Sleep
9(2):353–364, Raven Press, New York

Circadian Regulation Dominates Homeostatic Control of Sleep Length and Prior Wake Length in Humans

*Steven H. Strogatz, *Richard E. Kronauer, and †Charles A. Czeisler

**Division of Applied Sciences, Harvard University, Cambridge; and †Neuroendocrinology Laboratory, Department of Medicine, Harvard Medical School, Brigham and Women's Hospital, Boston, Massachusetts, U.S.A.*

Summary: During prolonged temporal isolation in caves or windowless rooms, human subjects often develop complicated sleep-wake patterns. Seeking lawful structure in these patterns, we have reanalyzed the spontaneous timing of 359 sleep-wake cycles recorded from 15 internally desynchronized human subjects. The observed sleep-wake patterns obey a simple rule: The phase of the circadian temperature rhythm at bedtime determines the lengths of both prior wake (α) and subsequent sleep (ρ). From this rule we derive an average α:ρ relationship that depends on circadian phase. The relationship reconciles the established negative α:ρ correlation observed in synchronized subjects with the positive α:ρ correlation found in desynchronized subjects. Our most surprising result concerns the residual deviations of α and ρ from their circadian phase-adjusted mean values. We report that there is no significant positive correlation between the residuals of α and ρ, contrary to the prediction of restorative models of sleep duration. Our findings illuminate the mechanisms underlying sleep regulation and provide much-needed tests of mathematical models of the sleep-wake cycle. **Key Words:** Circadian—Sleep-wake—Serial correlation—Mathematical model—Humans.

To better understand how human sleep is regulated, many researchers have studied the sleep-wake behavior of subjects living for weeks in unscheduled, time-free environments (1–9). These experiments have taken place in underground caves (6–8), bunkers (1,2,5), or soundproofed, windowless apartments (3,9). A common finding is that subjects frequently go to bed near the minimum of their circadian temperature cycle. The sleep-wake and temperature rhythms then remain synchronized at a period near 25 h. Aschoff (1) reported the striking phenomenon of spontaneous internal desynchronization, in which subjects unintentionally but repeatedly stay up past the temperature minimum, leading to average sleep-wake cycle lengths of 30–40 h. Sleep then occurs at unusual phases in the circadian temperature cycle, with concomitant changes in its internal organization (4).

Many mathematical models of the human sleep-wake cycle (10–13) have been proposed recently. Nearly all manage to simulate the qualitative aspects of internal de-

Accepted for publication January 1986.
Address correspondence and reprint requests to Dr. S. H. Strogatz at Division of Applied Sciences, Harvard University, Cambridge, MA 02138, U.S.A.

synchrony, but they have been difficult to assess rigorously. The problem has been that there are few solid empirical rules against which to test the proposed models (14,15). The motivation for our study was to find rules governing the duration and timing of unscheduled sleep and wake.

Several authors have studied the lengths of the self-selected sleep episodes observed during free-run. For internally synchronized subjects, sleep length (ρ) was found to be negatively correlated ($r = -0.53 \pm 0.22$) to length of prior wakefulness (α) (2,16,17). This finding is important and surprising: On the basis of a simple restorative model, one would have expected the α:ρ serial correlation to be positive, with long sleeps needed for recovery from long wakes. The negative serial correlation emphasizes the circadian regulation of sleep length (2,16,17); wake-up tends to occur on the rising limb of the temperature cycle, so that lengthened wake is compensated by shortened sleep.

The relation between α and ρ becomes more complicated when the sleep-wake cycle desynchronizes from the ongoing circadian rhythm of body temperature. Some researchers (6) have characterized the observed variations in sleep length as "wild" and "random." More recently, a pattern has been detected (3–5). The length of a sleep episode depends on the phase of the body temperature rhythm at bedtime: Sleep episodes begun near low temperature are comparatively short, whereas those begun near high temperature are long. This is due to a circadian gating of spontaneous awakening. With regard to the dependence on prior wakefulness, we have reported (4) a positive serial correlation ($r = +0.41$) between α and ρ, in contrast to the negative correlation observed in synchronized subjects. However, it was claimed that prior wake length was less important than circadian phase as the "major determinant of the length of sleep in normal man" (4).

The purpose of this article is twofold. First, we set out to reconcile the opposite results obtained for internally synchronized versus desynchronized subjects: Why is the α:ρ correlation negative during synchrony and positive during desynchrony? We show here that a correlation coefficient is inadequate to capture the subtle structure of the α:ρ relationship during desynchrony. The main defect of the correlation coefficient is that it ignores circadian phase. By lumping episodes together independently of their timing in the circadian cycle, vital information is lost. We have taken circadian phase into account and thereby show that the desynchronized α:ρ relationship is fully compatible with, and indeed subsumes, the synchronized case. Thus, the apparent contradiction is resolved.

Our second aim is to tease apart the determinants of sleep length. As stated above, during internal desynchronization, the length of a sleep episode is strongly dependent on the circadian phase at bedtime (3–5). The question we address is whether there is an additional influence of prior wake length on sleep length, above and beyond that of circadian phase. For example, imagine that a subject falls asleep at the same phase in the temperature cycle on two different occasions, but that because of random variations, on one occasion he or she has been awake longer than on the other. Will the sleep episode following the protracted wake be longer than that following the shorter wake? Our unexpected finding, which is a final blow to a simple restorative model of sleep duration, is that after adjustment for circadian phase has been carried out in this manner, the residuals of α and ρ show no significant positive correlation. Thus, during internally desynchronized free-run, spontaneous sleep length is a sum of a circadian component plus a random component, which is essentially independent of the length of prior wakefulness.

METHODS

Subjects

We have reanalyzed sleep-wake and temperature data from long-term studies carried out by research groups in France, the United Kingdom, the United States, and West Germany (Table 1). We included the available published instances of spontaneous internal desynchronization in which a lengthening of the sleep-wake cycle occurred. We excluded those records in which we had reason to doubt the accuracy of the reported sleep episodes [e.g., subject DL, ref. (8), had subjectively reported bedrest episodes of >35 h, which we assume are due to a failure to report some spontaneous awakenings]. The human subjects considered here were isolated from time cues for a combined total of >2 years. During that time 359 sleep episodes were recorded during spontaneous internal desynchronization in 15 subjects.

Normalization of sleep-wake records

We replotted each record in a standard cycle of length equal to the period of the educed temperature rhythm (3). Phases in the cycle are numbered from 0 to 25 "circadian hours," with phase 0 = 25. Zero phase corresponds to mid-trough of the averaged temperature waveform (Fig. 1). When temperature data were unavailable, periods and phases were derived from sleep data alone, as described elsewhere (3). The point of these conventions is that they normalize sleep-wake records on the basis of the circadian cycle (the physiologically important periodicity) instead of the usual 24 h (irrelevant during free-run).

Data analysis

For each sleep-wake cycle in each record, we calculated the circadian phase of sleep onset (ϕ), the length of the subsequent sleep episode (ρ), the length of the prior wake episode (α), and the wake-sleep cycle length. We pooled these data across subjects and

TABLE 1. *Published records of internally desynchronized human subjects*

Source reference[a]	Subject code	Age/sex	Free-run study length (days)	Desynchronized sleep episodes
(2):54	HN	27/M	18	7
(3):14	FR03	25/M	10	8
(8):4	G6	19/M	12	8
(3):14	FR04	22/M	12	9
(25):5	N/A	N/A	17	11
(3):14	FR10	51/M	19	12
(2):27	EvS	24/F	32	15
(26):4	F	N/A	17	16
(1):7	N/A	N/A	21	17
(2):36	KD	26/M	44	17
(27)	426F	23/M	28	18
(4):1	PR01	23/M	78	40
(6):10	MS	33/M	177	40
(7):2	JC	23/M	135	58
(28):2	LD03	24/M	179	83
Total			799	359

[a] Column identifies the source of the data: For example, (2):36 indicates reference (2), Fig. 36. N/A, unavailable information.

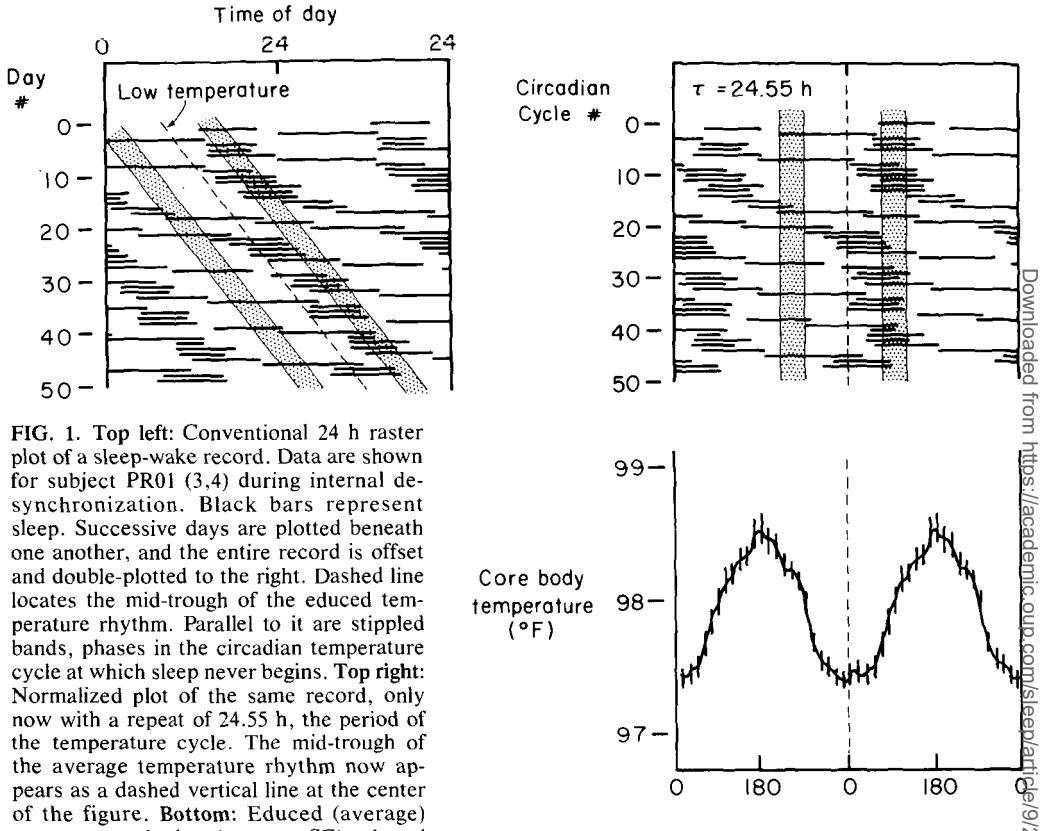

FIG. 1. **Top left:** Conventional 24 h raster plot of a sleep-wake record. Data are shown for subject PR01 (3,4) during internal desynchronization. Black bars represent sleep. Successive days are plotted beneath one another, and the entire record is offset and double-plotted to the right. Dashed line locates the mid-trough of the educed temperature rhythm. Parallel to it are stippled bands, phases in the circadian temperature cycle at which sleep never begins. **Top right:** Normalized plot of the same record, only now with a repeat of 24.55 h, the period of the temperature cycle. The mid-trough of the average temperature rhythm now appears as a dashed vertical line at the center of the figure. **Bottom:** Educed (average) temperature rhythm (mean ± SE), plotted in a cycle of 360°. In the text of this article the circadian cycle is divided into 25 circadian h instead of 360°. Mid-low temperature occurs at phase 0.

then used computer graphics to search for relationships among the various sleep-wake parameters.

To determine whether there was a relationship between ρ and α after correcting for any effects of circadian phase, we calculated residual deviations of both from their circadian phase–adjusted mean values. The relationship between these residuals was analyzed by computing their cross-correlation coefficient and by plotting their bivariate distribution.

RESULTS

Durations vary with circadian phase of sleep onset

Our data confirm and extend the previous reports (3–5) of a relationship between sleep length and circadian phase of sleep onset (Fig. 2a). Sleep length descends from ~18 h to 7 h along a ramp-shaped curve, then jumps to 18 h at a phase ~8–9 h after mid-low temperature. Near this phase, sleep length is bimodal.

We have used the method of least squares to fit a quadratic function, denoted $\hat{\rho}(\phi)$, to the raw data. This fitted curve may be regarded as an estimate of the average sleep length obtained at each circadian phase of sleep onset.

The phase of sleep onset also predicts the length of the prior wake episode (Fig. 2b). In this case, the fitted quadratic function is denoted $\hat{\alpha}(\phi)$, the average prior wake length at each phase of sleep onset. Prior wake length increases with phase of sleep onset, whereas sleep length decreases (Fig. 2a). Thus, $\hat{\rho}(\phi)$ and $\hat{\alpha}(\phi)$ vary inversely as functions of circadian phase. The longest and shortest wakes (Fig. 2b) overlap near phases 18–23, a reminder that there is also a phase where sleep length is bimodal (Fig. 2a). Curiously, where one curve is bimodal the other is smooth. The jumps in both sets of data reflect the fact that almost no wake-ups occur on the falling part of the temperature cycle, $\phi = 18$ to $\phi = 0$ (14,18).

The phase of sleep onset determines the lengths of *both* parts of the sleep-wake cycle and hence determines their sum: the combined sleep-wake cycle length (Fig. 2c). The

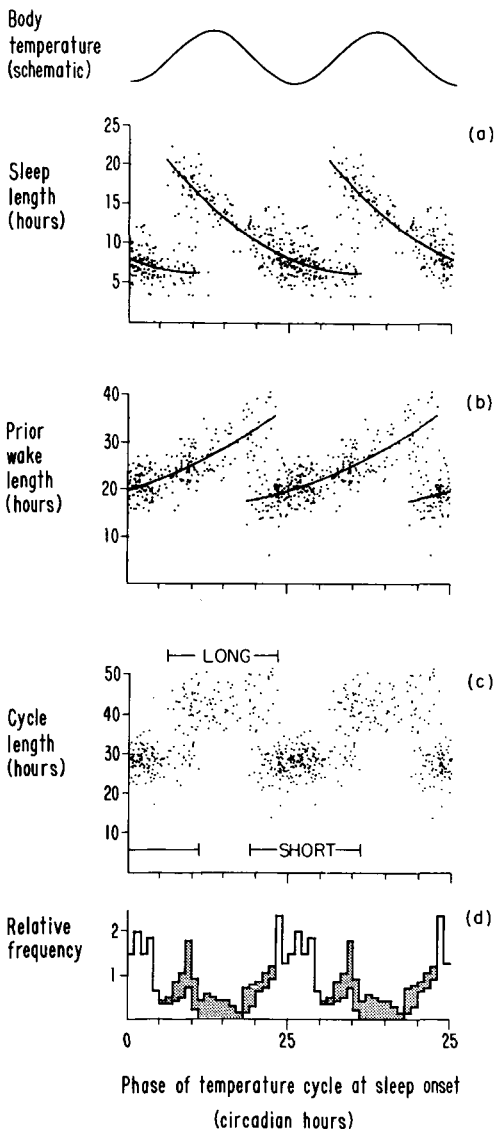

FIG. 2. (a): Circadian phase ϕ of sleep onset predicts subsequent sleep length ρ. Data are double-plotted to emphasize their periodicity. Method of least squares was used to fit a quadratic function $\hat{\rho}(\phi)$ to the data. Circadian temperature cycle is divided into 25 circadian hours, with phase 0 at the mid-trough of the temperature rhythm. (b): Circadian phase of sleep onset predicts prior wake length α. Fitted quadratic function is denoted $\hat{\alpha}(\phi)$. Conventions and curve-fitting as in (a). (c): Circadian phase of sleep onset predicts sleep-wake cycle length τ. Cycle length is defined as sleep length plus prior wake length. Square wave consists of overlapping plateaus called SHORT and LONG. (d): Histogram showing the number of bedtimes selected at different circadian phases. Vertical scale has been normalized so that a value of 1 corresponds to the average frequency across all phases. Overall distribution is partitioned into contributions from LONG (shaded) and SHORT.

square wave shape is remarkable. Its plateaus emphasize the constancy of cycle length observed in each of two regimes (denoted LONG and SHORT). The regimes are distinguished by circadian phase: Roughly speaking, SHORT or LONG correspond to bedtimes when temperature is low or high, respectively. The total distribution of sleep onsets is bimodal (Fig. 2d), although in each regime separately it is unimodal.

α:ρ scatterplot and average dependence on circadian phase

Figure 2a and b demonstrates that sleep length and prior wake length each vary as functions of circadian phase. How do sleep and prior wake length co-vary? A scatterplot of the raw data of ρ versus α is shown in Fig. 3. The main impression is that the data are noisy. Others (15) have commented on the apparent lack of structure in such scatterplots of sleep length versus duration of prior waking. A few features are clear: The data segregate into two diagonally sloping clouds, in each of which α and ρ are negatively correlated. The two clouds correspond to the SHORT and LONG regimes noted earlier (Fig. 2c).

It is possible to clarify Fig. 3 by incorporating circadian phase information and by averaging out some of the scatter in the raw data. To this end, we use the fitted curves $\hat{\rho}(\phi)$ and $\hat{\alpha}(\phi)$ of Fig. 2a and b. The strategy is as follows: Rather than plotting the raw α:ρ data, we plot instead the average values $\hat{\alpha}(\phi)$ and $\hat{\rho}(\phi)$ as ϕ moves through the circadian cycle. The joint variation of $\hat{\alpha}$ and $\hat{\rho}$ is shown in Fig. 4.

The construction of Fig. 4 will now be discussed in detail. To follow the construction, it is helpful to understand that Fig. 4 is based on a repetitive sequence of steps: (a) Select a circadian phase (ϕ) of sleep onset. (b) Refer to Fig. 2a and determine the average sleep length $\hat{\rho}(\phi)$ at that circadian phase. (c) From Fig. 2b determine the average length of prior wakefulness $\hat{\alpha}(\phi)$. (d) Plot $\hat{\rho}$ versus $\hat{\alpha}$. (e) Return to step (a), and choose a new phase. Steps (a–e) are repeated until the entire circadian cycle has been covered.

For example, at $\phi = 0$ we see from Fig. 2a that $\hat{\rho}(0) = 8.1$ h and from Fig. 2b that $\hat{\alpha}(0) = 19.7$ h. Therefore, the curve in Fig. 4 must include the point $(\hat{\alpha},\hat{\rho}) = (19.7,8.1)$. At that point on the curve, the adjacent tick mark with the 0 attached shows that the relevant phase of bedtime is $\phi = 0$. Next we proceed to $\phi = 5$ h after low temperature. Again referring to Fig. 2a and b we find $\hat{\rho}(5) = 6.8$ and $\hat{\alpha}(5) = 22.0$. Since sleep length has decreased and prior wake length has increased relative to their values at $\phi = 0$, the point (22.0,6.8) lies below and to the right of $[\hat{\alpha}(0),\hat{\rho}(0)]$, as indicated in Fig.

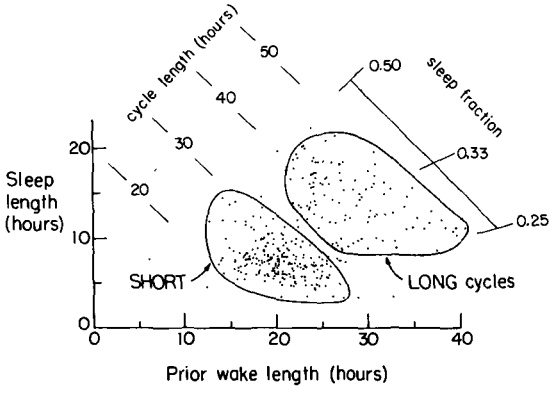

FIG. 3. Scatterplot of sleep length vs. length of the prior wake episode. Data segregate into two diagonal clouds corresponding to long and short wake-sleep cycles. Cycle length and sleep fraction vary widely within each cloud.

4. Continuing to $\phi = 10$, $\hat{\rho}$ has two values, one short ($\hat{\rho} = 6.3$) and one long ($\hat{\rho} = 16.9$). This double-valuedness at $\phi = 10$ arises from the bimodality in sleep length (Fig. 2a). Meanwhile, $\hat{\alpha}$ has the single value $\hat{\alpha}(10) = 25.0$. Thus, for $\phi = 10$ we plot *two* points, one at $(\hat{\alpha},\hat{\rho}) = (25.0,6.3)$ and one at $(\hat{\alpha},\hat{\rho}) = (25.0,16.9)$. At $\phi = 15$, both $\hat{\rho}$ and $\hat{\alpha}$ are single-valued again, but both are large: $\hat{\rho}(15) = 13.2$ and $\hat{\alpha}(15) = 28.6$, as seen from Fig. 2a and b. Therefore, $[\hat{\alpha}(15),\hat{\rho}(15)]$ lies on the LONG branch of the α:ρ average relationship. Proceeding in this way, we complete the shape of Fig. 4.

The shading along the curve indicates the number of sleep onsets that occur in each 1-h bin of circadian phase. The bin populations are divided into three equal groups, with black, grey, or white bins in order of decreasing population. As shown in Fig. 2d, the most likely phases of sleep onset are near $\phi = 0$ (mid-low temperature) and $\phi = 10$ h later. Therefore, the bins corresponding to those phases have been blackened in Fig. 4.

Figure 4 summarizes a great deal of information. Unlike Fig. 3, it includes circadian phase, as indicated by the numbered tick marks along the two branches of the curve. Figure 4 also shows how the density of sleep onsets varies with the phase of bedtime. Most importantly, it elucidates the α:ρ relationship during internal desynchronization —the average relationship is a two-branched curve. On each branch, α and ρ are negatively correlated. Moreover, the branches are distinguished by the circadian phase of sleep onset. Wake-sleep cycle length is approximately constant on each branch (averaging 28 h and 42 h, respectively), whereas daily sleep fraction varies considerably on each branch.

Figure 4 also enables us to reconcile the negative α:ρ correlation observed during internal synchronization (16,17) with the positive α:ρ correlation observed during desynchronization (4). First we explain how the α:ρ average relationship subsumes the results from internal synchrony. Synchronized subjects sample only the lower branch (SHORT) of Fig. 4, because they invariably fall asleep near the trough of the body temperature cycle (by definition of internal synchrony). Note that on the SHORT branch of the α:ρ relationship (Figs. 3 and 4), α and ρ are clearly correlated negatively. Indeed, if

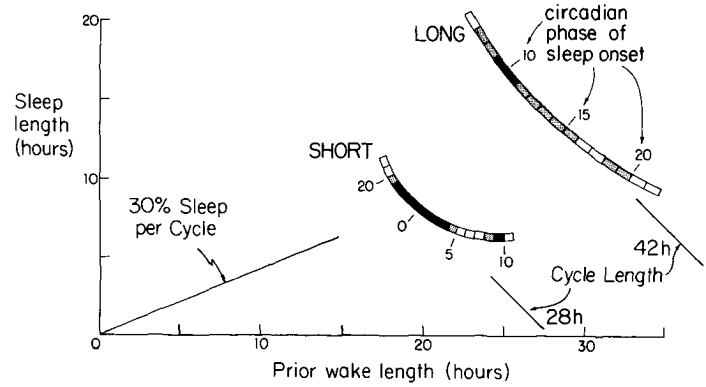

FIG. 4. Covariations of average sleep and prior wake length, conditioned on phase of sleep onset. Average curves in Fig. 2a and b are replotted here to reveal their joint variation. Circadian cycle is divided into 25 bins, each about 1 h wide; bin 0 begins at phase 0, the mid-trough of the temperature rhythm. Circadian phases of sleep onset are numbered along the curves. Phase bins have been divided into three equal groups and shaded in such a way that darker sections of the curve represent more frequently selected phases of bedtime. Cycle lengths of SHORT and LONG are about 28 h and 42 h, respectively. Daily sleep fraction averages about 0.3 but is highly variable. In both SHORT and LONG, sleep length and prior wake length vary inversely.

we calculate the α:ρ correlation for only the SHORT cloud in Fig. 3, we obtain $r = -0.47$, which agrees with the result $r = -0.53 \pm 0.22$ obtained for internally synchronized subjects (17). This finding suggests that synchronized and desynchronized subjects do not differ in their intrinsic α:ρ control mechanisms; they differ in that desynchronized subjects occasionally sample the LONG branch, whereas synchronized subjects never do.

Furthermore, Fig. 4 accounts for the positive α:ρ correlation observed in desynchronized subjects. These subjects most often sample the SHORT and LONG branches near $\phi = 0$ and $\phi = 10$, respectively. These are the blackened bins in Fig. 4. Note that these bins lie along a diagonal line of *positive* slope. Since they are most heavily populated, the dark bins dominate the correlation calculation, leading to a positive α:ρ correlation for desynchronized subjects. The value we obtain for the α:ρ correlation during desynchrony is $r = 0.34$, close to the value of $r = 0.41$ reported for a smaller sample (4).

Uncorrelated residuals of α and ρ

Thus far we have emphasized the circadian variation of sleep length and prior wake length. In particular, our construction of Fig. 4 depended on studying the average circadian components $\hat{\rho}(\phi)$ and $\hat{\alpha}(\phi)$ in Fig. 2a and b; we have neglected any discussion of the residuals of the observed data about those fitted curves. These residuals may contain interesting information.

By considering the residuals of α and ρ about their fitted curves, we may test a simple restorative model for the control of sleep duration. This model is motivated by a question about the scatter in Fig. 2a and b: at a fixed phase ϕ of sleep onset, why are some sleep episodes longer than others? Any circadian explanation is ruled out, because ϕ is being controlled for; that is, the phase of bedtime is the same for the sleep episodes in question. The restorative model tries to relate the differences in sleep length to differences in the length of prior wakefulness. It claims that, given two sleep episodes beginning at phase ϕ, the longer sleep episode will be that preceded by the longer wake episode.

In other words, after correcting for the dependence on circadian phase, any further lengthening of sleep might be due to an unusually long and tiring bout of prior wakefulness. This expectation would follow from a restorative model of sleep duration. To test it, we have calculated the deviations of sleep and wake length from the fitted curves of Fig. 2a and b. As shown in Fig. 5, we find no significant positive correlation between these deviations ($r = -0.10$), contrary to the prediction of the restorative model. Thus, circadian phase of sleep onset determines the average lengths of subsequent sleep and prior wake; above and beyond their phase-mediated relationship, these lengths are uncorrelated.

To avoid possible confusion, we emphasize that it is the *residuals* which are uncorrelated. More formally, the residuals $\Delta\rho$ and $\Delta\alpha$ are defined as follows:

$$\Delta\rho = \rho - \hat{\rho}(\phi)$$
$$\Delta\alpha = \alpha - \hat{\alpha}(\phi)$$

The novel aspect of our calculation is that we have corrected for the average circadian components $\hat{\alpha}(\phi)$ and $\hat{\rho}(\phi)$ of α and ρ, respectively. The more usual calculation (2,4,16,17) concerns the correlation of the raw data, α and ρ, *without* prior removal of

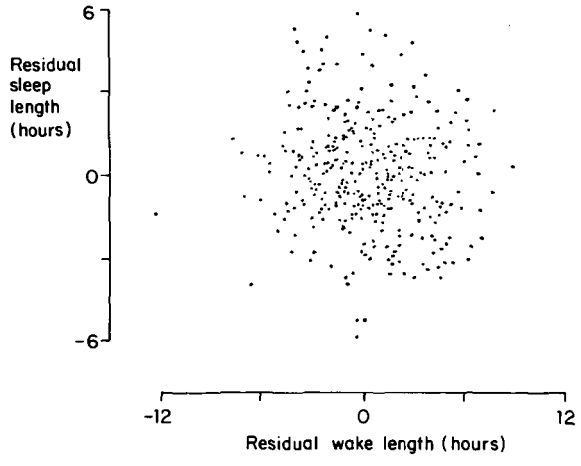

FIG. 5. Bivariate distribution of residuals of sleep length and prior wake length. Residuals are defined as deviations from the circadian phase-adjusted mean curves of Fig. 2a and b. Note that the axes are drawn to different scales to reflect the relative proportions of sleep and wake in the sleep-wake cycle.

the circadian components. Our calculation shows that the positive α:ρ correlation observed for desynchronized subjects is due to the circadian variations $\hat{\alpha}(\phi)$ and $\hat{\rho}(\phi)$; when adjustment is made for these circadian variations, the residuals $\Delta\alpha$ and $\Delta\rho$ are not significantly correlated. This lack of correlation is a damaging blow to the restorative model discussed above.

DISCUSSION

Testing mathematical models against empirical rules

The curves of Figs. 2 and 4 provide discriminating criteria for testing mathematical models (10–13) of the sleep-wake cycle. To begin with, any candidate model must be able to simulate the spontaneous desynchronization of the sleep-wake rhythm from the circadian temperature rhythm. Next, the model must generate synthetic sleep-wake data which, when analyzed as above, reproduce the shapes of the curves in Figs. 2 and 4. Beyond passing these qualitative tests, a successful model should account—in quantitative detail—for the relations among sleep length, prior wake length, probability of sleep onset, and circadian phase (Figs. 2 and 4).

Other studies have provided data relevant to the testing of mathematical models. The dependence of sleep length on the circadian phase of bedtime (Fig. 2a) has been reported by others (3–5), although they considered fewer sleep episodes (206 vs. 359 reported here). These sleep duration data have become a benchmark for the testing of models (10–13), first, because the ρ:ϕ relationship is so clear, and second, because few alternative tests have been available.

To the best of our knowledge, Fig. 2b depicts a new relationship. The quantitative relation between wake length and the phase of the subsequent sleep onset is somewhat odd, since it is backwards in time; circadian phase of bedtime *retrodicts* the length of the prior wake episode. Others have sought a predictive relationship, e.g., wake length versus phase of wake-up (14,19,20), with varying success. The main problem with using phase of wake-up as the independent variable is that it omits several hours of the circadian cycle—very few awakenings occur in the quarter-cycle before the tempera-

ture minimum (14,18). All of the figures in this paper would look far less structured if plotted relative to circadian phase of wake-up instead of phase of bedtime.

The square-wave plot of Fig. 2c is also new. Zulley (19,20) has found (independently) a clustering of wake-sleep cycle lengths near 28 h and 44 h, although he did not present data demonstrating the dependence of cycle length on the circadian phase of bedtime.

α:ρ relationship

We have found that the average α:ρ relationship during internal desynchronization is a two-branched curve (Fig. 4) whose branches are distinguished by circadian phase. One each of these branches, α and ρ are negatively correlated. Our results unify and reconcile earlier work on α:ρ correlations for internally synchronized (2,16,17) and desynchronized (4) subjects. In particular, we have shown that the negative correlation on the SHORT branch agrees with previous results (2,17) for internally synchronized subjects, even though all the subjects considered here were desynchronized. This agreement suggests that synchronized and desynchronized subjects differ only in the timing of their sleep, but not in the regulation of its length.

Others have presented α:ρ scatterplots [e.g., refs. (3,21)] for free-running human subjects. What is new in our work is the recognition that the scatterplot is organized by a hidden variable, the circadian phase of bedtime.

Uncorrelated residuals of α and ρ

Our most surprising finding concerns the residual deviations of α and ρ from their circadian phase–adjusted mean values: The residuals show no significant positive cross-correlation. This result contradicts a restorative model for the control of sleep duration.

Animal studies have been conducted to address restorative models. Webb and Friedman (22) found no relationship between sleep and wake lengths in rats on a 12:12 light-dark schedule. On the other hand, Mistlberger et al. (23) studied suprachiasmatic nuclei (SCN)–lesioned rats free-running in constant dim light, thereby attenuating the circadian regulation of sleep and wake. They reported significant positive correlations between the lengths of successive sleep and wake episodes. In particular, sleep was claimed to be not only restorative but also "preparative"; very long sleeps were likely to be followed by very long wakes. Taken together, the studies suggest that circadian regulation normally dominates any homeostatic control of sleep duration. In rats, homeostasis is only revealed by SCN lesions; in intact humans, homeostatic influences on spontaneous sleep duration are weak or absent.

In assessing the theoretical consequences of our results, it is important to distinguish between two possible restorative models. The first and simplest asserts that the length of an unrestricted sleep episode increases with the length of prior wakefulness. This first model was refuted long ago by studies (16) of humans with internally synchronized, free-running circadian rhythms, in which a negative α:ρ correlation was observed. A second, more sophisticated restorative model claims that the negative α:ρ correlation merely reflects the dominance of circadian regulation; if the circadian influence could somehow be eliminated, then (according to this second model) the homeostatic control of sleep duration would become evident. As in the preceding paragraph, Mistlberger et al. (23) followed the strategy of experimentally eliminating circadian influences; and their results were consistent with this second restorative model. The present study introduces a test of the second model as applied to humans with free-

running rhythms. We used statistics rather than surgery to remove circadian influences on sleep duration. Our finding is that, above and beyond their circadian-mediated correlation, the residual lengths of sleep and prior wake are uncorrelated, in contradiction to the second restorative model. Homeostatic mechanisms serve mainly to regulate the amount of slow wave sleep (24) rather than the overall duration of sleep. We conclude that it is the circadian system, not the prior sleep-wake history, which is most important in governing the length of unrestricted wake and sleep in humans.

Acknowledgment: Research was supported by grants from NIGMS, Grants 5 R01-GM-30719-03, and NIA, 1 R01 AG0491201 and AFOSR 83-0309. We thank J. Finkelstein and E. Hoey for data preparation; the Cornell Institute of Chronobiology for providing access to body temperature and sleep-wake data records; S. Lawson, W. Minty, and A. Dionne for preparation of the figures; M. Rosado for typing the manuscript; E. Brown for statistical advice; and A. Borbély and F. Bieber for suggestions regarding the manuscript.

REFERENCES

1. Aschoff J. Circadian rhythms in man. *Science* 1965;148:1427–32.
2. Wever R. *The circadian system of man*. Berlin: Springer, 1979.
3. Czeisler CA. Human circadian physiology: internal organization of temperature, sleep-wake and neuroendocrine rhythms monitored in an environment free of time cues. [Thesis]. Stanford, California: Stanford University, 1978.
4. Czeisler CA, Weitzman ED, Moore-Ede MC, Zimmerman JC, Knauer RS. Human sleep: its duration and organization depend on its circadian phase. *Science* 1980;210:1264–7.
5. Zulley J, Wever R, Aschoff J. The dependence of onset and duration of sleep on the circadian rhythm of rectal temperature. *Pflugers Arch* 1981;391:314–8.
6. Siffre M. Six months alone in a cave. *Nat Geographic* 1975;147:426–35.
7. Jouvet M, Mouret J, Chouvet G, Siffre M. Toward a 48-hour day: experimental bicircadian rhythm in man. In: Schmidt F, Worden F, eds. *The neurosciences: third study program*. Cambridge, Massachusetts: Massachusetts Institute of Technology, 1974:491–7.
8. Mills JN, Minors DS, Waterhouse JM. The circadian rhythms of human subjects without timepieces or indication of the alternation of day and night. *J Physiol* 1974;240:567–94.
9. Webb WB, Agnew HW. Sleep and waking in a time-free environment. *Aerospace Med* 1974;45:617–22.
10. Moore-Ede MC, Czeisler CA, eds. *Mathematical models of the circadian sleep-wake cycle*. New York: Raven Press, 1984.
11. Kronauer RE, Czeisler CA, Pilato SF, Moore-Ede MC, Weitzman ED. Mathematical model of the human circadian system with two interacting oscillators. *Am J Physiol* 1982;242:R3–17.
12. Daan S, Beersma DGM, Borbély AA. Timing of human sleep: recovery process gated by a circadian pacemaker. *Am J Physiol* 1984;246:R161–78.
13. Kawato M, Fujita K, Suzuki R, Winfree AT. A three-oscillator model of the human circadian system controlling the core temperature rhythm and the sleep-wake cycle. *J Theor Biol* 1982;98:369–82.
14. Winfree AT. Impact of a circadian clock on the timing of human sleep. *Am J Physiol* 1983;245:R497–504.
15. Winfree AT. Circadian timing of sleepiness in man and woman. *Am J Physiol* 1982;243:R193–204.
16. Aschoff J, Gerecke U, Kureck A, et al. Interdependent parameters of circadian activity in birds and man. In: Menaker M, ed. *Biochronometry*. Washington, DC: National Academy of Sciences, 1971:3–27.
17. Wever RA. Properties of human sleep-wake cycles: parameters of internally synchronized free-running rhythms. *Sleep* 1984;7:27–51.
18. Strogatz SH, Kronauer RE. The rules of the human circadian sleep-wake cycle. In: Lin JC, Feinberg BN, eds. *Proceedings of the 7th annual conference of the IEEE Engineering in Medicine and Biology Society*. Chicago: IEEE, 1985:1051–6.
19. Zulley, J. Die circadiane steuerung des schlafes. In: Ferstl R, Rey ER, Vaitl D, eds. *Klinische psychologie. Psychophysiologische merk male klinischer symptome*. Band II, Depression und schizophrenie. Weinheim: Beltz Verlag, 1985:18–29.
20. Zulley J. Regularity in circadian sleep-wake cycles. *Sleep Res* 1983;12:377.
21. Siffre M. *Experiences hors du temps*. Paris: Fayard, 1972:304–5.
22. Webb WB, Friedman J. Length of sleep and length of waking interrelations in the rat. *J Psychonom Sci* 1969;17:14–5.
23. Mistlberger R, Bergmann B, Rechtschaffen A. Relationships between adjacent wake and sleep episodes and NREM delta in suprachiasmatic nuclei lesioned rats. *Sleep Res* 1984;13:21.
24. Borbély AA. A two process model of sleep regulation. *Hum Neurobiol* 1982;1:195–204.

25. Aschoff J. Desynchronization and resynchronization of human circadian rhythms. *Aerospace Med* 1969;40:844–9.
26. Aschoff J, Gerecke U, Wever R. Desynchronization of human circadian rhythms. *Jpn J Physiol* 1967;17:450–7.
27. Czeisler CA, Brown EN, Ronda JM, Kronauer RE, Richardson GS, Freitag WO. A clinical method to assess the endogenous circadian phase (ECP) of the deep circadian oscillator in man. *Sleep Res* 1985;14:295.
28. Kronauer RE. Modeling principles for human circadian rhythms. In: Moore-Ede MC, Czeisler CA, eds. *Mathematical models of the circadian sleep-wake cycle*. New York: Raven Press, 1984:105–28.