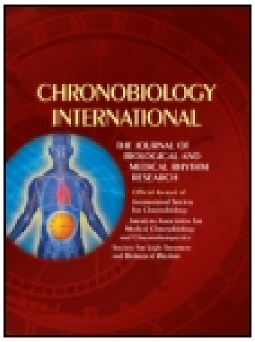

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Rapid Decline in Body Temperature Before Sleep: Fluffing the Physiological Pillow?

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Summary: A novel approach to the analysis of body core temperature was employed in an effort to further clarify the temporal relationship between the nightly decline in body temperature and the timing of the onset of nocturnal sleep. Core body temperature and EEG sleep recordings were obtained from 10 healthy elderly subjects while they lived in the laboratory and self-selected bedtimes and wake-up times. A rate-of-change curve was then generated for each temperature data set, showing the relative magnitude by which body core temperature declined (or increased) from minute to minute across the recording period. The time at which the maximum rate of decline (MROD) occurred was determined, and this time was compared with subjects' self-selected bedtimes and with subsequent EEG-defined sleep onsets. Eight of the 10 subjects' body temperature curves showed a maximum rate of decline well before (mean 41 min) the decision was made to retire. There was a significant positive correlation between the amount of wakefulness within the first hour after initial sleep onset and MROD relative to both bedtime and sleep onset ($r_s = 0.70$; $p < 0.04$). That is, the closer MROD occurred to either bedtime or sleep onset, the less wakefulness there was within the first hour after sleep onset. The findings indicate that the process of sleep initiation is most likely to occur when body temperature is declining at its maximum rate and is most successfully accomplished at this phase of the temperature cycle. **Key Words:** Body temperature—Sleep EEG—Circadian rhythms—Aging.

The temporal relationship between the timing of sleep onset and the circadian rhythm of body core temperature is well established. Under the entrained conditions of normal daily life, major nocturnal sleep is typically initiated 5–6 hours before the temperature minimum and is terminated shortly after the minimum. When subjects are studied in environments free of time cues, this relationship is altered somewhat, such that the onsets of major sleep episodes tend to occur in

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closer proximity to the trough of body temperature. In both conditions, however, sleep is initiated on the declining portion of the temperature curve (1,2).

This relationship has been the focus of investigation and debate for almost 200 years (3), with the central issue concerning the impact of sleep onset on body temperature measures. In 1898, for example, Pembrey and Nicol reported that sleep, as well as rest, contributed to the nightly drop in body temperature (4). In contrast, Piéron found that neither sleep onset nor sleep termination had an influence on body temperature as long as subjects remained lying quietly in bed (5). In a more systematic study, Kleitman and Doktorsky (6) also reported that the muscular relaxation associated with assuming a horizontal position induced a decrease in body temperature, but that the onset of sleep itself may or may not result in a further decline in temperature "depending on the time of day and probably on the degree of muscular relaxation attained in the waking state" (3).

Considerably less attention has been given to the examination of the alternative hypothesis—that temporal changes in body core temperature may have an impact on the initiation of sleep. One reason for the paucity of research in this regard is methodological. In the large majority of laboratory protocols, subjects are not permitted to initiate sleep spontaneously. Instead, bedtimes are defined by the experimental procedure. As a result, the natural temporal relationships between an individual's spontaneous decision to retire and the corresponding course of body core temperature cannot be adequately assessed. Moreover, the smoothing techniques frequently employed to evaluate circadian temperature data (e.g., cosine and other curve-fitting procedures) essentially filter out the more rapid fluctuations and can mask the very characteristics of the data that may prove to be most salient.

Despite the lack of studies to specifically examine the issue, there is suggestive evidence that changes in the course of body core temperature may influence the tendency to initiate sleep. It has been shown, for example, that the hypnotic effects of exogenous melatonin are accompanied by an abrupt decline in body core temperature, and it has been suggested that the putative somnogenic properties of melatonin may be a consequence of such thermoregulatory changes (7). In this report, we employ a novel approach to the analysis of body core temperature in an effort to further clarify the temporal relationship between the nightly decline in body temperature and the timing of the onset of nocturnal sleep. Specifically, we examined the relationship between nightly declines in body temperature and subjective decisions to retire in a group of older subjects.

METHODS

Subjects

This report is based on data from a subset of subjects (n = 10; six women, four men; mean age 69.1 years) undergoing a nondrug treatment for sleep maintenance insomnia (8). All subjects were in good general health, as determined by physical exams before enrollment. Informed consent was obtained from all subjects, and they were paid for their participation.

Procedure

After two consecutive nights of adaptation sleep in the laboratory (after which they were free to leave the lab and continue their normal daily activities), subjects reported back to the laboratory between 2000 h and 2100 h on night 3 to begin a 48-hour stay, encompassing two nighttime sleep recordings and the following 2 days. Within 30 min of their arrival at the lab, subjects inserted indwelling rectal thermistors (Yellow Springs series 4400) attached to ambulatory temperature recording devices. Body core temperature was recorded continuously, in 1-min epochs, throughout the subjects' stay in the lab, except for brief periods for personal hygiene.

On each evening, electrode placement for polysomnography was completed by 2200 h, after which subjects retired to private bedrooms to watch television, read, or engage in other leisure activities until bedtime. While in their bedrooms, subjects were monitored continuously by closed-circuit TV to ensure that they did not sleep before actual bedtime. All bedtimes and wake-up times were self-selected.

For the current analyses, 18-h temperature data sets were generated for each subject, which comprised the interval from 8 h before sleep onset on night 4 to 10 h after sleep onset. Each temperature curve was smoothed using a ninth-order polynomial curve fit, and a rate-of-change curve (degrees/minute) was then generated for each data set, showing the relative magnitude by which body core temperature declined (or increased) from minute to minute. Polynomial regression was chosen for the curve fits because such a procedure does not involve restrictive assumptions about the nature of the data, and because polynomial regression reliably accounts for more of the variance in a given data set (9). A sample temperature plot, with the corresponding rate-of-change curve, is shown in Fig. 1.

Following this procedure, the time at which the maximum rate of decline occurred was calculated, and this time was then compared with subjects' self-selected bedtimes and with subsequent EEG-defined sleep onsets (i.e., the first

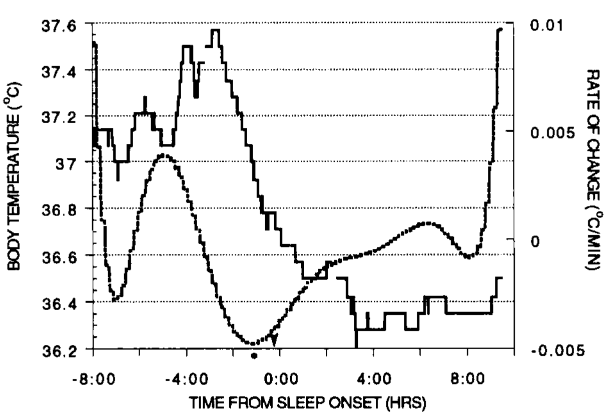

FIG. 1. Sample temperature plot beginning 8 h before sleep onset (0:00) on night 4 and continuing until 10 h after sleep onset. Arrow on horizontal axis designates subject's self-selected bedtime, and black dot below axis indicates point of maximum rate of decline (MROD). Dotted line shows rate of change of temperature (degrees per minute) across the 18-h recording interval, derived from the smoothed (ninth-order polynomial) curve.

epoch of stage 2). In addition, a series of correlation coefficients was generated to examine relationships between the maximum rate of temperature change and other sleep variables and subject characteristics.

RESULTS

Average self-selected bedtime for the group was 2329 h (SD = 46.8 min; median = 2332 h), and average latency to sleep (defined by the first 30-s epoch of stage 2 EEG) was 22 min (SD = 16.8 min; median = 14.3 min). Mean spontaneous final wake-up time was 0720 h (SD = 55.8 min; median = 0727 h).

Figure 2 shows the relationship between the time of maximum rate of decline (MROD) in body core temperature and self-selected bedtime and sleep onset times for each subject. Maximum rate of decline in temperature occurred *before* the decision to retire in eight of the 10 subjects. In only two subjects was this relationship reversed. For the group, MROD occurred on average 40.9 min before bedtime (SD = 103.9 min; median = 40.2 min) and 62.9 min before actual sleep onset (SD = 102 min; median = 60 min). The earliest MROD occurred 217 min before the decision to retire, and the latest occurred 89 min after bedtime. When only the data from those subjects who showed MRODs before bedtime were considered (n = 8), maximum temperature decline occurred 76.5 min before self-selected bedtime (SD = 81.6; range 217–0.3 min) and 95.9 min before sleep onset (SD = 82.8; range 224–10.2).

The timing of the maximum rate of decline in temperature relative to bedtime, or sleep onset time, was not significantly related to any global measure of sleep. There was, however, a significant positive correlation between the amount of wakefulness within the first hour after initial sleep onset and MROD relative to both bedtime and sleep onset (r_s = 0.70; $p < 0.04$). That is, the closer MROD occurred to either bedtime or sleep onset, the less wakefulness there was within the first hour after sleep onset.

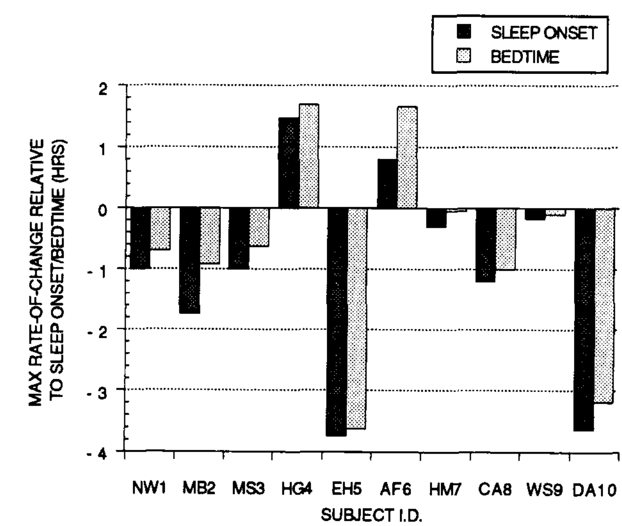

FIG. 2. Relationship between the time of maximum rate of decline in body core temperature (MROD) and self-selected bedtimes (light bars) and sleep onset times (dark bars) for each subject. MROD occurred *before* the decision to retire in eight of the 10 subjects. For the group, MROD occurred 40.9 min before bedtime and 62.9 min before actual sleep onset.

DISCUSSION

Before food consumption, virtually all mammals carry out a series of stereotypic movements and other behaviors that herald the onset of the feeding period. Such *appetitive behaviors* are often species specific and have been shown to be accompanied by significant changes in a number of physiological variables. Blood flow to certain brain sites increases, and saliva production is enhanced; gastric acids are secreted, and blood glucose levels show transient drops. These appetitive behaviors and their physiological correlates can precede actual food consumption by as much as 15–20 min.

In a similar way, virtually all animals, including humans, exhibit appetitive behaviors before initiating sleep (10,11). Grooming, preening, stretching, yawning, searching, stereotypic circling, assumption of a species-specific sleep posture, and in a number of species, nest building, are all patterned behaviors that may typically precede sleep onset. It is tempting to speculate that the steep decline in temperature before sleep observed in the current study is one physiological correlate of such appetitive behaviors in humans—a sort of fluffing of the physiological pillow. While it appears that no studies have examined this issue specifically, Moruzzi (12,13) has postulated that appetitive behaviors preceding sleep are likely to be accompanied by physiological and neurochemical changes that provide a "situation which will permit, or facilitate, the onset of sleep."

In the current experimental setting, subjects chose their own times of retiring. We assume that the choice of bedtime under these conditions accurately reflected subjective sleepiness. This assumption is supported by the finding that average sleep onset latency for this older sample was only ~20 min. The finding that eight of 10 subjects' body temperature curves showed a maximum rate of decline well before the decision was made to retire agrees with the hypothesis that nighttime sleep propensity is triggered by a steep decline in body core temperature. Moreover, the finding of a significant relationship between the proximity of MROD to bedtime (and sleep onset) and the amount of wakefulness within the first hour of sleep indicates that the process of sleep initiation not only is most likely to occur when body temperature is declining at its maximum rate it is most successfully accomplished at this phase of the temperature cycle as well.

Although the current study is apparently the first to establish the relationship between "successful" sleep initiation and maximum rate of temperature decline, several previous studies, in which the time course of body temperature before sleep was experimentally altered, indirectly support our findings. For example, when the usual nighttime drop in body temperature was arrested by bright light exposure (14,15) or by ingestion of capsaicin (16), sleep onset latency was delayed. Conversely, exogenous melatonin administration has been reported to be associated with subjective sleepiness and lowered sleep latency (17,18), and it has been shown that such administration is accompanied by transient declines in body temperature (7). As with our results, such findings strongly suggest intimate links among the rate of decline in body temperature, the decision to go to bed, and the capacity to initiate sleep. As more sophisticated analytical techniques are applied to body temperature data, perhaps a clearer picture will emerge regarding the causal nature of this relationship.

In conclusion, a couple of limitations of the current study should be noted. First, our subjects were older individuals, with sleep maintenance insomnia. Inasmuch as older individuals often exhibit alterations in the circadian course of body core temperature, in terms of both phase and amplitude, the generalizability of our results may be limited and should be replicated in a younger subject sample. Second, although electrodes were attached well in advance of bedtime, it is quite possible that electrode placement was accompanied by a general feeling of physical and mental relaxation, associated with the sense of approaching bedtime. The possibility that the wire-up procedure, per se, resulted in both a rapid decline in body temperature and a subsequent decision to retire cannot be ruled out.

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