Effects of whole-body and local thermal stress on hydrostatic volume changes in the human calf

Abstract In the present study, we examined the effect of thermal stress on the magnitude and pattern of change in leg volume during orthostatic stress and thigh occlusion in humans. Ten healthy volunteers underwent whole-body thermal stress produced by a cool- or hot-water-perfused suit and local heat stress of the calf. During whole-body thermal stress, changes of calf circumference during head-up tilt (HUT) at angles of 15° and 60° for 2 min each were monitored. In the supine position, the distensibility of the calf veins was evaluated from the magnitude and half-time of the change in calf circumference during thigh occlusions at 20, 30, 50, 70, and 80 mmHg. Skin blood flow in the calf was measured by laser-Doppler flowmetry. Skin blood flow increased by [mean (SEM)] 295 (71)% with whole-body heating and decreased by 31 (4)% with whole-body cooling. Local heating of the calf increased skin blood flow in the heated area by 263 (25)%. During HUT, the calf cross-sectional area, calculated from the circumference, increased rapidly during whole-body heating and slowly during the cooling. The magnitude of the increase in calf area with HUT did not alter during whole-body heating, whereas it was reduced during cooling compared with the normothermic control. Whole-body and local heating did not alter the magnitude of change in calf area at a given cuff pressure, whereas whole-body cooling decreased it. The time to the half-maximal response of the change in calf circumference was shortened by 35 (17)% during whole-body heating and by 44 (4)% during local heating, whereas it was prolonged by 31 (16)% during whole-body cooling compared with the normothermic control. These results indicate that the magnitude and the pattern of change in calf volume during the early phase of orthostatic stress are modulated due to the changes in venous distensibility and blood flow in the skin during thermal loading.

Keywords Skin blood flow · Leg volume · Venous compliance · Body temperature · Orthostatic stress

Introduction

The postural change from supine to an upright position induces a shift in blood from the upper body to the lower extremities. An increased venous distensibility in the lower extremities increases the volume of blood pooled there and reduces the venous return to the heart during orthostatic stress. Such changes in the leg veins lead to a reduction of blood pressure with a decrease in cardiac filling. It has been thought, therefore, that leg venous distensibility is a determinant factor of orthostatic tolerance in normothermic humans (Ludwig and Convertino 1994; Morikawa et al. 2001; Tsutsui et al. 2002). Since heat stress increases venous distensibility in the limbs (Henry et al. 1955; Tripathi et al. 1984), it is assumed that a greater increase of leg volume during orthostatic stress is induced by heating and may be related to the orthostatic intolerance experienced in a hot environment (Lind et al. 1968; Shvartz and Meyerstein 1970; Shvartz et al. 1975). However, the amount of information on the effect of thermal stress on the magnitude and pattern of change in leg volume during postural change remains small. Since orthostatic hypotension during heat stress has been observed frequently even during a short-term orthostatic stress for 5 min or less (Horvath and Botelho 1949; Lind et al. 1968; Yamazaki and Sone 2001), there is a need to observe the change of leg volume within a few minutes during postural change.

It is hypothesized that muscle venous volume accounts for approximately 85% of the leg venous
volume in normothermia (Buckey et al. 1988; Louisy et al. 1990). Whole-body heating induces venodilatation in the legs and arms (Henry and Gauer 1950; Tripathi et al. 1984) and will decrease the percentage of muscle venous volume in the total volume of leg veins with an increase of skin venous volume. Since the increase in muscle sympathetic nerve activity during whole-body heating is related intensively to a raised core temperature (Crandall et al. 1999), the leg venous distensibility during hyperthermia may differ from that during local heating of the leg in normothermia by a possible difference in venous distensibility in muscle.

In the present study, we examined the change of calf volume with a short-term orthostatic stress during whole-body heating and cooling. In addition, to examine the effects of whole-body and local thermal stress on the magnitude and pattern of change in calf volume over a wide range of gravitational stresses, we analyzed the speed and magnitude of the increase in calf volume at different thigh cuff occlusion pressures from 20 to 80 mmHg with the subjects in the supine position. This wide range of occlusion pressures was chosen because it induces a wide range of venous pressures in the calf similar to that observed during a postural change. We hypothesized that the speed and magnitude of the change in calf volume during thigh occlusion would be increased by heat stress, and the increase would be more remarkable during local heating than during whole-body heating, when the increase in skin blood flow was similar between the two heating conditions.

Methods

Subjects

Ten healthy volunteers (eight females and two males) participated in this study. The average [mean (SEM)] age, body mass, height, and body fat of the subjects was 22(1) years, 53.4 (3.5) kg, 161 (3) cm, and 22.5 (1.4)% respectively. The study was approved by the Human Research Committee of the University of Occupational and Environmental Health, and the subjects gave their written consent to participate after being informed about the procedures and protocols involved.

Experimental procedure and protocols

Each subject was tested in two series of experiments: one under whole-body thermal stress and the other under local thermal stress. Subjects were asked to refrain from taking alcohol and smoking for at least 12 h and to abstain from strenuous physical activity for at least 24 h before the experiment. Under a thermoneutral condition (28°C ambient temperature, 50% humidity), the subjects were rested in the supine position on a tilt table and then equipped with an esophageal temperature (T_{es}) probe, skin thermocouples, skin electrodes, a cuff, laser-Doppler flow probes, and a strain gauge. After instrumentation, the subjects underwent whole-body heating, whole-body cooling, local heating, or normothermia (control).

Whole-body thermal stress

The protocol for the experiment under whole-body thermal stress consisted of three thermal conditions: whole-body heating, whole-body cooling, and normothermic control. The subjects wore a tube-lined water-perfused suit that covered the body except for the head and the right calf. The mean skin temperature (T_{sk}) was controlled by changing the water temperature of the suit. The mean T_{sk} was 35°C in the normothermic condition, 38°C in the heating condition, and 30°C in the cooling condition. After the body temperature reached a steady state after thermal loading, the change in calf volume during thigh occlusion was evaluated under each thermal stress. A head-up tilt (HUT) test, which consisted of 2 min each of supine rest, 15° HUT, 60° HUT, and supine recovery was carried out in the experiments under whole-body thermal stress. The tilt table was raised to each angle within 4 s. During HUT, the right foot of the subject did not touch the foot rest to avoid the effect of the skeletal muscle activity on the volume change in the calf. The body of the subject was supported by the left leg and a wrist belt during HUT. Each experiment was performed at the same hour on separate days, and the order of three experiments was randomized.

Local thermal stress

The protocol for the experiment under local thermal stress consisted of two thermal conditions: normothermic control and local heating of the calf. Subjects wore shorts and a T-shirt, and the right calf was inserted into a sealed box. During normothermic control, the air temperature in the box was maintained at 28–29°C. After the evaluation of calf distensibility during thigh occlusion in normothermia, the right calf was heated by warming the air in the box. The T_{sk} in the right calf was maintained at 38–39°C during local heating. After the skin blood flow in calf reached a steady state during local heating, the change of calf volume during thigh occlusion was evaluated.

Measurements and analysis

Calf volume

In the supine position, the heel of the right leg was supported above the horizontal level (θ') at an angle of 20°. To calculate the cross-sectional area of the calf, the maximal circumference of the calf was measured with a measuring tape. A 15-cm-wide thigh cuff was positioned just above the knee. A mercury-in-Silastic strain gauge was positioned at the point of maximum circumference. We occluded abruptly the thigh at 20, 30, 50, 70, and 80 mmHg in this order in five subjects, and in the opposite order in the remaining subjects. The time for the increase of cuff pressure was constant among the thermal conditions (4 s or shorter). This enabled us to measure the swelling pattern of the calf with a wide range of transmural venous pressures, such as occur during changes in posture or tilt (Melchior and Fortney 1993). Between each occlusion pressure, the thigh cuff pressure was abruptly released to zero by opening the inflation bulb. The criteria for deflating the cuff were: (1) the calf circumference increase had reached a maximum, or (2) the increase of calf circumference was less than 0.5 mm for 30 s (Melchior and Fortney 1993). Between reinflations of the cuff, we waited 2–3 min, or the time for the circumference to return to a steady-state baseline. The change in the circumference resulting from a given occlusion pressure was taken as the difference between the circumference reached at the end of the occlusion and the circumference corresponding to the steady-state baseline after the release of the cuff (Fig. 1). For evaluating the speed of the expansion of calf volume, the half-time of circumference change during thigh occlusion was calculated (Fig. 1).

Calibration of the strain gauge was performed immediately after the experiment. Although the voltage output of the mercury strain gauge that we used increased with ambient temperature (0.013 V/°C), the sensitivity (i.e., the slope of the relationship between the voltage output and the length of the gauge) was constant within a wide temperature range (18-42°C). Therefore, it was possible to compare the change in calf circumference among the temperature condition. As it is assumed that the calf is cylindrical,