



# Performance of the Liquid-Cooling Garment With the Advanced Crew Escape Suit in Elevated Cabin Temperatures

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## ABSTRACT

Current flight rules restrict the maximum cabin temperature (<75°F) during reentry and landing to protect crewmembers from heat stress. Cabin temperature is affected by the amount of hardware in operation during these activities. To allow for additional operations, the maximum cabin temperature limit must be raised.

Space Shuttle crewmembers wear a liquid-cooling garment (LCG) under the Advanced Crew Escape Suit (ACES) during reentry and landing to protect against heat stress. The primary purpose of this ground-based project was to determine whether the LCG could provide adequate cooling when cabin temperature was allowed to reach 80°F. Eight subjects (4 men, 4 women) underwent a simulated cabin temperature profile in an environmental chamber while wearing the ACES. Core and skin temperatures, heart rate, subjective ratings of heat and comfort, LCG flow rate, and water temperature were measured in 15-minute intervals throughout the chamber stay. Subjects completed a 10-minute stand test as an assessment of orthostatic tolerance before and after the chamber stay. Mean skin, core, and body temperatures were reduced from the start to the end of the chamber stay. Ratings of temperature and comfort were increased during the chamber exposure, but these changes were small. The mean reporting of temperature sensation changed from “slightly cool” at chamber start to “slightly warm” by the end of the exposure. Similarly, subjects reported being “comfortable” at the beginning of the test and “slightly uncomfortable” at the conclusion. All subjects completed the 10-minute stand test without signs of orthostatic intolerance. The subjects were able to control sufficiently their body temperatures with the self-selected flow rates during these tests to avoid the deleterious effects of wearing the ACES.

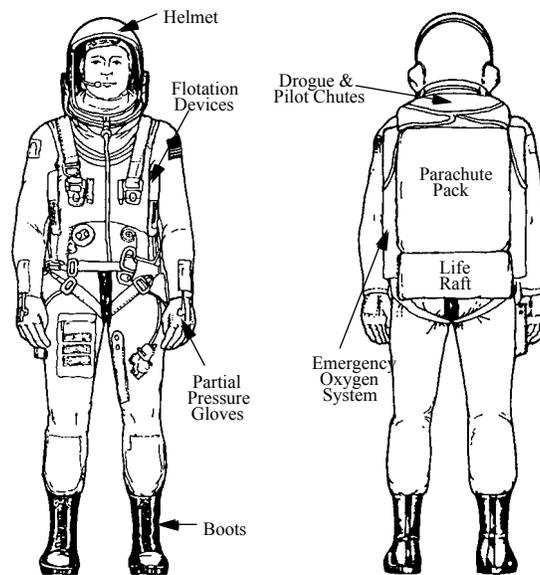
The secondary objective was to determine whether there was a graded effect of cabin temperatures when the cabin temperature maximums were 75, 80, and 85°F. Four subjects (2 men, 2 women) underwent the simulated cabin temperature profile at these maximum temperatures while wearing the ACES. Core and skin temperatures, heart rate, subjective ratings of heat and comfort, LCG flow rate, and water temperature were measured in 15-minute intervals throughout chamber stay. Subjects completed a 10-minute stand test as an assessment of orthostatic tolerance before and after the chamber stay. There was no discernible pattern observed with regard to core or skin temperatures in these subjects across the temperature profiles during the chamber stay. There appeared to be a trend for higher subjective ratings of comfort and heat across the temperature profiles, which also was reflected in an increased flow rate usage as the maximum cabin temperature increased. However, the subjects were able to control sufficiently their body temperatures with the self-selected flow rates during these tests.

## ACRONYM LIST

ACES	Advanced Crew Escape Suit
CTSD	Crew and Thermal Systems Division
DBP	Diastolic Blood Pressure
g-suit	Anti-gravity Suit
HI	High Temperature Profile
HR	Heart Rate
ICU	Individual Cooling Unit
LCG	Liquid Cooling Garment
LES	Launch and Entry Suit
LO	Low Temperature Profile
MAP	Mean Arterial Pressure
MID	Middle Temperature Profile
PP	Pulse Pressure
SBP	Systolic Blood Pressure
T <sub>in</sub>	Intestinal Temperature

# INTRODUCTION

Since 1988, all crewmembers have been required to wear a protective garment during Space Shuttle launch and landing (Bishop et al., 1999). The primary purpose of this garment is to provide protection against rapid decompression at high altitude, against hypothermia in case of bailout over cold water, and against toxic gases that may be emitted from the Orbiter after landing. The original garment worn was the Launch and Entry Suit (LES), which included an outer garment of two layers of polyurethane-coated nylon, a non-conformal (bubble-style) helmet, a lower-body positive pressure garment (anti-gravity suit; g-suit), boots, and polypropylene underwear.



**Figure 1.** External description of the NASA protective garments.

In the effort to provide the desired protection, the unintended side effect was that the insulating properties of the suit results in heat retention and heat load that may be detrimental to crew health. Elevated core temperature might be expected to further exacerbate the increased incidence of orthostatic intolerance observed following short- and long-duration spaceflight (Buckey et al., 1996; Fritsch-Yelle et al., 1996; Meck et al., 2001) and has been suggested to be the cause of an increase in orthostatic intolerance following the adoption of this protective garment (Nicogossian et al., 1995). To combat heat retention, an attempt was made to ventilate the suit with cabin air, but was proven to be ineffective (Pandolf et al., 1995; Sawin et al., 1998). In 1994, plastic tubes were integrated into the polypropylene underwear of the LES ensemble such that cool water could be circulated under the outer garment near the skin and heat could be removed to the cabin air (Perez et al., 2003); this became known as the liquid-cooling garment

(LCG). The water circulated from the suit was passed through a thermoelectric cooling unit where the heat was transferred from the water lines to the ambient air. Originally, two crewmembers shared each heat transfer unit. Since that time, individual cooling units (ICUs) have been developed and are in use on the Shuttle.

A new protective garment called the Advanced Crew Escape Suit (ACES) was developed by the David Clark Company, and its use has been gradually introduced into Space Shuttle flight since 1994 (first flown on Space Shuttle mission STS-64). The ACES externally resembles the LES, but the outer shell is constructed of a single layer of Goretex™. Theoretically, Goretex allows for perspiration transfer from the suit such that the heat load may be reduced. However, recent data from Rimmer et al. (1999) suggests that wearing the ACES still resulted in body heat storage. Four astronauts returning from a 16-day mission wearing the ACES during reentry and landing experienced core temperatures that were 0.4°C to 0.6°C higher than a comparable period earlier in the mission when they were unsuited.

NASA flight rules dictate the maximum cabin temperature prior to and during reentry to protect crew health and comfort (NSTS 07700, Volume X, Book 1, Revision M, November 10, 1998, Flight and Ground System Specifications). As a result, the number of crewmembers and the amount and type of operating hardware may be limited by the amount of heat that is anticipated to be generated. Further, predictions of heat load based upon on-orbit attitude and configuration may further modify the flight plan. Prior to de-orbit burn, cabin temperature is routinely reduced to the minimum possible while the payload doors remain open. Thereafter, cabin temperature increases as a result of the heat released by the Shuttle hardware as well as the heat retained by the Shuttle body during reentry. Previously, the upper limit of allowed temperature during descent and landing was 23.9°C (75°F). However, to meet the demands of mission objectives, waivers may be considered to allow higher cabin temperatures such that additional hardware could be in operation.

The purpose of this project was to determine whether the ICU with the LCG provides sufficient cooling to crewmembers at higher cabin temperatures than currently allowed by NASA flight rules. The primary objective of the investigation was to evaluate whether crewmembers could tolerate cabin temperatures of 26.7°C (80°F) and whether this exposure would result in significant changes in orthostatic responses to standing. The second objective of this project was to determine whether there were observable differences in temperature responses in a small number of subjects wearing the ACES across a range of temperature profiles. We examined three temperature profiles, including the currently allowed 23.9°C (75°F), the desired limit of

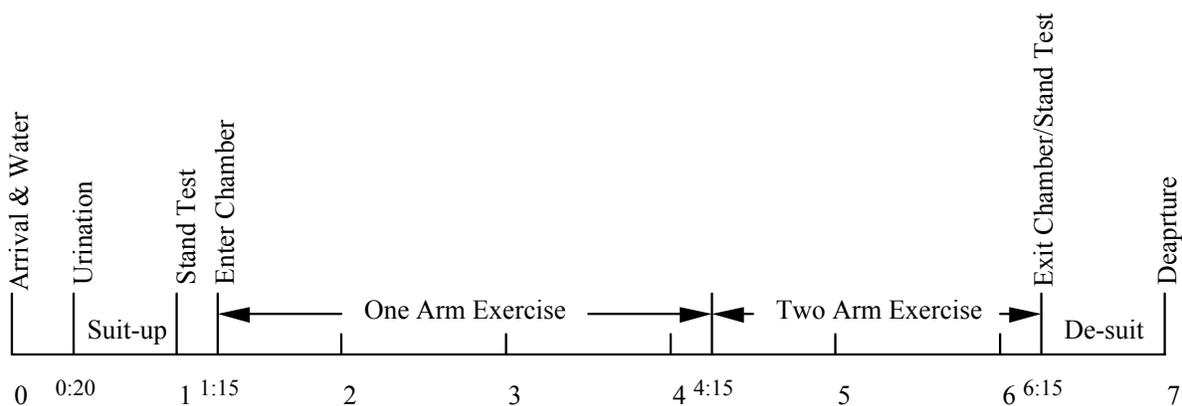
26.7°C (80°F), and an even higher temperature limit of 29.4°C (85°F). Orthostatic responses also were examined after each of the three chamber exposure profiles.

## METHODS

### Overall Protocol

The Exercise Physiology Laboratory at the NASA Johnson Space Center conducted this study in facilities provided by the Environmental Physiology Lab and with the support of the Crew and Thermal Systems Division (CTSD) Crew Escape Group. The testing protocol and procedures were reviewed and approved by the NASA Johnson Space Center Institutional Review Board. Testing procedures were fully explained to the test subjects, and written informed consent was obtained from each subject before participation in this study. Testing for this project was performed on Mondays, Wednesdays, and Fridays from July 19 through August 4, 2000. Eight subjects, four men and four women, participated in this investigation ( $33.6 \pm 6.1$  yr,  $67.3 \pm 2.7$  kg,  $155.5 \pm 24.8$  cm). All subjects passed a modified Air Force Class III physical, and were screened for illicit drug usage and for HIV and hepatitis antibodies.

Subjects were dressed in the ACES and remained within an environmentally controlled chamber for 5 hours (Figure 2). Temperature and humidity were controlled to simulate the environmental conditions to which crewmembers would be exposed during reentry and landing. Temperature profiles were patterned from actual data provided by CTSD personnel. Before and immediately after chamber exposure, subjects performed a 10-minute stand test in the ACES as a test of orthostatic tolerance.



**Figure 2.** Test timeline.

The scheduled time of the temperature profile was based upon several assumptions. First, the scenario with regard to the time in the ACES reflected the worst-case scenario, that of the commander and pilot. The commander and pilot don their suits approximately 2 hours before de-orbit burn. Second, including the time for one wave-off (an additional 90 minutes) and reentry maneuvers, the commander and pilot may be suited for approximately 4 hours before touchdown. After landing, the crew may be suited for an additional hour until the Shuttle is deemed safe for crew departure.

The primary purpose of this project was to determine whether the ICU and LCG could provide sufficient cooling to the subjects wearing the ACES to maintain comfort and protect against hyperthermia when the simulated cabin temperature followed a profile at the end of which 26.7°C (80°F) was achieved (MID). All eight subjects in the project were exposed to this condition. A secondary objective of this project was to examine whether a relationship existed between the cooling capacity of ACES/LCG system and the ambient temperatures. Four of the eight subjects (two men and two women) also were exposed to two additional temperature profiles, one which simulates the currently allowed peak temperature of 23.9°C (75°F; LO) and one in which the peak temperature was 29.4°C (85°F; HI).

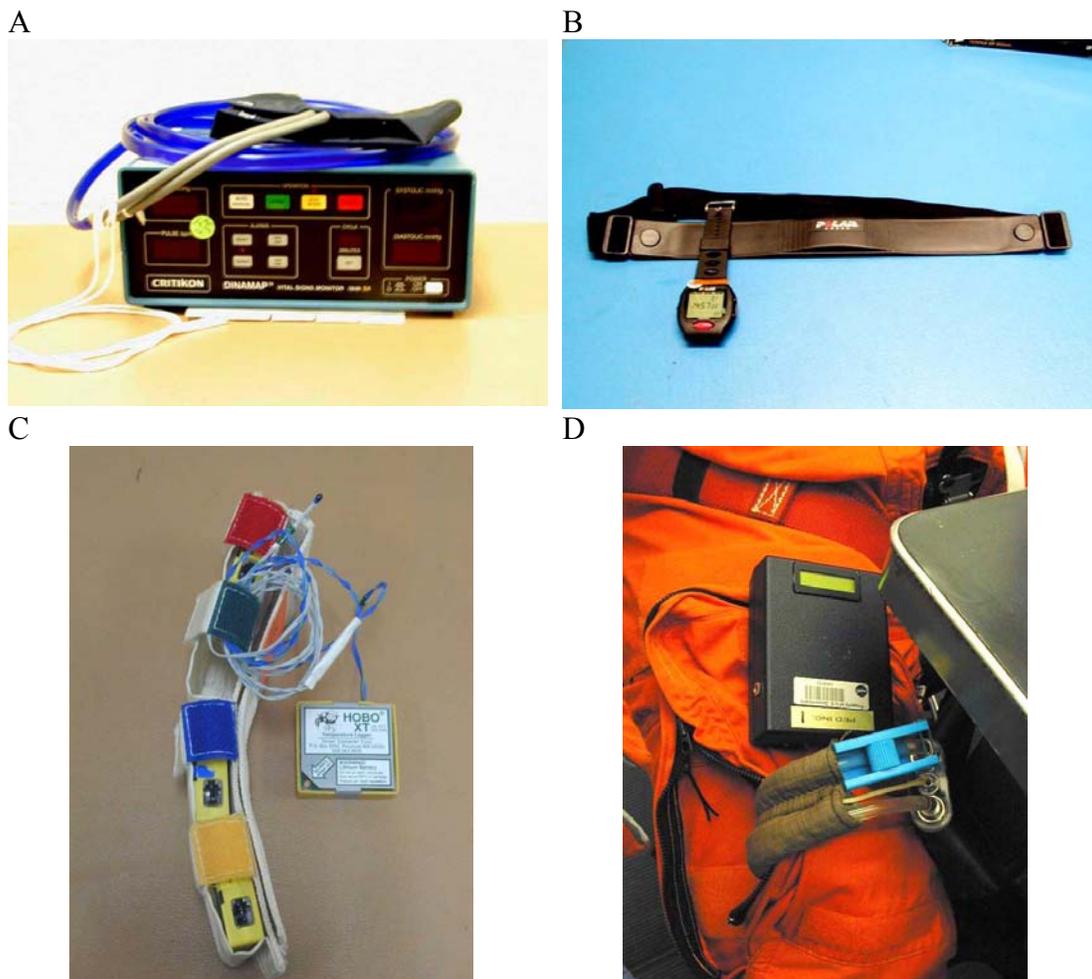
**Table 1. Temperature Profiles**

Time (hrs)	LO		MID		HI	
	Temp °C	Temp °F	Temp °C	Temp °F	Temp °C	Temp °F
0	20.0	68.0	22.8	73.0	25.6	78.0
1.0	20.6	69.0	23.3	74.0	26.1	79.0
1.5	21.1	70.0	23.9	75.0	26.7	80.0
2.0	21.7	71.0	24.4	76.0	27.2	81.0
2.5	22.2	72.0	25.0	77.0	27.8	82.0
3.0	22.8	73.0	25.6	78.0	28.3	83.0
3.5	23.3	74.0	26.1	79.0	28.9	84.0
4.0	23.9	75.0	26.7	80.0	29.4	85.0
5.0	23.9	75.0	26.7	80.0	29.4	85.0

## Subject Preparation

Due to the climate chamber size constraints, only two subjects participated in this evaluation on a given day. Upon an 8:00 AM arrival, subjects consumed 200 ml of water to ensure that they

were sufficiently hydrated before the test. After 20 minutes, subjects were given a chance to urinate, and then a pre-test weight was obtained on a digital scale with an accuracy of  $\pm 0.1$  lb (A&D Digital Floor Scale, Industrial Scale Co, Inc., Houston, TX). Subjects then donned an adult diaper (standard issue for astronauts wearing the ACES) since removing the ACES for urination would have resulted in test termination. Skin temperature ( $T_{sk}$ ) thermistors (Model 4499E, Yellow Springs Instrument Company, Inc., Yellow Springs, OH) were then attached using foam tape in such a manner as to avoid covering the sensor head. Thermistors were located on the upper arm, upper chest, thigh, and calf on the right side of the body.  $T_{sk}$  was recorded at 30-second intervals using data loggers (HOBO XT, Onset Instruments Corp., Pocasset, MA). The data loggers were secured to the waist of the g-suit. An automatic blood pressure cuff (Dinamap Vital Signs Monitor, Model 1846SX, Johnson & Johnson Medical, Inc., Arlington, TX) was attached on the left upper arm and the tubes were extended out through the sleeve of the ACES.



**Figure 3.** Subject instrumentation: (A) automatic blood pressure device, (B) heart rate monitor, (C) skin temperature data loggers, and (D) intestinal temperature data logger.

Heart rate (HR) was monitored and recorded using a heart rate monitor (Polar Vantage NV, Polar Electro, Inc., Port Washington, NY). Heart rate was detected from a chest strap against the skin that transmitted signals at a rate proportional to heart rate to the wrist watch data logger (Moore et al., 1997) attached to the outside of the ACES. Intestinal temperature ( $T_{in}$ ), as a measure of core temperature (Lee et al., 2000), was measured using a telemetry system (BCTM2, Personal Electronic Devices, Inc., Wellesley, MA) throughout the test from a pill (CorTemp Ingestible Sensor, Human Technologies, Inc., Medical Products Division, Palmetto, FL) swallowed the night before testing. The pill transmitted a signal proportional to  $T_{in}$  that was received by an external data logger that was attached on the upper leg of the ACES.

After instrumentation was complete, subjects continued to don the ACES and its associated gear with the assistance of the suit technicians (Figure 4). Subjects wore the standard issue long Capilene™ underwear, LCG, g-suit, flight boots, wool socks, and communication cap. The combined weight of the entire suit was approximately 27 kg (60 lb; Lee et al., 2001). The g-suit was not inflated during the test to simulate the worst-case scenario with regard to an orthostatic challenge. The helmet visor was kept open throughout the duration of the test.

## **Stand Test Procedure**

After both subjects donned the ACES, they simultaneously performed a 10-minute stand test. Subjects were assisted to the supine position on tables in the laboratory. The subjects rested in the supine position for 6 minutes, then stood immediately with assistance from laboratory personnel, and stood quietly for 10 minutes. HR was continuously monitored via the heart watch, and was recorded during the last 15 sec of each minute. The automatic blood pressure monitors were programmed to measure blood pressure at 1-minute intervals. The ACES gloves were not worn during the stand test to allow for the attachment of the blood pressure cuff hoses to the automatic blood pressure monitor. This same protocol was followed in the stand test performed at the completion of the chamber stay.



**Figure 4.** Subject donning the ACES with the assistance of the CTSD suit technicians.



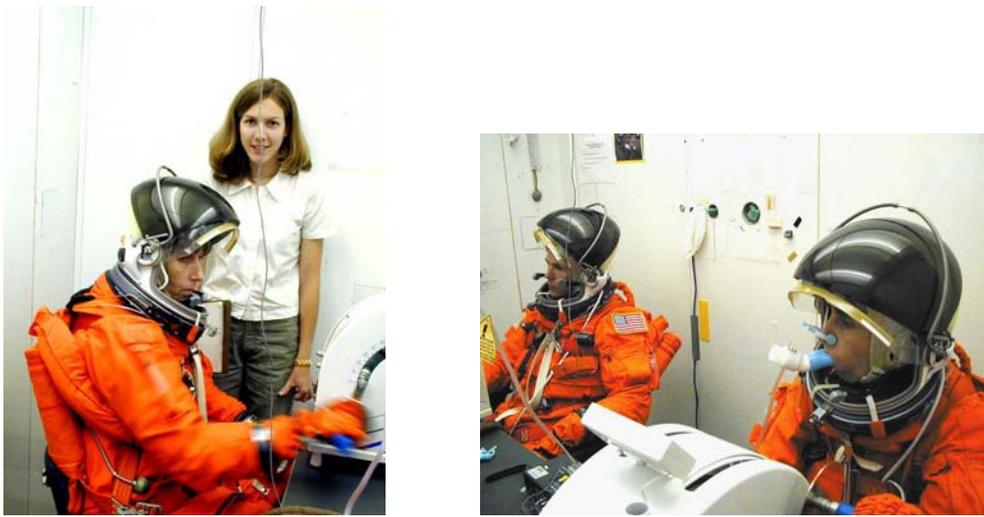
**Figure 5.** Subjects during supine and standing portions of stand test.

## **Chamber Stay**

After the stand test, subjects entered the environmental chamber. They were immediately attached to their ICUs. The cooling capability of the ICU was set on maximum for all subjects, but the flow of water through the LCG was controlled by the subject. The communication cap of each subject was connected to an intercom system so that subjects could provide feedback to the test administrators. Test administrators were positioned both inside and outside the chamber.

Subjects performed mild arm exercise using an arm ergometer to simulate the metabolic rates during normal landing activities. Subjects followed an activity pattern of 10 minutes of exercise followed by 5 minutes of rest. The tension belt of the arm ergometer was slack, and subjects were asked to maintain a rate between 30 and 40 RPM. For the first 3 hours in the chamber, exercise was performed with one arm only, with the option of alternating arms at the subject's discretion. However, during the final 2 hours in the chamber, exercise was performed

using both arms to simulate increased exertion during and after landing. Water and snack foods were available *ad libitum*.



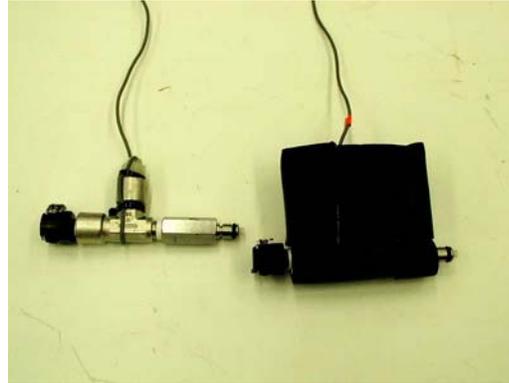
**Figure 6.** Subjects performed mild exercise during the test to simulate the activities of the commander and pilot during landing.

Starting at minute 10 and every 15 minutes thereafter (at the end of each exercise session),  $T_{in}$ , HR, LCG inlet temperature, LCG outlet temperature, and LCG flow rate were recorded for each subject. Also, subjective ratings of comfort and heat (Table 2) were reported and recorded. Additionally, chamber temperature and humidity were recorded at this time. LCG flow rate was measured with a calibrated flow meter. Temperature of the water flowing through the LCG was measured using calibrated thermistors (Model EU-U-VL1.5-2, Grant Instruments Ltd., Cambridge, England) in the flow of the water just external to the ACES. Chamber temperature also was measured with a calibrated thermistor, and these data were recorded using a data logger (Model 1256 Remote Squirrel meter/logger, Science Electronics, Dayton, OH). Ambient humidity was also measured and recorded.

A



B



C



D



**Figure 7.** Thermistors were placed within the flow from the ICU to the LCG (A), and the fitting was insulated to reduce heat transfer (B). Data from these thermistors and the one measuring ambient temperature were recorded using a data logger (C). An analog flow meter was used to measure water flow through the LCG (D).

**Table 2.** Comfort and Heat Rating Scales

Comfort		Heat	
0	Comfortable	-3	Cold
1	Slightly uncomfortable	-2	Cool
2	Uncomfortable	-1	Slightly cool
3	Very uncomfortable	0	Neutral
4	Intolerable	+1	Slightly warm
		+2	Warm
		+3	Hot

All temperature sensors (intestinal temperature pill and thermistors) were calibrated against a certified mercury thermometer (Ever Ready Thermometer Co., Inc., New York, NY) at four temperatures. Individual calibration curves were constructed for each sensor, and the resulting equation was applied to the data collected. The correlation coefficient for each of the resulting linear regressions was  $r^2 > 0.99$ .

### **Data Analysis: In-Chamber Mid-Temperature Profile (n=8)**

In-chamber data collected at each 15-minute interval during the MID temperature profile were averaged across all eight subjects for MID temperature profile.  $T_{sk}$  and  $T_{in}$  data were selected to correspond with these 15-minute intervals. Mean  $T_{sk}$  was calculated using the formula:  $\text{mean } T_{sk} = (0.3 \cdot T_{arm}) + (0.3 \cdot T_{chest}) + (0.2 \cdot T_{thigh}) + (0.2 \cdot T_{calf})$ . Mean body temperature ( $T_{body}$ ) was calculated using the formula:  $T_{body} = (0.65 \cdot T_{in}) + (0.35 \cdot \text{mean } T_{sk})$ . Total body sweat loss (TSL) was calculated using the following equation:

$$\text{TSL} = \text{Post BM} - \text{Pre BM} + (\text{Fluid In} + \text{Food In}) - (\text{Post DM} - \text{Pre DM}),$$

where BM refers to body mass and DM refers to diaper mass. DM was used only if the subject reported urination during the testing.

For comparisons of data from the beginning to the end of the chamber stay, the first two data points from the start of the test were averaged as were the last two data points from the end of the test. Start to end comparisons of the data were performed using a paired t-test.  $T_{arm}$  data were not available for two of the eight subjects. Therefore,  $T_{arm}$  and mean  $T_{sk}$  graphs and comparisons represent data from only six subjects.

### **Data Analysis: In-Chamber All Temperature Profiles (n=4)**

Data reduction was performed in a similar manner as that previously described for the comparisons within the MID temperature profile, except that comparisons across each of the three temperatures represented only the four subjects who completed all the tests. That is, only four sets of data were compared in the MID profile in these analyses. Because of the small number of subjects in this portion of the project, care should be taken in interpreting these results. Statistical analyses were performed to identify trends and should not be considered conclusive.

Comparisons between temperature profiles were made between mean responses across the duration of the chamber stay using a repeated measures analysis of variance (ANOVA) in which temperature profile was the repeated factor. However, because subjects completed chamber runs

concurrently, there was insufficient ambient data to make statistical comparisons; there were only two chamber stays per temperature profile. A separate repeated measures ANOVA was used to determine whether there were differences between the three profiles at the conclusion of the chamber stay. Comparisons within a temperature profile, from beginning to end of chamber stay, were made with paired t-tests.

## **Data Analysis: Stand Test Comparisons**

Supine and standing HR, systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP;  $\text{MAP} = 1/3 \text{ SBP} + 2/3 \text{ DBP}$ ), and pulse pressure (PP;  $\text{PP} = \text{SBP} - \text{DBP}$ ) were expressed as the mean of the last two minutes at each posture. For the MID temperature profile, pre- to post-chamber supine and standing HR, SBP, DBP, MAP, and PP were compared using a repeated measures ANOVA in which posture and pre- and post-chamber stay were factors. The changes from supine to standing in each variable were compared pre- to post-chamber using paired t-tests. Similar to the in-chamber data, only data collected on the four subjects who completed each temperature profile were used in comparisons across temperatures.

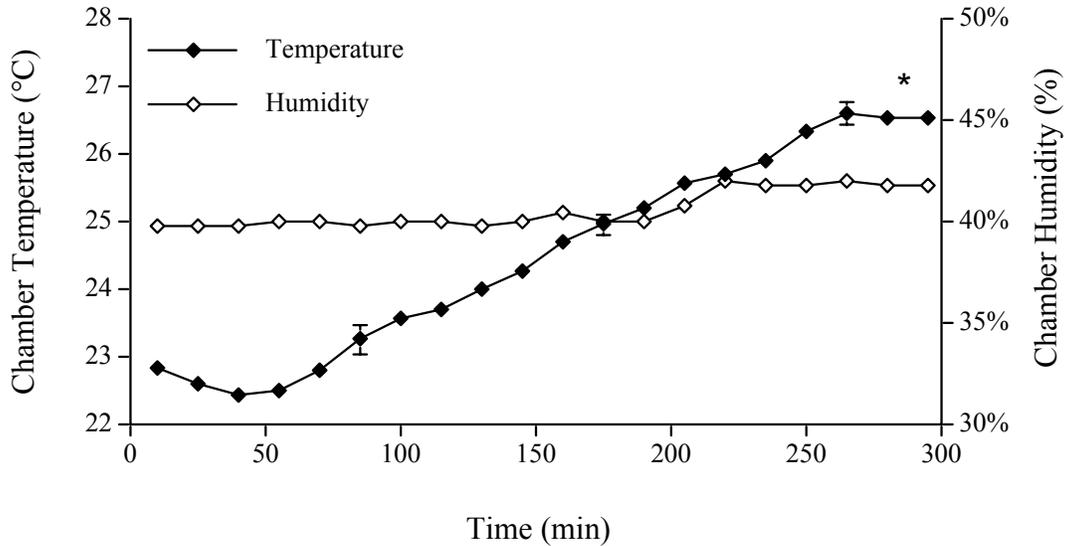
Statistical significance was accepted *a priori* at  $p \leq 0.05$ . Data are expressed as mean  $\pm$  SE unless otherwise noted.

## **RESULTS**

### **MID Temperature Profile (n=8): In-Chamber Data**

Chamber temperature increased significantly from the beginning ( $22.7 \pm 0.1^\circ\text{C}$ ) to the end of the chamber stay ( $26.6 \pm 0.0^\circ\text{C}$ ). There was no significant change in chamber humidity from the start ( $39.8\% \pm 1.2\%$ ) to the finish of the chamber stay ( $41.8\% \pm 0.2\%$ ).

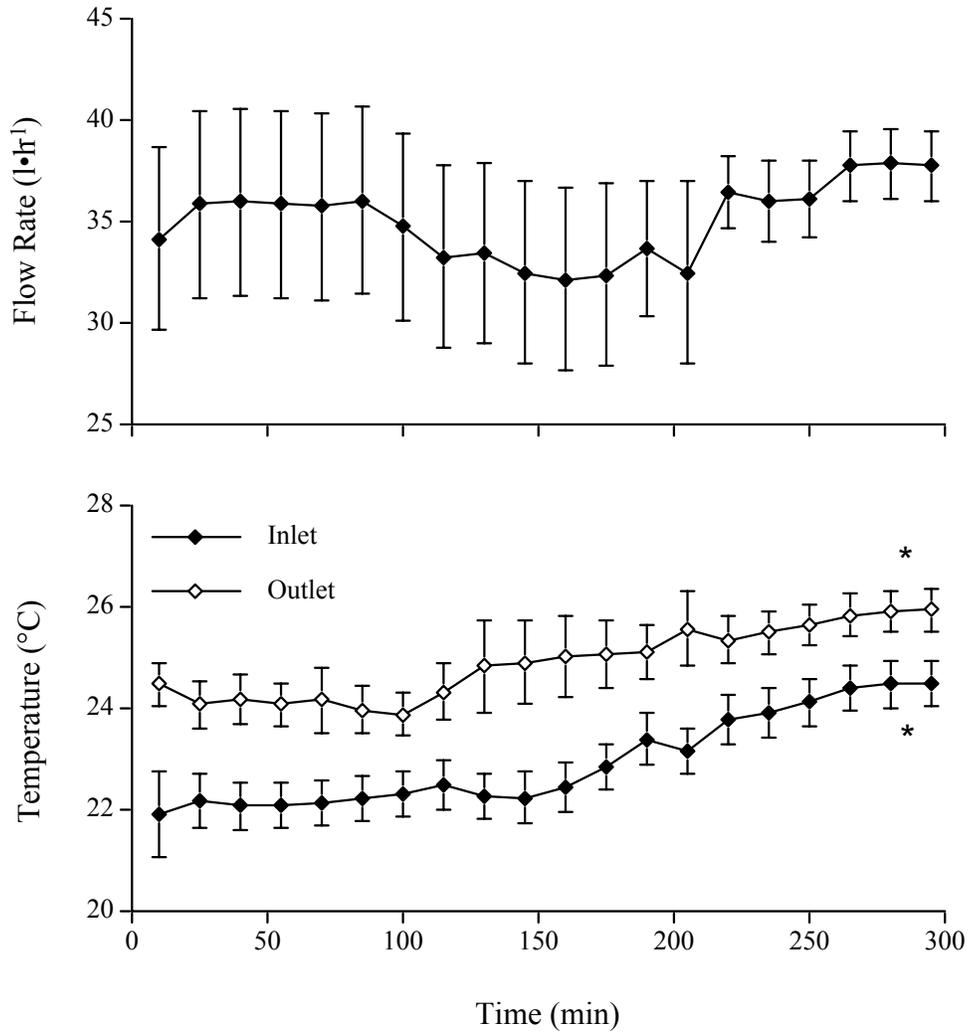
There was no change in the self-selected flow rate into the LCG from the beginning to the end of the chamber stay ( $35.1 \pm 4.5$  vs.  $37.8 \pm 1.7 \text{ l}\cdot\text{h}^{-1}$ ). The mean self-selected flow rate across the chamber stay was  $35.1 \pm 3.2 \text{ l}\cdot\text{min}^{-1}$ .



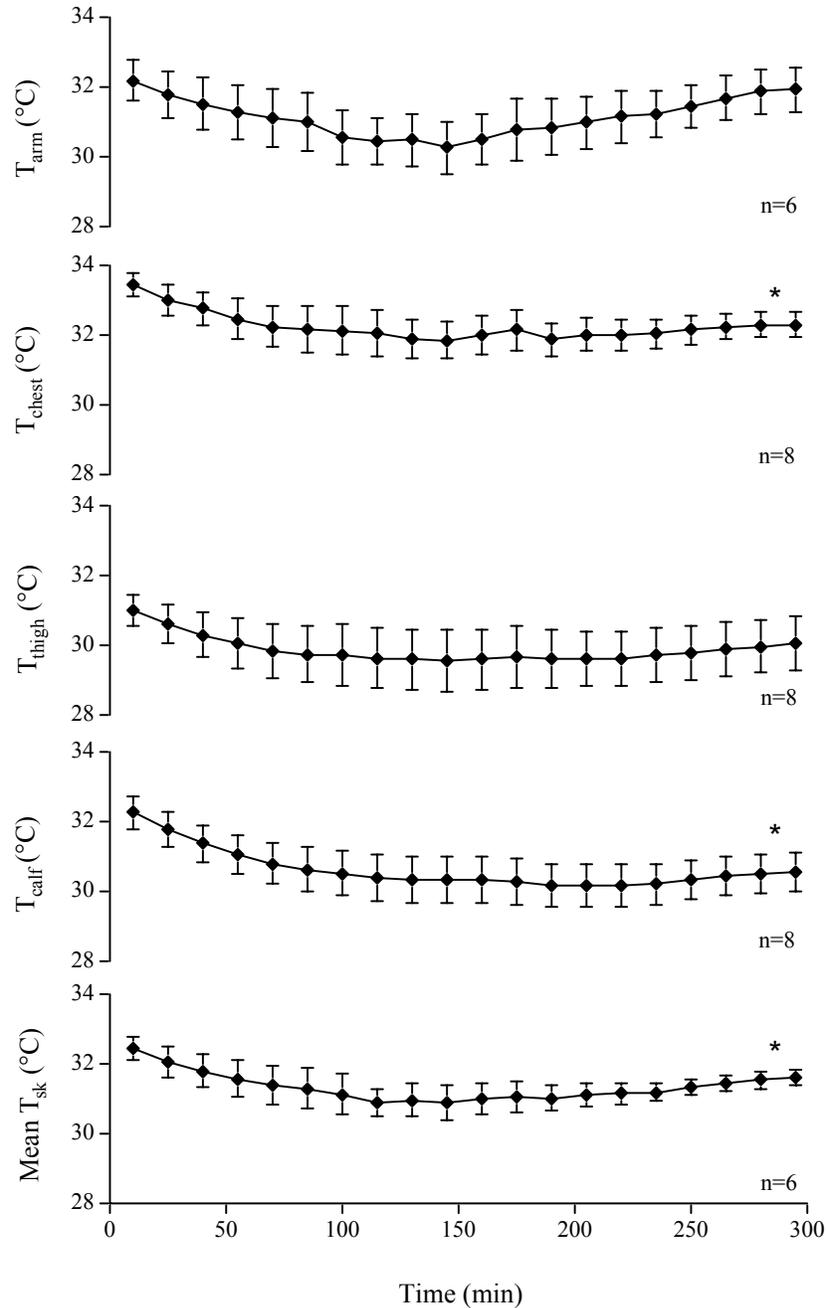
**Figure 8.** Measured chamber temperature and humidity during the four runs of two subjects, each using the MID temperature profile; \* $p < 0.05$ , significantly different from beginning of chamber stay.

The mean inlet temperature increased from the start ( $22.04 \pm 0.68^\circ\text{C}$ ) to the end of the chamber stay ( $24.47 \pm 0.45^\circ\text{C}$ ). The mean outlet temperature significantly increased from the beginning ( $24.27 \pm 0.45^\circ\text{C}$ ) to the end of the chamber stay ( $25.92 \pm 0.41^\circ\text{C}$ ). The mean outlet temperature ( $24.88 \pm 0.49^\circ\text{C}$ ) was significantly greater than the mean inlet temperature ( $22.93 \pm 0.42^\circ\text{C}$ ). The mean difference between the inlet and outlet temperatures was  $1.94 \pm 0.33^\circ\text{C}$ . The difference between the inlet and outlet temperatures significantly decreased from the start ( $2.22 \pm 0.37^\circ\text{C}$ ) to the end of the chamber stay ( $1.44 \pm 0.11^\circ\text{C}$ ).

$T_{\text{arm}}$  was not different from the beginning ( $32.01 \pm 0.62^\circ\text{C}$ ) to the end of chamber stay ( $31.92 \pm 0.65^\circ\text{C}$ ).  $T_{\text{arm}}$  appeared to decrease during the chamber exposure and to recover such that the mean  $T_{\text{arm}}$  was  $31.18 \pm 0.71^\circ\text{C}$ . Similarly,  $T_{\text{thigh}}$  did not change significantly (Pre:  $30.81 \pm 0.50$ , Post:  $30.02 \pm 0.76$ ) but appeared to decrease and recover during the chamber stay similar to that observed in  $T_{\text{arm}}$ . The mean  $T_{\text{thigh}}$  was  $29.88 \pm 0.75^\circ\text{C}$ ). In contrast,  $T_{\text{chest}}$ ,  $T_{\text{calf}}$ , and Mean  $T_{\text{sk}}$  decreased.  $T_{\text{chest}}$  decreased from  $33.23 \pm 0.38^\circ\text{C}$  to  $32.30 \pm 0.38^\circ\text{C}$  (mean:  $32.26 \pm 0.47^\circ\text{C}$ ),  $T_{\text{calf}}$  decreased from  $32.05 \pm 0.47^\circ\text{C}$  to  $30.56 \pm 0.56^\circ\text{C}$  (mean:  $30.66 \pm 0.57^\circ\text{C}$ ), and mean  $T_{\text{sk}}$  decreased from  $32.25 \pm 0.39^\circ\text{C}$  to  $31.56 \pm 0.24^\circ\text{C}$  (mean:  $31.33 \pm 0.39^\circ\text{C}$ ).

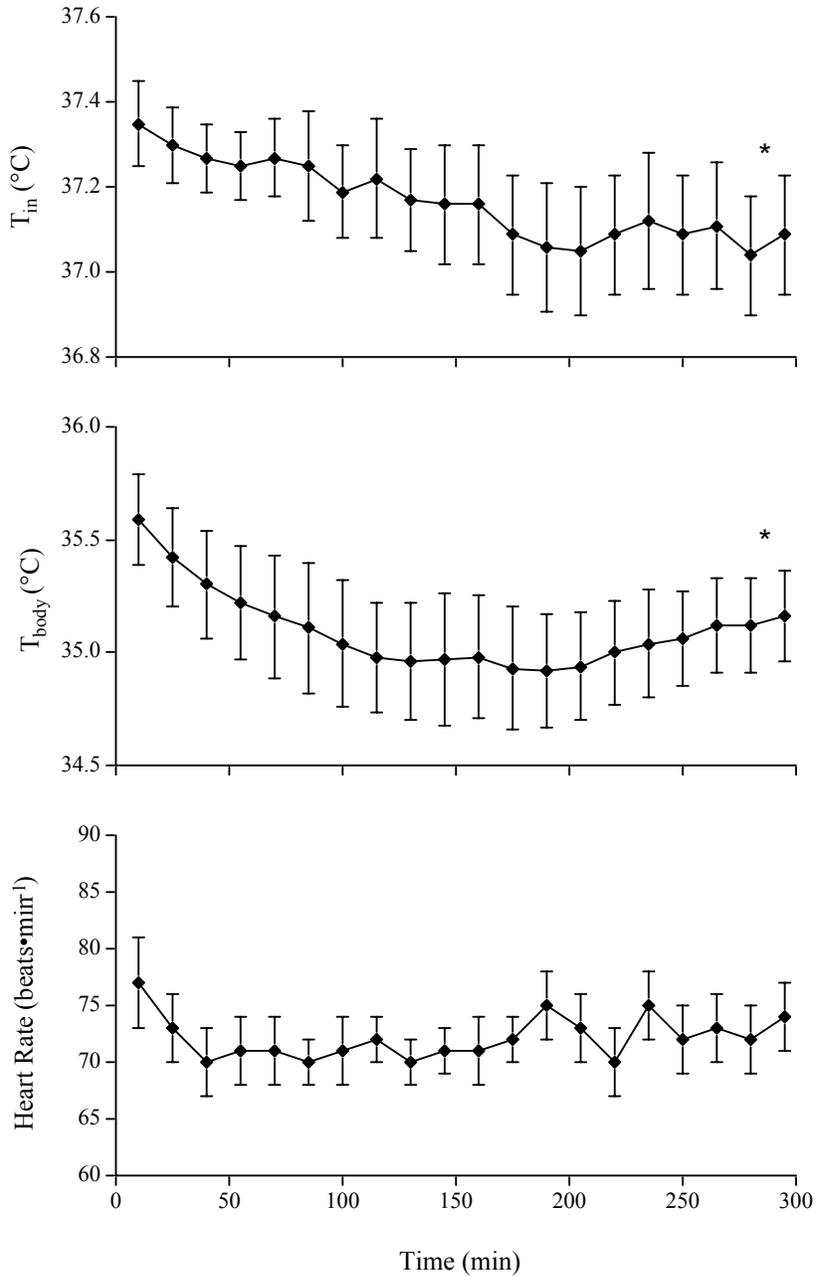


**Figure 9.** Mean self-selected flow rate, mean inlet temperature, and mean outlet temperature measured at 15-minute intervals during chamber exposure at MID temperature profile in eight subjects; \* $p < 0.05$ , significantly different from beginning of chamber stay.



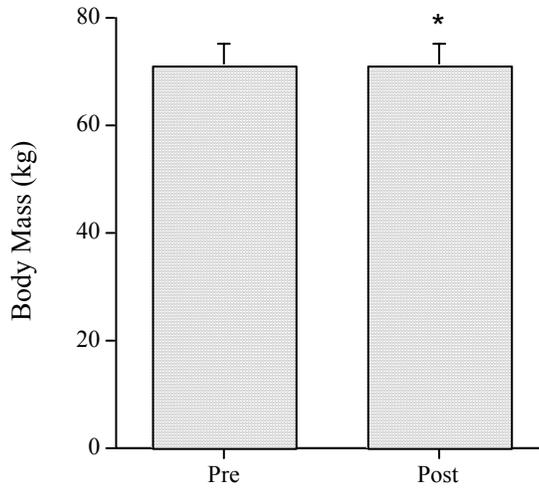
**Figure 10.** Local and mean skin temperature measured during chamber exposure at MID temperature profile in eight subjects; \* $p < 0.05$ , significantly different from beginning of chamber stay.

$T_{in}$  also decreased significantly from the beginning ( $37.3 \pm 0.1^\circ\text{C}$ ) to the end of the chamber stay ( $37.1 \pm 0.1^\circ\text{C}$ ). The mean  $T_{in}$  across the chamber stay was  $37.2 \pm 0.1^\circ\text{C}$ . There was no significant change in HR from the beginning ( $75 \pm 3 \text{ beats} \cdot \text{min}^{-1}$ ) to the end of the chamber stay ( $73 \pm 3 \text{ beats} \cdot \text{min}^{-1}$ ). The mean HR during the chamber stay was  $72 \pm 2 \text{ beats} \cdot \text{min}^{-1}$ .

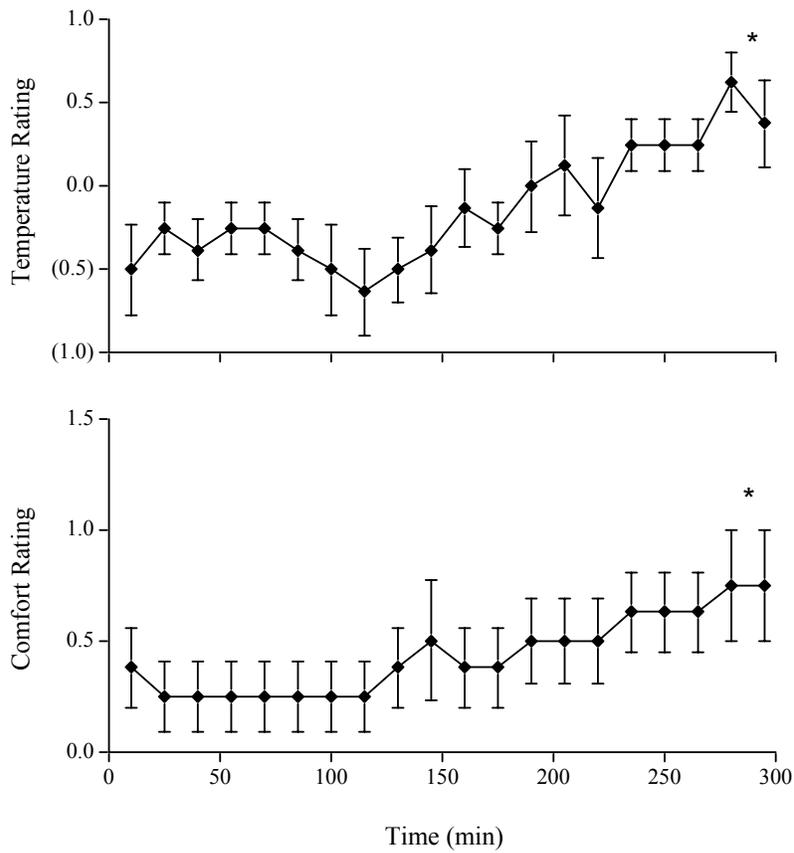


**Figure 11.** Mean  $T_{in}$ ,  $T_{body}$ , and HR measured at 15-minute intervals in eight subjects during the MID temperature profile; \* $p < 0.05$ , significantly different from beginning of chamber stay.

Subjects experienced a significant loss of body mass from the beginning to the end of the chamber stay (Pre:  $71.3 \pm 4.1$  kg; Post:  $71.2 \pm 4.0$  kg;  $\Delta$ :  $-0.1 \pm 0.0$  kg). Although they consumed  $0.10 \pm 0.03$  kg of food and fluid, the mean TSL was  $0.23 \pm 0.02$  kg.



**Figure 12.** Pre- and post-chamber body mass during the MID profile in eight subjects.

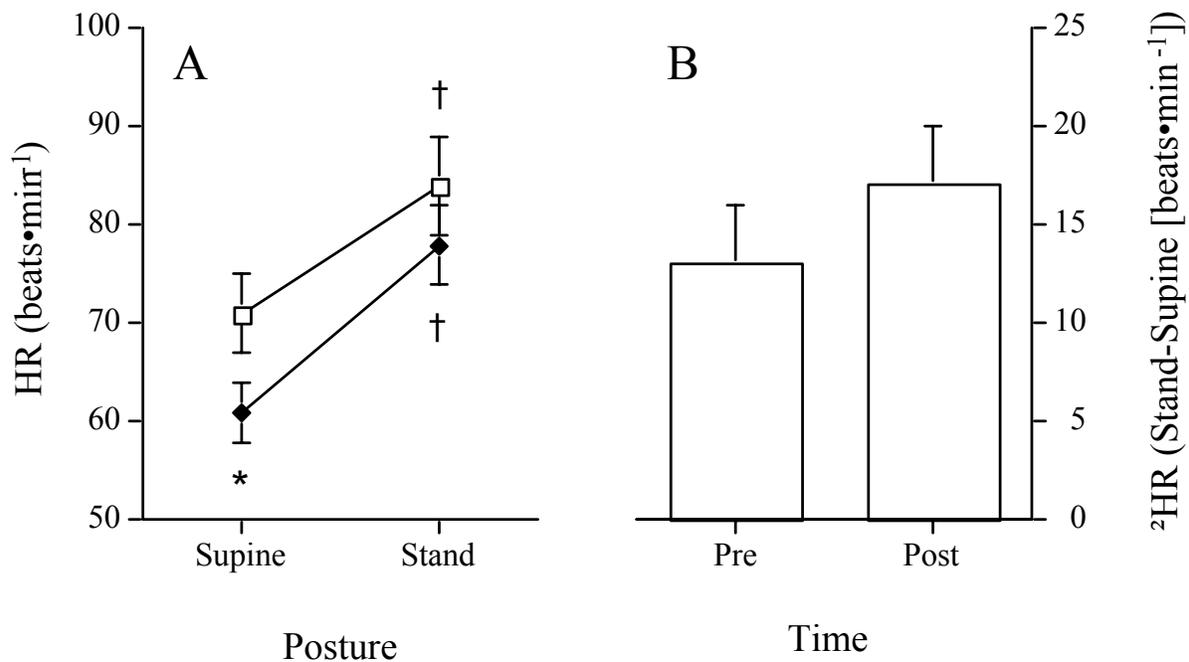


**Figure 13.** Mean subjective temperature and comfort rating measured at 15-minute intervals during MID temperature profile chamber in eight subjects; \* $p < 0.05$ , significantly different from beginning of chamber stay.

Subjects reported a significantly greater subjective temperature rating from the beginning ( $-0.4 \pm 0.2$ ) to the end of the chamber stay ( $0.5 \pm 0.2$ ). The mean subjective temperature rating during the chamber stay was  $-0.1 \pm 0.1$ . The subjects also reported significantly more discomfort from the beginning ( $0.3 \pm 0.2$ ) to the end of the chamber stay ( $0.8 \pm 0.3$ ). The mean comfort rating during the chamber stay was  $0.4 \pm 0.2$ .

### MID Temperature Profile (n=8): Stand Test Data

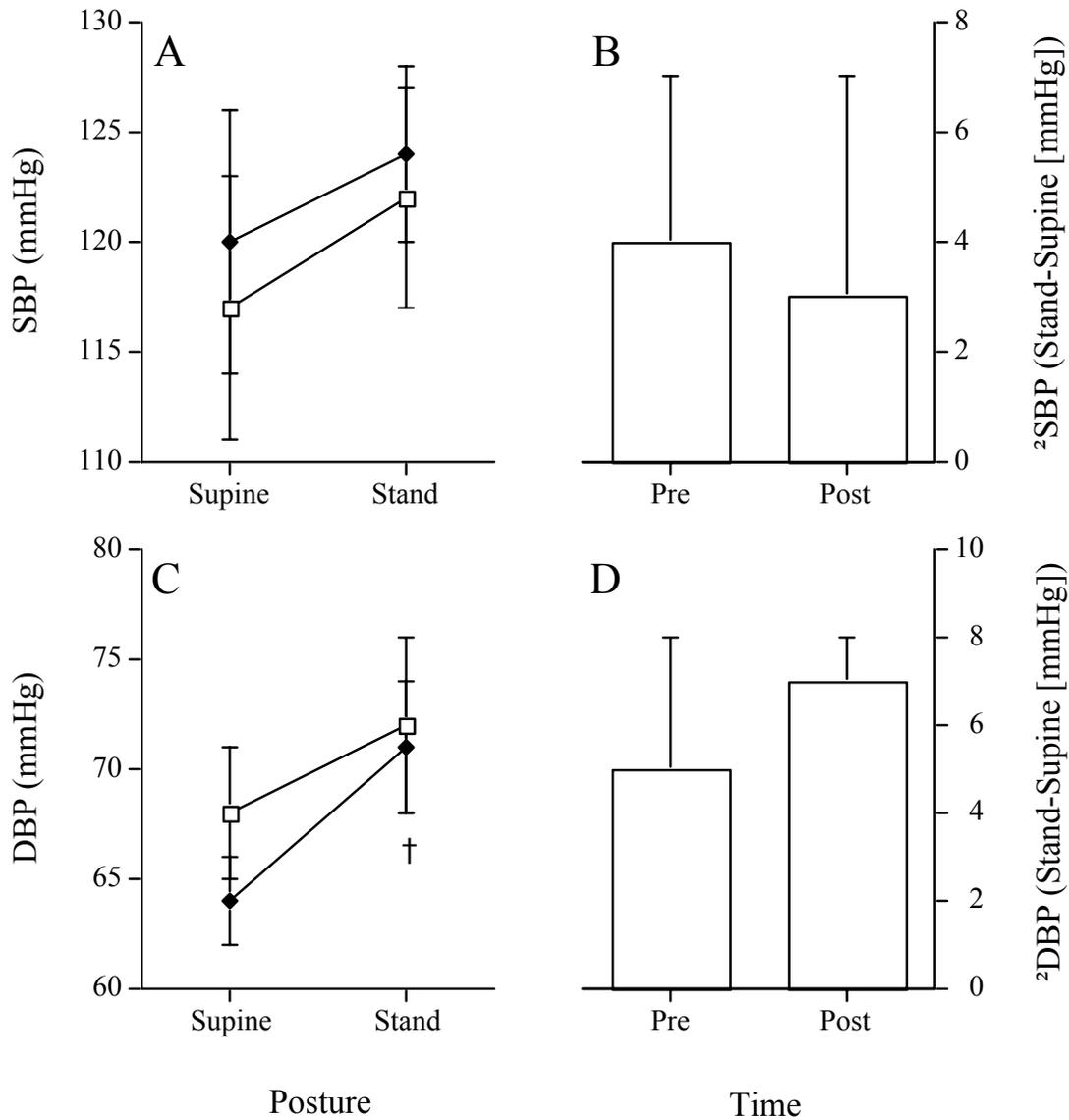
HR significantly increased from supine to standing both pre- and post-chamber (Figure 14). Supine heart rate was significantly less after the chamber stay, but standing HR was unchanged. There was no effect on the change in HR from supine to standing from pre- to post-chamber stay.



**Figure 14.** Supine and standing HR (Panel A) before (open squares) and after chamber stay (solid diamonds) and the change in HR (Panel B) from supine to standing before and after chamber stay at the MID temperature profile; \* $p < 0.05$ , significantly different from beginning of chamber stay; † $p < 0.05$ , significantly different than supine.

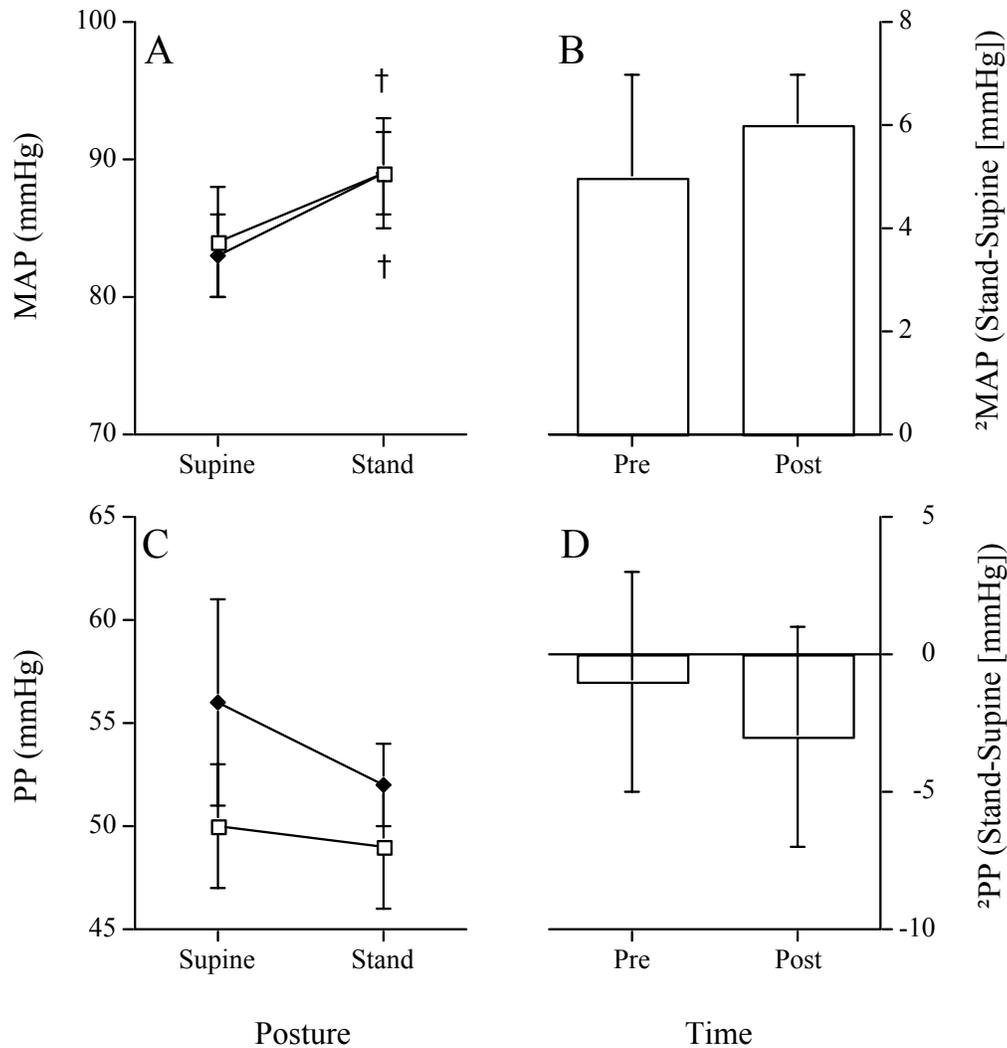
SBP did not change from supine to standing either before or after the chamber stay (Figure 15). There was a main effect of chamber stay on SBP such that SBP was elevated post-chamber, but the post-chamber SBP during supine and standing were not different from the corresponding pre-chamber values. Also, there was no difference from pre- to post-chamber in the change in

SBP from supine to standing. DBP tended to increase ( $p=0.051$ ) upon standing during pre-chamber testing and did significantly increase during post-chamber from supine to standing. However, there was no difference from pre- to post-chamber in the corresponding values of supine and standing DBP. Therefore, the change in DBP from supine to standing was similar pre- to post-chamber stay.

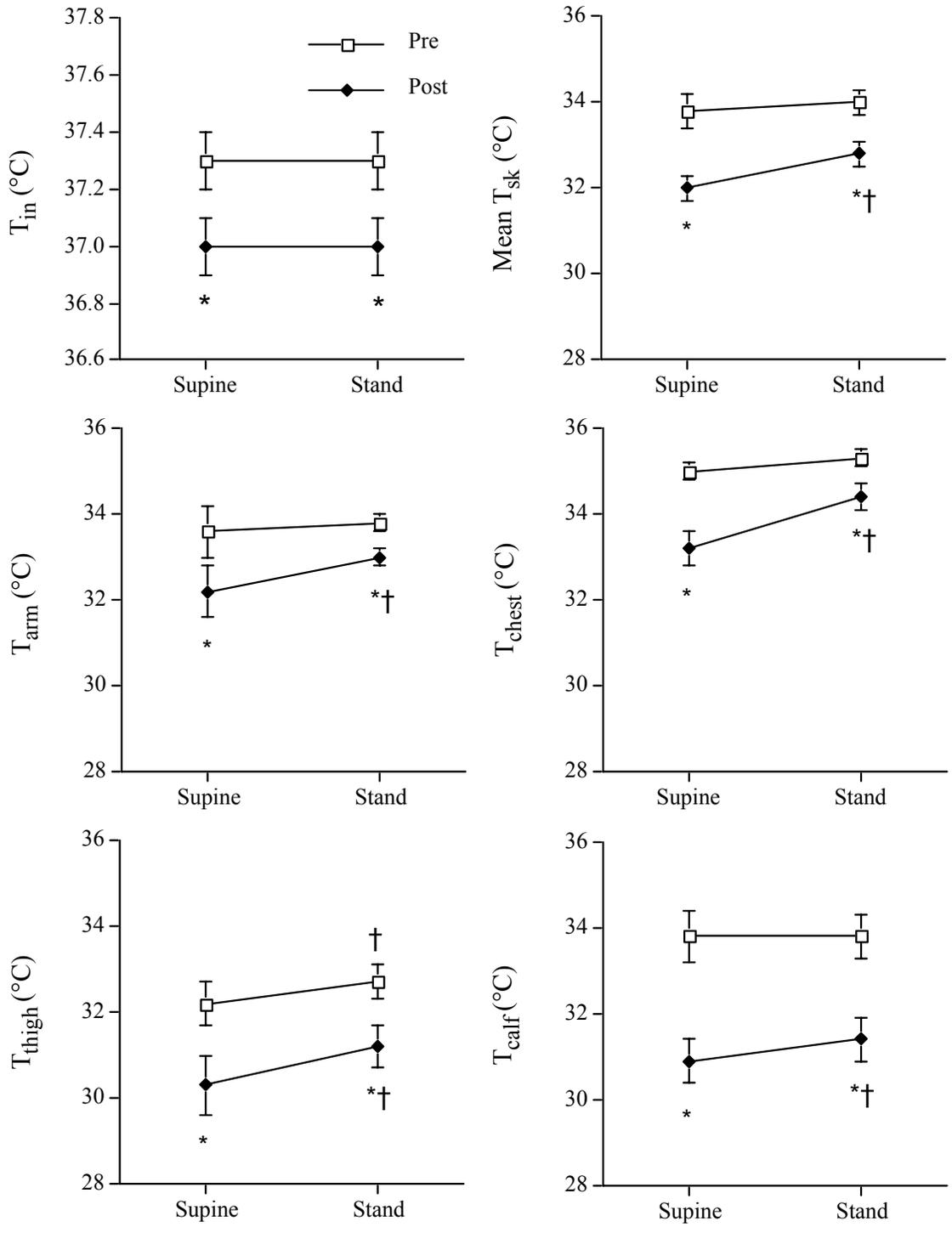


**Figure 15.** Supine and standing SBP (Panel A) before (open squares) and after chamber stay and the change in SBP (Panel B) from supine to standing before and after chamber stay at the MID temperature profile. Also, supine and standing DBP (Panel C) before (open squares) and after chamber stay (solid diamonds) and the change in DBP (Panel D) from supine to standing before and after chamber stay at the MID temperature profile; \* $p<0.05$ , significantly different from beginning of chamber stay; † $p<0.05$ , significantly different than supine.

MAP increased from supine to standing both pre- and post-chamber stay (Figure 16). The supine and standing MAP were similar pre- to post-chamber, and there was no difference pre- to post-chamber in the change in MAP from supine to standing. PP did not change from supine to standing either pre- or post-chamber. There was a main effect of chamber stay on PP such that PP was elevated post-chamber, but the post-chamber PP during supine and standing were not different from the corresponding pre-chamber values. Also, there was no difference from pre- to post-chamber in the change in PP from supine to standing.



**Figure 16.** Supine and standing MAP (Panel A) before (open squares) and after chamber stay (solid diamonds) and the change in MAP (Panel B) from supine to standing before and after chamber stay at the MID temperature profile. Also, supine and standing PP (Panel C) before (open squares) and after chamber stay (solid diamonds) and the change in PP (Panel D) from supine to standing before and after chamber stay at the MID temperature profile; \* $p < 0.05$ , significantly different from beginning of chamber stay; † $p < 0.05$ , significantly different than supine.



**Figure 17.** Change in core and skin temperature during the stand test performed before and after chamber stay (MID profile; n=8 except for  $T_{arm}$  and mean  $T_{sk}$ , n=6); \*p<0.05, significantly different from beginning of chamber stay; †p<0.05, significantly different than supine.

$T_{in}$  was not significantly different from the beginning to the end of the stand test during pre- or post-chamber exposure (Figure 17). However,  $T_{in}$  was significantly less after chamber exposure in both postures. Before chamber exposure mean  $T_{sk}$  did not increase significantly during the stand test from supine to standing. However, after chamber stay, mean  $T_{sk}$  was increased. The supine and standing mean  $T_{sk}$  also were significantly less after chamber stay, but the change in mean  $T_{sk}$  was significantly greater.

Prior to chamber exposure,  $T_{arm}$  did not increase from the start to the end of the stand test. However, after chamber stay, both supine and standing  $T_{arm}$  were lower than pre-chamber, and  $T_{arm}$  increased significantly during the stand test. Further, the change in  $T_{arm}$  was significantly greater after the chamber exposure.

Before chamber entry,  $T_{chest}$  did not increase significantly during the stand test. However,  $T_{chest}$  did increase significantly during the post-chamber stand test. Also, both supine and standing  $T_{chest}$  were significantly less after chamber stay. The change in  $T_{chest}$  during the stand test was significantly greater after chamber stay.

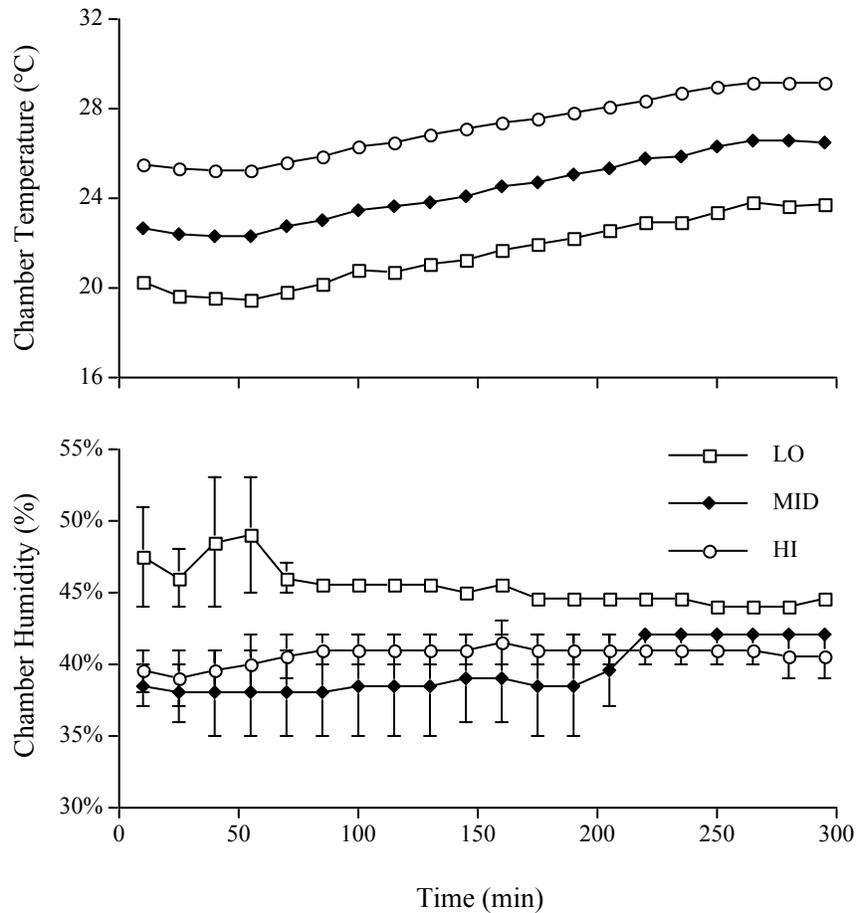
Supine and standing  $T_{thigh}$  were significantly lower after chamber stay than their respective pre-chamber values. At both testing times,  $T_{thigh}$  increased from the start to end of the stand test. However, the change in  $T_{thigh}$  from the start to the end of the stand test tended ( $p=0.07$ ) to be greater after chamber exposure.

Supine and standing  $T_{calf}$  were both significantly less after chamber stay compared to pre-chamber. Prior to chamber entry, the change in  $T_{calf}$  from the start to the completion of the stand test was not significant, but after chamber stay,  $T_{calf}$  did significantly increase during the stand test. The change in  $T_{calf}$  during the stand test was significantly greater after chamber exposure.

## **All Temperature Profiles (n=4): In-Chamber Data**

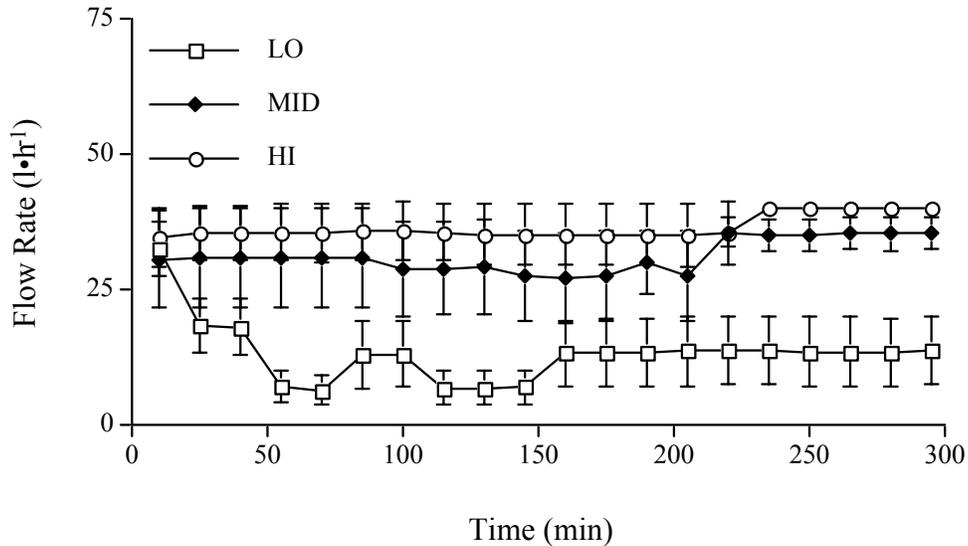
Because only two chamber runs were performed for each temperature profile (one chamber run per two subjects), no statistical analyses of the environmental conditions were possible. The chamber temperature increased from the start (LO:  $20.0\pm 0.1$ ; MID:  $22.6\pm 0.1$ ; HI:  $25.5\pm 0.0^{\circ}\text{C}$ ) to the end of the chamber stay (LO:  $23.7\pm 0.2$ ; MID:  $26.6\pm 0.1$ ; HI:  $29.2\pm 0.0^{\circ}\text{C}$ ) across each temperature profile. The mean chamber temperatures were  $21.6\pm 0.1$ ,  $24.4\pm 0.0$ , and  $27.2\pm 0.0^{\circ}\text{C}$  during the LO, MID, and HI profiles, respectively. The mean chamber humidity across the chamber stays were  $45.4\pm 0.9\%$ ,  $39.5\pm 2\%$ , and  $40.7\pm 1.3\%$  during the LO, MID, and HI profiles. There appeared to be no change in chamber humidity from the beginning (LO:  $46.8\pm 2.7\%$ ; MID:

38.3±1.8%; HI: 39.3±1.8%) to end of the chamber stay (LO: 44.3±0.2%; MID: 42.0±0.0%; HI: 40.5±1.5%) in any of the temperature profiles.



**Figure 18.** Mean chamber temperature and humidity across each temperature profile.

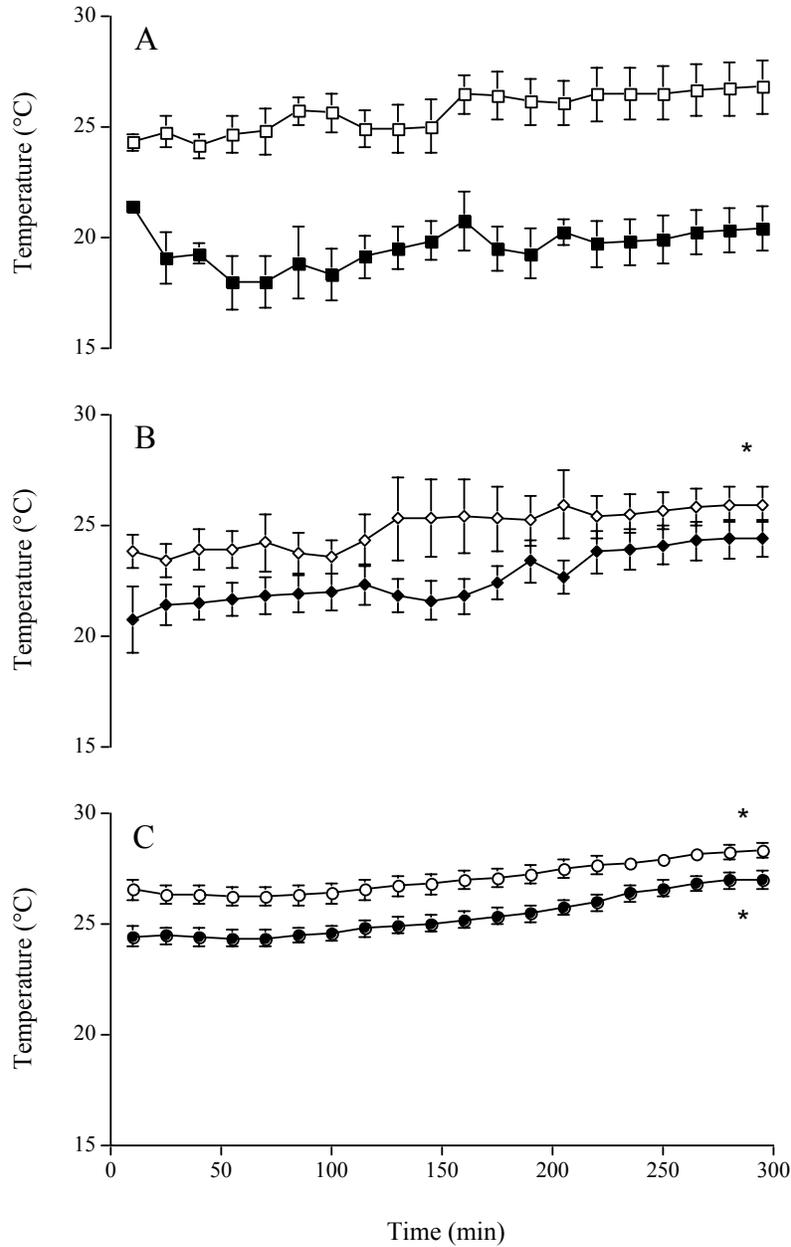
The mean flow rate selected by the subjects across the chamber stay was significantly different between temperature profiles. The flow rates during the MID ( $31.4 \pm 6.1 \text{ l} \cdot \text{h}^{-1}$ ) and HI temperature profile ( $36.7 \pm 4.3 \text{ l} \cdot \text{h}^{-1}$ ) were significantly greater than during the LO profile ( $13.4 \pm 4.2 \text{ l} \cdot \text{h}^{-1}$ ), but flow rate during the MID profile was not different than during the HI profile. Similarly, the flow rate at the conclusion of the chamber stay was significantly greater in the MID and HI temperature profiles than in the LO profile, but not different from each other. However, within each temperature profile, subjects did not significantly change the flow rate from beginning to end of the chamber stay (LO:  $25.7 \pm 2.7$  vs.  $13.7 \pm 6.3$ ; MID:  $31.0 \pm 9.1$  vs.  $35.5 \pm 3.1$ ; HI:  $35.2 \pm 5.2$  vs.  $40.1 \pm 0.7 \text{ l} \cdot \text{h}^{-1}$ ).



**Figure 19.** Mean self-selected flow rate measured at 15-minute intervals during chamber exposures at each temperature profile.

The mean inlet temperature was significantly less during the LO temperature profile ( $19.62 \pm 0.84^\circ\text{C}$ ) than during the MID ( $22.61 \pm 0.74^\circ\text{C}$ ) and the HI ( $25.35 \pm 0.36^\circ\text{C}$ ) temperature profiles; the mean inlet temperature during the MID profile also was less than during the HI. The inlet temperature was not different from the start to the end of the chamber stay during the LO temperature profile ( $20.27 \pm 0.57$  vs.  $20.44 \pm 1.00^\circ\text{C}$ ), but tended to increase during the MID profile ( $21.08 \pm 1.18$  vs.  $24.41 \pm 0.82^\circ\text{C}$ ;  $p=0.10$ ) and did significantly increase during the HI profile ( $24.44 \pm 0.39$  vs.  $26.96 \pm 0.39^\circ\text{C}$ ). At the conclusion of the chamber stay, the inlet temperature was significantly less in the LO profile than the MID and HI profiles, but the inlet temperatures at the end of the MID and HI profiles were not different than each other.

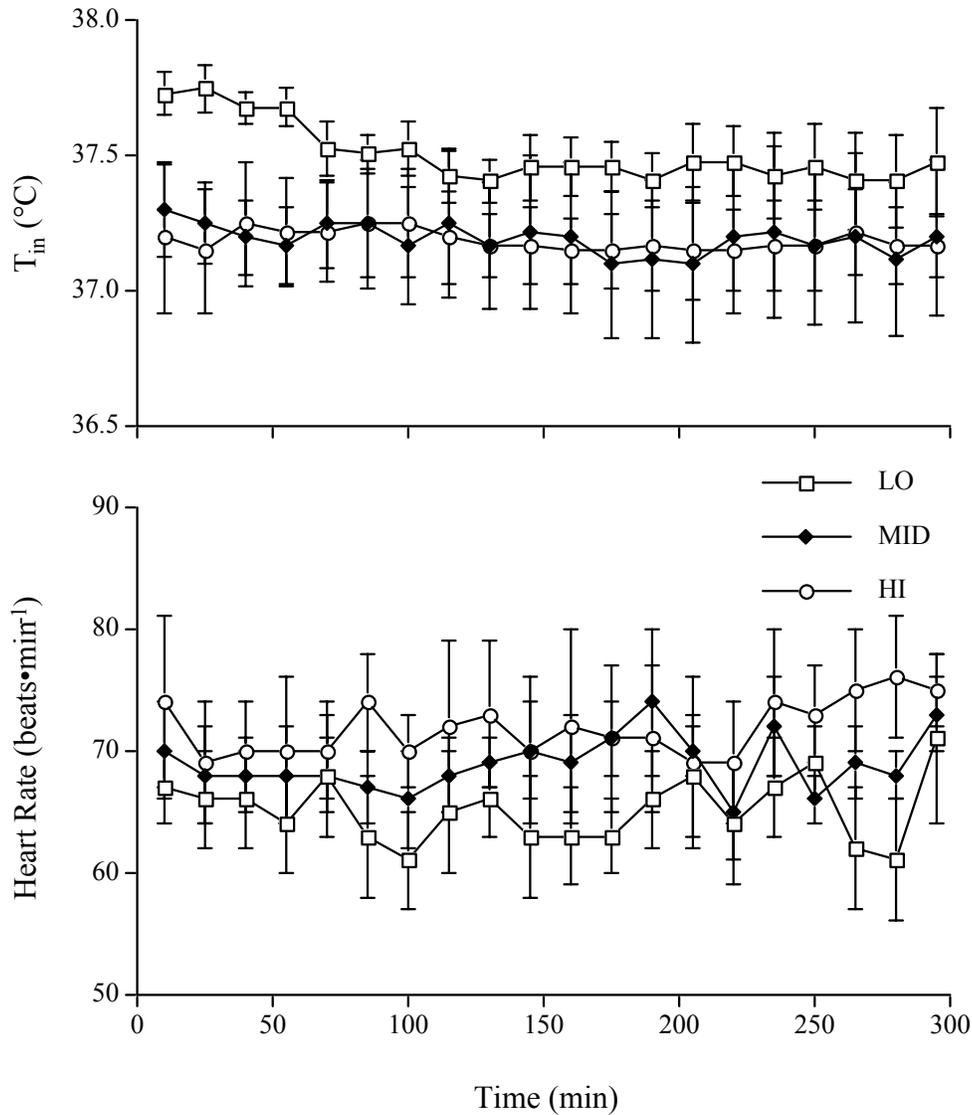
There were no significant differences in the mean outlet temperatures between the three temperature profiles (LO:  $25.72 \pm 0.85^\circ\text{C}$ ; MID:  $24.88 \pm 1.01^\circ\text{C}$ ; HI:  $27.04 \pm 0.39^\circ\text{C}$ ). Similarly, there was no difference in outlet temperatures between the temperature profiles at the conclusion of the chamber stay. Outlet temperature did not change from the beginning to the end of the chamber exposure during the LO ( $24.59 \pm 0.31^\circ\text{C}$  vs.  $26.80 \pm 1.18^\circ\text{C}$ ), but did increase during the MID ( $23.61 \pm 0.76^\circ\text{C}$  vs.  $25.93 \pm 0.80^\circ\text{C}$ ) and HI profiles ( $26.43 \pm 0.43^\circ\text{C}$  vs.  $28.26 \pm 0.34^\circ\text{C}$ ).



**Figure 20.** Mean inlet (solid symbols) and outlet (open symbols) temperatures during the LO (Panel A), MID (Panel B), and HI (Panel C) temperature profiles; \* $p < 0.05$ , significantly different from beginning of chamber stay.

The mean difference between the inlet and outlet temperatures was significantly greater during the LO profile ( $6.10 \pm 1.65^\circ\text{C}$ ) than during the MID ( $2.28 \pm 0.63^\circ\text{C}$ ) and HI ( $1.69 \pm 0.26^\circ\text{C}$ ) profiles, but there was no difference between the MID and HI profiles. Similarly, the difference between the inlet and outlet temperatures was significantly greater at the end of the chamber stay in the LO profile than the MID and HI profiles, but the end difference was not different between the MID and HI profiles. There also was no change in the difference between inlet and outlet

temperatures across time in any of the three profiles (LO:  $4.31 \pm 0.81^\circ\text{C}$  vs.  $6.36 \pm 1.97^\circ\text{C}$ ; MID:  $2.53 \pm 0.74^\circ\text{C}$  vs.  $1.52 \pm 0.20^\circ\text{C}$ ; HI:  $1.99 \pm 0.35^\circ\text{C}$  vs.  $1.29 \pm 0.12^\circ\text{C}$ ).



**Figure 21.** Mean  $T_{in}$  and HR at 15-minute intervals in four subjects across each temperature profile.

There were no significant differences in mean  $T_{in}$  between the three temperature profiles (LO:  $37.5 \pm 0.2^\circ\text{C}$ ; MID:  $37.2 \pm 0.3^\circ\text{C}$ ; HI:  $37.2 \pm 0.1^\circ\text{C}$ ).  $T_{in}$  tended to decrease ( $p=0.06$ ) during the LO temperature profile ( $37.7 \pm 0.1$  vs.  $37.4 \pm 0.2$ ), but there were no differences in intestinal temperature from the start (MID:  $37.3 \pm 0.2^\circ\text{C}$ ; HI:  $37.2 \pm 0.3^\circ\text{C}$ ) to the end of the chamber stay (MID:  $37.2 \pm 0.3^\circ\text{C}$ ; HI:  $37.2 \pm 0.1^\circ\text{C}$ ) during the other two temperature profiles.

The mean HR during the chamber stay was not significantly different between temperature profiles (LO:  $65\pm 4$ , MID:  $69\pm 3$ ,  $72\pm 5$  beats $\cdot$ min $^{-1}$ ). There also was no difference from the beginning to the end of the chamber stay within each temperature profile (LO:  $66\pm 3$  vs.  $66\pm 6$ ; MID:  $69\pm 4$  vs.  $70\pm 2$ ; HI:  $71\pm 6$  vs.  $75\pm 4$  beats $\cdot$ min $^{-1}$ ).

There was no difference between the three temperature profiles with regard to change in body weight during the chamber stay, TSL, or food and fluid consumed. There also was no difference in pre- to post-chamber body mass within any of the chamber profiles.

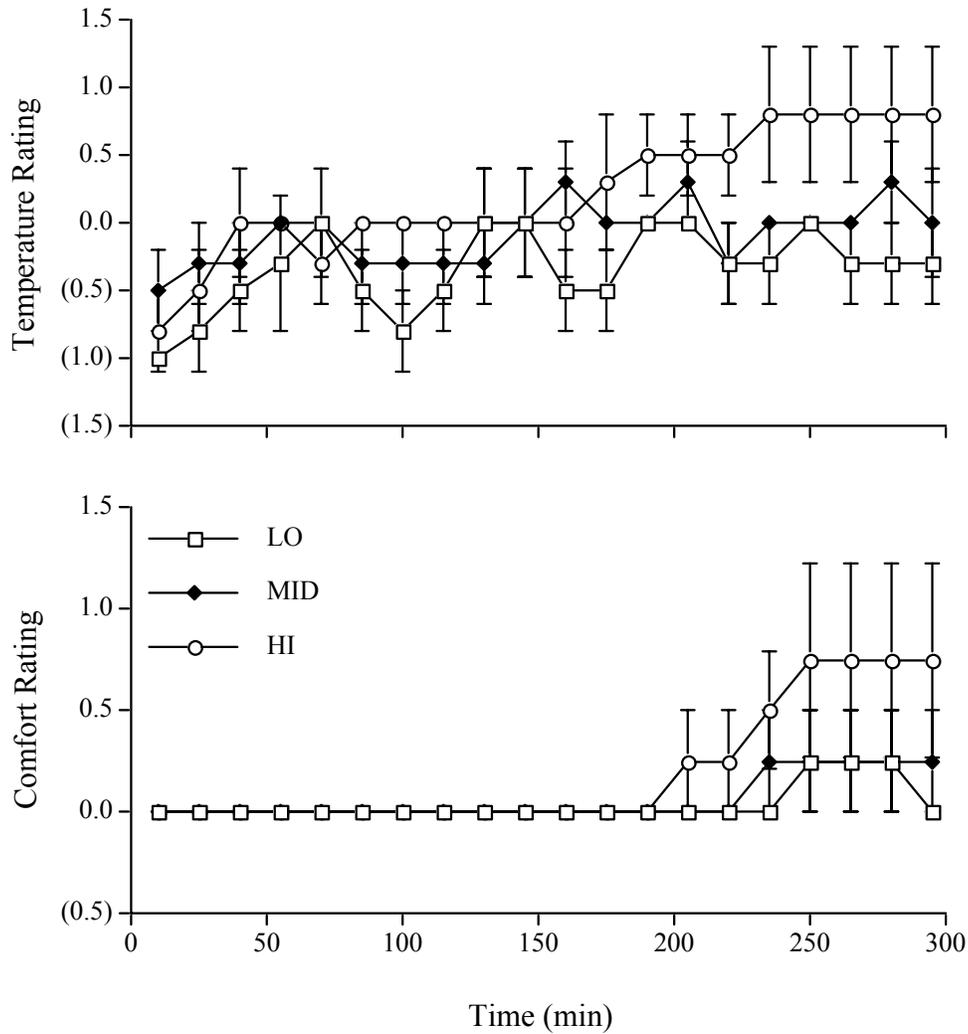
**Table 3.** Pre- and Post-Chamber Body Mass, Total Intake of Food and Fluids, and Total Sweat Loss Across the Three Temperature Profiles (n=4)

Profile	Pre BM (kg)	Post BM (kg)	Total IN (kg)	TSL (kg)
LO	$76.1\pm 6.1$	$75.8\pm 6.3$	$0.27\pm 0.16$	$0.39\pm 0.11$
MED	$76.6\pm 6.3$	$76.4\pm 6.3$	$0.06\pm 0.03$	$0.25\pm 0.02$
HI	$76.1\pm 6.1$	$75.9\pm 6.1$	$0.21\pm 0.08$	$0.30\pm 0.08$

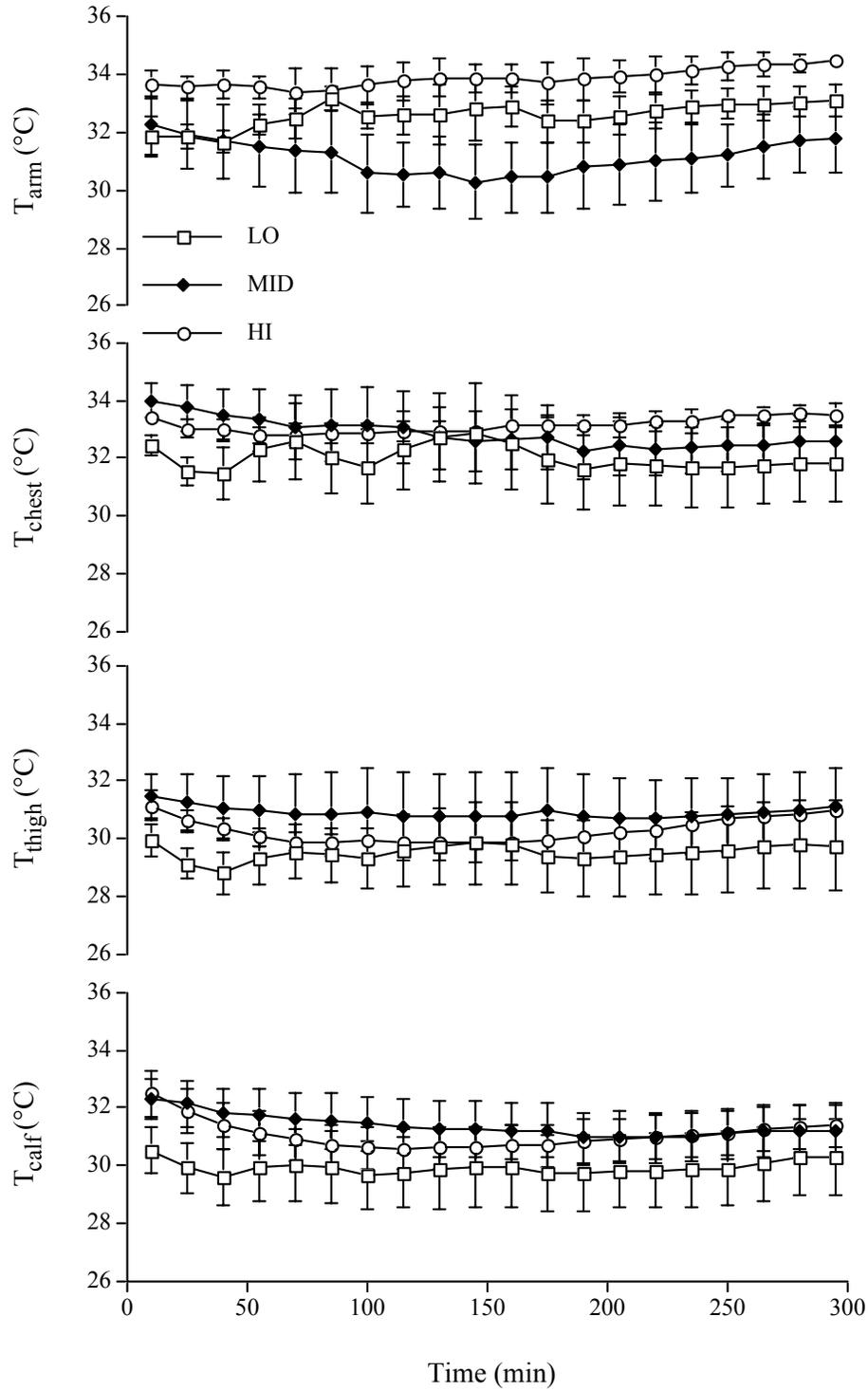
There was no difference in the mean subjective temperature rating between the temperature profiles (LO:  $-0.3\pm 0.1$ ; MID:  $-0.1\pm 0.1$ ; HI:  $0.2\pm 0.2$ ). There was no difference between the temperature ratings reported by the subjects from the start to the end of the chamber stay during the MID ( $-0.4\pm 0.2$  vs.  $0.1\pm 0.3$ ) and HI profiles ( $-0.6\pm 0.2$  vs.  $0.8\pm 0.5$ ), but the rating tended to increase during the LO profile ( $-0.9\pm 0.1$  vs.  $-0.3\pm 0.3$ ). However, there was no difference between temperature profiles in the subjective rating of temperature at the end of the chamber stay. There was no difference in mean subjective ratings of comfort between temperature profiles across the chamber stay (LO:  $0.0\pm 0.0$ ; MID:  $0.1\pm 0.1$ ; HI:  $0.2\pm 0.1$ ). There also was no difference between the comfort ratings reported by the subjects from the start to the end of the chamber stay during the LO ( $0.0\pm 0.0$  vs.  $0.1\pm 0.1$ ) and MID ( $0.0\pm 0.0$  vs.  $0.3\pm 0.3$ ), and HI profile ( $0.0\pm 0.0$  vs.  $0.8\pm 0.5$ ). There also was no difference between the subjective ratings of comfort reported at the conclusion of the chamber stays.

Mean  $T_{arm}$  across the chamber stay was not significantly different between LO and MID profiles (no statistical analysis of the HI profile was possible). Similarly, there was no significant difference in the end  $T_{arm}$  between the two temperature profiles. Also, there was no significant change in  $T_{arm}$  from the start to the conclusion of the chamber stay. There was no significant difference between the three temperature profiles in mean  $T_{chest}$  across the chamber stay nor in the  $T_{chest}$  at the end of chamber stay.  $T_{chest}$  did not significantly change from the start

to the end of chamber stay during any of the temperature profiles. Neither mean  $T_{\text{thigh}}$  nor the  $T_{\text{thigh}}$  at the conclusion of chamber stay was significantly different between temperature profiles.  $T_{\text{thigh}}$  did not significantly change from the start to the end of chamber stay during any of the temperature profiles. Mean  $T_{\text{calf}}$  across chamber stay was not different between the temperature profiles. In addition,  $T_{\text{calf}}$  at the conclusion of chamber stay was not different between temperature profiles.  $T_{\text{calf}}$  significantly decreased from the start to the end of the chamber stay during the HI profile, but did not change during the LO and MID profiles.



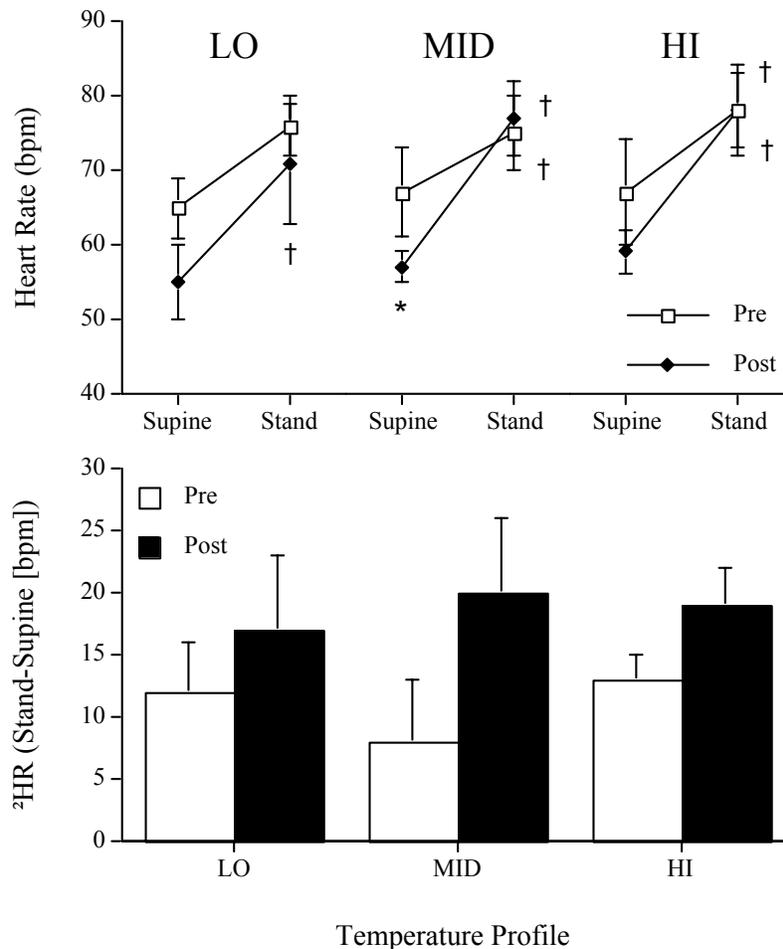
**Figure 22.** Mean subjective temperature and comfort rating measured at 15-minute intervals during chamber exposure at each temperature profile.



**Figure 23.** Mean skin temperatures at 15-minute intervals during the chamber exposure at each temperature profile.

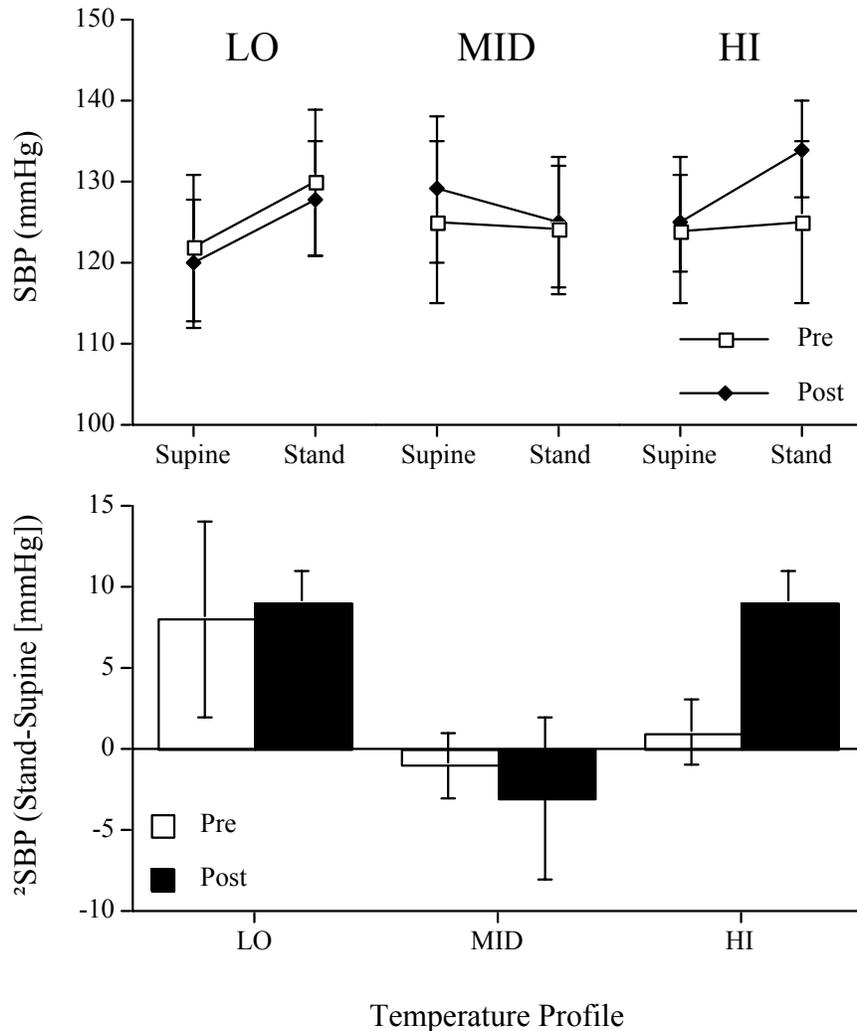
## All Temperature Profiles (n=4): Stand Test Data

During the LO profile, supine HR tended to decrease ( $p=0.10$ ) from pre- to post-chamber, but standing HR was similar after the chamber stay. Before the chamber stay, HR tended to increase ( $p=0.08$ ) from supine to standing, but did significantly increase after chamber stay during the LO profile; the HR response to standing was not different pre- to post-chamber in the LO profile. During the MID profile, supine HR was significantly less after the chamber stay, but standing HR was similar. HR significantly increased from supine to standing both pre- and post-chamber, and the HR response to standing was significantly greater after chamber stay. During the HI profile, supine HR tended to decrease ( $p=0.10$ ) from pre- to post-chamber, but standing HR was not different after the chamber stay. HR significantly increased from supine to standing both pre- and post-chamber, and the HR response to standing tended to be greater ( $p=0.08$ ) after the chamber stay.



**Figure 24.** Heart rate response to standing before and after chamber stay at each temperature profile (n=4); \*  $p<0.05$ , significantly different from pre-chamber; †  $p<0.05$ , significantly different from supine.

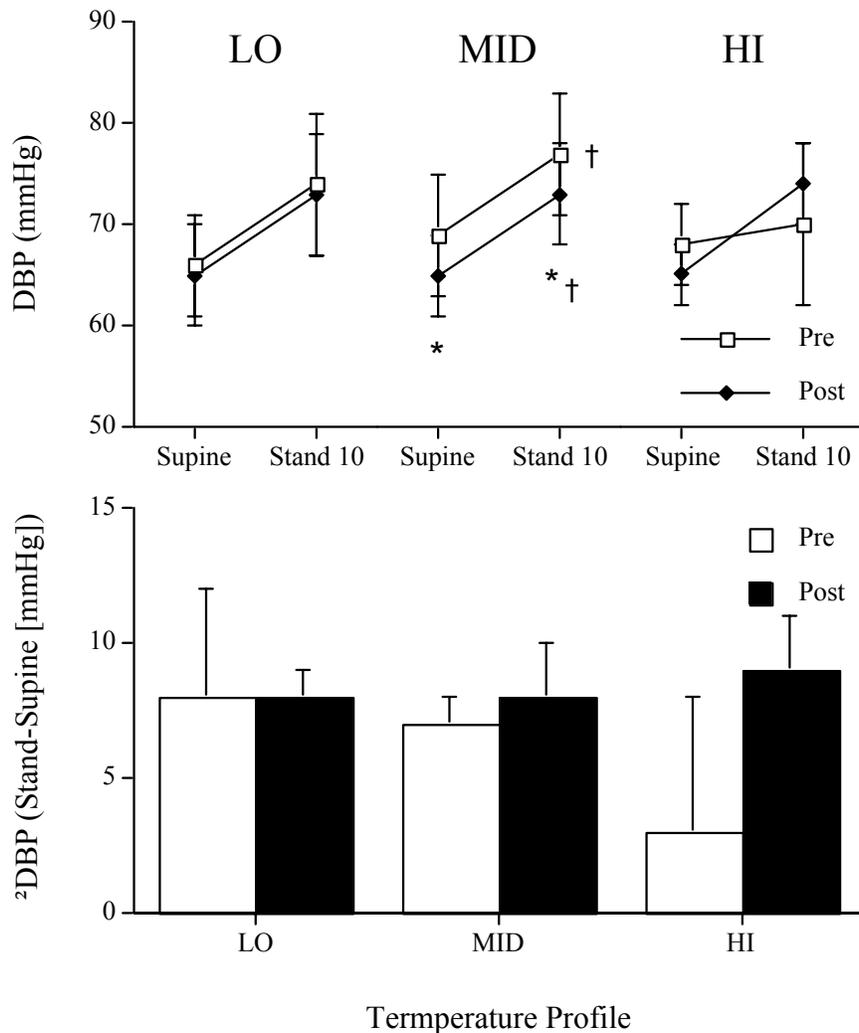
During the LO profile, supine and standing SBP were not different pre- to post-chamber, SBP did not change from supine to standing either pre- or post-chamber stay, and the response to standing was unchanged after the chamber stay. During the MID profile, there was a main effect of chamber stay on SBP, but no significant differences were observable in supine or standing SBP or the response to standing pre- to post-chamber stay. Similarly, during the HI profile, there was a main effect of posture on SBP, but no significant differences were observable in supine or standing SBP or the response to standing pre- to post-chamber stay.



**Figure 25.** Systolic blood pressure responses to standing before and after the chamber stay at each temperature profile (n=4).

Supine and standing DBP were not different from pre- to post-chamber during the LO profile. DBP tended to increase from supine to standing pre- (p=0.09) and post-chamber

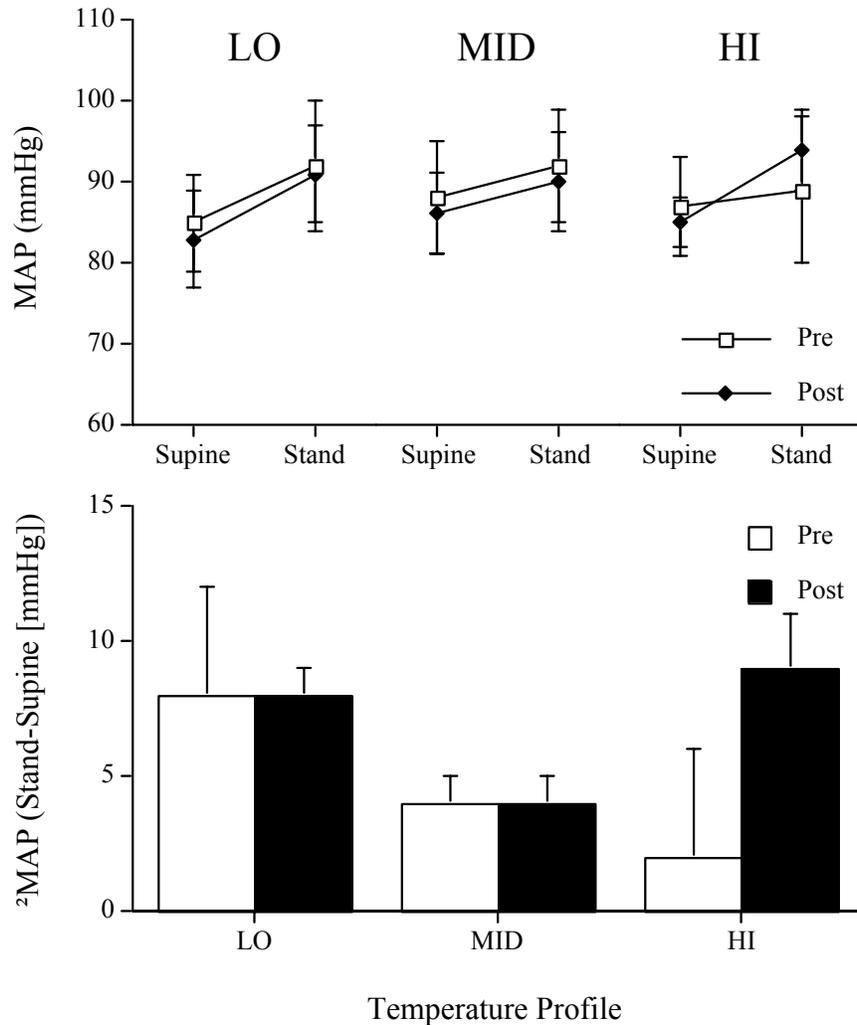
( $p=0.08$ ) during the LO profile, but there was no change in the DBP response to standing pre- to post-chamber. Supine and standing DBP were significantly less after chamber stay in the MID profile. DBP increased from supine to standing both pre- and post-chamber, but the response to standing was not affected by chamber stay. Supine and standing DBP were not different pre- to post-chamber in the HI profile, and DBP did not significantly increase with the change in posture. The DBP response to standing was not different pre- to post-chamber during the HI profile.



**Figure 26.** Diastolic blood pressure responses to standing before and after chamber stay at each temperature profile ( $n=4$ ); \* significantly different from pre-chamber; † significantly different from supine.

During the LO profile, supine and standing MAP were not different pre- to post-chamber, MAP did not change from supine to standing either pre- or post-chamber stay, and the response

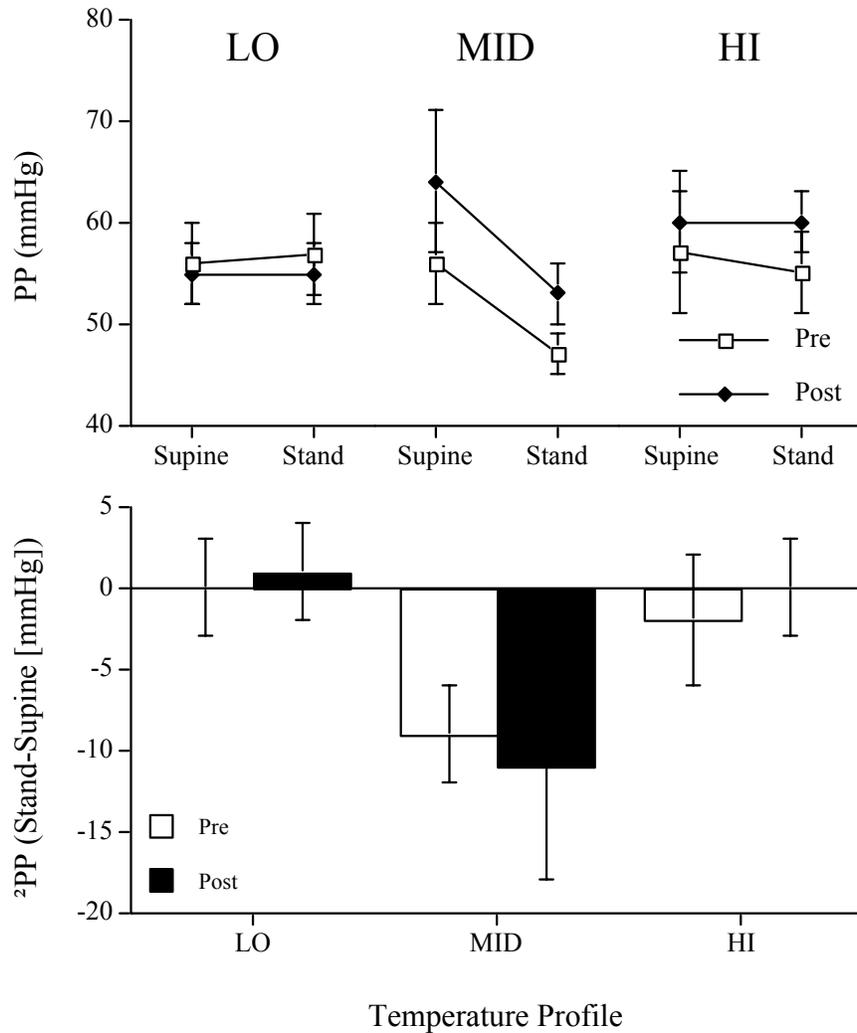
to standing was unchanged after chamber stay. During the MID profile, supine and standing MAP did not change from pre- to post-chamber stay. MAP tended to increase ( $p=0.08$ ) from supine to standing pre-chamber, but was not different from supine to standing post-chamber. Similarly, there was no change in the MAP response to standing from pre- to post-chamber. During the HI profile, supine and standing MAP were not different pre- to post-chamber, MAP did not change from supine to standing either pre- or post-chamber stay, and the response to standing was unchanged after chamber stay.



**Figure 27.** Mean arterial blood pressure responses to standing before and after chamber stay at each temperature profile (n=4).

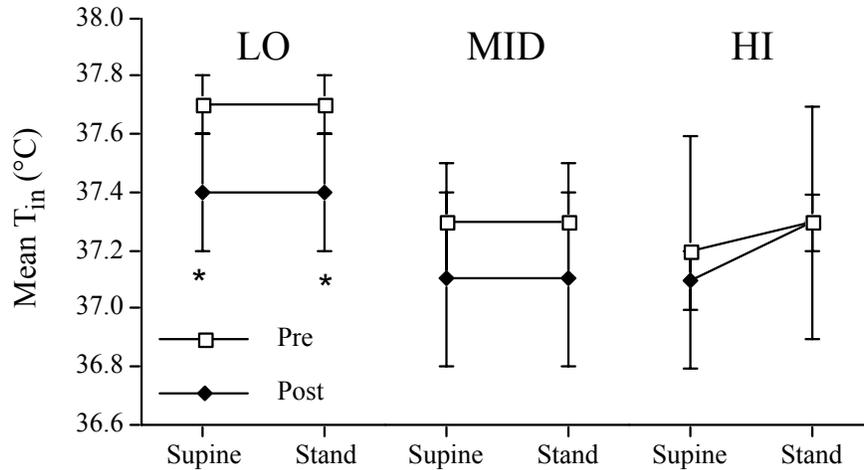
During the LO profile, supine and standing PP were not different pre- to post-chamber, PP did not change from supine to standing either pre- or post-chamber stay, and the response to standing was unchanged after chamber stay. During the MID and HI profiles, there was a main

effect of chamber stay on PP, but no significant differences were observable in supine or standing SBP or the response to standing pre- to post-chamber stay. However, during the HI profile, standing PP tended ( $p=0.08$ ) to be greater after chamber stay.



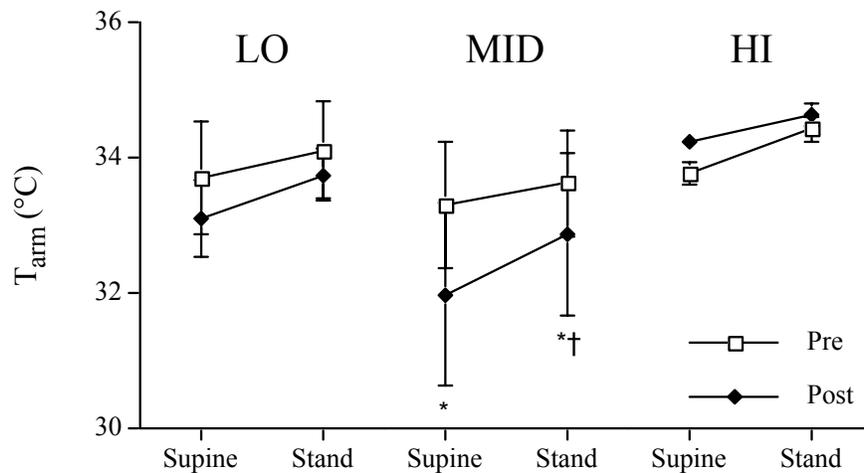
**Figure 28.** Mean pulse pressure responses to standing before and after chamber stay at each temperature profile ( $n=4$ ).

Before and after the LO chamber profile, there was no change in  $T_{in}$  from the start to the end of the stand test. However,  $T_{in}$  was significantly less, both supine and standing, after the LO temperature profile. Similarly, there tended ( $p=0.13$ ) to be a main effect of pre- to post-chamber exposure during the MID temperature profile, but no effect of stand test time on  $T_{in}$ . In contrast, there was a main effect of stand test time on  $T_{in}$  during the HI before and after the HI temperature profile, but there was no effect of chamber exposure.



**Figure 29.**  $T_{in}$  responses during the stand test performed pre- and post-chamber exposure; \* significantly different from pre-chamber.

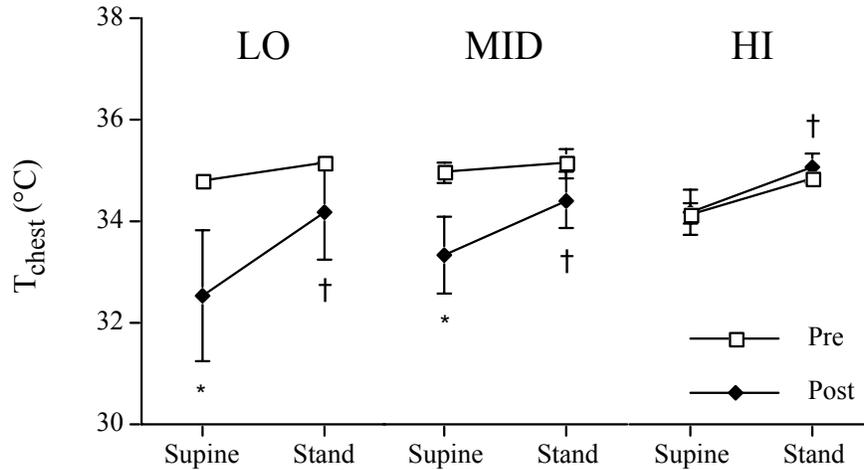
Before and after chamber stay at the LO temperature profile, there was a main effect of stand test time on  $T_{arm}$ , but there was no main effect of chamber stay. After exposure to the MID temperature chamber stay,  $T_{arm}$  was significantly less during both supine and standing and  $T_{arm}$  significantly increased from supine to standing after chamber stay. Because of missing data (n=2), no statistical analysis was possible on the  $T_{arm}$  during the HI temperature profile.



**Figure 30.**  $T_{arm}$  responses during the stand test performed pre- and post-chamber exposure. \*  $p < 0.05$ , significantly different from pre-chamber. †  $p < 0.05$ , significantly different from supine.

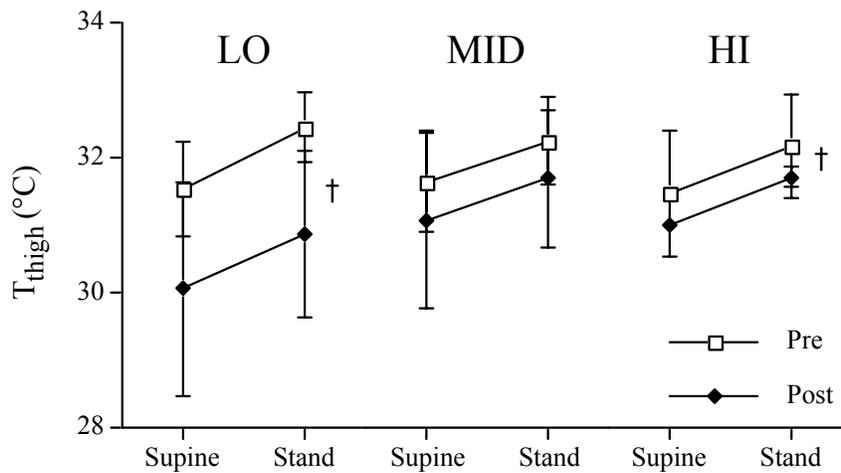
Prior to chamber stay at the LO profile,  $T_{chest}$  did not increase during the stand test. However, after chamber exposure,  $T_{chest}$  did significantly increase during the stand test. After

exposure to the LO temperature profile,  $T_{\text{chest}}$  was significantly less at rest. The same observations in  $T_{\text{chest}}$  were made in the MID as the LO profile. During the stand test,  $T_{\text{chest}}$  tended to increase ( $p=0.07$ ) prior to and increased significantly after HI temperature chamber exposure. However, there were no differences in the supine and standing  $T_{\text{chest}}$  pre- to post-chamber exposure.



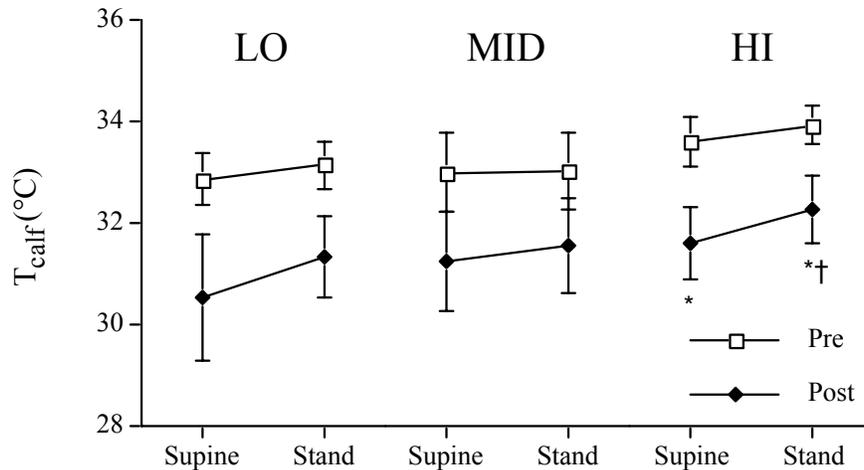
**Figure 31.**  $T_{\text{chest}}$  responses during the stand test performed pre- and post-chamber exposure; \*  $p < 0.05$ , significantly different from pre-chamber; †  $p < 0.05$ , significantly different from supine.

There was a main effect of the stand test time on  $T_{\text{thigh}}$  before and after the LO and HI chamber exposures such that the mean  $T_{\text{thigh}}$  increased during the stand test. Similarly, there tended ( $p=0.06$ ) to be a main effect of stand test time on  $T_{\text{thigh}}$  before and after the MID chamber exposure.

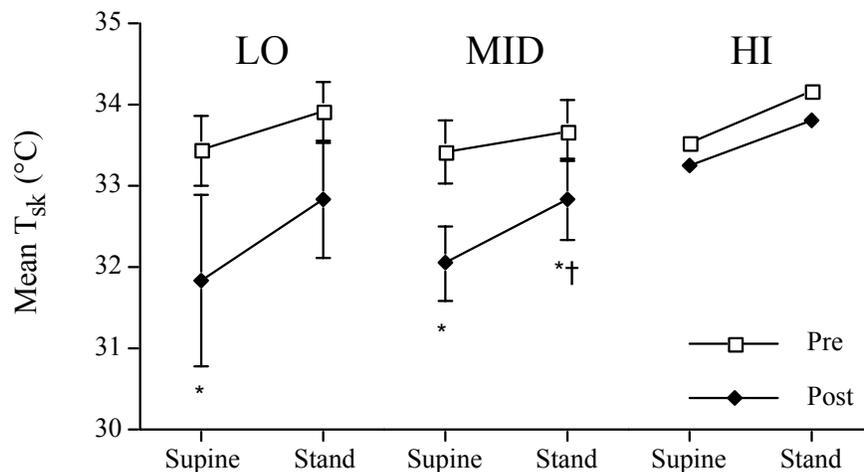


**Figure 32.**  $T_{\text{thigh}}$  responses during the stand test performed pre- and post-chamber exposure; †  $p < 0.05$ , significantly different from supine.

Before and after exposure to the LO temperature profile, there tended ( $p=0.12$ ) to be a main effect of stand test time on  $T_{\text{calf}}$ , but there was no effect of chamber exposure. Conversely, there tended to be a main effect of chamber stay on  $T_{\text{calf}}$  following the MID ( $p=0.10$ ) temperature profile, but there was no main effect of stand test on  $T_{\text{calf}}$ . Similarly,  $T_{\text{calf}}$  was significantly less after the HI temperature profile chamber stay while both supine and standing, but  $T_{\text{calf}}$  increased significantly during the stand test after chamber stay.



**Figure 33.**  $T_{\text{calf}}$  responses during the stand test performed pre- and post-chamber exposure; \*  $p<0.05$ , significantly different from pre-chamber; †  $p<0.05$ , significantly different from supine.



**Figure 34.** Mean  $T_{\text{sk}}$  responses during the stand test performed pre- and post-chamber exposure; \*  $p<0.05$ , significantly different from pre-chamber; †  $p<0.05$ , significantly different from supine.

Mean  $T_{sk}$  was significantly less after the LO chamber stay while supine and tended to be less ( $p=0.11$ ) while standing. However, there was no significant change in mean  $T_{sk}$  during the stand test pre- or post-chamber. After the MID chamber stay, mean  $T_{sk}$  was significantly less than pre-chamber during both the supine and standing postures. Also, mean  $T_{sk}$  significantly increased from supine to standing after chamber stay, but not pre-chamber. Unfortunately, due to missing data ( $n=2$ ), no statistical analyses of mean  $T_{sk}$  were possible at the HI temperature profile.

## **DISCUSSION**

There were two significant findings in this study. First, wearing the ACES with the LCG during an ambient temperature profile that was five degrees higher than the currently allowable temperature profile during Shuttle reentry and landing did not have a significantly negative effect on subject temperature, comfort, or orthostatic responses. Second, there did not appear to be a significant effect of chamber temperature across a range of profiles on thermoregulatory or orthostatic responses in this small subject population. In each of the three scenarios, the subjects were able to regulate their LCG and suit temperatures to provide adequate cooling.

Reentry is the time when crewmembers have the greatest concern about heat tolerance when wearing the ACES. Before launch, the crew cabin temperature is reduced to 68°F and the launch must occur with a cabin temperature no greater than 80°F. The crew have donned their suits with the assistance of suit technicians and remain relatively inactive in their seats for several hours before launch while receiving cooling. Further, the crew doff the ACES as soon as the crew compartment warms upon insertion into orbit. In contrast, although the cabin temperature is reduced before reentry, the crew is active and they exert a fair amount of energy to don the ACES. The commander and pilot are the first to be suited, and they are in the ACES for the greatest amount of time. The other crewmembers wear the ACES for a shorter period, but expend energy preparing the rest of the cabin for reentry as well as assisting others with donning the ACES. Cooling is provided to the crewmembers during reentry and landing but is discontinued upon egress from the Shuttle.

### **Subject Responses to the MID Profile**

During the MID profile, there was a large degree of variability among subjects with regard to the LCG flow rate used at the beginning of the chamber stay. Female subjects appeared to use little or no cooling initially, but increased the flow rate as the chamber exposure time and temperature increased. In contrast, male subjects adjusted the flow rate at higher levels, in some

subjects maximally, from the start of the chamber stay. Regardless of the flow rate used, however, mean skin, core, and body temperatures were reduced from the start to the end of chamber stay. Ratings of temperature and comfort were increased during the chamber exposure, but these changes were small. The mean temperature sensation changed from “slightly cool” to “slightly warm” by the end of the exposure. Similarly, subjects reported being “comfortable” at the beginning of the test and “slightly uncomfortable” at the conclusion.

These results are in contrast to what has been reported by Shuttle crewmembers (Smith Johnston, Crew Surgeon, Personal Communication) who previously have reported extreme heat discomfort during reentry and landing (Perez et al., 2003). Differences between our simulation and observations from actual Shuttle crewmembers may be the result of several factors. First, Shuttle crewmembers are required to close their helmet visor during reentry (Bishop et al., 1999), in contrast to the procedures employed during this test, which may cause the buildup and sensation of heat around the head. In addition, in the chamber there is no simulation for heat radiation from the avionics of the Shuttle. Further, our subjects had not been exposed to the effects of microgravity, which may significantly impair thermoregulatory responses (Crandall et al., 1994; Fortney et al., 1998; Lee et al., 2000).

As a result of the cooling from the LCG during the MID temperature profile, there were no negative effects of chamber exposure on orthostatic responses to standing. Observation of the heart rate data may even suggest a decreased stress on the subjects after chamber exposure as the supine and standing heart rates were reduced after the chamber stay compared to pre-chamber, with no significant effects on blood pressure parameters. No subject became presyncopal during either the pre- or post-chamber stand tests. Similar results were observed in a small group of subjects following Space Shuttle missions. Perez et al. (2003) reported that the heart rate was lower during reentry and during standing after wheelstop in three astronauts who wore the LCG following Shuttle flights up to 16 days than in crewmembers who did not wear the LCG.

## **Subject Responses Across Temperature Profiles**

The small subject number in this portion of the project limits one’s ability to make generalizations to the subject and/or astronaut population, but several observations were notable. First, there was a graded effect of temperature profile on self-selected flow rates during the chamber stay. As would be expected, as the chamber temperature profile increased, the subjects selected greater flow rates. At the completion during HI temperature profile, all subjects were using near maximal or maximal flow rates. This information suggests that the cooling capacity

of the suit may have been reached during the highest temperature profile. Supporting this notion, as the temperature profile increased, the inlet temperature increased and the difference between the inlet and outlet temperatures decreased. The ability of the ICU to remove heat from the cooling line was reduced as the temperature increased such that the return (inlet) temperature increased, limiting the ability of the cooling to remove heat from the subject.

There was no discernible pattern observed with regard to core or skin temperatures in these subjects across the temperature profiles. The subjects were able to maintain their body temperatures with the self-selected flow rates during these tests. However, there was an effect of temperature profile, although not statistically significant, on ratings of temperature and comfort. Ratings during the LO and MID profiles were similar, but these ratings were higher during the HI chamber runs than during the LO and MID profiles. These subjective responses would agree with the observations regarding LCG flow rates and the narrowing of inlet-outlet temperatures.

There was no effect of the temperature profiles on orthostatic responses to the stand test pre- to post-chamber stay. All subjects completed the stand test pre- and post-chamber without signs or symptoms of presyncope before and after chamber exposure, and there was no discernible pattern with regard to heart rate and blood pressure responses. This occurred despite an apparent trend for higher or more rapidly increasing skin temperatures during the stand test following the MED and HI temperature profiles, even though core temperatures did not increase appreciably. Thus, in subjects who had not been deconditioned by spaceflight, orthostatic responses were not impaired after 5 hours of exposure to elevated ambient temperatures.

## **Effect of Cabin Temperature Profile on Orthostatic Tolerance and Emergency Egress**

Protection against increased core temperature while wearing the ACES may be important to prevent heat-induced orthostatic intolerance. Orthostatic tolerance has been shown to be reduced in subjects exposed to heat stress (Lind et al., 1968; Shvartz, 1975). After an increase in core temperature of 0.6-1.0°C, Wilson et al. (2002) observed that four of nine subjects could not complete the same 10-minute 60-degree head-up tilt test that they were able to complete before whole-body heating. Elevated core temperature, as has been observed after bed rest and spaceflight, might be expected to exacerbate the increased incidence of orthostatic intolerance after spaceflight (Buckey et al., 1996; Fritsch-Yelle et al., 1996; Meck et al., 2001). Wilson et al. (2002) observed that even short-duration whole-body cooling (15°C) significantly improved orthostatic responses during tilting when heat stressed. When cooled during the tilt, all subjects completed the

tilt test, had an increased MAP, decreased HR response, and a protection against decreased cerebral blood flow velocity. Although the magnitude of cooling provided by the LCG in our study was less (higher temperature water and closer to skin temperatures), the cooling duration was greater and maintained normothermic core temperatures. However, it is unclear what effect rapid skin warming would have upon orthostatic tolerance after cooling is discontinued.

The results of this study do not consider the effects of cabin temperature on the crewmembers' ability to egress from the Shuttle under their own volition, especially in the event of an emergency. In this project, subjects were tested at rest, with mild exercise, and received cooling except during the pre- and post-chamber stand tests. Before the stand tests, the subjects were minimally active and the time without cooling was short. However, we observed that skin temperatures rapidly increased during the stand test and would be expected to increase at a greater rate in the event of emergency egress (Bishop et al., 1999). The commander and pilot may experience greater thermal stress than the other crewmembers during egress since their seats are the furthest from the Shuttle side hatch, are the most difficult from which to egress, and would require the greatest physical effort.

McClellan et al. (1999) reported that subjects are able to exercise longer with lower heart rate, core temperature, and skin blood flow when wearing a cooling garment with protective clothing, but these tests were conducted with subjects receiving cooling throughout the exercise. In an emergency egress scenario, the crewmembers would be disconnected from cooling as they left their seats to exit the Shuttle. In studies of pre-cooling prior to but no cooling during long-duration exercise, subjects have been able to exercise longer with lower core, skin, and mean body temperatures (Booth, 1997; Wilson, 2002b). However, these tests were not conducted during uncompensable heat stress conditions, such as wearing a protective garment, when body heat storage rates would be higher, and the exercise durations were longer (25-60 minutes) than the time required to complete an emergency egress (4-5 minutes; Bishop et al., 1999). In short-duration, high-intensity efforts, pre-cooling does not appear to have a significant effect (Marino et al., 2002) and even may impair performance if the working muscles are selectively cooled (Sleivert, 2001).

## **Limitations**

The primary limitation of this project was that the subjects were not microgravity deconditioned nor, we assumed, hypovolemic. Previous data from our laboratory (Fortney et al., 1998; Lee et al., 2002) and others (Crandall et al., 1994) have suggested that real and simulated

microgravity exposure may negatively effect the crewmember's ability to thermoregulate; skin blood flow was reduced for any given core temperature after real and simulated microgravity exposure such that the ability to dissipate heat was reduced. Specifically, the ability of the crewmember to exchange heat across the skin to the LCG may be reduced after spaceflight due to reduced skin vasodilation such that the effectiveness of the LCG might be limited. Skin vasoconstriction has been shown to decrease convective heat transfer from the core to the periphery (Veicsteinas et al., 1982).

It is assumed from previous bed rest and spaceflight data that crewmembers would be hypovolemic and not heat acclimated relative to pre-flight. In mathematical modeling (Pandolf et al., 1995) of crewmembers in air-ventilated suits, there was an estimated 1°C difference in core temperature at the end of a reentry simulation between the acclimated, euhydrated subjects (38°C) and the unacclimated, dehydrated subjects (39.1°C). Further, the cooling required to maintain core temperatures in the unacclimated, dehydrated subjects was expected to be almost three times greater than the acclimated, euhydrated individuals (Pandolf et al., 1995). In addition, the estimated capacity to complete an emergency egress would be reduced to 30% of that of an acclimated, euhydrated individual.

## **Conclusions**

The ICU and LCG appeared to provide adequate cooling when euhydrated, ambulatory subjects were exposed to temperature profiles in which the final ambient temperature was 23.9°C-29.4°C (75°F-85°F). Core temperature did not increase and orthostatic tolerance was maintained in these subjects following 5 hours in the ACES under these conditions. However, these results may not be directly applicable to crewmembers following spaceflight. Further studies are warranted in microgravity-exposed subjects, especially long-duration crewmembers, and during simulations of emergency egress.

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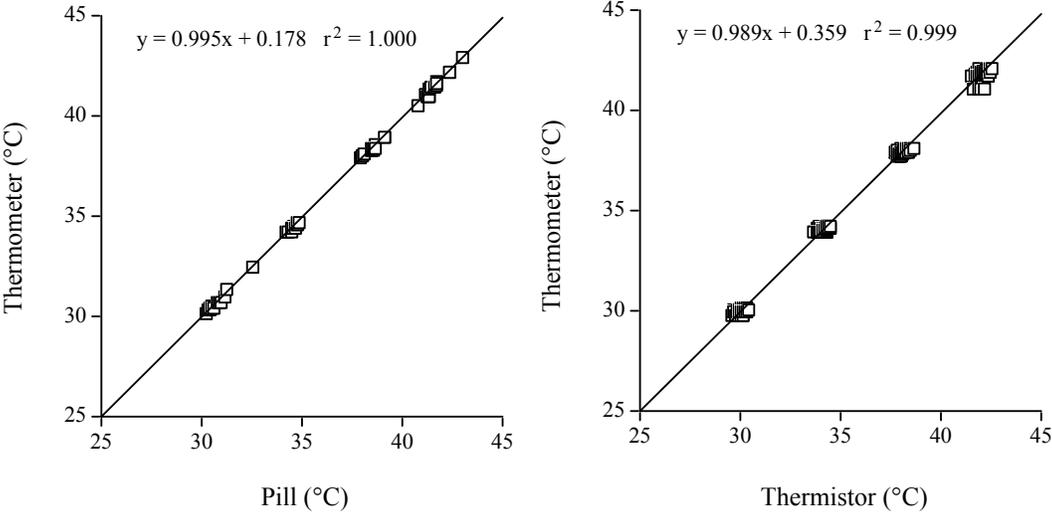
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## APPENDIX A: SUBJECT CHARACTERISTICS

Subject ID	Gender	Age	Height (in.)	Weight (lb)
1	F	33	66	150
2	F	31	64	120
3	F	29	65	155
4	F	45	67	138
5	M	41	72	204
6	M	32	70	170
7	M	28	68	162
8	M	30	66	145
Mean		33.6	67.3	155.5

# APPENDIX B: CALIBRATION DATA



Composite graphs of the calibration of the core temperature pills and thermistors.

## APPENDIX C: STAND TEST DATA

Stand Test Data-MID Temperature Profile only

	Supine	Stand	Change	Supine	Stand	Change
HR	71±4	84±5*	13±3	61±3†	78±4*	17±3
SBP	117±6	122±5	4±3	120±6	124±4	3±4
DBP	68±3	72±4	5±3	64±2	71±3*	7±1
MAP	84±4	89±4	8±2	83±3	89±3	6±1
PP	50±3	49±3	-1±4	56±5	52±2	-3±4

\*Significantly different than supine †Significantly different than pre-chamber

Stand Test Data-All Temperature Profiles

### Heart Rate

Group	Pre-Chamber			Post-Chamber		
	Supine	Stand	Change	Supine	Stand	Change
LO	65±4	76±4*	12±4	55±5†	71±8*	17±6
MID	67±6	75±5	8±5	57±2†	77±5*	20±6†
HI	65±7	78±6*	13±2	59±3	78±5*	19±3

\*Significantly different than supine †Significantly different than pre-chamber

### Systolic Blood Pressure

Group	Pre-Chamber			Post-Chamber		
	Supine	Stand	Change	Supine	Stand	Change
LO	122±9	130±9	8±9	120±8	128±7	9±2
MID	125±10	124±8	-1±2	129±9	125±8	-3±5
HI	124±9	125±10	1±2	125±6	134±6	9±2

\*Significantly different than supine †Significantly different than pre-chamber

### Diastolic Blood Pressure

Group	Pre-Chamber			Post-Chamber		
	Supine	Stand	Change	Supine	Stand	Change
LO	66±5	74±7	8±4	65±5	73±6	8±1
MID	69±6	77±6	7±1	65±4	73±5	8±2
HI	68±4	70±8	3±5	65±3	74±4	9±2

\*Significantly different than supine †Significantly different than pre-chamber

Mean Arterial Blood Pressure

Group	Pre-Chamber			Post-Chamber		
	Supine	Stand	Change	Supine	Stand	Change
LO	85±6	92±8	8±4	83±6	91±6	8±1
MID	88±7	92±7	4±1	86±5	90±6	4±1
HI	87±6	89±6	2±4	85±3	94±5	9±2

\*Significantly different than supine †Significantly different than pre-chamber

Pulse Pressure

Group	Pre-Chamber			Post-Chamber		
	Supine	Stand	Change	Supine	Stand	Change
LO	56±4	57±4	0±3	55±3	55±3	1±3
MID	56±4	47±2	-9±3	64±7	53±3*	-11±7
HI	57±6	55±4	-2±4	60±5	60±3	0±3

\*Significantly different than supine †Significantly different than pre-chamber



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13. ABSTRACT (Maximum 200 words) Current flight rules restrict the maximum cabin temperature during reentry and landing to protect crewmembers from heat stress. Cabin temperature is affected by the amount of hardware in operation during these activities. To allow for additional operations, the maximum cabin temperature limit must be raised. Crewmembers wear a liquid-cooling garment (LCG) under their suit during reentry to protect against heat stress. The purpose of our project was to determine whether the LCG could adequately cool when cabin temperature was allowed to reach 80°F. Eight suited subjects underwent a simulated cabin temperature profile in an environmental chamber. Subjects completed a 10-minute stand test as an assessment of orthostatic tolerance before and after the chamber stay. Mean skin, core, and body temperatures were reduced from the start to the end of the stay. Temperature and comfort ratings increased during the exposure. All subjects completed the test without signs of orthostatic intolerance and were able to control their body temperatures with self-selected flow rates to avoid the deleterious effects of wearing the suit. The secondary objective was to determine whether there was a graded effect of cabin temperatures when the maximums were 75, 80, and 85°F. Four suited subjects underwent the simulated temperature profile at these temperatures. Ratings were measured in 15-minute intervals throughout chamber stay on a 10-minute stand test. No discernible pattern was observed in core or skin temperatures across the temperature profiles. There appeared to be higher subjective ratings of comfort and heat across the temperature profiles. However, the subjects were able to control sufficiently their body temperatures with the self-selected flow rates during these tests.				
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