Role of skin blood flow and sweating rate in exercise thermoregulation after bed rest

STUART M. C. LEE,1 W. JON WILLIAMS,1 AND SUZANNE M. SCHNEIDER2
1Wyle Laboratories, Life Sciences Systems and Services Division, and 2National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas 77058

Received 20 February 2001; accepted in final form 23 January 2002

Lee, Stuart M. C., W. Jon Williams, and Suzanne M. Schneider. Role of skin blood flow and sweating rate in exercise thermoregulation after bed rest. J Appl Physiol 92: 2026–2034, 2002; 10.1152/japplphysiol.00105.2001.—Two potential mechanisms, reduced skin blood flow (SBF) and sweating rate (SR), may be responsible for elevated intestinal temperature (Tin) during exercise after bed rest and space-flight. Seven men underwent 13 days of 6° head-down bed rest. Pre- and post-bed rest, subjects completed supine submaximal cycle ergometry (20 min at 40% and 20 min at 65% of pre-bed rest supine peak exercise capacity) in a thermoneutral room. After bed rest, Tin was elevated at rest (+0.31 ± 0.12°C) and at the end of exercise (+0.33 ± 0.07°C). Percent increase in SBF during exercise was less after bed rest (211 ± 53 vs. 96 ± 31%; P < 0.05), SBF/Tin threshold was greater (37.09 ± 0.16 vs. 37.33 ± 0.13°C; P < 0.05), and slope of SBF/Tin tended to be reduced (536 ± 184 vs. 201 ± 46%/°C; P = 0.08). SR/Tin threshold was delayed (37.06 ± 0.11 vs. 37.34 ± 0.06°C; P < 0.05), but the slope of SR/Tin (3.45 ± 1.22 vs. 2.58 ± 0.71 mg·min⁻¹·cm⁻²·°C⁻¹) and total sweat loss (0.42 ± 0.06 vs. 0.44 ± 0.08 kg) were not changed. The higher resting and exercise Tin and delayed onset of SBF and SR suggest a centrally mediated elevation in the thermoregulatory set point during bed rest exposure.

core temperature; intestinal temperature; microgravity; spaceflight

ADAPTATION TO BED REST AND SPACEFLIGHT includes decreased postflight aerobic capacity, lower muscular strength and endurance, alterations in cardiovascular function, and reduced plasma volume (PV) (6). The ability to perform work during spaceflight, complete an unaided emergency egress on landing, and participate in rehabilitation activities after spaceflight are issues of concern that may be compromised by these adaptations. Physical work capacity may be further reduced by impaired body temperature regulation during rest and exercise, which in turn may lead to heat strain and injury. For example, the combined effects of PV loss and loss of heat acclimation may result in excessive heat strain for Space Shuttle crewmembers wearing protective garments during launch and landing (35). During a nominal landing (STS-90, April 1998), before exit from the Space Shuttle, intestinal temperature (Tin), a measure of core temperature (Tcore), was significantly elevated in four crewmembers wearing the launch and entry suit despite the use of a liquid cooling garment (37). In the event of an emergency egress from the Shuttle, crewmembers would be disconnected from the thermoelectric cooling unit supplying the liquid cooling garment to exit the vehicle and be required to ambulate to a safe distance. This activity would be completed fully suited and may require an effort in excess of 70% of the crewmember’s preflight peak oxygen consumption (V0₂peak; Ref. 4). The combined thermal load of the protective garment and the elevated metabolic rate during egress would be expected to rapidly increase Tcore.

We previously examined the thermoregulatory responses of two crewmembers after a 115-day spaceflight (11). Tin was elevated moderately at rest and during exercise in these two crewmembers. Each crewmember had a delayed onset of and/or a decreased slope of sweating rate (SR) response and skin vasodilation. These changes in thermoregulation were observed although crewmembers participated in an in-flight exercise countermeasures program, and data were collected 5 days after landing.

Previous investigators have found an impairment in thermoregulation after bed rest, an analog of spaceflight. A higher Tcore after bed rest has been observed during submaximal exercise in both warm (9) and temperate (8, 17) conditions. Elevation in Tcore was ascribed to a decreased ability to increase skin blood flow (SBF) (15) but also may be related to impaired sweating responses (17). Crandall et al. (7) passively heated subjects with a warm water-perfused suit before and after 15 days of bed rest. After bed rest, these subjects had reduced forearm blood flow and vascular conductance both before and during whole body heating.

The purpose of this study was to determine whether heat loss responses were responsible for the impairment of thermoregulation during submaximal exercise after 13 days of bed rest, a duration similar to current Space Shuttle missions. No previous study has measured SBF and SR continuously during exercise to...
determine their relative contributions to elevated Tcore after bed rest. We hypothesized that after bed rest T_in during exercise would be elevated significantly due to an increase in the T_in threshold and a decrease in the slope of the SBFT_in response and an increase in the T_in threshold and a reduced slope of the SR/T_in response.

METHODS

Subjects. Seven healthy men (29 ± 5 yr, 179.6 ± 7.1 cm, 77.2 ± 17.0 kg; mean ± SD) volunteered to participate in this investigation. All subjects completed a modified US Air Force class III physical and were screened for cardiovascular disease by using a Bruce protocol maximal treadmill test with 12-lead electrocardiogram. Subjects with significant ST-segment changes or ectopy were excluded as well as those with a history of hypertension or habitual tobacco, alcohol, and/or drug use. All subjects were given written and verbal explanation of testing and bed rest protocols and signed documentation indicating understanding and consent. All protocols were reviewed and approved by the National Aeronautics and Space Administration (NASA) Johnson Space Center and the University of Texas Medical Branch-Galveston Institutional Review Boards. Bed rest was conducted under medically supervised conditions at the National Institutes of Health General Clinical Research Center at the University of Texas Medical Branch in Galveston, TX. Some aspects of this study have been previously reported (2, 3).

Overall protocol. To examine the effect of bed rest on exercise thermoregulation, we employed a repeated measures design in which subjects served as their own controls. We compared pre-bed rest responses to responses measured after 13 days of 6° head-down bed rest.

Before bed rest, subjects completed three testing sessions in the exercise physiology laboratory at the NASA Johnson Space Center. The first session was a test of supine VO2_peak with the use of a cycle ergometer (Monark 818E) mounted on a specially constructed frame. Subjects returned to the laboratory on two separate days to complete a supine submaximal exercise test that consisted of a continuous protocol of 25 min of supine rest, 20 min of cycling at 40% VO2_peak, and 20 min at 65% VO2_peak. Tests were separated by no less than 48 h. Tarm, skin temperatures (Tsk), SBF, SR, and oxygen consumption (VO2) were measured during these tests. These exercise protocols and measurement techniques were used previously in our laboratory (11, 27).

Subjects were hospitalized for a total of 16 days: 1 day of ambulatory control, 14 days of 6° head-down bed rest, and 1 day of ambulatory recovery. On the morning of the first day of hospitalization, PV and red cell mass were measured. Thereafter, subjects remained active and upright and participated in muscle strength tests that were part of the companion study (2, 3). After breakfast on the following morning, subjects were placed in 6° head-down tilt. Subjects remained in the head-down position, including during meals and urination, but were allowed to defecate with the use of a bedside commode. In addition, subjects were placed in a horizontal position for 30 min/day as a control for the companion study in which another group of subjects performed resistance exercise in the horizontal posture. No subjects in our study performed any exercise during bed rest except for the supine submaximal exercise test that was part of this protocol on the 13th day of bed rest. On bed rest day 14, PV and red cell mass were measured at the same time of day as pre-bed rest.

Supine VO2_peak test. Subjects reported to the laboratory within 3 wk before the start of bed rest to complete a VO2_peak test on a supine cycle ergometer. The VO2_peak test consisted of cycling at a constant cadence of 60 rpm for one 2-min stage at 50 W followed by three 5-min stages of 100, 125, and 150 W. Thereafter, exercise intensity was increased each minute in 25-W increments until volitional fatigue. VO2 was measured with a metabolic cart (Qpex I, Quinton Instruments, Seattle, WA) interfaced with a mass spectrometer (MGA-1100, Marquette Electronics, St. Louis, MO) and averaged over 30-s intervals. The highest 1-min average was considered a measure of VO2_peak. Exercise intensities for the subsequent submaximal exercise test were estimated (40 and 65% pre-bed rest VO2_peak) from a simple linear regression of VO2 and exercise intensity from the VO2_peak test.

Submaximal exercise test. All subjects completed a submaximal exercise test for determination of thermoregulatory responses to exercise twice pre-bed rest and on day 13 of bed rest. Subjects refrained from exercise for 24 h, alcohol ingestion for 24 h, caffeine ingestion for 12 h, and food consumption for 4 h.

Each day of testing, subjects reported to the laboratory at the same time of day and were instrumented for measurement of thermoregulatory responses to supine exercise. Subjects rested for 20 min in the supine position on the cycle ergometer frame. Thereafter, data was collected during 5 min of supine rest and then during supine exercise for 20 min at 40% and 20 min at 65% pre-bed rest VO2_peak. The same absolute exercise intensities (49 ± 7 and 88 ± 11 W) were performed during pre- and post-bed rest testing, respectively. T_in was measured at 1-min intervals with an ingestible Tcore pill (CorTemp ingestible temperature sensor, Human Technologies, St. Petersburg, FL) swallowed ~6 h before the test with a small amount of fluid. The temperature signal from the pill was transmitted to and stored on an external data logger (CorTemp Ambulatory Recorder, Human Technologies). We (27) and others (23) have found that this measure of Tcore is similar to esophageal temperature (Tes) during moderate levels of exercise, including the specific exercise protocol used in this investigation. Tsk was measured on the upper arm (Tskarm), upper chest (Tskchest), thigh (Tskhigh), and calf (Tskcal) also at 1-min intervals with the use of a separate data logger (Squirrel 1250, Science Electronics, Dayton, OH). Mean Tsk (Tskav) was calculated as (0.3Tskarm) + (0.3Tskchest) + (0.2Tskhigh) + (0.2Tskcal), as described by Ramanathan (36). Mean body temperature (Tbody) was calculated as (0.65Tskav) + (0.35Tskav). Body heat content was calculated at the beginning and end of the exercise protocol by using the equation body heat content = 0.83 kcal·kg⁻¹·C⁻¹·BW·Tbody, where 0.83 is the specific heat of body tissues and BW is body weight in kilograms, as described by Horstman and Horvath (19). Body heat storage during exercise was calculated as the difference between body heat content at the end of preexercise rest and body heat content at the end of the 65% VO2_peak exercise stage.

SBF was measured continuously on the forearm by using an integrating laser Doppler probe and measurement system (Pertiflux PFS4001, Perimed, Stockholm, Sweden). Local Tsk at the site of SBF measurement was held constant at 38°C by using a heated probe holder collar (PeriTemp 4005, Perimed). Local heating was performed to control the effect of local Tsk on SBF. Analysis of SBF responses were made by using the manufacturer-provided software (Perisoft, Perimed).

SR was measured by using a multichannel dew point hygrometer system (Bitronics, Guilford, CN) interfaced with a computer for calculations of SR at 1-min intervals. The dew point sensor was ventilated (500–800 ml/min) with ambient air. SR was measured with an accuracy of ±0.05 mg·cm⁻²·min⁻¹. Total body sweat loss was calculated from dry body weight measured immediately before and after exercise on a standard calibrated scale (Detecto Scale, Rosa-
lymphocytes (LN). VO2 was measured in 30-s intervals by using a metabolic gas analyzer system (MedGraphics, St. Paul, MN) specifically designed for use on the Space Shuttle and Russian Mir Space Station. Heart rate (HR) was measured with the use of a commercially available heart watch (Vantage XL, Polar Electro, Oy, Finland) previously validated in our laboratory (30).

All measurement devices were calibrated before each testing session. Ingestible pills and Tsk thermistors were calibrated at four different temperatures against a certified mercury thermometer in a water bath at temperatures ranging from 30 to 42°C. A linear regression of the relationship between the measured temperatures and those from the certified thermometer was used posttest to adjust pill and thermistor measurements. The laser Doppler probe was calibrated by using the manufacturer-provided motility standard and zero cell. SBF values were expressed as percent change from rest (%SBF) because absolute values within an individual can vary markedly over the surface of the forearm (21). The gas analysis system was calibrated with standard gas concentrations (21% O2, balance N2, 10% O2, 10% CO2, balance N2), and the pneumotach was calibrated by using a 3-liter syringe. The cycle ergometer was calibrated to ±10 W.

PV and red cell mass. PV and red cell mass were measured during the morning of the first day of hospitalization (ambulatory control) and at the same time on the last day of bed rest (day 14) by using the 125I-labeled human serum albumin dilution method and a red blood cell labeling technique with 51Cr (14). Subjects remained supine for at least 30 min before and throughout PV and red cell mass measurements. Blood volume was calculated as the sum of PV and red cell mass. Peripheral hematocrit was measured by using the microhematocrit method. Whole body hematocrit was calculated from the ratio of red cell mass to calculated blood volume. F-cell ratio was calculated as the ratio of whole body hematocrit to venous hematocrit corrected for trapped plasma (0.96).

Data analysis. The first submaximal exercise test was considered a familiarization session. Data from the second pre-bed rest submaximal exercise test were compared with the data collected during the post-bed rest test. Measurements of Tin, %SBF, SR, VO2, HR, Tsk, Tarm, Tchest, Thigh, and Tcalf at specific time points in the testing protocol were expressed as the means of 2 min of data collected at the end of rest and ending at minutes 5, 10, 15, and 20 of the 40% VO2peak stage, and at minutes 5, 10, 15, and 20 of the 65% VO2peak stage. Pre- to post-bed rest comparisons of these variables were made by using a two-way ANOVA in which bed rest and exercise time were repeated factors. Tukey’s honest significant difference test was used to determine when specific differences occurred. Pre- to post-bed rest changes in the variables of body weight, body heat storage, total sweat loss, PV, hematocrit, and red cell mass were compared by using paired t-tests.

Tin was plotted against %SBF and SR for each subject pre- and post-bed rest. A linear regression describing the linear portion of the slope of each response was determined. Tin thresholds for initiation of sweating and cutaneous vasodilation were calculated from the regression equation at a local SR of 0.05 mg cm−2 min−1 (24) and a %SBF relative to preexercise baseline. Pre- to post-bed rest thresholds for the onset of sweating and vasodilation and the slope of these responses were compared by using paired t-tests.

Data are reported as means ± SE, unless otherwise stated. Statistical significance was determined a priori as P ≤ 0.05.

RESULTS

Mean pre-bed rest supine VO2peak of the subjects was 2.52 ± 0.54 l/min (31.6 ± 2.6 ml·kg−1·min−1). Subjects attained a peak maximal HR of 174 ± 15 beats/min [91 ± 7% of age-predicted maximal HR (220 – age)] and a peak respiratory exchange ratio of 1.19 ± 0.11. Peak exercise intensity was 146 ± 37 W.

All subjects completed the entire submaximal exercise protocol both pre- and post-bed rest. Resting or exercise VO2 were similar pre- to post-bed rest at rest and during the 40% VO2peak stage (Fig. 1). However,
Table 1. Blood pressure responses to submaximal exercise before and after bed rest at minutes 5 and 15 of each exercise stage

<table>
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<th>Rest</th>
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<th>40% VO2 peak, 15 min</th>
<th>65% VO2 peak, 5 min</th>
<th>65% VO2 peak, 15 min</th>
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<td>SBP</td>
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<tr>
<td>Pre</td>
<td>119 ± 3</td>
<td>149 ± 5</td>
<td>153 ± 4</td>
<td>173 ± 5</td>
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<tr>
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<td>Pre</td>
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Values are means ± SE. VO2 peak, peak oxygen consumption; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; pre, before bed rest; post, after bed rest.

%SBF from rest during the 40% VO2 peak stage was not different from pre- to post-bed rest (Fig. 2A). However, by minute 5 of the 65% VO2 peak stage and throughout the remainder of the exercise, post-bed rest %SBF was significantly less than pre-bed rest. The threshold for the SBF-Tin relationship was delayed significantly after bed rest (37.09 ± 0.16 vs. 37.33 ± 0.13°C) and the slope of the response tended to be reduced (536 ± 184 vs. 201 ± 46%·°C⁻¹; P = 0.08, Fig. 2B).

There was no difference in total sweat loss during submaximal exercise pre- to post-bed rest (0.42 ± 0.06 vs. 0.44 ± 0.08 kg). Mean post-bed rest chest SR was not significantly different from pre-bed rest at any time point (Fig. 3A). The slope of SR response (4.03 ± 1.69 vs. 2.33 ± 0.90 mg·min⁻¹·cm⁻²; P = 0.48) was not changed significantly after bed rest, but Tin at the onset of sweating was increased significantly (37.06 ± 0.11 vs. 37.34 ± 0.06°C; Fig. 3B).

Tsk was not different at rest or during exercise from pre- to post-bed rest, but regional differences existed (Fig. 4). Tarm and Tthigh were unchanged from pre- to post-bed rest. However, at rest, Tchest was higher and Tcalf tended to be lower (P = 0.08) after bed rest compared with pre-bed rest. There was a significant interaction between bed rest and exercise time in Tchest. Before bed rest, Tchest from minute 10 of the 65% VO2 peak stage to the end of exercise was significantly greater than at rest. After bed rest, Tchest did not increase from rest to the end of exercise. Similarly, there was a significant interaction between bed rest and exercise time in Tcalf. Before bed rest Tcalf did not increase from rest to the end of exercise. However, after bed rest Tcalf at minute 20 of the 40% VO2 peak stage through the remainder of the exercise protocol was significantly greater than at rest.

PV decreased significantly (−11.0 ± 1.5%) as a result of bed rest whether expressed in absolute units (3,259 ± 177 and 2,894 ± 138 ml for pre- and post-bed rest, respectively) or relative to body mass (43.3 ± 0.9 and 38.4 ± 0.9 ml/kg for pre- and post-bed rest, respectively). However, there was no change in body weight from pre- to post-bed rest (pre: 77.2 ± 6.4 kg; post: 76.8 ± 6.5 kg).

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Fig. 2. A: percent change in skin blood flow (%ASBF; n = 6) was reduced after bed rest (●) compared with pre-bed rest (○) at 5, 10, 15, and 20 min of exercise at 65% pre-bed rest VO2peak. B: onset of cutaneous vasodilation was significantly delayed and the slope of the response tended to decrease (P = 0.08) relative to Tin from pre- to post-bed rest. *Significantly different from pre-bed rest.
77.7 ± 6.3 kg). Red cell mass was also significantly decreased from pre- to post-bed rest (−5.5 ± 2.1%) when expressed as absolute values (pre: 1,982 ± 115 ml; post: 1,869 ± 89 ml) or relative to body mass (26.4 ± 0.8 vs. 24.8 ± 0.8 ml/kg, respectively). Consequently, there was a significant decrease in blood volume (pre: 5,258 ± 313 ml; post: 4,770 ± 232 ml). Peripheral (pre: 42.8 ± 0.9; post: 44.5 ± 1.2) and whole body (pre: 37.9 ± 0.8; post: 39.3 ± 1.0) hematocrit were significantly greater after bed rest compared with pre-bed rest. F-cell ratio was unchanged from pre- (0.92 ± 0.1) to post-bed rest (0.92 ± 0.0).

**DISCUSSION**

Our current findings confirm the results of previous studies that reported an impairment of thermoregulation after bed rest as an analog of spaceflight. Our results suggest that this impairment is due to changes in both the vasodilatory and sweating responses. Delayed onset of SBF and SR responses relative to T_in after bed rest may suggest a resetting of the central control of thermoregulation. Although not statistically significant, the strong tendency for a reduced slope of the SBF/T_in relationship may also suggest a peripheral vascular adaptation. These changes did not prevent our subjects from completing this relatively mild exercise protocol after bed rest. However, the changes could have a negative impact during exercise in less temperate conditions, with more intense or upright exercise, after long duration bed rest or spaceflight (11), and/or during work in impermeable garments such as the launch-and-entry or extravehicular-activity suits.

**T_{core}**. Resting T_in was significantly elevated after bed rest in our subjects by an average of 0.31 ± 0.12°C. Under conditions similar to our study, Ertl et al. (8) reported that rectal temperature (T_{rec}) was signifi-
cantly elevated during supine rest and after 24 h of bed rest. Fortney (9) also reported that $T_{cs}$ was significantly elevated after 12 days of bed rest during semi-recumbent rest in a warm environment (30°C, 50–60% relative humidity). Crandall et al. (7) observed a significant increase in supine resting oral temperature after 15 days of bed rest in subjects wearing a water-perfused suit before the introduction of warm water. In contrast, Greenleaf and Reese (17) observed no change in supine resting $T_{rc}$ in a cool environment in male subjects after 14 days of bed rest. An explanation for differences in these results is unclear, but an increased resting $T_{core}$ after bed rest appears to be the predominant finding.

During exercise in our investigation, $T_{in}$ was elevated after bed rest compared with pre-bed rest ($0.30 \pm 0.03°C$), similar to other investigations (8, 9, 17). However, the change in $T_{in}$ from rest to the end of exercise in our study after bed rest was not different than pre-bed rest. Ertl et al. (8) reported similar results during 70 min of moderate exercise (58% pre-bed rest $V_{O2 \text{peak}}$) after only 24 h of bed rest. In contrast, both Greenleaf and Reese (17) and Fortney (9) observed a greater increase in $T_{core}$ from rest to the end of exercise after 14 days of bed rest. Subjects in the study by Greenleaf and Reese (17) performed supine exercise at a lower exercise intensity than in our study but exercised for 70 min. Fortney (9) employed a shorter exercise protocol (30 min) but a higher exercise intensity (60% pre-bed rest $V_{O2 \text{peak}}$) in a semirecumbent position and in a warm room (30°C). The differences between the results of these studies and ours may be related to the greater severity of the post-bed rest exercise challenge in the other investigators’ studies.

Increased $T_{core}$ during rest and exercise may be the result of increased heat production, changes in set point of $T_{core}$ for heat loss responses, and/or a reduced transfer of heat from the body. Heat production at rest and during submaximal exercise has been reported to be unchanged (17, 16) or decreased (16) as a result of bed rest; there have been no reports of increased submaximal exercise $V_{O2}$ (13). In our subjects, there was no change in heat production either at rest, during 40% $V_{O2 \text{peak}}$, and the first half of the 65% $V_{O2 \text{peak}}$ exercise stage, as exhibited by no change in $V_{O2}$, $V_{O2}$ was significantly less after bed rest at the end of the 65% $V_{O2 \text{peak}}$ stage.

$T_{core}$ set point and thresholds for the onset of SBF and SR. A change in $T_{core}$ set point in this bed rest study may be related to loss of heat acclimation or changes in circadian rhythm. Heat acclimation is associated with decreased resting and exercise $T_{rec}$ and no change in heat storage (5). Our subjects had elevated $T_{in}$ at rest and during exercise, consistent with deacclimation, and no change in heat storage from pre- to post-bed rest. Buono et al. (5) observed in data from earlier investigations that the thresholds for the onset of sweating and vasodilation appear to decrease to a similar magnitude after acclimation as the decrease in resting $T_{core}$. In our study, $T_{in}$ was elevated at rest ($+0.31 \pm 0.12°C$) after bed rest to a similar magnitude as the increase in $T_{in}$ at the onset of vasodilation ($+0.33 \pm 0.09°C$) and sweating ($+0.28 \pm 0.11°C$).

Change in $T_{core}$ set point also may have been the result of a circadian shift induced by bed rest. In a 17-day bed rest, Monk et al. (29) demonstrated that the sinusoidal shape of the circadian curve describing $T_{core}$ was maintained during bed rest but that the amplitude of the curve was reduced. In agreement with this observation, Lkhagyva (28) observed that the nadir of the circadian curve was increased by 0.22°C in three men after 7 days of bed rest. Therefore, although our testing was conducted at the same time of day from pre- to post-bed rest (mid- to late morning), the post-bed rest $T_{in}$ may have been elevated relative to pre-bed rest due to a change in the amplitude of the circadian curve.

This circadian change also may have influenced the thresholds for the onset of SBF and SR. The onset of SBF and SR with exercise (42) and passive heating (1) have been shown to be correlated with circadian rhythm.

SBF. Resting $T_{in}$ in the present study also may have been elevated due to changes in SBF; SR at rest was very small and was not affected by bed rest. Resting SBF could not be assessed by the laser Doppler technique that we used in this investigation, but $T_{sk}$ is often used as an index of regional SBF. Although resting mean $T_{sk}$ was not altered after bed rest, resting $T_{calf}$ was reduced and $T_{chest}$ was elevated after bed rest. Similar observations were made during short-duration (90 min) head-down tilt (34), bed rest (25, 44), and spaceflight (33). These changes may be reflective of an altered blood flow distribution, an increased central vs. peripheral distribution of blood volume, which has been a consistent finding after bed rest (13), and/or a greater relative vasoconstriction in the lower body after bed rest. Perhaps heat loss in our subjects at rest was reduced and $T_{in}$ increased due to a shift in blood flow away from the limbs, where the high surface area-to-volume ratio facilitates heat exchange, and toward the trunk, where the opposite is true. These regional $T_{sk}$ differences disappeared in our subjects once exercise was commenced.

Our results suggest a significant impairment of SBF responses after bed rest. During exercise, the %SBF from rest was reduced from pre- to post-bed rest in our subjects by minute 5 of exercise at 65% $V_{O2 \text{peak}}$. The onset of vasodilation from the preexercise baseline was delayed, and the sensitivity (slope of the response relative to $T_{in}$) tended to be reduced. Ertl et al. (8) reported no change in SBF from pre- to post-bed rest during exercise despite an increased $T_{rec}$, suggesting a decreased sensitivity of the SBF response to increased $T_{rec}$. Crandall et al. (7) reported a delayed onset of skin vasodilation and a decreased SBF sensitivity in men at rest after 15 days of bed rest when oral temperature was raised passively with a water-perfused suit.

Altered SBF responses observed during exercise after bed rest may be due to several factors. A reduction in PV, even without a decreased red cell mass, has a powerful inhibitory effect on SBF during exercise (31). Lower PV may increase competition between the skin
and muscle vascular system to supply their respective needs (39). The reduced red cell mass as observed in this study may further reduce SBF as decreased oxygen carrying capacity of the blood may require that blood flow be diverted from the skin to the exercising muscles, although this has not been conclusively proven (41). Crandall et al. (7) suggested that changes observed in thermoregulatory control of FBF after bed rest during passive heating may be related to a significant hypovolemia coupled with an increased plasma sodium and osmotic concentration, although PV loss during bed rest is typically isotonic (13).

In addition, there may be a decreased ability to translocate blood from the splanchnic region to the skin. Savilov et al. (40) observed a decreased ability to reduce blood volume in the gut during lower body negative pressure after bed rest, and this decreased ability to decrease splanchnic blood flow also may occur during exercise stress. Previous investigators (38) have suggested that fitness alters the slope of the SBF response and that fitness may affect the ability to increase SBF by shunting blood from the viscera (18). In our subjects, although not measured, aerobic fitness would have been expected to decline by 9–10% as a result of bed rest (6), and the slope of the SBF response tended to be reduced.

It is unclear at this time whether the reduction in SBF after bed rest is related to increased vasoconstriction or decreased active vasodilation. Previous investigators have suggested that active vasodilation is impaired by a reduction in PV (22) or a decrease in fitness (43) as would occur after bed rest. However, in this study, we were unable to discriminate whether the reduced SBF was due to enhanced vasoconstriction or reduced vasodilation due to the possible effects of local heating at the site of the SBF measurement.

SR. In the present study, we observed no change in local SR during exercise, in the slope of the SR/Tin response, or in total sweat loss but a delayed onset of SR relative to Tin. Results with regard to SR from other bed rest investigations vary. After 24 h of bed rest, neither local SR nor change in body weight during exercise were different from that after 1 h of bed rest (8). After 14 days of bed rest, total sweat loss during exercise was unchanged despite a significantly greater increase in Tem (17). However, after 12 days of bed rest, women in the study by Fortney (9) had a significantly elevated total sweat loss. Alterations in SR response as a result of bed rest are unclear at this time; Johnson and Park (20) observed high variability in SR responses. By using our specific protocol, long-duration bed rest (>14 days) may be required to observe significant changes in the slope of the SR-Tin response, as was seen after long-duration spaceflight (11).

Data from ambulatory subjects would suggest that reduced PV, as observed during bed rest, would be expected to alter SR responses. Hypovolemic subjects would be expected to have a decrease in the slope of the SR/Tes response, decreased total sweat loss, and no change in the Tes threshold for the onset SR during exercise (12). In contrast, we observed a delayed onset of the SR relative to Tin and no change in the slope of the response. Contradictions in the findings of these studies may be related to an acute response to decreased PV due to diuretic usage in ambulatory subjects vs. an adaptation to a gradual PV loss through inactivity and bed rest. However, it is more likely that the shift in the Tin threshold for SR observed in our bed rest subjects was related to a circadian effect.

Limitations. Several limitations were inherent in the design and the implementation of this investigation. First, the protocol for this study was designed to be applied to our laboratory’s previous long-duration spaceflight investigation (11). We selected a protocol that would allow crewmembers to complete the exercise protocol without exceeding HR limits imposed by the flight crew surgeon, could be performed in ambient conditions as a climate chamber was not readily available at all potential landing sites, and would not result in excessive fatigue or risk to crewmembers. The present protocol was selected as a compromise to elicit sufficient stress to produce the desired thermoregulatory responses yet require minimal time so as not to interfere with a limited testing schedule available in consideration of other postflight investigations.

Second, our interpretation of SBF results was somewhat limited by the methods with which we chose to measure SBF. First, we were able to assess only relative changes in SBF from rest and did not measure an absolute resting SBF. However, resting SBF has been reported to be reduced after bed rest (7), and it is therefore possible that the absolute impairment of SBF is more severe than the relative responses that we currently report. Second, local heating at the measurement site may have obscured observations possible at lower Tsk. Finally, the vasodilator response to the application of local heating to establish preexercise baseline SBF may not have been equal before and after bed rest. If the response to local heating were increased after bed rest, then it is possible that the maximal SBF was reached early in exercise and would be observed as a decrease in the change in SBF relative to resting conditions. However, if the response to passive heating were reduced as suggested by Crandall et al. (7), then the reduced absolute vasodilatory response would have been more extreme than that which we observed.

Third, due to constraints imposed by other companion investigations, PV and red cell mass measurements were obtained within 24 h after the performance of the submaximal exercise protocol performed on bed rest day 13. High-intensity exercise has been shown to increase PV for up to 48 h. Although the intensity of exercise in this study was low, it is possible that the exercise performed in this study may have partially restored the bed rest-induced PV loss at the time of measurement.

Perspectives. The microgravity and spacecraft environment may further challenge the thermoregulatory system. Previous authors (26) have suggested that sweating responses may be reduced during spaceflight through the formation of a film of sweat on the surface of the skin because of reduced sweat drippage, which...
may impair air flow across the skin and sweat evaporation. Furthermore, the reduced gravity may impair the natural convection in which air rises or falls due to differences in density (32), and low air flow in the cabin of space vehicles may limit heat loss capacity (10).

Changes in thermoregulatory control may be more extreme after long-duration spaceflight than that observed in the present investigation. In a previous study, our laboratory (11) reported that the thermoregulatory mechanisms were severely impaired in two crewmembers when performing this same testing protocol after 115 days of spaceflight despite participating in an in-flight exercise countermeasures program. Postflight, neither crewmember completed the 65% preflight VO_2_peak stage, and there was a faster rise in T_m. Both crewmembers had reduced SBF and SR responses. Therefore, impaired thermoregulation also may impact rehabilitation plans after long-duration spaceflight. Care has been taken to limit exposure to conditions of heat, humidity, and intense activity. In summary, 13 days of bed rest resulted in higher T_m both at rest and during exercise without a significant increase in body heat storage. Higher T_m during rest and exercise appears to be related to reduced heat loss due to altered SBF and SR responses. These effects have the potential to impact the activities of astronauts during and after spaceflight, especially after long-duration missions. In addition, patients in bed rest who may be undergoing heat or exercise therapies also may be adversely affected.

The authors thank the subjects for participation in this investigation; Dr. Steve Leberman and Dr. Todd Schlegel for medical monitoring; Dr. Marcos Bamman, Laura Steinman, and the NASA Test Subject Facility at Johnson Space Center for assistance with coordinating subjects, interactions with companion studies, and exercise testing; Dr. Charles Stuart and the General Clinical Research Center Staff at University of Texas Medical Branch in Galveston, TX, for monitoring of bed rest subjects; Dr. Martin Nuynowitz and Walter Durham for measurement of PV and red cell mass; Dr. Steven Siconolfi for the measurement of VO_2_peak; and Richard Racusetti for his assistance with the dew point hygrometry system.

This work was supported by the NASA-Mir Pathfinder program and NASA Contract no. NAS9-18492. This study was conducted in the General Clinical Research Center at the University of Texas Medical Branch at Galveston, TX, funded by National Center for Research Resources Grant M01 RR-00073.

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