q}$  declined similarly ( $P < 0.05$ ) (Fig. 2). There were no differences in MAP across the submaximal LBNP levels for either group, either before or after training. Forearm vascular conductance decreased below rest in the last completed stage in both groups only in the preintervention trial. The LBNP stage at which TPC decreased below rest in the exercise group was  $-20$  mmHg preintervention and  $-30$  mmHg postintervention ( $P < 0.05$ ; Fig. 3), whereas TPC in the control group did not differ significantly from rest for either trial.



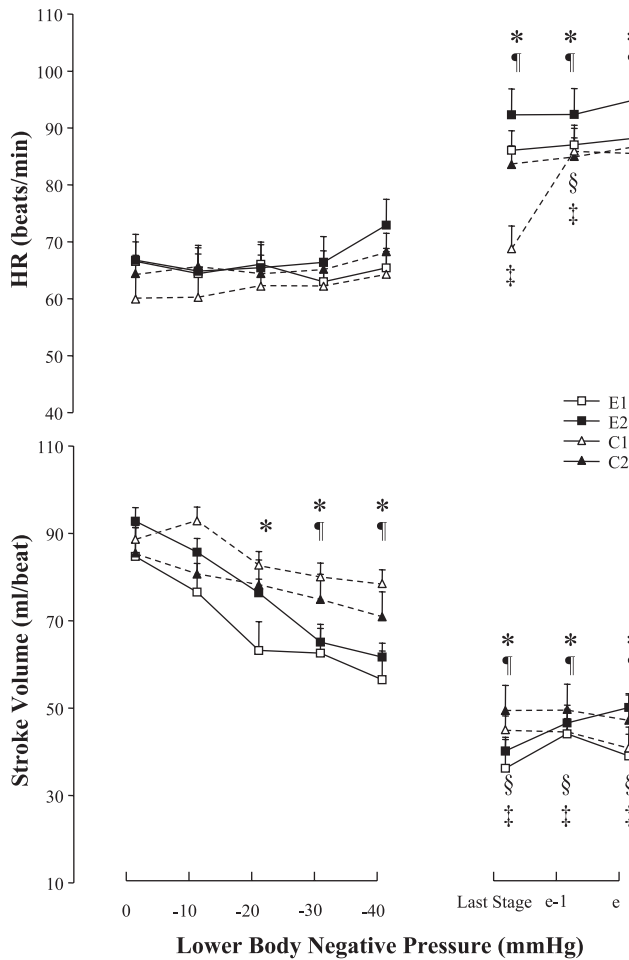


Fig. 1. Heart rate (HR) and stroke volume responses to lower body negative pressure. Last stage, last stage completed in the protocol; e-1, 1 min before end of test; e, last minute of test; E1, exercise group, preintervention; E2, exercise group, postintervention; C1, control group, preintervention; C2, control group, postintervention. Values are means  $\pm$  SE. \* $P < 0.05$  for preexercise vs. rest; ‡ $P < 0.05$  for postexercise vs. rest; § $P < 0.05$  for precontrol vs. rest; ¶ $P < 0.05$  for postcontrol vs. rest. See text for group  $\times$  trial interactions.

**Presyncope.** The LBNP trials were stopped due to presyncope symptoms in 19 of the 20 participants pretraining and all of the participants posttraining. One man in the control group completed the LBNP protocol. Results are presented as the last completed stage, e-1, and the last minute of the test (Figs. 1–3). HR was significantly higher than rest, and SV was significantly lower than rest in both groups before and after the intervention ( $P < 0.05$ ) (Fig. 1).  $\dot{Q}$  was lower than rest for all groups in the last completed stage of LBNP, but it was lower than rest at  $-20$  mmHg for the exercise group preintervention and at  $-30$  mmHg postintervention ( $P < 0.05$ ). MAP was significantly lower than rest at e-1 and the last minute of the test for only the preintervention trial in both groups ( $P < 0.05$ ) (Fig. 2).

**Venous compliance.** There were no differences in calf volume between groups either before or after the intervention (Table 1). There were no differences in either the slope of the pressure-volume relationship or the compliance between groups preintervention or after 3 mo of endurance training ( $P > 0.05$ ). For brevity, the 3-mo data are not presented here. The slope of the pressure-volume curves tended to be greater postintervention in the exercise group ( $P = 0.08$ ; Fig. 4, Table

2). Calf venous compliance was 20–30% greater postintervention in the exercise group. No differences were found between trials in the control group (Fig. 4, Table 2).

**DISCUSSION**

To the best of our knowledge, the present investigation is the first longitudinal study designed to assess the effects of an endurance-training program on both calf venous compliance and the responses and tolerance to the orthostatic stressor of maximal LBNP in older men and women. We hypothesized that calf venous compliance would improve with training, and, subsequent to this, tolerance to maximal LBNP would decrease following the endurance-training protocol. Calf venous compliance increased 20–30% postintervention, but there were no differences in tolerance to maximal LBNP. Regression analysis of LTI and calf venous compliance pre- and postintervention in the exercise group showed no relationship (preintervention  $R^2 = 0.002$ , postintervention  $R^2 = 0.116$ ) between the two. Similarly, when change in LTI is plotted against change in compliance at 20 mmHg for both groups over the 6 mo, there was

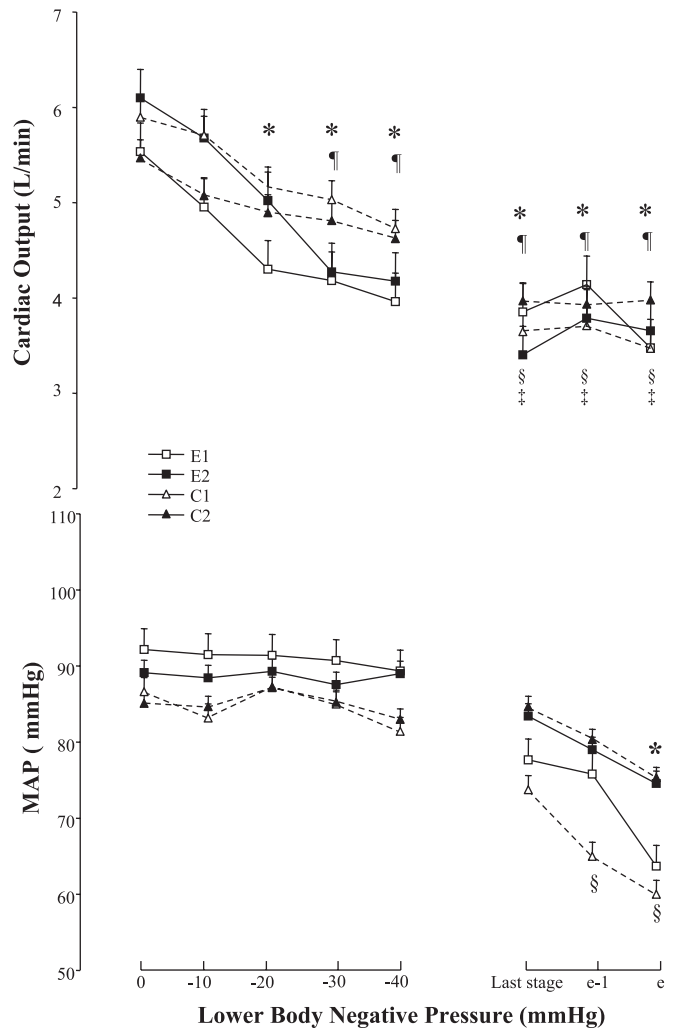


Fig. 2. Cardiac output and mean arterial pressure (MAP) responses to lower body negative pressure. Values are means  $\pm$  SE. \* $P < 0.05$  for preexercise vs. rest; ‡ $P < 0.05$  for postexercise vs. rest; § $P < 0.05$  for precontrol vs. rest; ¶ $P < 0.05$  for postcontrol vs. rest.

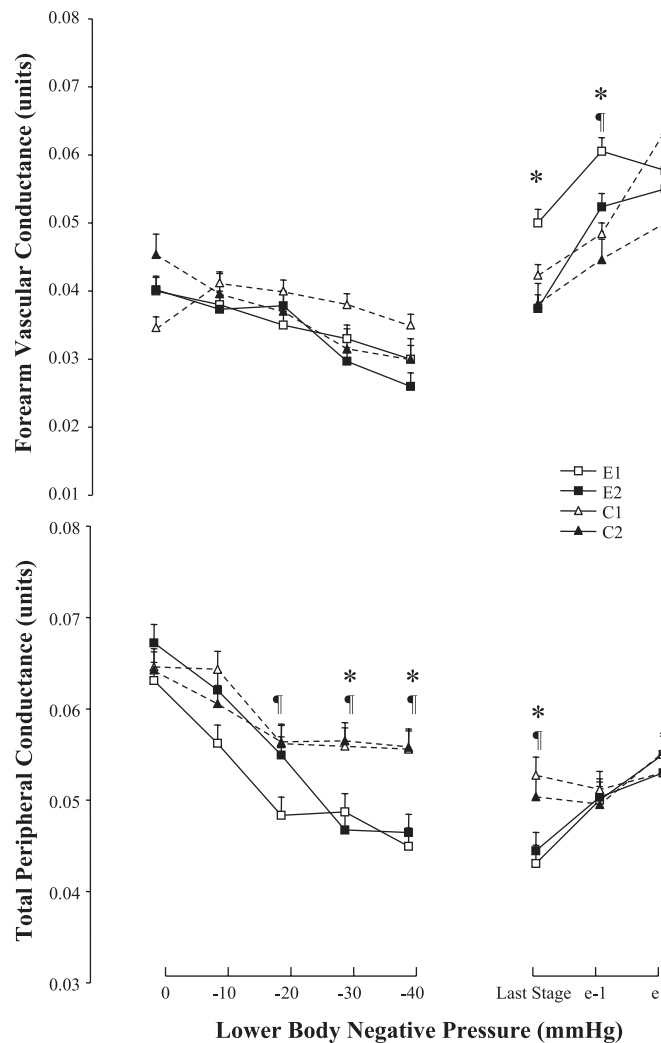


Fig. 3. Forearm vascular and total peripheral conductance responses to lower body negative pressure. Values are means  $\pm$  SE. \* $P < 0.05$  for preexercise vs. rest;  $\nabla P < 0.05$  for postexercise vs. rest.

no relationship ( $R^2 = 0.007$ ; Fig. 5). Likewise, the posttraining changes in the cardiovascular responses to LBNP were modest and seen only at submaximal levels of LBNP. Thus the present data suggest that marked changes in calf venous compliance can be found with a relatively short training program, and these changes will not affect orthostatic tolerance.

The effects of age on orthostatic tolerance are unclear. An attenuated increase in HR is seen among the older population compared with younger persons in response to similar submaximal orthostatic stress (3, 7, 12). Recently, using a cross-sectional design, we found no differences in tolerance to maximal LBNP between fit and unfit older and younger participants (16, 17). However, the young fit group had a more rapid decline in SV and greater increase in HR in response to submaximal LBNP than did the unfit and older fit groups. The older unfit group had a higher resting MAP than the other groups, and this difference was maintained throughout the protocol (16). The older fit group had an earlier decline in TPC than the other groups ( $-20$  vs.  $-40$  mmHg). Similar to the present study, we found no relationship between LTI and venous compliance (17).

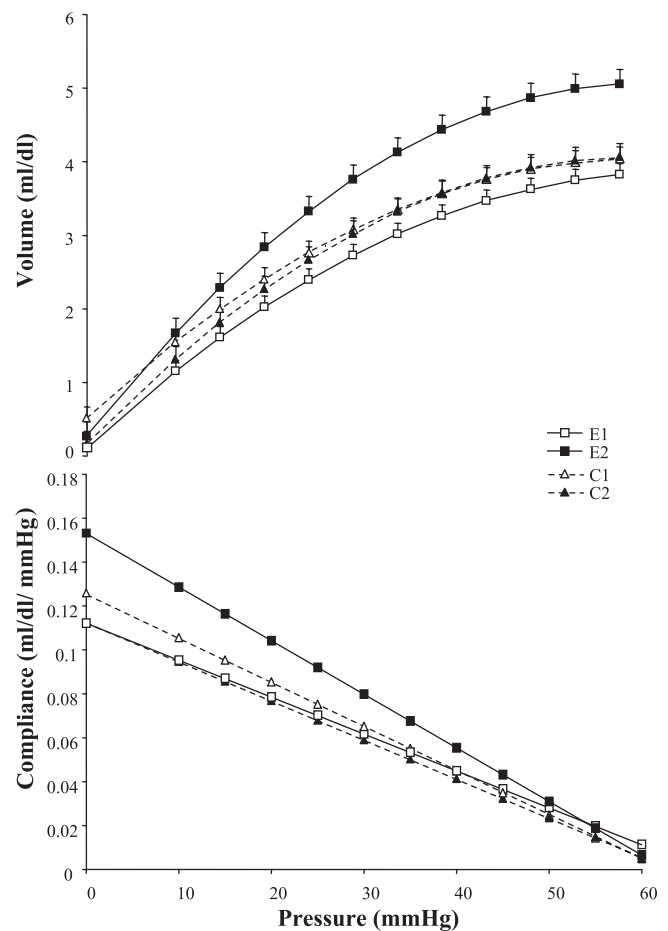


Fig. 4. Pressure-volume curves and pressure compliance slopes.

Carroll and colleagues (2) found that a 26-wk endurance-training protocol did not alter cardiovascular responses to  $70^\circ$  head-up tilt in older men and women. Similarly, Gabbett and colleagues (12) found that a 12-wk cycling endurance-training program in healthy physically active older men elicited increases in  $\dot{V}O_{2\text{ peak}}$  (10%) without significant changes in cardiovascular responses to  $90^\circ$  head-up tilt. In neither study was orthostatic tolerance explicitly assessed (2, 12). Both in the present longitudinal study and in our cross-sectional work (16), we found small but statistically significant differences in the cardiovascular responses to submaximal LBNP. It is unclear if the disparate findings across these studies are due to differences in the individuals tested, the duration of the training programs, or the orthostatic challenge. Nevertheless, the relatively small differences pre- and posttraining that we have found, when coupled with the negative findings of these other

Table 2. Pressure-volume regression equations

Group	Equation
Exercise	
Pre	$\Delta LV = 0.115 \pm 0.018 + 0.112 \pm 0.002(\text{CP}) - 0.00084 \pm 0.000(\text{CP})^2$
Post	$\Delta LV = 0.263 \pm 0.101 + 0.153 \pm 0.012(\text{CP}) - 0.00122 \pm 0.000(\text{CP})^2$
Control	
Pre	$\Delta LV = 0.509 \pm 0.132 + 0.113 \pm 0.041(\text{CP}) - 0.00089 \pm 0.000(\text{CP})^2$
Post	$\Delta LV = 0.153 \pm 0.022 + 0.125 \pm 0.008(\text{CP}) - 0.00101 \pm 0.000(\text{CP})^2$

$\Delta LV$ , change in limb volume; CP, cuff pressure.

studies (2, 12), suggests that improving fitness via endurance exercise training has little to no substantive influence on the cardiovascular responses to a submaximal orthostatic stress in an older population. On the other hand, the present investigation utilized a 6-mo endurance-training intervention that elicited a 14% improvement in fitness. Training, sufficient to increase fitness beyond that seen here, may have yielded different results (27). For example, Fortney and colleagues (8) tested very fit older individuals ( $52.4 \pm 1.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) and saw differences in cardiovascular responses to submaximal LBNP compared with their less fit controls.

Carroll et al. (3) reported increased orthostatic tolerance in previously symptomatic older participants following 26 wk of combined endurance and resistance training that failed to alter maximum  $\dot{V}O_{2\text{max}}$  significantly. In the present study, no differences in LTI were found between trials in the exercise group, suggesting that chronic endurance training does not alter tolerance to maximal LBNP in older men and women. However, the standard deviation and range of individual scores was lower after training (standard deviation: preintervention = 96 vs. postintervention = 70; range: preintervention = 369, postintervention = 260 mmHg/min; Fig. 6). In other words, the less tolerant participants generally became more tolerant after 6 mo of training, while the more tolerant participants did not change. This deserves further investigation since, as suggested elsewhere (4), it implies that endurance exercise training might improve orthostatic tolerance in less tolerant older individuals or, perhaps, those with symptomatic orthostatic hypotension.

The present finding of 20–30% ( $P = 0.08$ ) improvements in calf venous compliance with 6 mo of endurance exercise training in older men and women is both meaningful and novel. Cross-sectional investigations have shown that decrements in venous compliance with age may be attenuated by maintaining high fitness levels (17, 23). For example, we previously found that, compared with their less fit peers, calf venous compliance was 50% greater in more fit young and older groups, but tolerance to maximal LBNP did not differ (17). The present investigation extends this finding and suggests that sedentary older men and women may improve calf venous compliance

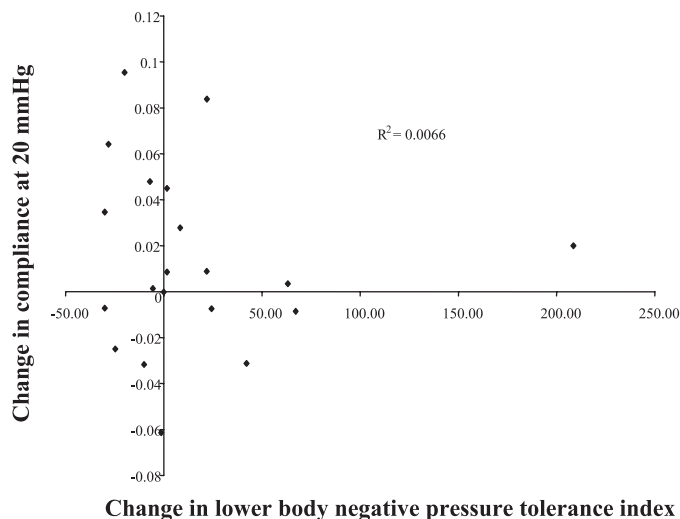


Fig. 5. Relationship between changes in lower body negative pressure tolerance index and changes in compliance (20 mmHg) for all participants.

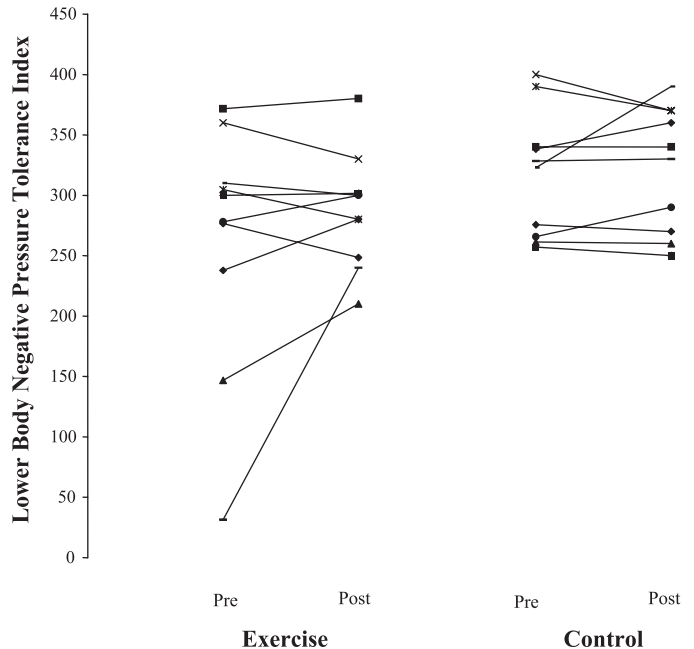


Fig. 6. Changes in lower body negative pressure tolerance index with training.

with endurance training. More importantly, improvements in calf venous compliance may be made without altering tolerance to maximal LBNP. While no differences were found after 3 mo of training, 6 mo of training were enough of a stimulus to elicit physiologically meaningful improvements in calf venous compliance in older individuals. Longer duration training may elicit even larger changes in calf venous compliance. For example, Monahan and colleagues (23) found 70–120% higher venous compliance in older participants who had been running at least 2 yr and with a mean  $\dot{V}O_{2\text{peak}}$  of  $45 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ .

There might be gender differences in the responses of the cardiovascular system to endurance exercise training in older adults (34, 35). For example, women increase their  $\dot{V}O_{2\text{max}}$  primarily by increasing oxygen extraction (34) without significant changes in left ventricular filling dynamics (35), whereas men predominantly increase  $\dot{V}O_{2\text{max}}$  by improving left ventricular filling dynamics (35) and increasing SV (34). Regarding calf venous compliance, Monahan and Ray (24) found that young women and men differ in compliance both at rest and in response to baroreceptor unloading. However, in the present study, there were no gender differences found. Collectively, these two studies suggest that the gender difference seen in young adults (24) is removed with aging. Our findings also suggest that there is not a gender difference in the venous compliance responses to endurance training. However, the small sample sizes seen when gender is considered separately necessarily warrants caution when generalizing these results.

The effects of age and chronic exercise training on central arterial compliance (37) are reported to be very similar to the effects on calf venous compliance (17, 23). Compliance of both arteries and veins appears to decline with age and improve with chronic exercise (17, 23, 37). The mechanisms of change in compliance of both vessel types may be related to either alterations in the composition of the vessel wall, specifically the ratio of elastin to collagen, or to alterations in sympathetically mediated vascular tone. Aging is associated with a

decrease in the elastin-to-collagen ratio in the venous wall (1) and is, therefore, the most likely contributor to decreasing compliance with age.

The mechanisms associated with adaptations to endurance exercise training are less clear. Tanaka and colleagues (37) found an increase in central arterial compliance in response to 13 wk of endurance training. They speculated that one potential functional determinant affecting compliance might be a reduction in sympathetic-adrenergic tone, either directly or by enhancing endothelial release of nitric oxide (37). While this mechanism is appealing, Halliwill and colleagues (14) demonstrated that sympathetic stimulation reduced unstressed venous volume without affecting venous compliance. These findings suggest that this is not a mechanism by which venous compliance is increased through endurance training (14). Therefore, it is most likely that venous vasculature compliance is increased by alterations in the composition of the vessel wall. These alterations would take time to occur, which may be why no changes in calf venous compliance were found after 3 mo of training in the present study but tended to be seen after 6 mo of training. Further research investigating the mechanisms responsible for increasing arterial and venous compliance with exercise training is warranted.

Several limitations exist with the present investigation. First,  $\dot{V}O_{2\text{ peak}}$  was estimated initially but American College of Sports Medicine's 6-min walk test was used as the comparison measure of cardiovascular fitness pre- and postintervention. Given that performance on a graded exercise test is typically limited due to local leg fatigue (e.g., poor muscular endurance), we felt the 6-min walk test was functionally more appropriate. However, there were no differences in  $\dot{V}O_{2\text{ peak}}$  or 6-min walk performance between groups before training, yet training led to a 14% improvement in the latter. Improvements in the 6-min walk test should equate to improvements in cardiovascular fitness. In this context, the exercise group went from the 56th percentile in the 6-min walk test norms, which is what would be expected of a healthy older population, to the 84th percentile postintervention (29). It has been suggested that young participants with  $\dot{V}O_{2\text{ peak}} > 55$  (27) or  $65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  (4) are prone to reduced orthostatic tolerance, although this finding is not universally seen (10). This suggests that there might be a threshold of fitness for deleterious effects of increasing fitness on blood pressure regulation in response to orthostatic stress. However, the association between chronic endurance training and orthostatic tolerance is certainly multifactorial. It is unknown if a fitness threshold exists for older adults and, if it does exist, what it is.

Second, while LBNP causes central hypovolemia, it is not literally an orthostatic stressor, since the participants remain in the supine position. Thus, while there is considerable overlap in the responses to head-up tilt, passive standing, and LBNP, this difference should be remembered when comparing the present results with studies using these other tools. Third, our participants were clinically healthy, and the results seen here may differ from those seen in less healthy older populations. Finally, the use of venous occlusion plethysmography to measure compliance is a measure of whole limb compliance that varies with age (14). This method assumes that venous-collecting cuff pressure is equal to venous pressure. The use of an 8-min collecting period should account for possible age-related differences in whole limb blood flow (14, 23).

In summary, to the best of our knowledge, this study is the first to utilize a longitudinal design to assess both orthostatic tolerance and calf venous compliance in older adults before and after an endurance exercise training program. The present investigation found that a 6-mo endurance-training program tended to improve venous compliance in older individuals and did so without compromising tolerance to maximal LBNP.

## REFERENCES

1. Bouissou H, Julian M, Pieraggi MT, Maurel E, Thiers J, and Louge L. Structure of healthy and varicose veins. In: *Return Circulation and Norepinephrine: An Update*, edited by Vanhoutte PM. Paris: Libbey Eurotext, 1991, p. 139–150.
2. Carroll JF, Convertino VA, Pollock ML, Graves JE, and Lowenthal DT. Effect of 6 months of exercise training on cardiovascular responses to head-up tilt in the elderly. *Clin Physiol* 15: 13–25, 1995.
3. Carroll JF, Wood CE, Pollock ML, Graves JE, Convertino VA, and Lowenthal DT. Hormonal responses in elders experiencing presyncopal symptoms during head-up tilt before and after exercise training. *J Gerontol A Biol Sci Med Sci* 50: M324–M329, 1995.
4. Convertino V. Endurance exercise training: conditions of enhanced hemodynamic responses and tolerance to LBNP. *Med Sci Sports Exerc* 25: 705–712, 1993.
5. Convertino VA, Montgomery LD, and Greenleaf JE. Cardiovascular responses during orthostasis: effect of an increase in  $\dot{V}O_{2\text{ max}}$ . *Aviat Space Environ Med* 55: 702–708, 1984.
6. Convertino VA. Aerobic fitness, endurance training, and orthostatic intolerance. *Exerc Sport Sci Rev* 15: 223–259, 1987.
7. Dineno FA, Jones PP, Seals DR, and Tanaka H. Limb blood flow and vascular conductance are reduced with age in healthy humans: relation to elevations in sympathetic nerve activity and declines in oxygen demand. *Circulation* 100: 164–170, 1999.
8. Fortney S, Tankersley C, Lightfoot JT, Drinkwater D, Clulow J, Gerstenblith G, O'Connor F, Becker L, Lakatta E, and Fleg J. Cardiovascular responses to lower body negative pressure in trained and untrained older men. *J Appl Physiol* 73: 2693–2700, 1992.
9. Foster C, Jackson AS, Pollack ML, Taylor MM, Hare J, Sennett SM, Rod JL, Sarwar M, and Schmidt DH. Generalized equations for predicting functional capacity from treadmill performance. *Am Heart J* 107: 1229–1234, 1984.
10. Franke WD, Mills KK, Lee K, and Hernandez JP. Training mode does not affect orthostatic tolerance in chronically exercising subjects. *Eur J Appl Physiol* 89: 263–270, 2003.
11. Fry MA and Hoffer GW. Association of sex and age with responses to lower body negative pressure. *J Appl Physiol* 65: 1752–1756, 1988.
12. Gabbett TJ, Gass GC, Thalib L, Morris N, and Gass EM. Does endurance training affect orthostatic responses in healthy elderly men? *Med Sci Sports Exerc* 33: 1279–1286, 2001.
13. Greenleaf JE, Brock P, Sciaraffa D, Polese A, and Elizondo R. Effects of exercise-heat acclimation on fluid, electrolyte and endocrine responses during tilt and +Gz acceleration in women and men. *Aviat Space Environ Med* 56: 683–689, 1985.
14. Halliwill JR, Minson CT, and Joyner MJ. Measurement of limb venous compliance in humans: technical considerations and physiological findings. *J Appl Physiol* 87: 1555–1563, 1999.
15. Halliwill JR, Lawler LA, Eickhoff TJ, Joyner MJ, and Mulvagh SL. Reflex responses to regional venous pooling during lower body negative pressure in humans. *J Appl Physiol* 84: 454–458, 1998.
16. Hernandez JP, Karandikar A, and Franke WD. Effects of age and fitness on tolerance to lower body negative pressure. *J Gerontol A Biol Sci Med Sci*. In press.
17. Hernandez JP and Franke WD. Age- and fitness-related differences in limb venous compliance do not affect tolerance to maximal lower body negative pressure in men and women. *J Appl Physiol* 97: 925–929, 2004.
18. Herwaldt LA and Pottinger JM. Preventing falls in the elderly. *J Am Geriatr Soc* 51: 1175–1177, 2003.
19. Lanne T and Olsen H. Decreased capacitance response with age in lower limbs of humans: a potential error in the study of cardiovascular reflexes in ageing. *Acta Physiol Scand* 161: 503–507, 1997.
20. Lightfoot TJ and Tsintgiras KM. Quantification of tolerance to lower body negative pressure in healthy population. *Med Sci Sports Exerc* 27: 697–706, 1995.



21. **Lipsitz LA.** Orthostatic hypotension in the elderly. *N Engl J Med* 321: 952–957, 1989.
22. **Louisy F, Jouanin JC, and Guezennec CY.** Filling and emptying characteristics of lower limb venous network in athletes: study by postural plethysmography. *Int J Sports Med* 18: 26–29, 1997.
23. **Monahan KD, Dinunno FA, Seals DR, and Halliwill JR.** Smaller age-associated reductions in leg venous compliance in endurance exercise-trained men. *Am J Physiol Heart Circ Physiol* 281: H1267–H1273, 2001.
24. **Monahan KD and Ray CA.** Gender affects calf venous compliance at rest and during baroreceptor unloading in humans. *Am J Physiol Heart Circ Physiol* 286: H895–H901, 2004.
25. **Olsen H, Vernersson E, and Lanne T.** Cardiovascular response to acute hypovolemia in relation to age. Implications for orthostasis and hemorrhage. *Am J Physiol Heart Circ Physiol* 278: H222–H232, 2000.
26. **Pawelczyk JA, Kenney WL, and Kenney P.** Cardiovascular responses to head-up tilt after an endurance training program. *Aviat Space Environ Med* 59: 107–112, 1988.
27. **Raven P and Pawelczyk J.** Chronic endurance exercise training: a condition of inadequate blood pressure regulation and reduced tolerance to LBNP. *Med Sci Sports Exerc* 25: 713–721, 1993.
28. **Raven RB, Rohm-Young D, and Blomqvist CG.** Physical fitness and cardiovascular response to lower body negative pressure. *J Appl Physiol* 56: 138–144, 1984.
29. **Rikli RE and Jones JJ.** *American College of Sports Medicine: Senior Fitness Test Manual*, edited by Wright JP and Cole A. Champaign, IL: Human Kinetics, 2001, p. 43, 127.
30. **Robbins A and Rubenstein L.** Postural hypotension in the elderly. *J Am Geriatr Soc* 32: 769–774, 1972.
31. **Sherwood A, Allen MT, Fahrenberg J, Kelsey RM, Lovallo WR, and van Dooren LJ.** Methodological guidelines for impedance cardiography. *Psychophysiology* 27: 1–23, 1990.
32. **Shi X, Wray DW, Formes KJ, Wang H, Hayes PM, O-Yurvati A, Weiss M, and Reese IP.** Orthostatic hypotension in aging humans. *Am J Physiol Heart Circ Physiol* 279: H1548–H1554, 2000.
33. **Shvartz E and Meyerstein N.** Relation of tilt tolerance to aerobic capacity and physical characteristics. *Aerospace Med* 43: 278–280, 1972.
34. **Spina RJ, Ogawa T, Kohrt WM, Martin WH, Holloszy JO, and Ehsani AA.** Differences in cardiovascular adaptations to endurance exercise training between older men and women. *J Appl Physiol* 75: 849–855, 1993.
35. **Spina RJ, Miller TR, Bogenhagen WH, Schechtman KB, and Ehsani AA.** Gender-related differences in left ventricular filling dynamics in older subjects after endurance exercise training. *J Gerontol A Biol Sci Med Sci* 51: B232–B237, 1996.
36. **Stevens GHJ, Foresman BH, Shi X, Stern SA, and Raven PB.** Reduction in LBNP tolerance following prolonged endurance exercise training. *Med Sci Sports Exerc* 24: 1235–1244, 1992.
37. **Tanaka H, Dinunno FA, Monahan KD, Clewenger CM, DeSouza CA, and Seals DR.** Aging, habitual exercise, and dynamic arterial compliance. *Circulation* 102: 1270–1275, 2000.
38. **Tsutsui Y, Sagawa S, Yamauchi K, Endo Y, Yamazaki F, and Shiraki K.** Cardiovascular responses to lower body negative pressure in the elderly: role of reduced leg compliance. *Gerontology* 48: 133–139, 2002.

