Thermoregulation of exercising men in the morning rise and evening fall phases of internal temperature

Masafumi Torii*† PhD, Hideaki Nakayama‡ MD PhD and Takashi Sasaki§ MD PhD

*Bioregulation and Physical Fitness Laboratory, Faculty of Engineering, Kyushu Institute of Technology, Kitakyushu 804, Japan; †Department of Hygiene, Faculty of Medicine, Tottori University, Yonago 683, Japan and §Environmental Physiology Laboratory, Ginkyo Junior College, Kumamoto 860, Japan

The purpose of this study was to compare the thermoregulatory responses during exercise in the morning rise (0900 h) and evening fall phases (2000 h) in circadian variation of body temperature. Five healthy volunteers performed bicycle exercises at 30% and 60% of maximal aerobic power (\( V_{\text{O2 max}} \)) at 26°C with a relative humidity of 50%. Whole-body sweat rate (SR), rectal (\( T_r \)), mean skin (\( T_s \)), and mean body (\( T_b \)) temperature, pulmonary ventilation (\( V_{p} \)), oxygen uptake (\( V_{\text{O2}} \)), and carbon dioxide output (\( V_{\text{CO2}} \)) and heart rate (HR) were measured during the experimental period. SR during exercise at 30% \( V_{\text{O2 max}} \) was significantly higher at 2000 h than at 0900 h. However, the circadian variation of SR during exercise was not observed at 60% \( V_{\text{O2 max}} \). At the two experimental times, there were no significant differences in \( V_{\text{O2}} \), \( V_{\text{CO2}} \), \( V_{p} \), and \( T_{b} \) in both workloads. In HR, \( T_{r} \), and \( T_{s} \) circadian effects were demonstrated as well as in workload levels. As \( T_{b} \) was plotted against SR during exercise, positive correlations were observed. The data showed that there was a parallel shift in the SR to \( T_{b} \) relationship during exercise in the morning and evening. This rightward shift indicated that there was an increased \( T_{b} \) threshold for the onset of sweating in the evening. Resting \( T_{b} \) at 2000 h was significantly higher when compared with \( T_{b} \) at 0900 h. The present results suggest that the circadian influence on the thermoregulatory response to exercise may be evident only at low workloads.

Keywords: temperature regulation, sweat rate, work intensity, circadian rhythm

The circadian rhythm in human body temperature appears to be regulated, rather than just the consequence of passive imbalances in the rate of heat production and heat loss.1-5 Several of the following thermal physiological parameters to exercise and heat stress were shown to exhibit circadian rhythmicity: sweating,6-8 skin blood flow,6,8,9 body temperature,5-8 and heart rate10. Aschoff and Heise11 estimated that in a resting man the circadian variations of heat loss were responsible for about 75% of the range of oscillation in internal temperatures, while the variation in heat production contributed only 25%.

Hirdebrandt12 reported that the circadian control of human body temperature was the result of the following thermoregulatory adjustments: warming-up in the morning and cooling-down in the afternoon. However, identification of the factors that cause the circadian fluctuation has been more controversial. It was previously reported by Niwa et al.8 that there was a circadian rhythm of thermoregulatory response. Under the condition of an environmental temperature at 13°C with a relative humidity of 60%, the sweating response during bicycle exercise at workload of 450 kpm min\(^{-1}\) (75 W) was at its maximum at 1800 h and its minimum at 0600 h, but heat production during exercise was identical at various periods during the day. However, no report was given on thermoregulatory response at different work intensities. The aim of the present study, therefore, was to investigate temperature regulatory responses at two different work intensities in the morning rise and evening fall phases in the human body temperature, and to discuss the circadian control mechanism contributed by the work factor.

Materials and methods

Subjects

The subjects selected were five healthy male college students, mean(s.e.m.) age 21.6(0.7) years, 171.8(2.7) cm in height, 68.8(2.5) kg in weight, 1.83(0.04) m\(^2\) of body surface area (= height\(^{0.178}\) × weight\(^{0.427}\) × 71.84 of Takahira’s equation13, and with maximal aerobic power (\( V_{\text{O2 max}} \)) of 3.07(0.16) L min\(^{-1}\) (mean(s.e.m.)). During the first visit to the laboratory, each subject was orientated to the basic equipment and procedures used in the experiment. Practice time was provided for riding the bicycle ergometer and performing the mouth piece for oxygen uptake (\( V_{\text{O2}} \)) measurement. Before the main experiments, each participant’s \( V_{\text{O2 max}} \) was determined by an incremental work rate protocol on a Monark bicycle ergometer using the Douglas bag technique.14 The pedalling rate was kept constant at 50rpm and timed with a metronome. After 2 min of pedalling with a constant load 720–780 kpm min\(^{-1}\) (120–130 W), the work intensity was increased by 150 kpm min\(^{-1}\) (30 W) every minute up to exhaustion. Before the main experiment, we...
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also measured circadian variation of oral temperature in our subjects (Figure 1), and confirmed morning rise and evening fall in oral temperature.

Experimental protocol

The subjects arrived at the laboratory at least 1 h before the experiments, and sat quietly until the designated time. They undressed except for their underwear. The experiments were done at two different times of the day, and each experiment was on a different day. The experiments were at 0900 h and 2000 h, with all studies starting within 30 min of the target time. The four experiments were carried out from October to early November, with the order randomized. The work intensities were both 50% and 60% of VO₂max in each subject. After sitting on a chair for 30 min at the condition of thermoneutrality, they conducted a bicycle exercise for 40 min in a mean(s.d.) ambient temperature (Tₐ) of 26°C(0.7°C) with a mean(s.d.) relative humidity (rh) of 50%(7.3%). An experimental work test was performed on 20 separate days, two at each of following times: 0900 h and 2000 h. No muscular work was performed for 24 h before any test. In the morning on an experimental day, the subjects conducted the cycle exercise without taking breakfast, and in the case of the experiments in the evening on another day kept no caloric intake six to eight h after taking lunch (usual foods) at 1300–1400 h.

Measurements

Sweating rate (SR) was measured continuously from whole body weight loss, using a bed scale (Model 33B, sensitivity, ± 1.0 g, J.A. Potter Co., Southington, Connecticut, USA) technique, as described previously. The best curve shown in Figure 2 was drawn through the weight record for each experiment and rate of whole-body weight loss was then calibrated prior to each experiment. Respiratory evaporative weight loss was estimated by Mitchell et al.

The temperatures of four skin surface locations and rectum (Tₐ) at a depth of 15 cm from the anus were recorded every 5 min by a copper-constantan thermocouple recording system (AM-300, Ohkura Electric Co., Ltd, Japan) with an accuracy of ±0.05°C throughout the experimental period. Mean skin temperature (Tₘₖ) and mean body temperature (Tₘₖ)

![Figure 1](https://example.com/figure1.png)

Figure 1. Circadian variations of mean oral temperature (Tₒ) of resting subjects (n = 5). Shaded areas represent the time period of the experiment. Resting oral temperature shows a diurnal increase and a nocturnal decrease, followed by an early morning increase. In the figure a quadratic line indicates its equation, y = 35.3 + 0.229x - 8.3160x², r = 0.933. ○ = 1st measurement, ● = 2nd measurement. The periods of the present experiments are represented by two shaded areas.

![Figure 2](https://example.com/figure2.png)

Figure 2. A recording example of the whole body weight loss measured by a bed scale. After 15 min of exercise (at 100 W = 600 kpm min⁻¹) the weight loss increased markedly. 100 g scales were indicated in the centre of a chart. The curve of weight losses was modified at the point a, because a thermocouple sensor dropped.
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were calculated from Ramanathan's\textsuperscript{18} and Stolwijk-Hardy's\textsuperscript{19} equations, respectively.

Heart rate (HR) was recorded by electrocardiography with a telemeter system (Model 270 and 1418, Sanet Sotoki, Japan). \( \dot{V}O_2 \) was determined by the Douglas bag technique at rest and during exercise, 5-, 10-, 20-, 30-, 40-min after the beginning of exercise and during recovery. The gas samples were immediately analysed for oxygen (F-3, Beckman Fullerman, California, USA) and carbon dioxide (MCD-L, Horiba Seisakusho, Japan). Expired gas volume was measured with a gas meter (WT-10, Shinagawa Seisakusho Co, Japan).

Statistical analysis

Values represent the mean ± s.e.m., and statistically significant differences of mean values were assessed by a paired t-test and one-way ANOVA. We also evaluated time of day and work intensity to thermal response during exercise by means of two-way ANOVA. The significance of the regression line was also evaluated by covariance analysis. A probability level of 0.05 or less was accepted as a significant difference.

Results

No individual differences were found among the subjects in all the data related to sweating responses at rest and during exercise (\( P > 0.05 \), one-way ANOVA).

Figure 3 shows the time courses of \( \dot{V}O_2 \) during exercise at two different work intensities at 0900h and 2000h. While all subjects sat quietly on a bicycle ergometer, their mean(s.e.m.) \( \dot{V}O_2 \) was not significantly different between 0900h (309(19.2) ml min\(^{-1}\), \( n = 10 \)) and 2000h (306(12.2) ml min\(^{-1}\), \( n = 10 \)). At the end of the two test periods at 30% \( \dot{V}O_{2\text{max}} \) and 60% \( \dot{V}O_{2\text{max}} \), \( \dot{V}O_2 \) measured during exercise averaged 1.000(0.06) and 1.611(0.06) l min\(^{-1}\) and 1.041 (0.05) and 1.635 (0.03) l min\(^{-1}\) (\( P > 0.05 \), respectively. At all phases of the two test periods, \( \dot{V}O_2 \) during exercise at 60% \( \dot{V}O_{2\text{max}} \) was significantly higher than 30% \( \dot{V}O_{2\text{max}} \) (two-way ANOVA). There were also no significant differences in carbon dioxide output and pulmonary ventilation in both workloads and at the conducted experimental time.

The time courses of HR during exercise at two different work intensities at 0900h and 2000h are represented in Figure 4. HR, at 25–40 min after the onset of exercise at 60% \( \dot{V}O_{2\text{max}} \) was significantly higher at 2000h than 0900h. However, there was not a significant difference in the HR between 0900h and 2000h during exercise at 30% \( \dot{V}O_{2\text{max}} \). At all phases of the two test periods, HR during exercise at 60% \( \dot{V}O_{2\text{max}} \) was significantly higher than 30% \( \dot{V}O_{2\text{max}} \) (two-way ANOVA).

The time courses of SR during exercise at two different work intensities at 0900h and 2000h are shown in Figure 5. SR during exercise at 30% \( \dot{V}O_{2\text{max}} \) (left), was significantly higher at 2000h than 0900h. At 60% \( \dot{V}O_{2\text{max}} \), exercise (right), SR was not significantly different, except for 20 min after the onset of exercise at 0900h in comparison with 2000h. At all phases of the two test periods, SR during exercise at 60% \( \dot{V}O_{2\text{max}} \) was significantly higher than 30% \( \dot{V}O_{2\text{max}} \) (two-way ANOVA). As shown in Table 1, at 30% \( \dot{V}O_{2\text{max}} \) exercise, TSR and \( SR_{\text{max}} \) were significantly higher at 2000h than at 0900h. In contrast, other parameters showed no significant differences between 0900h and 2000h in exercise at 60% \( \dot{V}O_{2\text{max}} \). Furthermore, at 60% \( \dot{V}O_{2\text{max}} \) exercise, the time of reaching \( SR_{\text{max}} \) was faster at 2000h than at 0900h (\( P < 0.01 \)), but there was not significant difference of the time of reaching \( SR_{\text{max}} \) between 0900h and 2000h.

Figure 3. Time courses of \( \dot{V}O_2 \) in exercising men at two different workloads, about 30% [left] and 60% [right] of \( \dot{V}O_{2\text{max}} \) in the later morning [□] and evening [■]. Horizontal bars indicate an exercise period. Data represent mean(s.e.m.) for five subjects.
in exercise at 30% $\dot{V}O_2_{\text{max}}$. At rest insensible perspiration also was significantly higher at 2000 h and 0900 h (Table 1).

Figure 6 illustrates the time courses of $T_{re}$ (top), $T_{sk}$ (middle) and $T_b$ (bottom) during exercise at two different work intensities at 0900 h and 2000 h. Mean(s.d.) $T_{re}$ had an initial value of 37.49(0.03)$^\circ$C ($n = 5$), and did not change during the 40 min of work at 2000 h (Figure 6, top and left). At 0900 h, $T_{re}$ increased slightly reaching values of 37.17(0.12)$^\circ$C ($n = 5$) at HR (beats·min$^{-1}$)

**Figure 4.** Time courses of HR in exercising men at two different workloads, about 30% [left] and 60% [right] of $\dot{V}O_2_{\text{max}}$ in the later morning [O] and evening [●]. Horizontal bars indicate an exercise period. Data represent mean(s.e.m.) for five subjects. Significantly different (paired t test), 0.900 h vs. 2000 h, *$P<0.05$, **$P<0.01$, ***$P<0.001$

**Figure 5.** Time courses of SR in exercising men at two different workloads, about 30% [left] and 60% [right] of $\dot{V}O_2_{\text{max}}$ in the later morning [O] and evening [●]. Horizontal bars indicate an exercise period. Data represent mean(s.e.m.) for five subjects. Significantly different (paired t test) 0900 h vs. 2000 h, *$P<0.05$, **$P<0.01$
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Table 1. Circadian variation of thermoregulatory responses in exercising men at two different work intensities

<table>
<thead>
<tr>
<th></th>
<th>30% $\dot{V}O_2\text{max}$</th>
<th>60% $\dot{V}O_2\text{max}$</th>
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<tbody>
<tr>
<td></td>
<td>0900 h</td>
<td>2000 h</td>
</tr>
<tr>
<td>TSR (g m$^{-2}$ h$^{-1}$)</td>
<td>83.0(8.0)</td>
<td>117.3(2.8)*</td>
</tr>
<tr>
<td>SR max (g m$^{-2}$ h$^{-1}$)</td>
<td>138.4(10.0)</td>
<td>167.4(6.1)*</td>
</tr>
<tr>
<td>TR SR max (min)</td>
<td>37(1.2)</td>
<td>33(3.0)</td>
</tr>
<tr>
<td>$\Delta T_{re}$ (°C)</td>
<td>0.27(0.07)*</td>
<td>0.11(0.04)</td>
</tr>
<tr>
<td>$\Delta T_{sk}$ (°C)</td>
<td>1.20(0.11)</td>
<td>1.42(0.36)</td>
</tr>
<tr>
<td>$\Delta T_b$ (°C)</td>
<td>0.45(0.05)</td>
<td>0.37(0.09)</td>
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Data represent mean(s.e.m.) for five subjects; TSR, total sweat rate for 40 min of exercise; SR max, maximum rate of sweating during exercise; TR SR max, time of reaching SR max after the onset of exercise; $\Delta T_{re}$, $\Delta T_{sk}$ and $\Delta T_b$, changes from pre-exercise value in $T_{re}$, $T_{sk}$ and $T_b$, respectively; Significant difference (paired t test), 0900 h vs 2000 h, *P<0.05, **P<0.01; 30% $\dot{V}O_2\text{max}$ vs 60% $\dot{V}O_2\text{max}$, $^tP<0.01$

Figure 6. Time courses of $T_{re}$, $T_b$, and $T_{sk}$ in exercising men at two different workloads, about 30% [left] and 60% [right] of $\dot{V}O_2\text{max}$ in the later morning [O] and evening [•]. Horizontal bars indicate an exercise period. Data represent mean(s.e.m.) for five subjects. Significantly different (paired t test), 0900 h vs. 2000 h, *P<0.05, **P<0.01, ***P<0.001
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40 min. There was no significant difference between T_re at 0900 h and at 2000 h, except for 40 min after the onset of exercise at 30% VO_2max exercise. There was a significant difference in the rate of increase in T_re between 0900 h and 2000 h during exercise at 30% VO_2max. In both periods, T_bk levels peaked during exercise at 60% VO_2max. None of these changes were significant, suggesting no significant changes in T_b during the exercise in both periods. However, at 30% VO_2max, exercise T_bk was significantly higher at 0900 h than at 2000 h. No significant difference in T_sk was found between 2000 h and 0900 h in both workloads (Figure 6, bottom). After a transient fall, T_sk slightly increased during exercise at the two different workloads of the two test periods. For sitting on a bicycle ergometer (at rest) T_re and T_bk also were significantly higher at 2000 h and 0900 h. There was no significant difference in T_sk between 0900 h and 2000 h in the resting condition on a bicycle ergometer (Table 1).

As T_bk was plotted against SR during exercise, positive correlations were observed (Figure 7). In all subject data concerning SR vs T_re, T_sk and T_b relations (or the relation of SR to T_re, T_sk or T_b), the best correlation coefficient (r = 0.8201) was observed in the SR vs T_b relation. The regression equations and correlation coefficients are presented in Figure 7. Analysis of covariance revealed significant differences of the slope and intercept between the regression lines (SR vs T_b, relationship) at 0900 h and 2000 h to exercise at 30% VO_2max (P < 0.05, respectively). At 60% VO_2max exercise the intercept shifted to a higher temperature (P < 0.05).

Discussion

The circadian rhythm of different physiological and biochemical variations has been well established. A number of investigators studied the daily courses of SR, peripheral blood flow, VO_2max, HR in muscular working humans. A nocturnal lowering human core temperature has been correlated with a lowering to the core temperature threshold for cutaneous vasodilation and sweating during exercise and rest to a heat exposure. Timbal et al. investigated at 0200 h, 1000 h and 1800 h during a heat exposure of 90 min, sweat rate, body temperature and heat storage of the body of human subjects. According to their calculating and measuring data, the relationship between the change of heat storage of the body (ΔS) in the morning and that during the night is expressed in the following equation: ΔSnight = 0.69S_morning - 6.24. In the present study, SR during exercise at the lower work intensity was significantly higher in the evening than in the morning. In this case, we were in agreement with the previous reports. However, the circadian variation of SR during exercise was not observed at the heavy work intensity. In the previous studies, there was no comparison made of the effects of work intensity on the circadian control to temperature regulation. In the present study T_re and T_bk at rest (values before exercise) were significantly higher at 0900 h than 2000 h. From our data, it suggests that heat dissipating activity in the central control system is activated more in the evening than in the later morning.

At the heavy workload, the HR of exercising men in the evening was significantly higher than that in the later morning. VO_2, however, increased in proportion to workloads, not to time of day (two-way ANOVA). No measurements were made of other physiological parameters in cardiorespiratory function. The present study suggests that, for cardiorespiratory function and skin circulation during exercise, the regulatory system circulation may be modified by the work factors. Cohen and Muehl reported that there was circadian variation of HR during submaximal exercise. In resting HR, they also noted 50 beats min⁻¹ at 0400 h and 70 beats min⁻¹ at 1800 h during the time of day. We, however, did not observe HR in a resting condition, and did not compare directly with their subject laying (supine) on a bed, because our subjects were seated on a bicycle ergometer. Further studies are required to measure other physiological parameters such as cardiac output, stroke volume and skin blood flow.

A typical rightward shift in T_b threshold for SR was
shown in the data (Figure 7). SR was graphed as a function of \( T_b \) during two different exercises in the morning and evening. The data showed that there was a parallel shift (rightward) in the SR to \( T_b \) relationship during exercise in the later morning and evening. This rightward shift indicated that there was an increased \( T_b \) threshold for the onset of sweating in the evening. The increased threshold temperatures for sweating and vasodilation, observed by Stephenson et al.\(^5\), were affected by the normal circadian rhythm in resting internal temperature. In our experiment, resting \( T_b \) in the evening was significantly higher (\( P<0.001 \)) in comparison with that in the later morning. This result supported the concept that the regulation of sweating is related to a critical level of \( T_b \) or heat storage of the body\(^22\). In another study\(^23\), the regulation of sweating was analysed in terms of the interaction between central and peripheral inputs to the thermoregulatory system. Inputs from the skin thermosensors stimulated by the rate of change in skin temperature, have been shown to play a major role in the regulation of sweating in exercising subjects\(^24\).

Although core temperature is the primary thermoregulatory drive in the control of skin sweating, skin temperature can also affect SR\(^24\). In the present study, however, there were no significant differences in skin temperature in the exercising men at two different work intensities in the later morning and the evening. These data suggest that skin temperature shifted the minimum levels to maximum levels in the early morning, or the maximal levels to the minimum levels in the afternoon, if we accept Hildebrandt’s hypothesis\(^12\) on circadian control in human thermoregulation; that is, circadian regulatory mechanisms change to warming-up after 0300 h and the regulatory function change to cooling-down after 1500 h. Examining the effect of a step change in environmental temperature upon the skin temperature and blood flow of a seated human, Sasaki and Carlson\(^25\) observed that the circadian change of core temperature was paralleled by variations in both skin temperatures and peripheral blood flows. They have reported cycles in the heat dissipating responses which are not readily explained by simultaneous changes in core temperature. On the other hand, the rise in core temperature of an exercising man was proportional to work intensities and largely independent of ambient temperatures between 5–30°C. This rise in core temperature was not due to a failure in body temperature regulation, but was attributed to the setting of the body thermostat at a higher level\(^26,27\). At the same work intensity, our data differ in the rate of increase of core temperature presented by \( T_e \) due to exercise between the later morning and evening (Table 1). Moreover, evaporative cooling indexes as TSR, \( S_{R_{\text{max}}} \) and the time to reach \( S_{R_{\text{max}}} \) did differ markedly by means of work intensity (Figure 5 and Table 1); that is, TSR and \( S_{R_{\text{max}}} \) during exercise at the heavy workload did not observe the circadian variation.

Furthermore, our data indicate that the two major independent experimental variables in evaluating the effect of exercise on temperature regulation are the condition of the internal environment such as the ‘biological clock’\(^28\) and the workload. Figures 5 and 6 show how these two variables cause changes in regulatory sweating, core temperature and skin temperature. In the cooling-down period, heat dissipation activity was stimulated compared to the warming-up period at the lower workload. However, effector responses dissipating heat at the heavy workload are not distinguished in both phases.

It has been reported that in an exercising human the thresholds for sweating moved toward a lower core temperature early in the morning (0400 h). On the other hand, in the present study a tendency was observed in humans for the changes in core temperature during thermal transient caused by exercise to be larger at the later morning phase that at the evening phase. The rise in core temperature in a man during heat and cold exposure was reported to be higher at early morning (0200 h) than later morning (1000 h) and evening (0600 h). These findings may reflect the fact that the thermosensitivity of an exercising man is reduced during the night. As illustrated in Figure 7, the slopes of the temperature characteristic lines might also be reduced as indicated by temperature sensitivity during the light phase in addition to the parallel shifts mentioned above. This could cause a further downward shift of set-point temperature from day to evening.

Recently, the significance of exercise prescription for a healthy lifestyle has been recognized\(^29\) but there is little practical knowledge about the physiological-thermoregulating functions in humans, especially as affected by internal conditions\(^30\). Many works\(^30-32\) have reported that the risk factors for coronary heart disease decrease with an increase in aerobic exercise and sports (or muscular activity). Thus, an exercising man is affected by the time of day, and prescribers of exercise programmes must pay attention to factors such as exercise intensity. These findings are applicable to practical-exercise activity; that is, our data may be important in planning the practice of and in evaluating the effectiveness of a physical exercise programme.

In conclusion, the results of this study indicate that the circadian control of thermoregulatory response to exercise may be modulated by the workloads in the later morning and evening. It is suggested that the rise in human body temperature normally observed during exercise at the light workload in the later morning is due partly to the proportional nature of the circadian control mechanism and partly to the lower level in sweating which locally inhibits the heat dissipating responses due to evaporating sweat. These findings seem to have important implications for further research; for example, disappearance or lowering of the circadian variation in sweating response to exercise at the higher work intensity. The circadian variation of thermal regulation during exercise may be modulated by this factor.

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References