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Fundamental Research

The Sleep-Evoked Decrease of Body Temperature

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Summary: The circadian rhythm of deep body temperature consists of both an endogenous component and evoked components resulting from exogenous influences. Previous studies of the sleep-evoked effect have failed to control confounding influences, so that the effect of sleep per se has not been established. In the present study, eight good sleepers had their rectal temperatures recorded for 24 hours in each of two laboratory conditions employing a constant routine to control exogenous influences. Sleep was allowed at night in one condition. Following sleep onset, body temperature dropped more rapidly and remained lower than when wakefulness continued over the same time, resulting in a mean sleep-evoked decrease of 0.31 ± 0.09°C. Fourier regression analysis showed a significant 24-hour (circadian) temperature rhythm, together with a 12-hour harmonic rhythm, in each condition. Circadian rhythm parameters were also altered by the sleep-evoked (or masking) effect, with the amplitude increased and the mean decreased when subjects slept at night in the constant routine. It was suggested that a constant routine methodology be used in studies of circadian rhythm differences and that Fourier regression be used in preference to simple cosine curve fitting to give a better approximation of the temperature rhythm. **Key Words:** Circadian rhythms—Temperature rhythm—Sleep—Masking effects—Constant routine.

Deep body temperature shows a strong circadian rhythm, with a usual range of variation of about 1°C. It has been suggested that this is due, at least in part, to an endogenous variation of the thermoregulatory set point, which is higher in the afternoon than in the morning (1). However, deep body temperature also varies in response to a variety of imposed behavioral and external stimuli, including sleep (2), physical activity (3), postural changes (4), ambient temperature (5) and meals (6). Thus, the measured circadian rhythm of core body temperature consists of both an endogenous component (driven by an internal oscillator) and an exogenous or evoked component (due to imposed influences) (7). An evoked component has also been termed a masking effect (8), as it masks characteristics of the endogenous rhythm.

Although the endogenous component of the temperature rhythm is large (7), several exogenous influences can make substantial contributions to the overall variation. Physical activity is perhaps the most dramatic of these. For example, temperature increase during exercise was found to be proportional to the workload relative to a subject's maximum capacity, with a relative workload of 69% raising temperature by approximately 2.0°C (9). Even mild activity can produce a rhythm maximum about 0.2°C higher than that measured during bed rest (10), and mere change of posture from standing upright to lying down can cause a drop in rectal temperature of about 0.1°C (4).

Ambient temperature changes can alter both the mean and the shape of the body temperature rhythm. For example, exposure to cold both decreases body temperature (11) and causes temperature to decrease more rapidly at night (12,13), whereas hot conditions completely obscure the nocturnal temperature decrease (5). Food raises the metabolic rate for a period after the ingestion of a meal, but its thermogenic effect is relatively small (14). The menstrual cycle of women also affects their temperature rhythm, with the post-ovulatory temperature rise increasing the overall mean (15), thus confounding comparison of temperature rhythms recorded at different menstrual cycle phases.

Effect of sleep on body temperature

It has been a common observation that body temperature falls after sleep onset, both in entrained and in free-running conditions (16). The effect has been

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attributed to a combination of circadian variation and sleep-evoked decrease. Concomitant with the temperature decrease, a decrease in the heat gain mechanism of metabolism (17) and an increase in the heat loss mechanism of sweating (18) have been observed. It has also been suggested that during sleep the set point for thermoregulation is adjusted to a lower level (19).

Several investigators have examined the effect of sleep on the circadian rhythm of deep body temperature. Mills et al. (2) compared temperature rhythms from subjects who slept in different conditions and at different times of the day. They found that sleep had an overall lowering effect on temperature and that the effect had a circadian variation with a maximum of 0.4°C just before midnight. However, the study did not control for effects of activity, postural changes or meals during wakefulness. In a study comparing rhythms from seven conditions, each with a different bedtime, Gillberg and Akerstedt (20) observed an initial drop of temperature at sleep onset. However, across the 24 hours, temperatures during sleep did not differ significantly from those during wakefulness. This study did control ambient temperature and food intake and kept activity to a minimum.

Moline et al. (21) studied subjects undergoing acute time shifts, thereby providing waking and sleeping data for the same time of day. Comparisons showed the sleep-evoked temperature drop to comprise approximately 50% of the normal rhythm amplitude and the effect to be phase dependent. The findings were supported by data from an internally desynchronized subject living on a 25.8-hour day (22). Using temperature data obtained from internally desynchronized subjects participating in free-running experiments, Wever (23) concluded that the masking effect of sleep had an average value of approximately 0.28°C and also that the effect was phase dependent, being largest close to the maximum and descending phases of the temperature rhythm. However, none of these three studies controlled activity or posture during wakefulness.

The effects of activity/inactivity and wakefulness/sleep are usually coincident, but they make separate contributions to the observed temperature rhythm. With these variables confounded, part of the temperature decrease attributed to the effect of sleep in the previous studies could have been due to cessation of activity and change of posture. The result of the more controlled Gillberg and Akerstedt study (20) did suggest that the effect of sleep per se could be minimal.

The major aim of the present study was to assess the magnitude of the nocturnal sleep-evoked decrease in deep body temperature. The study used two laboratory conditions in which exogenous influences on temperature were controlled by a "constant routine" procedure. This procedure was based on a method first described by Mills et al. (24) and later refined by Czeisler et al. (25). Nocturnal sleep was chosen because this represented the masking effect present in many circadian rhythm studies, where temperature was recorded in the normal environment. In addition, since the effect of sleep per se was expected to be small and since previous investigators had found the sleep-evoked effect to be phase dependent with a maximum during the usual sleeping hours, nocturnal sleep was considered most likely to demonstrate a measurable evoked decrease.

METHOD

Subjects

Eight adult subjects (five males and three females, mean age 28.5 years, range 22–40) participated in the study. All subjects were reportedly good sleepers, in good health, had fairly regular bedtimes and maintained regular sleep/wake schedules for at least 1 week preceding the experimental sessions.

Materials and apparatus

Rectal temperature was recorded at 1-minute intervals using a Vitalog Portable Physiological Monitor PMS-8.

Polysomnographic recording used a Devices Ltd. M19 polygraph and criteria specified by Rechtschaffen and Kales (26) to ascertain the times of sleep onset and awakening, any nighttime awakenings during sleep and any sleep episodes at night in the awake condition. Examination of the recordings subsequently confirmed that no subject fell asleep during the instructed periods of wakefulness. During the nighttime period of allowed sleep there were no awakenings of longer than 3 minutes.

Procedure

From 1 week before the first laboratory recording until completion of their involvement in the study, subjects kept a daily sleeping/waking log to ensure regular bedtimes and rising times, to confirm that no sleeping medication was taken and to confirm their status as good sleepers. The mean of a subject's five bedtimes prior to the first laboratory session was chosen as the time for the start of allowed sleep in the laboratory. For female subjects, all temperature recording was scheduled during the first 2 weeks of their

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menstrual cycle, and basal body temperature (BBT) was recorded to confirm that all recording had been completed prior to the ovulatory temperature rise. All recording was done in the winter months to avoid seasonal effects on the temperature rhythms (27).

The two laboratory sessions were conducted in counterbalanced order, with four subjects assigned first to the nocturnal WAKE condition, and four first to the nocturnal laboratory sleeping (SLEEP) condition. For all but one subject, the laboratory sessions were separated by approximately 1 week, whereas for the remaining subject the separation was 3 weeks. Both laboratory conditions were the same with the sole exception that in the laboratory wakeful (WAKE) condition subjects remained awake throughout, whereas in the SLEEP condition they slept at their usual sleeping time. Two subjects were run concurrently in adjacent, similar bedrooms. For each session, subjects came to the sleep laboratory between 0900 and 1000 hours on the first day. Upon arrival they changed to comfortable clothes, connected the Vitalog and its sensors and then lay down in bed for the next 25 hours.

Throughout the session, subjects remained supine, with head elevated slightly. They remained as inactive as possible, reading or watching videotapes. Toileting was accomplished using bedpans. Ambient temperature was controlled by air-conditioning at approximately 20°C, and always remained within the range 19–21°C. The dim room lighting, as measured at the subject's head, remained at a constant 40 lux. To spread the effect of food evenly across the normal waking hours, the total daily intake was divided into 15 isoenergetic "snacks", which were given hourly. The diet was relatively low-protein (protein provided approximately 10% of total metabolizable energy) and high-carbohydrate, with a typical snack consisting of a quarter of a sandwich, a small piece of fruit, a piece of health biscuit and 50 ml of fruit juice. To meet individual requirements this amount was adjusted after the first snack and then remained constant for both conditions. Additional sips of water were allowed as required. The first hour was treated as an adaptation period. This also allowed sufficient time for body temperature to stabilize after the sharp decline which occurred on cessation of activity and lying down.

Approximately 1 hour before the subject's usual bedtime, electroencephalograph (EEG) and electrooculograph (EOG) electrodes were attached while the subject remained lying in bed. In the SLEEP condition, subjects were told at their usual bedtime that they could now go to sleep. In the WAKE condition they continued as before, but no food was given during normal sleeping hours. Also, during the early morning hours of the WAKE condition, experimenters remained in constant attendance to ensure wakefulness.

Analyses

A commonly used method of testing circadian variation is cosinor analysis (28), in which a cosine curve is fitted to the data. The present study used a simple extension of this to examine the effect of sleep on the temperature rhythm. Least-squares regression was used to fit a short Fourier series consisting of the sum of a 24-hour period sinusoidal rhythm and a 12-hour period harmonic rhythm. Using an analysis of variance method described by Bliss (29), significance of the 24- and 12-hour rhythms was tested, and fitted temperature curves from the two conditions were compared. The mean, amplitude and phase of the rhythms were obtained. Although temperature was recorded at 1-minute intervals for descriptive purposes, these analyses used data sampled each 15 minutes to avoid violating analysis of variance (ANOVA) assumptions with a serial correlation of adjacent data points (30).

The significance and size of the sleep-evoked temperature decrease was tested using repeated measures analysis of variance (31), with two within-subjects factors of condition (SLEEP or WAKE) and time. For each subject, means were taken of temperature across the periods of time required to produce four levels on the time factor. The method of planned comparisons (32) was used throughout to test for specific effects.

RESULTS

Circadian temperature rhythms

For each condition, 24 hours of continuous temperature data were used. Fourier regression analysis confirmed that, for all subjects, both SLEEP and WAKE temperatures showed highly significant ($p < 0.001$) 24-hour (circadian) rhythms and significant ($p < 0.05$) 12-hour harmonic rhythms. Figure 1 shows the individual temperature curves and their associated best-fit Fourier series for a typical subject in each condition. The figure demonstrates how the fitted curve differs from the sinusoidal form obtained in cosinor analysis, so that the addition of the harmonic component is able to represent an apparent postlunch dip. The smaller amplitude of the WAKE condition curve is also apparent.

Mean temperature curves were calculated for each condition by taking the mean of each individual's temperature at the same time of day. The resulting curves are shown in Fig. 2. Periodic regression showed a highly significant 24-hour rhythm present in each condition, together with a significant 12-hour harmonic rhythm. Table 1 gives the resulting F ratios and their associated ω^2 for proportion of explained variance (32). Table 2 gives the rhythm parameters for the two conditions.

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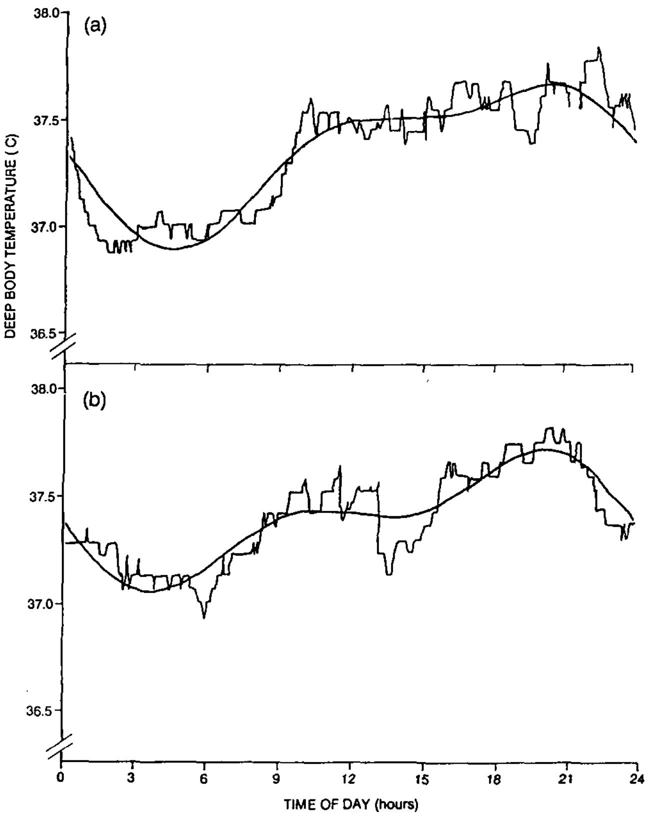

FIG. 1. An individual subject's rectal temperature curves for each condition. Each temperature record is shown as a function of time of day, together with the associated best-fit Fourier series consisting of a 24-hour fundamental rhythm with a 12-hour harmonic rhythm. The conditions shown are (a) the laboratory sleeping (SLEEP) condition, and (b) the laboratory wakeful (WAKE) condition.

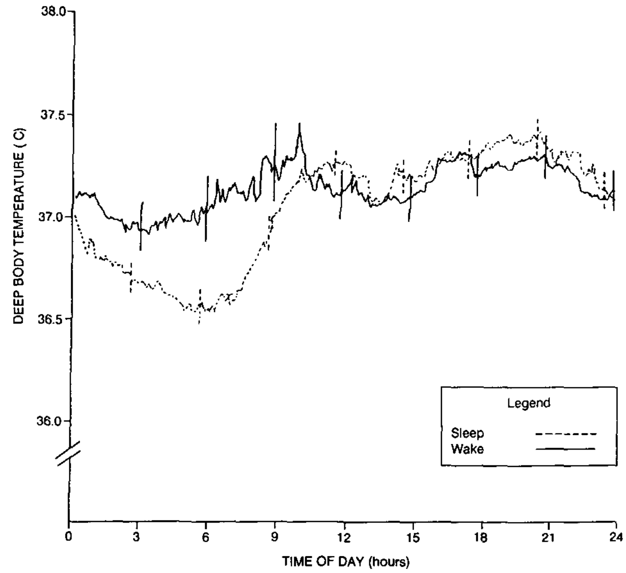

FIG. 2. Group mean rectal temperature as a function of time of day, for the SLEEP and WAKE conditions. Vertical bars indicate standard errors. (n = eight subjects.)

Using the method of Bliss (29), conditions were compared to assess the effects on the rhythm parameters of a night's sleep. This showed the SLEEP condition to have a mean that was 0.1°C lower [$F(1,191) = 162.12$, $p < 0.001$], and a 24-hour rhythm amplitude that was 0.27°C larger [$F(1,191) = 623.59$, $p < 0.001$]. The 29-minute delay in acrophase estimation fell short of significance [$F(1,191) = 2.46$, $p > 0.05$] (see Table 2).

Effect of sleep on temperature

To obtain group data that could be analyzed for the effect of sleep, adjusted curves were produced by aligning the sleep onset times of each temperature record prior to taking means. For the WAKE condition, the time of sleep onset was taken to be the same time as in the SLEEP condition. The sleep onset-adjusted mean temperature curves were then obtained by averaging from 12 hours before to 12 hours after sleep onset time. Figure 3 shows the resulting sleep adjusted curves, which follow the same general pattern as the time of day means.

All subjects provided at least 6 hours of sleeping time in the SLEEP condition. So for the first 6 hours after sleep onset time, using means at consecutive 1½-hour epochs, subjects' waking and sleeping temperatures were compared by repeated measures analysis of variance. This showed that SLEEP temperatures were significantly lower than WAKE temperatures [$F(1,7) = 11.88$, $p < 0.05$] by a mean amount of 0.31 ± 0.09°C. Time had a highly significant effect on temperature [$F(3,21) = 13.42$, $p < 0.001$]. This was due to a significant linear trend [$F(1,7) = 16.27$, $p < 0.01$] and a significant quadratic trend [$F(1,7) = 13.76$, $p < 0.01$]. These trends are seen in Fig. 3 as the curvilinear decrease in both curves following sleep onset time. This is consistent with the finding of highly significant rhythms in the periodic regression analyses. The condition by time interaction was not significant because the use of 1½-hour epoch means obscured the rapid decrease in sleeping temperatures following sleep onset.

To confirm that the finding of a sleep-evoked effect was not due to uncontrolled influences, SLEEP and WAKE conditions were compared across the 12 hours before and the 6 hours after sleep onset time, using

TABLE 1. *Significance of the 24-hour period fundamental (circadian) rhythm and 12-hour period harmonic rhythm for time of day mean Fourier regressions, for each experimental condition. The proportion of explained variance is given by ω^2. In all cases df = 2,95 for the* F *ratio, $p < 0.001$*

Condition	24-hour fundamental		12-hour harmonic	
	F value	ω^2	*F* value	ω^2
SLEEP	835.64	0.82	131.27	0.13
WAKE	93.49	0.39	95.96	0.40

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TABLE 2. *Estimates of rhythm parameters for the time of day mean temperatures in the SLEEP and WAKE conditions, obtained from Fourier regressions. Standard errors are shown in brackets, amplitude is measured from mean to peak, phase stands for acrophase*

		24-hour fundamental		12-hour harmonic	
Condition	Mean °C	Amplitude °C	Phase hour:min	Amplitude °C	Phase hour:min
SLEEP	37.04 (0.005)	0.37 (0.01)	17:16 (4)	0.15 (0.01)	20:42 (14)
WAKE	37.14 (0.005)	0.10 (0.01)	16:47 (15)	0.10 (0.01)	17:16 (15)

6-hour temperature means. Repeated measures analysis of variance showed that although mean temperatures across the 18 hours did not differ between conditions [$F(1,7) = 0.41$, $p > 0.05$], there was a significant condition by time interaction [$F(1,7) = 22.51$, $p < 0.01$]. This was due to a mean temperature difference (of 0.31°C) after sleep onset time, but no difference for the preceding 12 hours of wakefulness. As expected, time had a significant effect on temperature [$F(2,14) = 17.82$, $p < 0.01$].

Sleep onset and waking transitions

An important aspect of the effect of sleep is the change that occurs with sleep onset, which is assumed to cause a discontinuity in the slope of the temperature curve. Temperatures for the two conditions were compared for the hour after sleep onset time, showing a trend to lower sleep temperatures that fell just short of significance [$F(1,7) = 4.39$, $p > 0.05$]. A significant condition by time interaction [$F(3,21) = 10.12$, $p < 0.001$] due to a linear trend [$F(1,7) = 10.73$, $p < 0.01$] confirmed that the mean slope of the temperature curve was significantly steeper in the SLEEP condition. In contrast, before sleep onset time neither mean temperature values nor slope differed between conditions.

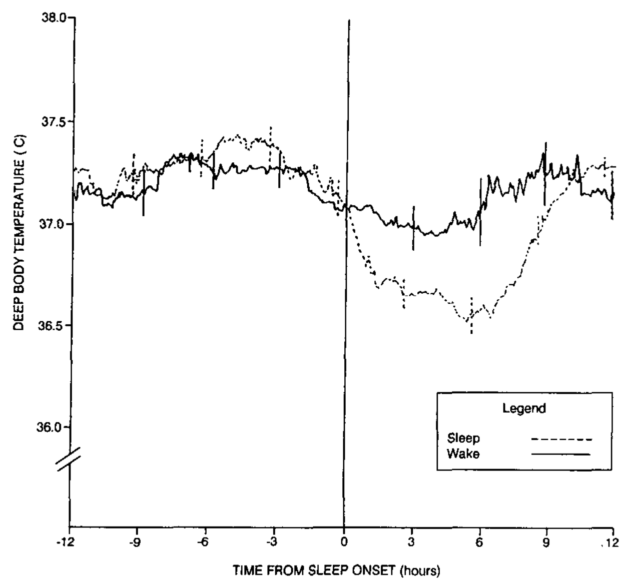

FIG. 3. Group mean rectal temperature as a function of time from sleep onset, for the SLEEP and WAKE conditions. Vertical bars indicate standard errors, and the vertical line shows sleep onset time. (n = eight subjects.)

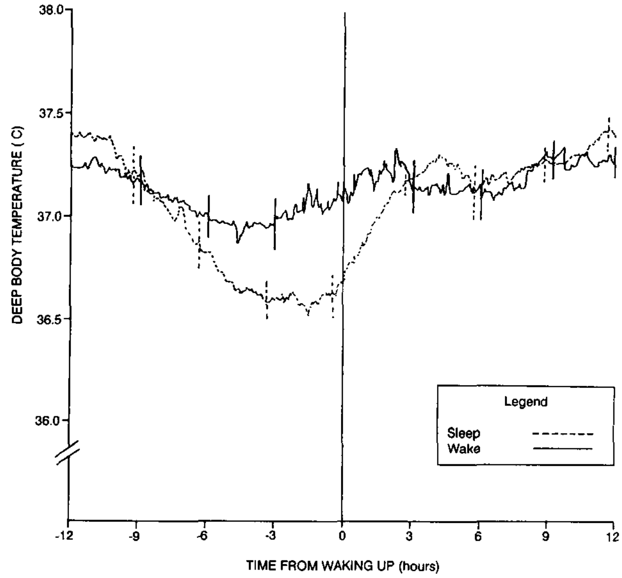

FIG. 4. Group mean rectal temperature as a function of time from morning waking, for the SLEEP and WAKE conditions. Vertical bars indicate standard errors, and the vertical line shows wake-up time. (n = eight subjects.)

The transition to wakefulness was examined in a manner analogous to that for sleep onset. Individual temperature curves were adjusted to wake-up time before taking means and producing the adjusted curves shown in Fig. 4. In the last hour of sleep, temperatures were a mean of 0.46 ± 0.13°C lower than corresponding wakeful temperatures [$F(1,6) = 13.33$, $p < 0.05$]. The effect of time and the interaction were not significant. In the hour after waking there was a trend to lower temperatures after sleep, which fell short of significance [$F(1,7) = 4.57$, $p > 0.05$]. Across the waking transition, slopes of the two temperature curves did not differ significantly.

DISCUSSION

Effect of sleep on temperature

The present study demonstrated that, in conditions where other exogenous influences were controlled, sleep had a clear and unambiguous effect in lowering nocturnal body temperature. Across the first 6 hours of sleep, sleeping temperatures were lower than the corresponding waking temperatures by a mean amount of 0.31 ± 0.09°C. This was accomplished by a sharper

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drop in body temperature following sleep onset, after which the sleep-evoked decrease remained at a relatively constant level (Fig. 3). The sharper fall in temperature was confirmed by the finding of a difference in the slope of the sleeping and wakeful temperature curves after, but not before, the time of sleep onset. This is in agreement with a number of studies (5,17,18,33) and is also consistent with the hypothesis of a lowered set point for thermoregulation during sleep (19).

The results of the present study are also consistent with findings that the nocturnal decrease in oxygen consumption, or metabolic rate, resulted from both the circadian cycle and a sleep-evoked component (34). For oxygen consumption also, the sleep-evoked decrease resulted from a rapid fall in the first half-hour of sleep, after which it remained relatively constant (34). Heat loss during sleep has also been found to be 8–10% higher than during a basal awake condition, to be greatest at the beginning of sleep, and to decline across the sleep period (35). Heat production was lower than heat loss, but did not decline as much across the night, accounting for the initial rapid drop in core temperature and the later levelling off. Thus, the onset of sleep appears to evoke a decrease of core temperature over the following 1–2 hours through the mechanisms of decreased energy production and increased heat loss.

Waking up was accompanied by a slower transition, as temperatures tended to remain lower in the first hour after waking, and the slopes of the curves after sleep or wakefulness did not differ significantly. It might have been expected that temperature after sleep would increase more sharply as it adjusted to a higher set point. However, Mills et al. (2) also observed body temperatures to remain lower than expected for a time after waking.

The results of the present study are in general agreement with previous findings for the effect of sleep on body temperature. The greater difference between nocturnal sleeping and wakeful temperatures of 0.4°C found by Mills et al. (2) could show lack of control for evoked effects due to activity and postural changes during wakefulness. For acutely phase-shifted subjects, Moline et al. (21) reported the sleep-evoked decrease in core temperature to be 50% of the amplitude of the normal rhythm. If the normal amplitude is taken to be approximately 1°C, then the 50% would be a larger effect than that found here. But Moline et al. make no mention of the activity level of their subjects during wakefulness, and this could account for the larger effect. The same could be true of the studies of desynchronized subjects. For example, Fookson and Moline (22) also found a larger effect, comprising 40% to 60% of the normal environment amplitude, and Wever (23) found a sleep-evoked effect of 0.36°C on the descending phase of the rhythm. In the only study that failed to find an overall lowering effect of sleep on temperature across the 24 hours, Gillberg and Akerstedt *(20) did* find trends in the expected direction. In particular, they did find an initial fall in temperature following sleep onset at most times of the day, and a sleep evoked decrease at sleep onset during the normal sleeping hours.

Several of these studies found a circadian variation in the sleep-evoked effect. This is consistent with circadian variation in thermoregulatory responses, which show greater responsivity of heat gain mechanisms in the morning, and a greater responsivity of heat loss mechanisms in the evening (1,36,37). Thus, sleep, which has been shown to increase heat loss by sweating (18,33), could be expected to show a greater effect in the evening than in the morning. The circadian variation of the sleep-evoked effect remains to be tested under controlled conditions, such as the constant routine procedure used here.

Sleep and the circadian temperature rhythm

Time of day mean temperatures showed 24-hour and 12-hour rhythms, which differed significantly between conditions. In particular, the 24-hour rhythm showed significant differences in the parameter estimates for both mean and amplitude. The 0.1°C sleep-evoked decrease in the mean was relatively small, but the increase in amplitude of 0.27°C represented a larger difference.

Because of its consistency and relative ease of measurement, the temperature rhythm is the most frequently used marker of the deep circadian oscillator. Many studies have found rhythms driven by the deep oscillator to show between-group differences in either amplitude or phase (38). Yet to date, most measures of the temperature rhythm have relied on data collected in the normal environment, where measurements would include the combined effects of several masking influences that could alter the rhythm parameter estimates. One example of how masking effects can obscure the true result is given in a study by Mills et al. (24), who compared a constant routine measure of subjects' adaptation to an abrupt time shift (such as would result from an intercontinental flight) with another measure based on rhythms recorded during everyday activity. They found that measures taken in the everyday environment overestimated the degree of adaptation, sometimes considerably.

The study also found a significant 12-hour temperature rhythm component with similar amplitude in each condition, so that it contributed substantially to the waveform in the wakeful constant routine. From the temperature curve, it appears that this was due to a midafternoon dip, the existence of which has been

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recognized for some time (e.g. 39). Carskadon et al. (40) concluded that a midafternoon decline in temperature and alertness occurred independently of whether meals were eaten, which is consistent with the present results. These findings give good reason to recommend that future studies use a Fourier regression, including both the 24-hour and 12-hour terms, rather than the simpler 24-hour cosine curve fitting.

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